ANGELES LINK PHASE 1

HYDROGEN LEAKAGE ASSESSMENT

FINAL REPORT – DECEMBER 2024

SoCalGas commissioned this Hydrogen Leakage Assessment from Stantec Consulting Services Inc. The analysis was conducted, and this report was prepared, collaboratively.

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Acronyms and Abbreviations

CAPCOA	California Air Pollution Control Officers Association
CARB	California Air Resources Board
CEC	California Energy Commission
CFR	Code of Federal Regulations
CPUC	California Public Utilities Commission
DOC	Department of Commerce
DOE	Department of Energy
DOT	Department of Transportation
EF	Emission Factor
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FET	Field-Effect Transistor
LDAR	Leak Detection and Repair
LEL	Lower Explosive Limit
LF	Leak Factor
MEMS	Microelectromechanical System
MMTPY	Million metric tonnes per year
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
NPC	National Petroleum Council
NIST	National Institute of Standards and Technology

NREL	National Renewable Energy Lab
PEM	Proton-Exchange Membrane
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovation Technology Administration
SMR	Steam Methane Reforming
UC	University of California
UCI	University of California Irvine

1.0 EXECUTIVE SUMMARY

Southern California Gas Company (SoCalGas) is proposing to develop a clean renewable hydrogen[1] pipeline system to facilitate the transportation of clean renewable hydrogen from multiple regional third-party production sources and third-party storage sites to various delivery points and end users in Central and Southern California, including the Los Angeles Basin. The California Public Utilities Commission's (CPUC) Phase 1 Decision, approving the Memorandum Account for SoCalGas's proposed Angeles Link requires SoCalGas to assess the risks and mitigations associated with the potential for hydrogen leakage. The leakage assessment (Study) evaluates the potential for hydrogen leakage associated with new hydrogen infrastructure (i.e., clean renewable hydrogen transportation and compression, in addition to third-party production and third-party storage), as well as opportunities to minimize the potential for hydrogen leakage. While this Study explores the potential for leakage from production, compression, storage, and transportation, the Angeles Link proposal is focused on the transmission of clean renewable hydrogen, including compression and ancillary equipment.

The objective of this Study is to evaluate, through a literature review, a range of values for potential hydrogen leakage, as well as opportunities to minimize the potential for leakage. This range of values is presented as percentages for each component of new proposed infrastructure and as percentages for each minimization opportunity. This Study does not provide extensive evaluation of the potential for leakage at end users' equipment.

Key Findings

The key findings are presented below and are discussed further within this document.

- As described in the literature reviewed for this Study, potential sources of leakage include production equipment such as electrolyzers, compression equipment such as reciprocating and centrifugal compressors, storage equipment such as aboveground vessels and underground salt caverns, and transmission infrastructure such as pipelines.

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[1] In the California Public Utilities Commission (CPUC) Angeles Link Phase 1 Decision (D).22-12-055 (Phase 1 Decision), clean renewable hydrogen refers to hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuels in the hydrogen production process; where fossil fuels are defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.

- The magnitude of the potential for hydrogen leakage depends on the quantity and type of equipment used for production, compression, and storage, how the infrastructure is designed and engineered, whether the pipelines are above ground or below ground, the sizing and routing of the pipelines, and how the infrastructure is operated and maintained, among other factors.
- Leakage estimation methodologies include direct measurement such as leak detection sensors, as well as information published in the literature based on a variety of methodologies, including calculations via proxies such as natural gas, laboratory experiments, and theory-based models or simulations.
- Mitigations and opportunities to minimize the potential for leakage from various processes are available in the design and engineering of new infrastructure, operation of equipment and systems, as well as maintenance procedures. In addition to design and engineering, the use of existing and emerging sensor technologies supports early identification of leaks and facilitates timely repairs, thereby mitigating potential leaks.

Stakeholder Feedback

The input and feedback from stakeholders including the Planning Advisory Group (PAG) and Community Based Organization Stakeholder Group (CBOSG) has been essential to the development of this final Leakage Study Report. For example, in response to stakeholder comments, the Study includes a preliminary high-level volumetric estimate of the potential for leakage from hydrogen infrastructure. In addition, the Study includes a review of relevant literature provided by stakeholders, as applicable. The feedback that has been received related to this Study and how those comments have been addressed is summarized in Section 7.

2.0 STUDY APPROACH

The Study evaluates, through a review of existing technical literature, potential sources of hydrogen leakage and leakage mitigation for the production, compression, storage, and transmission of hydrogen associated with Angeles Link and third-party hydrogen infrastructure. Where applicable, the Study relies on specific technical information that is available including from other ongoing Phase 1 feasibility studies and other information primarily from existing technical literature. When specific information is not available, estimates based on availability of related data, such as correlations to natural gas, or documented assumptions, were developed. Figure 1 depicts the study approach for this Study.

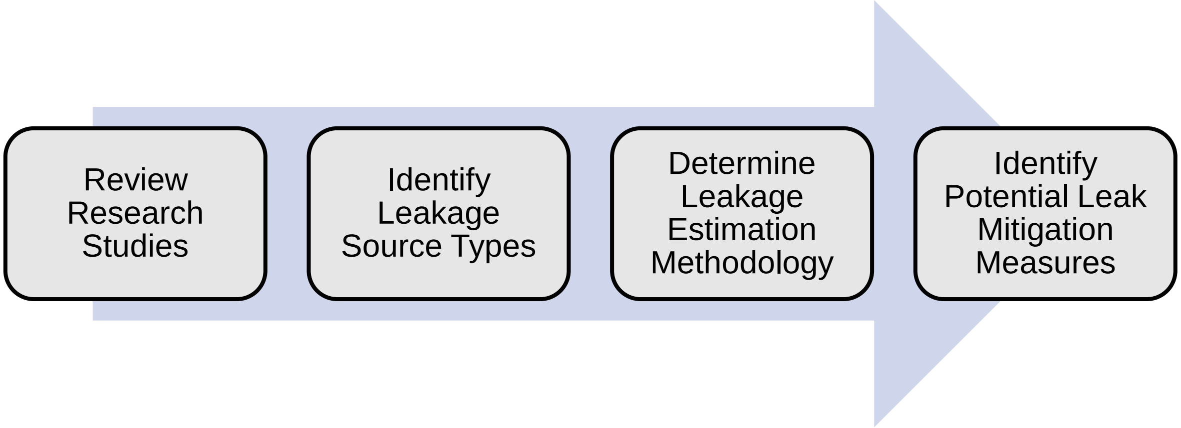

Figure 1: Hydrogen Leakage Study Approach

2.1 TECHNICAL RESEARCH

The Study collected, reviewed, and analyzed technical literature studies and information related to the potential for hydrogen leakage and opportunities to minimize and mitigate hydrogen leakage. The objectives of conducting the technical research were to obtain information to execute the four steps identified in Figure 1 and to develop an understanding of: (1) the availability of recent hydrogen leakage studies; (2) potential leak sources associated with Angeles Link infrastructure; (3) leak estimation methodologies and associated data needs; (4) potential leakage mitigation and minimization opportunities. This analysis included the following:

- Studies from research-based academic institutions such as the University of California Irvine (UCI) Combustion Laboratory, Georgia Institute of Technology, University of Wyoming, Imperial College London, Center on Global Energy Policy at Columbia University; and private organizations such as the Electric Power Research Institute (EPRI), National Petroleum Council (NPC), and Frazer-Nash Consultancy.

- Existing, proposed, and potential future regulatory requirements from federal agencies including the Environmental Protection Agency (EPA), the Pipeline and Hazardous Materials Safety Administration (PHMSA), the Department of Energy (DOE), state agencies such as the California Air Resources Board (CARB) and the California Energy Commission (CEC).
- Technological developments from manufacturers working on hydrogen monitoring technology including sensor development and opportunities to minimize the potential for leakage. Manufacturers include Aerodyne, Fukuda, and PDC Machines.
- Technical literature and data releases from public entities, non-profits, and government agencies and laboratories including the DOE and the National Renewable Energy Lab (NREL), the Environmental Defense Fund (EDF), Netherlands Environment Assessment Agency, and Joint Research Centre (JRC) of the European Commission.

The research began by investigating a broad range of publications that could be potentially related to the hydrogen leakage. As the Study progressed, research was targeted toward topics of the most value to the Study. Types of sources reviewed include, but were not limited to, peer-reviewed scientific papers, scientific and industry white papers, government workshops, regulations, standards, presentations, data releases, manufacturer press releases, news articles, books, blogs, technology reports, and other available sources.

Each reviewed source was evaluated, and the key takeaways were summarized to facilitate review of pertinent information from each source. The sources were then further categorized by topic: leakage calculation methodology, measurement technology, etc. The sources consulted were not limited to the United States. Relevant studies from the European Union and the United Kingdom (UK) were also consulted and included as references.

2.1.1 Technical Approach

The technical approach for this Study included identifying sources of potential leakage and opportunities to minimize leakage by reviewing literature published on these topics. Additionally, research was conducted regarding anticipated technological advancements and the expected evolution of regulatory frameworks, such as additional requirements related to measuring and minimizing hydrogen leakage.

Based on the information gathered, leakage estimation methodologies were evaluated. Specifically, two leakage estimation methodologies were identified: total value chain approach (top-down) and component-count level approach (bottom-up).

2.1.1.1 Total Value Chain Approach

The top-down total value chain methodology focuses on assessing mass balance at the system level and evaluating the proportion of product that can be allocated to various components of the system and determining the potential loss of product in the form of leakage. The total value chain approach provides general component (production, compression, aboveground and underground storage, and transmission through pipelines) leakage ranges that are summarized from the literature reviewed. Leakage rates are estimated as a percentage of total hydrogen in the respective supply chain component. The total value chain approach provides high-level estimates of potential for leakage based on general datasets.

2.1.1.2 Component-Count Level Approach

The bottom-up component-count level methodology focuses on unit level leakage rates and can be presented as an aggregation of total leakage from anticipated units. The component-count level methodology relies on project-specific and detailed equipment, process, and component counts. These details include: the type and number of production, compression, and storage equipment, as well as details about the piping, including number of valves, flanges, and connections. The component-count level methodology provides more accurate results and can be used for development of more precise leakage estimates.

For those industries with volatile organic compounds (VOC) emissions associated with leakage that regularly estimate and report VOC emissions, the EPA has developed numerous sets of emission factors and correlation equations for the various types of processes being considered. Historical data collection on emissions from equipment leaks in synthetic organic chemical manufacturing industry, refineries, marketing terminals, and oil and gas production operations have yielded emission factors and correlations for these source categories for natural gas and other hydrocarbon fuels. Since hydrogen does not contain VOC, these EPA methodologies are not applicable. Additionally, emission factors and correlations for hydrogen have not been developed at this time. However, preliminary work has been conducted comparing natural gas leaks with hydrogen leaks for different types of components[2] limited to low pressure systems only.

There are four bottom-up approaches for estimating leakage, in the order of increasing accuracy, that include using: 1) facility-level average emission factors; 2) equipment-level average emission factors; 3) component-level average emission factors; and 4)

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[2] Hormaza Mejia, Alejandra, Jacob Brouwer, Michael Mac Kinnon, 2020, *Hydrogen Leaks at the Same Rate as Natural Gas in Typical Low-Pressure Gas Infrastructure*, International Journal of Hydrogen Energy, Vol 45: 15, 8810-8826, https://www.sciencedirect.com/science/article/abs/pii/S0360319919347275?via%3Dihub

component-level measurement approaches.[3] The component-level measurement approach has the highest accuracy of the four methods; however, this approach requires measured hydrogen leakage rates, which are currently not available since design and engineering have not yet been developed for Angeles Link infrastructure. The methodology with the next level of accuracy uses the component-level average emission factors. This methodology is consistent with approaches outlined for hydrocarbons in EPA's 1995 Protocol for Equipment Leak Emission Estimates[4], and later enhanced by California Air Pollution Control Officers Association's (CAPCOA's) 1999 California Implementation Guidelines for Estimating Mass Emissions of Fugitive Hydrocarbon Leaks at Petroleum Facilities,[5] and South Coast Air Quality Management District's (South Coast AQMD) 2015 Guidelines for Reporting VOC Emissions from Component Leaks. However, correlation factors for hydrogen are also currently not available based on the research performed.

The component-count level approach can provide project-specific leakage estimates using the equipment and systems information. Under this approach, the following calculation method is used to determine the leakage rates. The leak factor (LF) is an average value determined from data collected during industry case studies. Units are in mass per time such as pounds per hour. The following equation is used to estimate leaks for each type of component separately (valves, flanges, connections, pressure safety valves, fittings, etc.).

$$LF = (\#\ of\ components) \times (leak\ rate\ per\ component) \qquad (equation\ 1)$$

Since the actual number of components, operating conditions, and equipment/facility specifics are not available at the time of this Study, the component-count level methodology could not be applied. Detailed engineering and design information regarding equipment types and component counts would support the development of leakage estimates once correlation factors and/or direct hydrogen measurement data becomes readily available.

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[3] American Petroleum Institute, 2009, Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Natural Gas Industry, August, available from CARB online at https://ww2.arb.ca.gov/sites/default/files/2020-04/API%20Compendium%202009.pdf

[4] EPA, 1995, Protocol for Equipment Leak Emission Estimates, Office of Air Quality, EPA-453/R-95-017 November 1995, https://www.epa.gov/sites/default/files/2020-09/documents/protocol_for_equipment_leak_emission_estimates.pdf

[5] CAPCOA and CARB, 1999, California Implementation Guidelines for Estimating Mass Emissions of Fugitive Hydrocarbon Leaks at Petroleum Facilities, February 1999, https://ww2.arb.ca.gov/sites/default/files/2020-04/CAPCOA%201999.pdf

2.1.2 Calculation Methodology

The Study identified the total value chain approach as the most appropriate for preparing high level preliminary estimates of the potential for leakage associated with Angeles Link, including the transmission of hydrogen, as well as third-party production and third-party storage. Detailed Angeles Link design and engineering information has not been developed and therefore was not available at the time of this Study. Without specific equipment details, pipeline lengths and pressures, and counts of valves and flanges, amongst other detailed design information, the high-level assumptions made for purposes of this Study may lead to a wide range of leakage estimates with relatively low confidence levels.

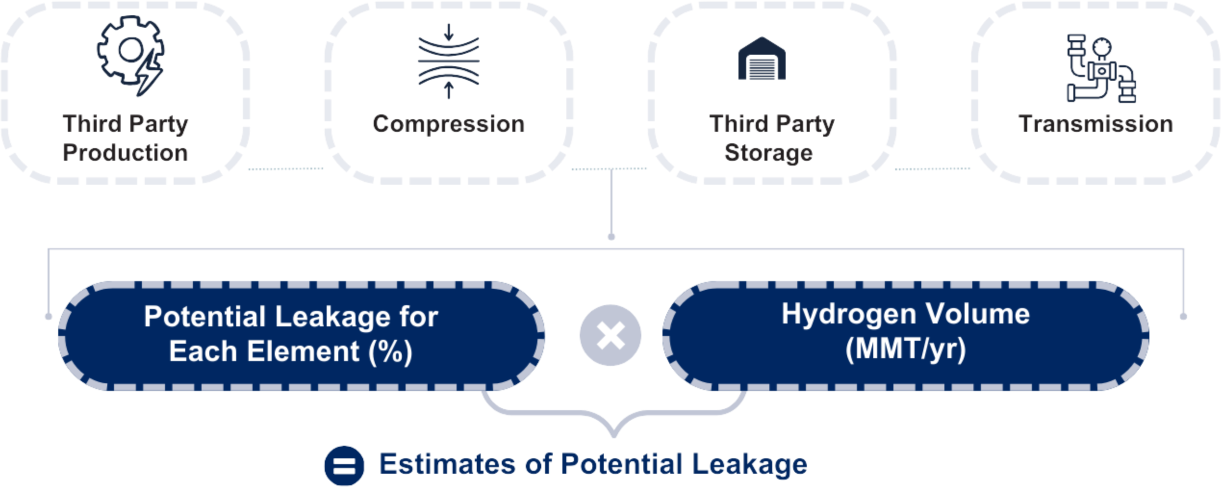

Figure 2: Top-Down Value Chain Leakage Calculation Approach

Figure 2 provides a graphic illustration of the top-down value chain estimation approach. The potential for leakage is provided in the literature as estimated percentages for each of the value chain components (i.e., production, compression, storage, and transmission). These percentages would need to be multiplied by the quantity of hydrogen passing through each value chain component to obtain the estimated leakage for hydrogen. The estimates reviewed in the literature were based on calculations via proxies such as natural gas, laboratory experiments, and theory-based models or simulations. At the time of this Study, project design and engineering of the proposed infrastructure had not been developed to the level of detail needed to prepare a meaningful estimate. This total value chain approach calculation methodology could be performed in the future once additional detail is available.

3.0 BACKGROUND INFORMATION

This section provides background information relating to the properties of hydrogen, leakage in the natural gas industry, the regulatory requirements relevant to the potential for leakage and mitigation of leakage, as well as information regarding types of equipment related to the anticipated Angeles Link infrastructure, as well as third-party production and third-party storage.

3.1 PROPERTIES OF HYDROGEN

The physical and chemical properties of hydrogen are relevant to its leakage potential. Physical properties such as weight and density can affect the amount of leakage and its dispersion characteristics. Chemical properties can affect how the gas interacts with its surrounding materials.

Hydrogen is a colorless, odorless, tasteless, flammable gas. A molecule of hydrogen in its common molecular form consists of two hydrogen atoms. It is the smallest existing molecule. Under ordinary ambient conditions, hydrogen is a gas. Common hydrogen has a molecular weight of about 2 grams per mole. As a gas, it has a density of 0.071 grams per liter at 0^oC and 1 atmosphere (atm). Its relative density, compared with that of air, is 0.0695. Hydrogen being lighter than air causes the gas to quickly flow upward if a release occurs. The viscosity, or resistance to flow, of hydrogen is lower than methane, which can contribute to the potential for higher leakage through orifices when compared to natural gas based on fluid dynamics theory. Experimental studies show that hydrogen may leak at the same rate or faster compared to methane and more research is needed to understand hydrogen leakage behavior under various conditions.[6] Hydrogen is slightly more soluble in organic solvents than in water. Many metals absorb hydrogen which is important for designing hydrogen gas enclosures.[7]

3.2 LEAKAGE IN NATURAL GAS INDUSTRY

There is the potential for natural gas leakage from natural gas infrastructure. Sources include compressor rod packing and pipeline connection points such as valves and fittings. Potential leaks may occur during normal operations or may result from improper equipment installation or equipment malfunction. Leaks may also occur during routine maintenance.

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[6] National Petroleum Council, 2024, “Harnessing Hydrogen: A Key Element of the U.S. Energy Future https://harnessinghydrogen.npc.org/downloads.php

[7] Jolly, W. Lee, 2023, Hydrogen, Encyclopedia Britannica, https://www.britannica.com/science/hydrogen/Production-and-applications-of-hydrogen

Leak Detection and Repair (LDAR) regulations typically provide a classification, or grade, for leak size, and outline a timeframe for repair. The EPA estimated in 2016 that 37% of natural gas supply chain leakage was attributable to production, 27% to gathering, 16% to transmission and storage, 13% to processing, and 7% to distribution.[8] The EPA estimates that the nationwide average leak rate is approximately 2% of natural gas produced whereas other studies estimate a weighted average of 2.95% across several basins and global regions.[9]

In California, CARB issued the Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities that became effective January 1, 2018. This regulation requires quarterly LDAR inspections among other requirements to minimize methane emissions to the atmosphere. The latest amendments, which include reduced leak repair times, were effective April 1, 2024. The most recent 2020 Annual LDAR Summary report by CARB, published November 2023, states that the average leakage rates within the regulated natural gas industry (natural gas production, storage, transmission, gathering and boosting, and processing) under this program ranged from 0.4% to 1.66% (number of leaks compared to unique components surveyed).[10] Valves and connectors were observed to contribute more than 70% of the components found to be leaking in 2020.

Senate Bill (SB) 1371 in California requires the implementation of best management practices to minimize methane emissions to the atmosphere. Compliance plans are prepared and annual reports of methane reductions are provided to CARB. With these requirements, measures have been evaluated and are being implemented that can potentially be adopted and applied for future hydrogen infrastructure projects.

3.3 REGULATORY REQUIREMENTS

Regulatory requirements may provide limits regarding allowable leakage associated with hydrogen infrastructure. A review of regulations was conducted to understand the potential drivers and requirements for potential mitigation measures to minimize leakage.

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[8] PBS NewsHour, 2018, The U.S. natural gas industry is leaking way more methane than previously thought, July 4, https://www.pbs.org/newshour/science/the-u-s-natural-gas-industry-is-leaking-way-more-methane-than-previously-thought

[9] National Petroleum Council, 2024, Ibid. (at Chapter 2, page 49)

[10] CARB, 2023, CARB's Oil and Gas Methane Regulation 2020 Annual LDAR Summary, https://ww2.arb.ca.gov/sites/default/files/2023-11/CARBOilandGasMethaneRegulation2020AnnualLDARSummary.pdf

The US Department of Transportation (DOT) has regulated the safety of hydrogen pipelines since 1970 via Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations, codified in Title 49 Code of Federal Regulations (CFR) Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards. PHMSA regulations cover pipeline design, construction, operation, maintenance, and spill response.[11]

In May 2023, PHMSA proposed LDAR regulatory amendments to implement congressional mandates in the Protecting Infrastructure of Pipelines and Enhancing Safety Act of 2020 to reduce emissions from new and existing gas transmission pipelines, distribution pipelines, and regulated (Types A, B, C and offshore) gas gathering pipelines.[12] This includes the approximately 1,600 miles of hydrogen pipelines in operation today and the proposed amendments apply to both natural gas and hydrogen pipelines. This recent LDAR proposal outlines grading and repair of leaks based on a classification, or grade, for leak size or specified percentages of the lower explosive limit (LEL), and outlines a timeframe for repair. An LEL for hydrogen gas is given as 4% gas by volume.[13]

PHMSA is participating with the DOT, Research and Innovation Technology Administration (RITA), the DOE, U.S. Department of Commerce (DOC), National Institute of Standards and Technology (NIST) and others towards establishing a National Hydrogen Energy Roadmap. The goal of this roadmap is to expedite the production, processing, delivery, storage, and use of clean hydrogen to help meet the federal goal of 100% carbon pollution-free electricity by 2035.[14]

Regulations can impact the potential for leakage via design requirements and mitigation measures. The inclusion of hydrogen pipelines within PHMSA's proposed LDAR regulation may increase the speed at which leaks are detected and repaired, and minimize the total volume of gas leaked, by requiring regular leak detection monitoring and by providing structured requirements around how quickly repairs are required.

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[11] Congressional Research Service, 2021, Pipeline Transportation of Hydrogen: Regulation, Research, and Policy, March 2, CRS Report R46700, https://crsreports.congress.gov/product/pdf/R/R46700

[12] Federal Register, 2023, *Pipeline Safety: Gas Pipeline Leak Detection and Repair*, 88 Fed. Reg. 31890, May 18, 2023, (amending 40 CFR 191, 192, 193)

[13] DOE, Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen Safety – H1 fact sheet series, https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheet.pdf

[14] U.S. State Department and Executive Office of the President, The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, November 2021, available at: https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

3.4 INFRASTRUCTURE COMPONENTS AND EQUIPMENT

Snapshot 1: Expected Components and Equipment for Hydrogen Infrastructure

Overview of Expected Components and Equipment for Hydrogen Infrastructure

Third-Party Production

- **Electrolysis:** A process that uses electricity to split water into hydrogen and oxygen, providing a clean source of hydrogen when powered by renewable energy.
- **Biomass Gasification:** Converts organic materials such as agricultural residues into hydrogen, carbon monoxide, and carbon dioxide through high-temperature processing in a controlled environment with limited oxygen.
- **Steam Methane Reforming (SMR):** A common method for producing hydrogen by reacting methane with steam over a catalyst to produce hydrogen and carbon dioxide.

Compression

- **Reciprocating Compressor:** Uses a piston within a cylinder to compress and transport hydrogen at high pressures, commonly used for small to medium-scale operations.
- **Centrifugal Compressor:** Employs a rotating disk or impeller to accelerate and then decelerate captured air or gas to pressurize and transport it, suitable for large-scale hydrogen movement.

Third-Party Storage

- **Aboveground Tanks/Vessels:** Storage units located above the earth’s surface for holding compressed or liquefied hydrogen, designed to handle various pressure levels.
- **Underground Storage:** Caverns or reservoirs used for large-scale underground storage of hydrogen

Transmission

- **Pipelines:** Specially designed conduits made from materials compatible with hydrogen to safely transport hydrogen gas from production sites to points of use, considering hydrogen’s specific properties like its small molecular size and reactivity.

Third-Party Production

Clean Renewable Hydrogen Production Methods

Three primary methods for generating clean renewable hydrogen were evaluated:

- **Electrolysis:** This process employs electricity to dissociate water into hydrogen and oxygen, with the electrical power sourced exclusively from renewable energies.
- **Steam Methane Reforming with Renewable Natural Gas:** In this catalytic process, renewable biogas reacts with steam, producing hydrogen and carbon dioxide.
- **Biomass Gasification:** Organic materials, including agricultural and forest residues, energy-specific crops, and organic municipal solid waste, undergo thermochemical conversion in low-oxygen or anaerobic conditions at temperatures above 1,300°F. This conversion process yields hydrogen, carbon monoxide, and carbon dioxide.

Compression, Third-Party Storage, and Transmission of Clean Renewable Hydrogen

Compression

The process of compression involves increasing the pressure of hydrogen gas to facilitate its storage and transmission. This is typically accomplished using specialized compressors such as reciprocating or centrifugal compressors. Each type is selected based on specific system requirements, including the required pressure levels and flow rates. Compressors should be efficient and designed and operated to minimize leaks.

Third-Party Storage[15]

- **Above Ground Storage:** Above Ground Hydrogen Storage offers a flexible, scalable option for hydrogen containment, utilizing advanced vessel technologies to store gaseous hydrogen under high pressure. This method capitalizes on the properties of materials such as high-strength steel and composite structures for safety and durability. Aboveground tanks are particularly beneficial for their accessibility and ease of integration into existing hydrogen infrastructure, making them ideal for dynamic systems with variable demand. This storage solution is well-suited for short-term and medium-term energy storage needs, providing an important buffer to accommodate fluctuations in supply and demand.

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[15] Various storage technologies are discussed and explored in greater detail within the Pipeline Sizing & Design Report.

- **Underground Storage:** Underground storage solutions can offer a large-scale option for hydrogen storage, utilizing natural geological formations to contain vast amounts of hydrogen under high pressure. Storage can play a particularly important role for long-term energy storage, providing a buffer against supply and demand fluctuations. Storage technologies such as salt cavern storage or hydrocarbon reservoirs are discussed in further detail within the Storage Chapter of the Pipeline Sizing & Design Report.

Transmission

Approximately 1,600 miles of hydrogen pipelines are currently operating in the United States.[16] Owned by merchant hydrogen producers, these pipelines are typically located where large hydrogen users, such as petroleum refineries and chemical plants, are concentrated, such as in the Gulf Coast region. As of 2021, there are 14 miles of hydrogen pipelines in California.

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[16] DOE, 2023a, Office of Efficiency & Renewable Energy, Hydrogen Pipelines available at: https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

4.0 POTENTIAL FOR LEAKAGE

As measurement technology is further developed over time, and more data is available, more specific estimates of potential for leakage may be developed. It should be noted that consistent with the Phase 1 Decision, Angeles Link is intended to transport only 100% clean renewable hydrogen, and any analysis of hydrogen blending refers strictly to potential end users' "behind-the-meter" operations, and not hydrogen use within SoCalGas's control.

4.1 SOURCES OF POTENTIAL LEAKAGE

To identify sources of potential hydrogen leakage, this Study evaluated the potential for hydrogen leakage from anticipated equipment and systems that would be associated with Angeles Link, as well as third-party production and storage. The following potential hydrogen value chain leakage sources were identified in the consulted literature and are evaluated in this Study: production, compression, storage (above ground & underground), and transmission through pipelines. Table 1 was developed to represent the subset of potential sources of leakage that may be applicable to the Angeles Link infrastructure (e.g., transmission and compression) identified based on the evaluation of the general hydrogen value chain (e.g., includes transmission, compression, and third-party production and storage) considered by EDF and UCI in their research and specifically in their recent publication, "Wide range in estimates of hydrogen emissions from infrastructure."[17] This information is also referenced in another recent article from EDF.[18] This publication summarizes the more relevant studies over the past two decades, to estimate total value chain and component-level hydrogen leaks, in order to assess the potential risk of large-scale hydrogen use on the climate. The estimation methods in the background studies referenced in the publication are dependent on assumptions, calculations via proxies, laboratory experiments, as well as theoretical models or simulations.

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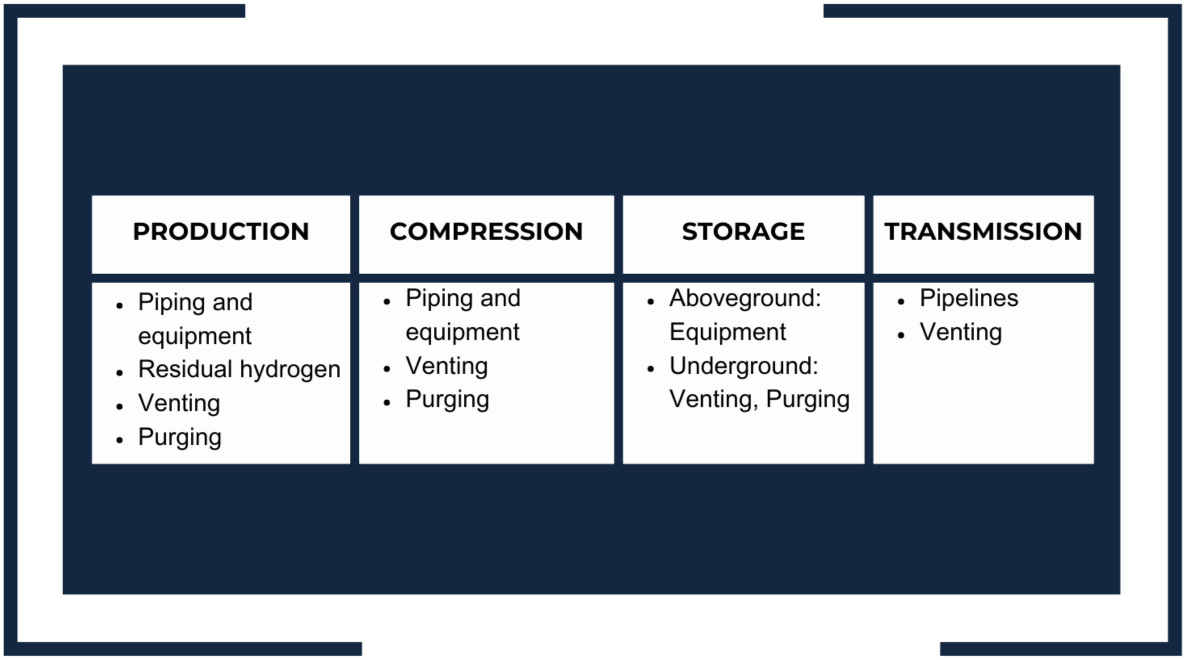
[17] Esquivel-Elizondo, Sofia, Alejandra Hormaza Mejia, Tianyi Sun, Eriko Shrestha, Steven P. Hamburg and Ilissa B. Ocko, 2023, Wide Range in Estimates of Hydrogen Emissions from Infrastructure, Frontiers in Energy Research Vol. 11: 1207208, https://www.frontiersin.org/articles/10.3389/fenrg.2023.1207208/full

[18] Sun, T., E. Shrestha, S. Hamburg, R. Kupers, I. Ocko, Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales, Environ. Sci. Technol., February 21, 2024, available at: https://pubs.acs.org/doi/10.1021/acs.est.3c09030.

Table 1: Potential Sources of Leakage from Hydrogen Infrastructure



PRODUCTION	COMPRESSION	STORAGE	TRANSMISSION
• Piping and equipment • Residual hydrogen • Venting • Purging	• Piping and equipment • Venting • Purging	• Aboveground: Equipment • Underground: Venting, Purging	• Pipelines • Venting

Hydrogen Production: Angeles Link will transport hydrogen from third-party producers. The primary pathways for potential hydrogen leakage related to production of clean renewable hydrogen are via operation of the production equipment and associated piping such as during purging and the process of removing impurities. Leakage may also occur from piping components such as valves and connections.

Information regarding electrolyzer and steam methane reformer production options available in the literature was reviewed. In electrolyzers, the vented oxygen stream may also carry residual hydrogen due to hydrogen crossover through the membrane between the electrodes. Leakage of hydrogen through the casing of the electrolyzer is assumed to be negligible and mitigated through laminated gaskets and welded joints.[19]

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[19] Frazer-Nash Consultancy, 2022, Fugitive Hydrogen Emissions in a Future Hydrogen Economy, prepared for the U.K. Department for Business, Energy & Industrial Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067137/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf

In steam methane reformers, the hydrogen purification process removes CO2 and other impurities from the primary syngas stream. Depending on the calorific value of the rejected stream, it could be used as fuel or combusted. In either case, hydrogen could be captured and minimized by following proper design and operational procedures.

Hydrogen Compression: Hydrogen compression is a subcategory of both storage and transmission since both may use compressors. Seals and packing vents of compressors have the potential to release hydrogen. Blowdowns, purging, and other venting processes may result in hydrogen releases during maintenance activities. These sources of potential leakage can be mitigated by, for example, routing the hydrogen for recompression into the process stream. Potential leaks may also occur from pipeline components, including valves and connectors. Current research related to compression focuses on the need for lower cost, more reliable, and more durable hydrogen compression technology.

Hydrogen Storage: Third-party operated hydrogen storage facilities may connect to Angeles Link. For the purpose of this evaluation, hydrogen storage may occur above ground or below ground. This Study focused on leakage as it pertains to storage of hydrogen in gaseous form. Liquid storage was not evaluated for this Study. Both above ground and underground storage technologies are discussed in detail within the Pipeline Sizing and Design Study. These include, and are not limited to, compressed gas cylinders, pressure vessels, and tanks for aboveground storage; and salt caverns and depleted oil and gas reservoirs for underground storage.

Aboveground storage technologies pose a potential for leakage from components such as during equipment maintenance activities. Underground storage technologies for hydrogen such as salt caverns, depleted oil and gas reservoirs, and engineered cavities present a potential for leakage associated with maintenance operations and geologic migration/diffusion. At the surface level, underground facilities have maintenance plants from which there is potential for leakage during maintenance activities. The potential for underground hydrogen leakage in salt caverns is considered to be low since the hydrogen gas is within the salt that is effectively impermeable.[20] This highlights the intrinsic feature of salt formations in preventing hydrogen escape (because of their natural impermeability).

Development of assumptions regarding aboveground and underground storage volumes and pressures can support refinement of leakage estimates. The sealing potential of a caprock to hydrogen gas depends on the caprock's ability to withstand mechanical and hydraulic gas infiltration.[21]

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[20] Gaffney Cline Consultancy Company, 2022, Underground Hydrogen Storage, https://www.gaffneycline.com/sites/g/files/cozyhq681/files/2022-07/gaffneycline_underground_hydrogen_storage_article.pdf

[21] Derouin, Sarah, 2023, Materials Highlight: What makes a salt cavern useful for hydrogen storage? | ASCE

Geochemical reactions that may take place during hydrogen injection in underground hydrogen storage include oxidation-reduction reactions with iron minerals such as iron bearing clays, micas, hematite, and goethite impacting rock strength as well as formation of leakage pathways in the caprock. Hydrogen can diffuse easily and can, therefore, begin to move through fractures and across faults in the caprock, potentially leading to leakage.[22] The low solubility of hydrogen in water may minimize hydrogen loss due to diffusion as the water saturated caprock acts as a permeability barrier to hydrogen.[23]

Recent research and studies have evaluated the technical aspects of hydrogen storage in various types of reservoirs. Initial conclusions indicate that salt caverns are currently being used for storage and successfully minimizing leakage; while depleted oil and gas reservoirs are currently being piloted and researched.[24]

Hydrogen Transmission: Hydrogen is anticipated to be transmitted via pipelines to operational assets and end users. Traditional operations and maintenance activities that require pipelines to be cleared of gas, such as blowdowns, purging, and/or other venting processes, may result in hydrogen releases unless controlled through capture and control practices. These sources of potential leakage can be mitigated by routing the hydrogen for recompression into the process stream. Potential leaks may also occur from pipeline components, including valves and connectors, and other equipment handling hydrogen. However material selection and gas specific design considerations coupled with best management practices can mitigate or greatly reduce potential leaks. Material properties and recommendation information are available in the Pipeline Sizing & Design Criteria Study.

Current research focuses on overcoming technical issues that can potentially lead to leaks related to pipeline transmission, including:

- Embrittlement: the potential for hydrogen to embrittle steel and welds used to fabricate the pipelines (hydrogen embrittlement is mechanical damage of a metal due to the penetration of hydrogen into the metal causing loss in ductility and tensile strength).
- Permeation: the potential for hydrogen permeation and leaks (hydrogen permeation is the diffusion of hydrogen ions through the thin metal isolation diaphragms used in pressure transmitters).

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[22] Gaffney Cline Consultancy Company, 2022, Ibid.

[23] Panfilov, M., 2016, Underground and pipeline storage, Compendium of Hydrogen Energy, vol. 2: Hydrogen Storage, Transportation and Infrastructure, 91–115, https://www.sciencedirect.com/science/article/pii/B9781782423621000043.

[24] Gaffney Cline Consultancy Company, 2022, Ibid.

4.1.1 Last Mile Delivery and End Users

Stakeholders requested that leakage associated with last-mile delivery of hydrogen beyond the Angeles Link project be evaluated. Stakeholders also included a request to analyze the potential for leakage associated with end users of hydrogen.

Analysis of last mile delivery was not included in any of the Phase 1 studies because the preferred route has not yet been selected and end user details have not been finalized. Uncertainty and insufficient data regarding potential leakage sources precluded preparation of estimates of potential leakage for last mile delivery.

Additionally, supplemental information would be required to expand the scope of the Leakage Study to project hydrogen leakage rates for each sub-sector within the three primary sectors of potential end-users (mobility, power generation, and hard-to-electrify industrial). The Phase 1 analysis was conducted using a top-down approach, at a high level rather than at a granular facility level and equipment specific level.

In response to stakeholder comments, limited information concerning end users that has been found provides anticipated ranges of the potential for leakage from hydrogen liquefaction and refueling stations at approximately 0.15% to 10% and 2% to 15%, respectively.[25] Regarding the power generation end use sector, the potential for leakage from power generation is identified as 0.01% to 3%.[26] Further investigation, outside the scope of this study, would be needed to evaluate whether any of these estimated values, within these wide ranges, would be appropriate predictors for Angeles Link end users. Moreover, end user information regarding the potential for leakage is not available for the hard-to-electrify industrial sector.

4.2 LEAK ESTIMATION METHODOLOGIES

Leakage estimation methodologies include direct measurements, as well as wide-ranging estimation methodologies comprised of calculations via proxies such as natural gas, laboratory experiments, and theory-based models or simulations as discussed in studies evaluated in the literature. These methodologies are important in identifying and quantifying potential hydrogen leaks, offering a nuanced understanding that informs mitigation strategies.

- **Detection Sensors:** Instrumental in the early detection of hydrogen leaks, these technologies include semiconductor sensors, electrochemical cell sensors, and ultrasonic detectors. Deployed at junctures within the infrastructure, their function could be pivotal in enhancing leak mitigation by providing timely notifications upon detecting hydrogen presence, thus enabling swift initiation of containment procedures.

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[25] Esquivel-Elizondo, et. al., 2023, Ibid.
[26] Esquivel-Elizondo, et. al., 2023, Ibid.

- **Measurement Tools:** Post-detection, accurately quantifying the leak's magnitude is imperative for assessing its severity and deciding on appropriate remedial measures. Measurement tools are employed to determine the concentration of hydrogen, enabling precise calculation of leak rates. This quantification is helpful for impact assessments, informing repair strategies, and ensuring regulatory compliance.

Information regarding hydrogen sensors as leak detection instruments, which are important for conducting direct measurements, is elaborated upon in Section 4.2.1. Additionally, estimates of potential leakage, derived from a review of existing literature and encompassing both direct measurement data and theoretical estimations, are detailed in Section 4.2.2. This comprehensive approach to leakage estimation leverages both advanced detection technologies and sophisticated measurement tools, ensuring a robust framework for identifying, quantifying, and mitigating the potential for hydrogen leakage associated with the infrastructure.

4.2.1 Hydrogen Detection Sensors and Direct Measurement Tools

The direct measurement of hydrogen leakage is pivotal for refining leakage estimation methodologies, such as the development of leakage factors for both top-down and bottom-up assessments across the hydrogen value chain or its specific components. The infancy of direct hydrogen measurement is primarily due to the existing lack of instruments capable of accurately measuring hydrogen at very low concentrations.[27] The measurement tools for monitoring hydrogen leakage have historically been focused on safety and economics, measuring at the parts per million (ppm) levels and have not been capable of quantifying hydrogen at the facility level.[28]

Current commercially available sensors for industrial applications have detection levels down to parts per million,[29] and research is underway regarding part per billion levels. Measurement tools with more accuracy may also be used to quantify leakage concentrations, such as with sensitivity at the parts per billion level, as well as the ability to respond in seconds and correctly identify hydrogen amongst other compounds. Direct measurement used to estimate leakage is dependent on the sensitivity and accuracy of the instruments used. Emerging detection technologies provide opportunities to further enhance leak detection and measurement. For example, semiconductor sensors and electrochemical sensors have high sensitivity and can accurately detect concentrations of hydrogen less than 10 ppm with potential for operational integration into regulatory frameworks, which could substantially enhance both proactive and reactive responses to

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[27] Esquivel-Elizondo, et. al., 2023, Ibid.

[28] National Petroleum Council, 2024, Ibid.

[29] Najjar, Y.SH. and Mashareh S, 2019, Hydrogen Leakage Sensing and Control: (Review), Biomedical Journal of Scientific and Technical Research 21(5), https://biomedres.us/pdfs/BJSTR.MS.ID.003670.pdf

hydrogen leak scenarios. [30] [31] Additional details are available in the Future Considerations section of the Draft Pipeline Sizing and Design Study Report.

This Study reviewed several types of leak detection equipment and evaluated anticipated advancements in sensor technology. Specific existing and emerging hydrogen leakage detection and measurement technologies reviewed are summarized in Snapshot 2. Information regarding other hydrogen detection equipment is provided in the parallel “Plan for Applicability Safety Requirements” document based on a literature review, manufacturer’s specifications, and vendor inquiries. Additional details regarding each technology follow the snapshot.

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[30] Wang, Chao, Jiaxuan Yang, Jiale Li, Chenglin Luo, Xiaowei Xu, and Feng Qian, 2023, Solid-state electrochemical hydrogen sensors: A review, International Journal of Hydrogen Energy: 48 (80) pgs 31377-31391, https://doi.org/10.1016/j.ijhydene.2023.04.167

[31] Zhang, Haozhi, Hao Jia, Zao Ni, Ming Li, Ying Chen, Pengcheng Xu and Xinxin Li, 2023, 1ppm-detectable hydrogen gas sensors by using highly sensitive P+/N+ single-crystalline silicon thermopiles, Microsystems & Nanoengineering: 9(29), https://doi.org/10.1038/s41378-023-00506-2

Snapshot 2: Summary of Leak Detection Sensor and Measurement Technologies

Aerodyne Analyzer

Range: 10 ppb

> Utilizes laser spectroscopy to identify and quantify hydrogen gas concentrations. It is known for its precision and ability to provide real-time, accurate measurements.

Semiconductor Sensors

Range: 0.5 ppm to 5,000 ppm

> Detect hydrogen through changes in electrical resistance that occur when hydrogen gas interacts with a chemically treated surface, typically involving metal oxides.

Electrochemical Sensors

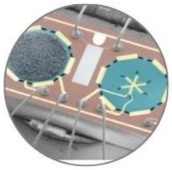
Range: 10 ppm and greater

> Operate on the principle of electrochemical oxidation, and produce an electrical current as hydrogen interacts with an electrode, allowing for the detection of hydrogen concentrations.

Catalytic Combustion Sensors

Range: 1,000 ppm and greater

> Detect hydrogen by catalyzing a combustion reaction at the sensor surface, measuring the temperature increase to determine the presence and concentration of hydrogen.



Highly Sensitive Single-Crystalline Silicon Thermopiles Sensors

Range: 1 ppm to 20,000 ppm

> Use microelectromechanical systems (MEMS) technology to measure temperature differences caused by the chemical reaction of hydrogen on a sensitive layer, which is converted into an electrical signal.

Detection Tapes

Range: 1,000 ppm and greater

> Utilizes chemochromic materials, these tapes change color in the presence of hydrogen gas, providing a visual indicator of leakage.

Aerodyne Analyzer

Aerodyne Research, Inc., in collaboration with EDF and funded through the DOE, developed an analyzer[32] that uses laser spectroscopy to detect and quantify hydrogen concentrations down to 10 parts per billion (ppb). The objective is to be able to quantify hydrogen emissions at the facility level. During testing in January 2023 at Colorado State University, precision measurements were collected every second with 98% accuracy. The Aerodyne Analyzer's portability allows it to be utilized in a variety of settings, including vehicles and small aircraft.

Semiconductor Sensors

A key example of a sensor used for hydrogen leak detection is the semiconductor type, which features a sintered structure where tin oxide is vitrified. At normal room temperature, this type of sensor does not allow electricity to flow. However, when operating in ambient air conditions, oxygen in air is adsorbed to the sensor surface of the detector. The adsorbed oxygen inhibits the flow of electrons, causing high electric resistance and a condition where electricity is difficult to flow (with no oxygen, electricity starts to flow when the sensor is exposed to a high temperature of approximately 752°F). When hydrogen gas is pulled in during the measurement, hydrogen molecules attach to oxygen (oxidation reaction) and oxygen attached to tin oxide decreases. Since the amount of oxygen on the sensor surface decreases, the electric resistance value decreases and electricity starts to flow easily. Leakage of hydrogen gas and gas concentrations are detected through this change of electric current. Figure 3 depicts these principles of a hydrogen leak test using semiconductor sensors.

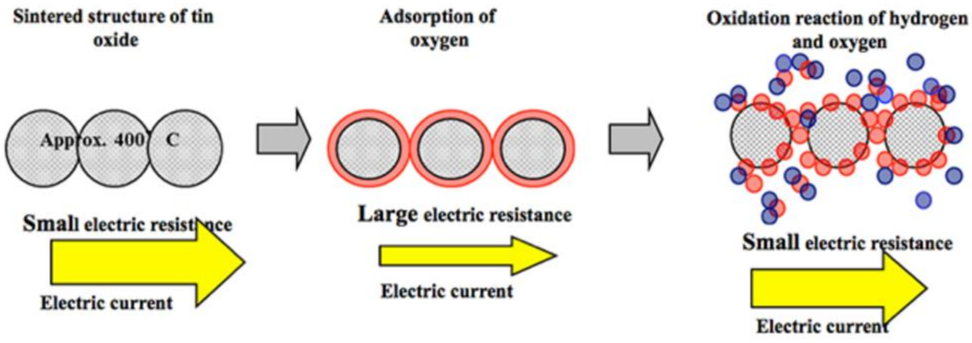


Figure 3: Semiconductor Sensors

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[32] Environmental Defense Fund, 2023, As Climate Concerns About Hydrogen Energy Grow, New Tech Unveiled at CERAWeek Delivers Unprecedented Results Measuring Leaks, Other Emissions, March 2023, https://www.edf.org/media/climate-concerns-about-hydrogen-energy-grow-new-tech-unveiled-ceraweek-delivers-unprecedented

For example, the Fukuda portable hydrogen leak detector HDA-0100 is an example of one of these detectors, with a sensitivity range of 0.5 to 5,000 ppm. It can detect relatively low levels of hydrogen (gas volume: 1×10^{-6} Pa･m3 /s) emitted from capillaries.[33] According to the variation of electrical and optical properties of semiconductor oxide (SMO) sensors under a hydrogen-containing atmosphere, the SMO hydrogen sensors can be divided into four types: resistance based, work function based, optical, and acoustic.[34]

Resistance Based: These sensors operate on the principle that the resistance of a semiconductor metal oxide layer changes upon exposure to hydrogen. Typically constructed with an SMO layer on an insulating substrate, flanked by two electrodes, and a heater beneath the sensitive layer, these sensors are engineered for optimal performance at elevated temperatures—often several hundred degrees Celsius. This thermal management enhances the adsorption and reaction kinetics of hydrogen on the sensor surface, resulting in a measurable change in electrical resistance directly correlated to hydrogen concentration levels. The linear response within a specified concentration range provides a reliable method for detecting hydrogen leaks, offering a balance between sensitivity and operational stability.

Work Function Based: Employing a change in work function as the primary detection mechanism, these sensors manifest in various configurations: the Schottky diode type, metal/oxide/semiconductor (MOS) capacitor type, and the MOS field-effect transistor (MOSFET) type. Field-effect transistor (FET) and Schottky diode hydrogen sensors are two different types of work function sensors. The interaction between hydrogen and the sensor's surface alters the work function, modulating the sensor's electrical properties in a manner that can be quantitatively related to the hydrogen concentration. These devices highlight the intricate interplay between materials and sensor technology, offering nuanced detection capabilities that extend beyond simple resistance changes, potentially enabling more precise and selective hydrogen sensing solutions.

Optical: Optical hydrogen sensors utilize a variety of light-based techniques to detect hydrogen, among which, Raman scattering stands out for its specificity and feasibility for hydrogen detection. Unlike other optical methods that may lack the specificity for hydrogen gas, Raman scattering exploits inelastic light scattering to produce a spectral fingerprint unique to hydrogen. This specificity is further enhanced in optical SMO hydrogen sensors, which detect changes in the optical properties of semiconductor materials upon exposure to a hydrogen-containing

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[33] FUKUDA, 2024, Measurement Principle of Hydrogen Leak Test, industry webpage [Portable Hydrogen Leak Detector / FUKUDA CO., LTD. (fukuda-jp.com)](fukuda-jp.com)

[34] Gu, Haoshuang, Zhao Wang and Yongming Hu, 2012, Hydrogen Gas Sensors Based on Semiconductor Oxide Nanostructures, https://www.mdpi.com/1424-8220/12/5/5517

environment. Typically configured with thin films applied to the tips or sides of optical fibers, these sensors—known as optrodes or optodes—transform optical property variations into detectable optical signals, offering a unique approach to hydrogen detection.

Acoustic: Acoustic hydrogen sensors operate by detecting changes in the acoustic wave properties (e.g., resonance frequency) of piezoelectric materials, which occur due to the adsorption of hydrogen onto the sensing layers. This method relies on the principle that the resonance frequency of both bulk and surface acoustic wave (BAW, SAW) devices is sensitive to the accumulation of mass on the surface of the piezoelectric materials. The adsorption of hydrogen molecules leads to a measurable change in mass, thus altering the resonance frequency. With its high sensitivity and capability of detecting minute concentrations of hydrogen in various conditions, these devices could be invaluable for monitoring.

Highly Sensitive Single-Crystalline Silicon Thermopiles Sensors

The Single-Crystalline Silicon Thermopile technology, leveraging Micro Electro-Mechanical Systems (MEMS) to create differential thermopile gas sensors, represents a promising avenue in the sensitive and rapid detection of trace hydrogen gas in the air. Integrating two identical temperature-controlled thermopiles, these sensors can detect minute temperature changes resulting from the catalytic reaction of hydrogen on a sensing thermopile. The use of single-crystalline silicon, chosen for its Seebeck coefficient (the Seebeck effect is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances), along with high-density thermocouples, endows the thermopiles with a temperature sensitivity of 28 millivolt per °C and sub-millikelvin level temperature resolution. This technology provides a detection limit of 1 ppm, spanning a broad linear detection range from 1 ppm to 20,000 ppm, coupled with swift response and recovery times of 1 to 2 seconds. Additionally, these sensors are distinguished by their selectivity towards hydrogen, which supports reliable repeatability and long-term stability, making them indispensable for applications demanding high precision and reliability in hydrogen detection.[35]

Electrochemical Sensors

Electrochemical hydrogen sensors utilize electrochemical reactions at the sensing electrode to delineate hydrogen concentrations, with the sensor's output signal changing proportionally to the hydrogen levels at the electrode surface. The advantages of such sensors include their ability to operate at room temperature with relatively low power requirements, marking them as energy-efficient solutions for continuous hydrogen monitoring. The underlying principle of these sensors is that hydrogen reacts with the

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[35] Zhang, Haozhi, et. al., 2023, Ibid.

sensing electrode material to produce electron transfer, hydrogen is oxidized at the anode, oxygen is reduced at the cathode, and the concentration of hydrogen is obtained by detecting the change of electrical signal.[36] This reaction mechanism allows for the accurate quantification of hydrogen concentration, providing relevant data for ensuring efficiency in hydrogen-fueled systems.

Catalytic Combustion Sensors

These sensors incorporate sensing elements alongside catalytic metals like Palladium, Platinum, and Ruthenium to facilitate the detection of hydrogen through spontaneous oxidation reactions. Hydrogen is spontaneously oxidized at a temperature above its ignition point (1,085°F) when the environment does not contain a catalyst or ignition source. However, hydrogen's ignition point decreases to 572 to 932°F in the presence of a catalytic metal such as Platinum. When the temperature of the sensing element increases during an exothermic reaction between hydrogen and oxygen on the surface of the catalytic metal, the resistance value of the sensing element changes, and the hydrogen concentration is measured in terms of the change in the resistance value. Despite their effectiveness, the high operating temperatures and power consumption of catalytic combustion sensors limit their utility in portable applications, highlighting the need for innovations that balance efficacy with operational efficiency.[37]

Detection Tapes

Detection tapes, developed through extensive collaboration between research institutions and supported by agencies such as the DOE Hydrogen and Fuel Cell Technologies Office and NREL, offer a simple yet effective approach to hydrogen detection. These tapes, made from a silicone base impregnated with transition metal oxides, exhibit a visible color change upon exposure to hydrogen, facilitating rapid detection at concentrations as low as 1,000 ppm. The tape can be readily used on flanges, welded seams and joints, rigid pipelines, and flexible tubing.38 Their ease of use, coupled with the ability to provide immediate visual indications of hydrogen presence, makes them a valuable tool for initial leak detection and safety inspections across a variety of settings, including industrial sites, laboratories, and fuel cell installations. The integration of chemochromic materials

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[36] Wang, Chao, et. al., 2023, Ibid.

[37] Leea, Jun-Seo, Jin Woo Ana, Sukang Baeb, and Seoung-Ki Leea, 2022, Review of Hydrogen Gas Sensors for Future Hydrogen Mobility Infrastructure, Applied Science and Convergence Technology 31(4) pgs 79-84, https://doi.org/10.5757/ASCT.2022.31.4.79

[38] Fan, Zhiyuan, Hadia Sheerazi, Amar Bhardwaj, Anne-Sophie Corbeau, Kathryn Longobardi, Adalberto Castañeda Vidal, Ann-Kathrin Merz, Dr. Caleb M. Woodall, Mahak Agrawal, Sebastian Orozco-Sanchez, Dr. Julio Friedmann, 2022, Hydrogen Leakage: A Potential Risk for the Hydrogen Economy, report from Colombia Center on Global Energy Policy, July, HydrogenLeakageRegulations_CGEP_Commentary_070722_0.pdf

into the tape design represents a novel approach to gas detection, combining chemical sensitivity with physical durability to provide effective monitoring over extended periods.[39]

4.2.2 Published Studies Regarding Hydrogen Leakage

The estimates of potential for leakage from components of new hydrogen infrastructure (e.g., production, compression, storage, and transmission) in available literature were reviewed to gather information for potential future implementation of the total value chain approach estimate. The total value chain approach is a top-down methodology and considers the leaks for a complete system such as hydrogen production assets, compression, storage systems, and transmission. In some cases, the systems are analyzed to consider a large group of facilities and in some cases, across an entire country.[40] This approach uses generalized datasets and leads to a wide range of emissions estimates. Many of the estimated leakage rates found in the literature are based on hydrogen leak assumptions and estimates from natural gas systems. Estimates of leakage rates are uncertain due to the lack of empirical data regarding real-world infrastructure and facilities.[41] The publications reviewed appear to generally agree on the need of performing additional research and investigation to generate more refined estimates of the potential for leakage.

This Study leaned heavily on an article that was prepared by EDF and the National Fuel Cell Research Center at UCI in 2023 that compiled information gathered from several articles published over the past two decades to estimate total value chain and component-level hydrogen leaks, in order to assess the potential risk of large-scale hydrogen use on the climate.[42] The estimation methods in the background studies referenced in the publication used various methods to develop the potential for leakage estimates which included assumptions, calculations via proxies such as natural gas, laboratory experiments, and theory-based models or simulations.

Another article prepared by EDF was also reviewed for this Study.[43] Key findings from this research highlighted the substantial variability in hydrogen leakage rates across different system components. The insights into the disparate sources and scales of potential leaks are instrumental for developing targeted mitigation strategies, supporting the environmental integrity of clean renewable hydrogen. Additionally, highlighting the

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[39] Zhang, Haozhi, et al., 2023, Ibid

[40] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Hydrogen Emissions from a Hydrogen Economy and their Potential Global Warming Impact, Publications Office of the European Union EUR 31188 EN, ISBN 978-92-76-55848-4, doi:10.2760/065589, JRC130362. https://publications.jrc.ec.europa.eu/repository/handle/JRC130362

[41] Esquivel-Elizondo, et al., 2023, Ibid.

[42] Esquivel-Elizondo, et al., 2023, Ibid.

[43] Sun, et. al., 2024, Ibid.

variability and potential sources of hydrogen leaks spurs innovation in detection, measurement, and mitigation technologies.

A summary of unmitigated estimates for the total value chain approach that may be applicable to new hydrogen infrastructure, such as Angeles Link and the associated production and storage infrastructure of third parties, is provided in the snapshots 3, 4, 5, and 6. These estimates range significantly, reflecting the variability in methodologies, assumptions, and technological efficiencies considered in the literature.

The background studies were evaluated to determine the assumptions that were used to develop these estimates. This information is provided below. These values may be reduced by applying the opportunities to minimize and mitigate leakage discussed in Section 4.4 of this document.

As shown below, there is considerable variability in the values. The background studies were evaluated more closely to determine the assumptions that were used to develop these estimates. This information is provided below.

Snapshot 3: Overview of Potential Sources of Leakage for Third-Party Production

Third-Party Production

0.0001% to 4%

Potential Sources of Leakage during Third-Party Production

- Piping and equipment
- Venting
- Purging
- Residual hydrogen

[Namely: 0.0001%, 0.03%, 0.1%, 0.2%, 0.24%, 0.25%, 0.5%, 0.52%, 4%, 4%]
Contributions from Harrison & Peters (2013), Frazer-Nash (2022), Arrigoni and Diaz (2022), and Cooper et al. (2022).

Research Insights on Leakage Rates during Third-Party Production

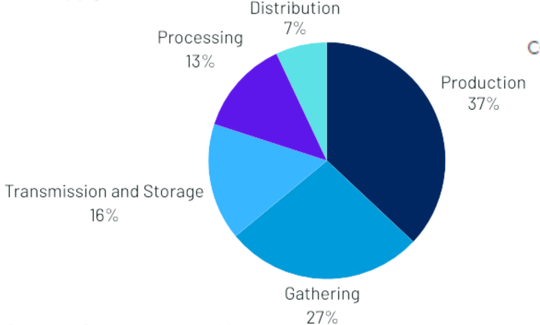
Steam Methane Reforming (SMR) Leakage Rate at **0.0001%** reflects the lowest value. **Electrolyzer Technologies** show a wide range of leakage rates **(0.03% to 4%)**. Rates of **0.1% and 0.2%** represent current variability with losses due to hydrogen and oxygen crossover through the membrane and the dryer's regeneration process. A **4%** rate in **PEM electrolyzers** points to substantial losses in the dryer phase, indicating specific areas for technological enhancements.

Leakage rates of **0.24% to 0.52%** reflect both expected and upper-threshold leakage under various scenarios, including electrolytic production with full recombination of hydrogen from purging and crossover venting, and CCUS-enabled production. Expected improvements by 2030 could reduce leakage to as low as **0.03%**, highlighting the anticipated role of advancements in reducing membrane crossover.

Natural Gas Supply Chain Leakage

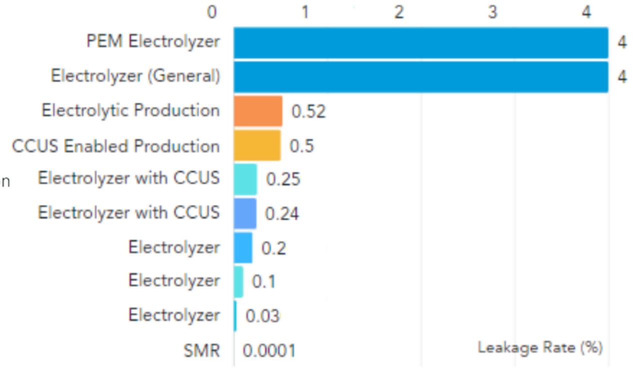
US EPA Estimates, 2016.

This pie chart illustrates the percentage breakdown of natural gas leakage across the supply chain.



Source: US EPA Estimates, 2016.

Leakage Rates by Infrastructure Components



Source: Harrison & Peters (2013), Frazer-Nash (2022), Arrigoni and Diaz (2022), and Cooper et al. (2022).

Third-Party Production

Steam Methane Reforming (SMR)

Leakage Rate: 0.0001%[44] is associated with SMR technology.

Electrolyzer Technologies

Leakage Rates: 0.03%[45], 0.1%[46] 0.2% [47], and 4%[48], with another 4%[49] rate specifically tied to PEM electrolyzers.

- The **0.03%** rate is based on the expectation that hydrogen losses in production will drop by 2030 due to maturing technologies, expected to minimize hydrogen loss, particularly through reduced membrane crossover.
- The **0.1%** rate is derived from a comprehensive analysis of various electrolyzer technologies, representing the lower end of estimated losses for hydrogen production for domestic and international supply chains evaluated.
- The **0.2%** estimate was presented as the current understanding of losses during electrolysis. In addition to inadvertent leakage, the losses are generally due to hydrogen and oxygen crossover through the membrane and to the dryer's regeneration process.
- The first **4%** leakage rate, associated with PEM electrolyzers, emerges from laboratory examinations highlighting that the bulk of hydrogen losses can occur in the dryer phase (3.4%).
- The other **4%** reflects the upper end of a calculation performed to estimate losses for a variety of electrolyzer technologies for green hydrogen production for domestic and international supply chains that were evaluated.

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[44] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Ibid.

[45] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Ibid.

[46] Cooper, Jasmin, Luke Dubey, Semra Bakkaloglu, Adam Hawkes, 2022, Hydrogen Emissions from the Hydrogen Value Chain -Emissions Profile and Impact to Global Warming, Science of the Total Environment Vol. 380: 154624, July 15, https://www.sciencedirect.com/science/article/pii/S004896972201717X#s0070

[47] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Ibid.

[48] Harrison, Peters, 2013, National Renewable Energy Laboratory, 2013 DOE Hydrogen and Fuel Cells Program Review, Renewable Electrolysis Integrated System Development & Testing, Project ID PD031. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review13/pd031_harrison_2013_o.pdf

[49] Cooper, et. al., 2022, Ibid.

Conventional Fluid Mechanics-Based Modeling

Leakage rates: 0.24%[50] 0.25%[51], 0.50%[52], and 0.52%[53]

0.24% and 0.25% Leakage Rates: These rates were predicted with a 50% confidence level, representing expected leakage under standard conditions. The **0.24%** rate is applied to electrolytic production scenarios where there is full recombination of hydrogen from purging and crossover venting. The **0.25%** rate is associated with Carbon Capture, Utilization, and Storage (CCUS) enabled production, indicating an average projection of leakage based on current technological practices and operational efficiencies.

0.50% and 0.52% Leakage Rates: These higher rates were derived using models with a 99% confidence level, indicating the upper threshold of potential leakage in less optimized scenarios. Specifically:

- The **0.50%** rate applies to CCUS enabled production, highlighting the potential for increased leakage in these systems despite the utilization of CCUS technologies. This projection accounts for the inherent variability in operational practices and the efficiency of technology in minimizing hydrogen loss.
- The **0.52%** rate is attributed to electrolytic production scenarios that incorporate full recombination of hydrogen from purging and crossover venting. This rate underscores the potential for higher leakage even in electrolytic processes designed to minimize loss, reflecting the challenges in achieving complete containment.

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[50] Frazer-Nash Consultancy, 2022, Ibid.
[51] Frazer-Nash Consultancy, 2022, Ibid.
[52] Frazer-Nash Consultancy, 2022, Ibid.
[53] Frazer-Nash Consultancy, 2022, Ibid.

Snapshot 4: Overview of Potential Sources of Leakage for Compression

Compression

0.14% and 0.27%

Representing the lower and upper limits.

Contributions from Cooper et al. (2022).

Potential Sources of Leakage during Compression

- Piping and equipment
- Venting
- Purging

Relatively narrow range from 0.14% and 0.27%, suggesting a relatively consistent leakage profile.

Research Insights on Leakage Rates during Compression

Compression Leakage Rates: Identified at **0.14% and 0.27%**. Based on modeling, these rates established the lower and upper bounds for hydrogen leakage during compression.

Methodology: Utilized natural gas leakage data as a proxy, based on its documented properties and leakage rates, to estimate hydrogen leakage, informed by a study on natural gas leakage in reciprocating compressors, Cooper et al. (2022).

Compression

The leakage rates of **0.14% and 0.27%**[54] represent the modeled lower and upper bounds for potential hydrogen leakage during the compression process. This range was determined through modeling due to the lack of specific data on hydrogen. In these estimations, natural gas served as a proxy, leveraging its well-documented physical properties and leakage rates to infer those of hydrogen. The rationale behind this approach is anchored in a 2015 study[55] that examined natural gas leakage rates in reciprocating compressors, which then informed the model's assumptions about hydrogen leakage.

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[54] Cooper, et. al., 2022, Ibid.

[55] Subramanian, R., Williams, L.L., Vaughn, T.L., Zimmerle, D., Roscioli, J.R., Herndon, S.C., Yacovitch, T.I., Floerchinger, C., Tkacik, D.S., Mitchell, A.L., Sullivan, M.R., Dallmann, T.R., Robinson, A.L., 2015. Methane emissions from natural gas compressor stations in the transmission and storage sector: measurements and comparisons with the EPA greenhouse gas reporting program protocol. Environ. Sci. Technol. 49, 3252–3261.

Snapshot 5: Overview of Potential Sources of Leakage for Third-Party Storage

Third-Party Storage

Potential Sources of Leakage during Third-Party Storage

⊘ Aboveground: Equipment

⊘ Underground: Venting, Purging

Aboveground Third-Party Storage

2.77% to 6.52%

2.77% corresponds to a 50% confidence level over a 2-day storage period. 6.52% corresponds to a 99% confidence level over a 30-day Third-Party Storage period. Contributions from Frazer-Nash (2022).

Underground Third-Party Storage

0.02% and 0.06%

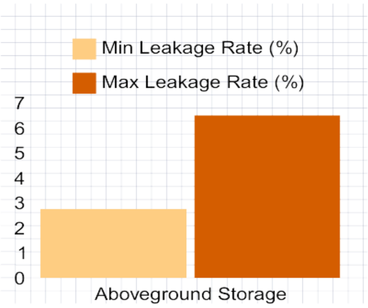
Salt cavern storage leakage rates are predicted to be very low, with primary concerns around surface plant maintenance or venting. Contributions from Frazer-Nash (2022)

Research Insights on Aboveground Third-Party Storage and Underground Third-Party Storage

Aboveground Third-Party Storage: These rates are derived from probabilistic modeling of hydrogen in compressed gas tanks. The confidence intervals (**50% for 2.77% and 99% for 6.52%**) reflect the statistical likelihood of these rates occurring under specified conditions, with storage duration being a critical factor.

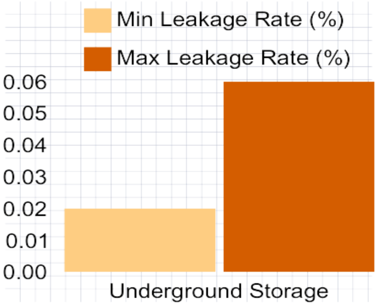
Underground Third-Party Storage: The low leakage rates anticipated for salt cavern storage **(0.02% to 0.06%)** suggest geological advantages that minimize environmental risks.

Aboveground Storage Leakage Rates



Source: Frazer-Nash (2022)

Underground Storage Leakage Rates



Source: Cooper et al. (2022)
Frazer-Nash, (2022)

Third-Party Storage

Aboveground Storage

- The **2.77%**[56] leakage estimate originates from an uncertainty model designed to calculate probabilistic leakage outcomes for hydrogen in compressed tanks, assuming a 50% confidence level. Input data for the model included leakage rates from compressed gas cylinders, specifically 0.005% to 0.01% per hour[57], acknowledging the impact of storage duration on leakage, with a two-day period being the basis for this rate.
- The **6.52%**[58] is derived using a similar uncertainty model but at a 99% confidence level, this rate also examines hydrogen stored in compressed tanks. The model uses the same hourly leakage inputs as the 2.77% estimate but extends the assumed storage duration to thirty days, emphasizing the role of time influencing leakage outcomes.
- Stakeholder comment identified that the potential for leakage from aboveground storage should be less than **1%.**

Underground Storage

- Underground storage of hydrogen is envisaged in various geological formations, including depleted oil and gas reservoirs, aquifers, and specifically engineered caverns in salt, coal, igneous, and metamorphic rocks.[59]
- The expected leakage rates from such underground storage, particularly in salt caverns are projected to be low with values of **0.02% and 0.06%**[60]. This low potential for leakage primarily arises from the structural integrity of the storage sites and the controlled environment. However, it is noted that the main areas where leakage could potentially occur are at the surface facility, particularly during maintenance operations or instances of emergency venting. The Study suggests that with further technological advancements, it may be possible to reduce these leakage risks. The quantity of caverns is highlighted as a factor influencing the overall potential for leakage, underscoring the importance of cavern management in mitigating risk.

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[56] Frazer-Nash Consultancy, 2022, Ibid.

[57] Referring to a DOE Conformable Hydrogen Storage Pressure Vessel.

[58] Frazer-Nash Consultancy, 2022, Ibid.

[59] Zivar, Davood, Sunil Kumar, and Jalal Foroozesh, 2021, *Underground hydrogen storage: A comprehensive review*, International Journal of Hydrogen Energy 46(45) pages 23436-23462, https://doi.org/10.1016/j.ijhydene.2020.08.138

[60] Frazer-Nash Consultancy, 2022, Ibid.

Snapshot 6: Overview of Potential Sources of Leakage for Transmission

Transmission

0.02% to 1%

[Namely: 0.02%, 0.04%, 0.06%, 0.1%, 0.2%, 0.4%, 0.48%, 1%.]
Contributions from Arrigoni & Diaz (2022; Cooper et al. (2022); Frazer-Nash (2022); Van Ruijven et al. (2011).

Potential Sources of Leakage during Transmisssion

⊘ Pipeline

⊘ Venting

Research Insights on Leakage Rates during Transmission

0.1% is the estimated leakage rate for new pipelines dedicated to hydrogen transport, based on simulations incorporating findings from global energy system and atmospheric models.

Modeled Leakage Rates **(0.02% and 0.06%)**: These rates are derived from modeling that uses natural gas data as a proxy, reflecting an analytical approach to approximate hydrogen leakage in transmission pipelines.

Leakage Estimates **(0.04% to 1%):** Ranging from lower estimates **(0.04%)** to higher estimates (up to **1%**), these rates underscore the variability in leakage potential.

Transmission

- **Leakage Rates of 0.02% and 0.06%**[61]: These values represent the modeled lower and upper bounds for hydrogen transmission leakage, respectively. The use of natural gas as a proxy was essential in this estimation process, informed by a 2015 study[62] that provided data on natural gas leakage rates in pipelines.
- **0.04%[63] Estimate**: This rate, established with a 50% confidence level, is derived from the Digest of U.K. Energy Statistics concerning natural gas transmission.
- **0.1%[64] Rate for New Pipelines:** Specifically focusing on pipelines constructed for hydrogen transmission, this estimate incorporates findings from both a global energy system model and a global atmospheric model. It explores the environmental implications of hydrogen as a key component of the global energy matrix, using the TIMER model to assess various application scenarios and their consequent leakage rates.
- **Estimates of 0.2% and 0.4%[65]**: These figures are inferred from data on natural gas leakage within local distribution systems, utilizing in-field activity data—including miles of pipeline and leaks per mile—collected from six locations along the U.S. East Coast.[66] This methodology emphasizes the role of empirical evidence in shaping our understanding of leakage dynamics in hydrogen distribution.
- **0.48%[67] Rate**: With a 99% confidence level, this estimate is based on comprehensive data from the Digest of U.K. Energy Statistics for natural gas transmission, serving as a high-confidence marker for potential leakage in hydrogen transmission systems.
- **1%[68] Rate for Transmission:** Reflecting the current understanding of hydrogen leakage in European pipeline transmission, this rate is anticipated to improve to

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[61] Cooper, et. al., 2022, Ibid.
[62] Subramanian, R., et. al., 2015. Ibid.
[63] Frazer-Nash Consultancy, 2022, Ibid.
[64] Van Ruijven, B., J.F. Lamarque, D.P. van Vuuren, T. Kram, and H. Eerens, 2011, Emission scenarios for a global hydrogen economy and the consequences for global air pollution. Glob. Environ. Change 21, 983–994. https://doi.org/10.1016/j.gloenvcha.2011.03.013
[65] Fan, Zhiyuan, et. al., 2022, Ibid.
[66] Weller, Zachary D., Steven P. Hamburg, and Joseph C. von Fischer, 2020, A National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems, Environmental Science and Technology 54, no. 14 (July 21): 8958–67. https://pubs.acs.org/doi/full/10.1021/acs.est.0c00437
[67] Frazer-Nash Consultancy, 2022, Ibid.
[68] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Ibid.

below 0.7% by 2030, indicative of ongoing advancements in pipeline technology and management aimed at enhancing efficiency and reducing leakage.

4.3 HIGH LEVEL PRELIMINARY LEAKAGE ESTIMATE

In response to stakeholder comments requesting that the Study quantify potential leakage for Angeles Link, a high-level range of estimated potential for leakage has been developed for both general hydrogen infrastructure and Angeles Link infrastructure even though detailed design and engineering information is not available for the Angeles Link project. General infrastructure is comprised of production, compression, storage, and transmission. The estimates for Angeles Link infrastructure include the compression and transmission categories.

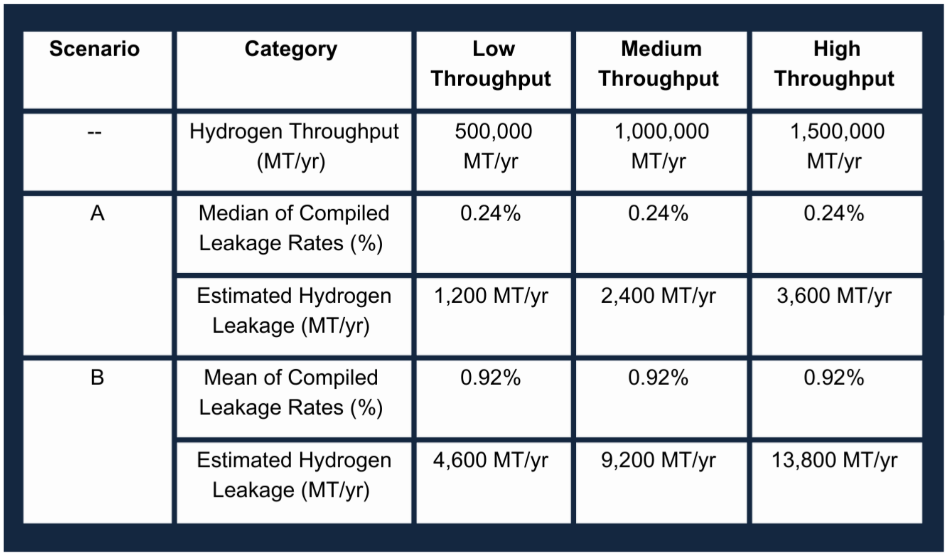
To prepare a preliminary high-level estimate of the potential for leakage associated with general hydrogen infrastructure, the leakage estimates provided in the literature for production, compression, aboveground storage, underground storage, and transmission, as shown in snapshots 3, 4, 5, and 6, were compiled. Additionally, the value of 1% leakage rate provided by stakeholder comment for aboveground storage was utilized. The median and mean of these 25 values were calculated and determined to be 0.24% and 0.92%, respectively. Then these values were applied to the low, medium, and high throughput scenarios for Angeles Link using equation 2.

$$\text{Estimated Hydrogen Leakage} = \text{Throughput} * \text{Leakage Rate (\%)} \qquad \text{(equation 2)}$$

The low throughput scenario is 0.5 million metric tonnes of hydrogen per year (MMTPY); the medium throughput scenario is 1.0 MMTPY; and the high throughput scenario is 1.5 MMTPY. This estimation methodology and results are shown in Table 2A. As shown in Table 2A, the high-level estimate of potential for leakage ranges from 1,200 MT per year for the low throughput scenario with the median of the leakage estimates to 13,800 MT per year for the high throughput scenario with the mean of the leakage estimates found in the literature.

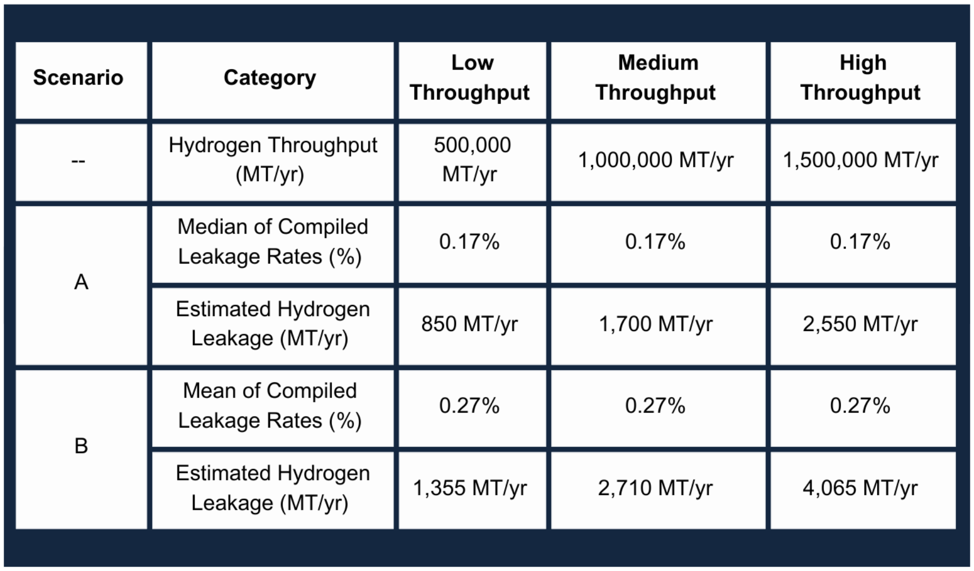
To prepare a preliminary high-level estimate of the potential for leakage associated with anticipated Angeles Link hydrogen infrastructure, the leakage estimates provided in the literature for compression and transmission as shown in snapshots 4 and 6 were compiled. The median and mean of these 10 values were calculated and determined to be 0.17% and 0.27%, respectively. Then these values were applied to the low, medium, and high throughput scenarios for Angeles Link using equation 2. The estimation methodology and results are shown in Table 2B. As shown in Table 2B, the high-level estimate of potential for leakage ranges from 850 MT per year for the low throughput scenario with the median of the leakage estimates to 4,065 MT per year for the high throughput scenario with the mean of the leakage estimates found in the literature.

Table 2A: Preliminary Leakage Estimate for General Infrastructure



Scenario	Category	Low Throughput	Medium Throughput	High Throughput
--	Hydrogen Throughput (MT/yr)	500,000 MT/yr	1,000,000 MT/yr	1,500,000 MT/yr
A	Median of Compiled Leakage Rates (%)	0.24%	0.24%	0.24%
	Estimated Hydrogen Leakage (MT/yr)	1,200 MT/yr	2,400 MT/yr	3,600 MT/yr
B	Mean of Compiled Leakage Rates (%)	0.92%	0.92%	0.92%
	Estimated Hydrogen Leakage (MT/yr)	4,600 MT/yr	9,200 MT/yr	13,800 MT/yr

Table 3B: Preliminary Leakage Estimate for Angeles Link Infrastructure



Scenario	Category	Low Throughput	Medium Throughput	High Throughput
--	Hydrogen Throughput (MT/yr)	500,000 MT/yr	1,000,000 MT/yr	1,500,000 MT/yr
A	Median of Compiled Leakage Rates (%)	0.17%	0.17%	0.17%
	Estimated Hydrogen Leakage (MT/yr)	850 MT/yr	1,700 MT/yr	2,550 MT/yr
B	Mean of Compiled Leakage Rates (%)	0.27%	0.27%	0.27%
	Estimated Hydrogen Leakage (MT/yr)	1,355 MT/yr	2,710 MT/yr	4,065 MT/yr

The Advanced Research Projects Agency – Energy (ARPA-E) has indicated that there is a need to develop a large-area quantitative hydrogen estimation methodology to assess the rate of hydrogen leakage associated with production, transportation, and storage infrastructure.[69] The ARPA-E is a United States government agency tasked with promoting and funding research and development of advanced energy technologies. The proposal is to use sensor measurements of hydrogen concentrations in parts per billion on representative sites identified as 100 meters by 100 meters that would be used as input into an emissions model to determine the estimated hydrogen emission rate in kilograms per hour associated with the infrastructure. The components of the emissions model would include site data, sensor data, weather data, a transport model, and a predictive model.

4.4 OPPORTUNITIES TO MINIMIZE LEAKAGE

The Study evaluated three primary types of mitigation opportunities: 1) Design and Engineering; 2) Operation; and 3) Maintenance & Repair. This includes manufacturer's improvements to design including incorporation of technological advancements, such as use of equipment and components less prone to leaks, as well as operational and maintenance improvements to minimize the quantity and duration of leaks. Table 3 summarizes these opportunities and provides an estimated range of mitigation as a percentage that may be achieved. Although detailed reduction estimates have not been provided for each mitigation opportunity described, based on the potential mitigation measures identified, the overall reductions could be more than 90% from assumed leakage rates in the literature. Detailed information regarding each of these opportunities follows Table 3.

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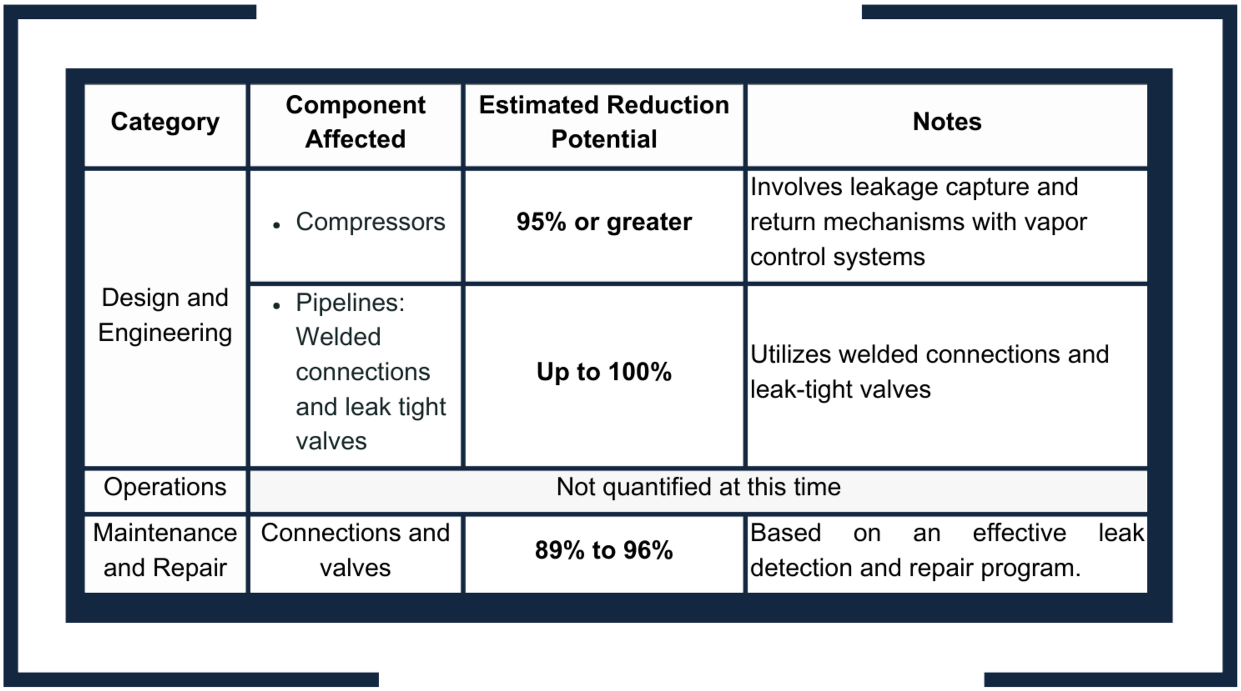
[69] ARPA-E Webinar: Hydrogen Sensing, April 18, 2024, https://arpa-e.energy.gov/about

Table 4: Opportunities to Minimize Leakage



Category	Component Affected	Estimated Reduction Potential	Notes
Design and Engineering	• Compressors	**95% or greater**	Involves leakage capture and return mechanisms with vapor control systems
	• Pipelines: Welded connections and leak tight valves	**Up to 100%**	Utilizes welded connections and leak-tight valves
Operations	Not quantified at this time		
Maintenance and Repair	Connections and valves	**89% to 96%**	Based on an effective leak detection and repair program.

The NPC's Report[70] includes Recommendation 20 "Technology – Detecting, Quantifying, and Mitigating Environmental Impact" suggesting that the DOE direct the national labs jointly with other researchers to develop and improve leak detection, prevention, and mitigation technologies, as well as the accuracy of the technologies; and to use these tools to measure and quantify hydrogen leak rates. The recommendation mentions that EPA can use this information to develop guidance regarding monitoring and repair of hydrogen leakage.

Additional opportunities to minimize the potential for leakage provided in the NPC Report[71] include: 1) encouraging RD&D investments to develop more robust measurement, monitoring, and verification of hydrogen leakage; 2) eliminating venting of hydrogen as much as possible and applying oxidation for vented hydrogen when possible; 3) proper treatment of hydrogen leakage during electrolysis such as recombination of hydrogen with oxygen; 4) strong insulation of pipes and storage vessels and use of proper materials such as plastic lining; 5) minimizing transport of hydrogen by co-locating facilities; 6) minimizing points of pressurization and depressurization; and 7) conducting regular, timely facility inspections.

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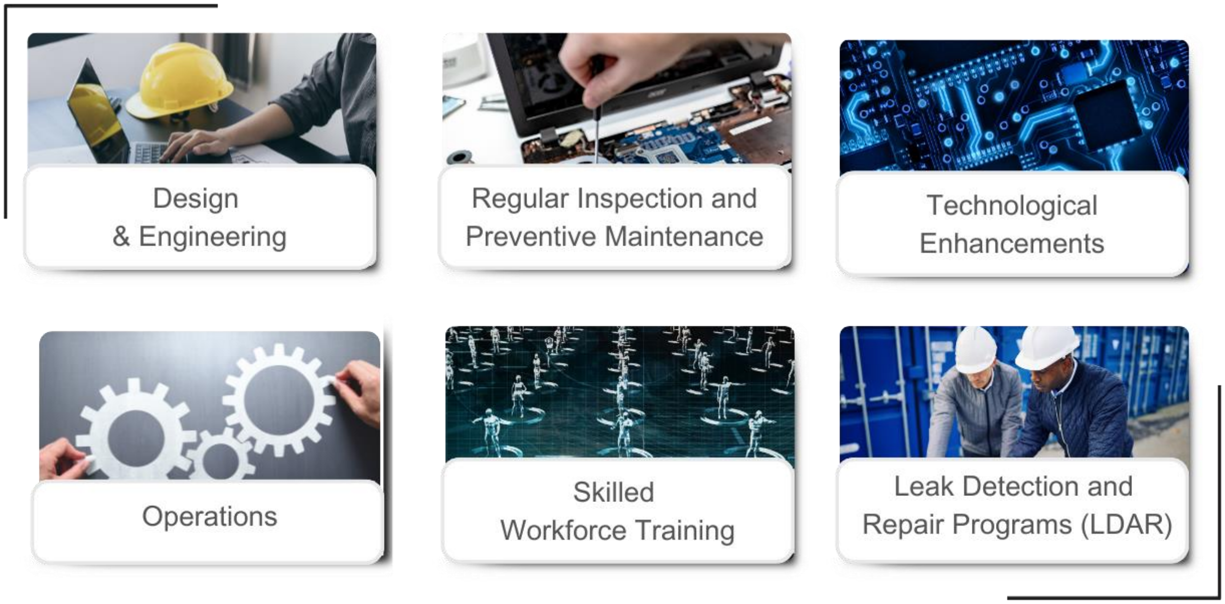
[70] National Petroleum Council, 2024, Ibid.
[71] National Petroleum Council, 2024, Ibid.

Snapshot 7: Overview of Leakage Minimization/Mitigation Strategies



4.4.1 Design and Engineering

The incorporation of leakage minimization within the initial design and engineering for new infrastructure projects provides lifetime benefits for both the project and interconnection facilities. This includes consideration with respect to the processes, equipment, systems, and materials that could be used in the project. Engineering systems and processes that, do not normally vent hydrogen to the atmosphere, minimizes leakage.[72]

Codes, regulations, and standards applicable to hydrogen value chain systems and equipment provide guidance for the design, construction, and operation of systems to minimize leakage. Design-based mitigation measures may result in up to zero, near-zero leakage or potential to minimize leakage and should be implemented during the design and engineering phases as much as possible. Opportunities to minimize leakage include, but are not limited to, the following.

Leak detection system on diaphragm compressors: Each compressor could also include a leak detection system that monitors the integrity of the diaphragms and static O-rings. Breaches in these components can signal an alarm and or automatically shut down the compressor.[73]

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[72] Ocko I., S. Hamburg, July 19, 2023, EDF Blog: New research reaffirms hydrogen's impact on the climate, provides consensus. https://blogs.edf.org/energyexchange/2023/07/19/new-research-reaffirms-hydrogens-impact-on-the-climate-provides-consensus/

[73] PDC Machine, 2023, Diaphragm Compressors, industry brochure, https://www.pdcmachines.com/wp-content/uploads/2023/02/PDC_Brochure_V21_USA_SM.pdf

Leakage capture and return mechanism for compressors and electrolyzers: A collection and recompression system can be used to capture leakage and route it to another portion of the process, such as the compressor suction, thereby eliminating leakage. These re-compression systems can be used for any leakage source that can be captured and routed to a closed system. In the case of the compressors, gas leakage through seals could in many cases be captured and directed to the suction of the unit for reprocessing. For example, reciprocating compressors used for natural gas compression vent natural gas from piston rod packing systems during normal operations, which could also occur for hydrogen compression. The rod packing systems are designed to have a sufficient fit around the piston rod to reduce leakage, but not so tight as to bind the rod and cause faster wear.[74] Since the packing cannot eliminate leakage from the inboard side of the cylinder, the leakage could be captured and returned to the system. Potential leakage reductions from implementing designs to capture and reroute process gas, using vapor control systems, can be estimated to be at least 95%, using data from natural gas operations as a proxy.[75] In the case of electrolyzers, venting and purging is considered one of the main causes of leakage, and when captured, leakage could be reduced significantly.

Purge system for compressors: Potential leaks from compressor seals can be mitigated by using a purge system to contain the leakage and prevent it from escaping the seal system.

Dry seals on compressors: A similar scenario that occurs in natural gas centrifugal compressors may happen in hydrogen compressors as well. These compressors contain rotating shafts that require seals to prevent high-pressure natural gas from escaping the compressor casing. Traditionally, these seals used high pressure oil as a barrier against escaping gas; these seals are referred to as “wet seals.” Alternatively, centrifugal compressors can be equipped with mechanical seals, called “dry seals,” which have substantially lower potential for leakage.[76]

Diaphragm compressors: Diaphragm compressors are designed for zero leakage through the sealing. A diaphragm compressor is a positive displacement machine, which consists of a hydraulic system and a gas compression system. Most compressors used today for gaseous hydrogen compression are either positive displacement compressors or centrifugal compressors. Triple metal diaphragm compressors are unique because they are leak-free and non-contaminating since they do not utilize dynamic seals and the diaphragm set completely isolates the process gas from the hydraulic system. Diaphragm compressors are an option for high pressure, low volume situations such as filling aboveground storage tanks. Each compressor could also include a leak detection system

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[74] EPA, 2023a, Natural Gas STAR Program - Reciprocating Compressors, Agency website, https://www.epa.gov/natural-gas-star-program/reciprocating-compressors

[75] EPA, 2023b, Natural Gas STAR Program: Vapor Recovery Units, webpage, https://www.epa.gov/natural-gas-star-program/vapor-recovery-units

[76] EPA, 2023c, Natural Gas STAR Program - Centrifugal Compressors, Agency website, https://www.epa.gov/natural-gas-star-program/centrifugal-compressors

that monitors the integrity of the diaphragms and static O-rings. Breaches in these components can signal an alarm and or automatically shut down the compressor.[77]

Storage Vessels: A compressed hydrogen gas storage system has two main components: the aboveground storage vessel or underground reservoir and the compressors that may be needed to achieve the storage pressure. For aboveground storage, minimizing the number of connections, which are dependent of the number of vessels used and the operating conditions of the vessels (pressure, storage time, cycles) will directly impact the potential for leakage. Engineering and design considerations include: 1) optimize/reduce the total surface storage to meet system operational needs; 2) use the combination commercial vessel size and design pressure that decreases the number of total required vessels; 3) minimize the number of connections and valves; and 4) evaluate alternate gas storage technologies being developed, which could be commercial in the near future, such as multi-vessel aboveground storage modules.[78]

Transmission via Pipeline: Design to minimize potential for leakage by reducing the number of pipe connections, by using welded connections rather than flanges, and by checking the valves and tightening them to prevent leaks. Welded pipes are continuous, minimizing leak points, whereas flanged connections can leak at the flanged connection. Leak tight valves have additional packing in the valve to minimize the leaks for the valve stem. Welded joints in place of flanged joints can also reduce the potential for leaks.

4.4.2 Operations

Operations of the infrastructure to enhance leakage minimization opportunities are associated with operators’ knowledge, which is linked to having staff with the proper level of experience and training and detailed written operations procedures. Operational staff with the knowledge and expertise for efficient operation of hydrogen infrastructure requires training. The hydrogen economy will require the development of a new work force or/and the retraining of existing workers to operate future hydrogen facilities. In reference to training, there are several organizations that provide operator training services,[79] [80] and it is expected that when the market grows, more organizations will be added to the list. Operations manuals detailing procedures should contain the information regarding the operation of the systems and facilities. The manual could include day-to-day activities necessary for the facility, its systems, equipment, and occupants/users to perform their intended functions. These functions may include required environmental protection protocols, as well as opportunities to minimize potential for hydrogen leakage.

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[77] PDC Machine, 2023, Ibid.

[78] FIBA Technologies, Inc., 2023, Seamless Pressure Vessels, industry webpage, https://www.fibatech.com/products/seamless-pressure-vessels/ https://www.fibatech.com/products/seamless-pressure-vessels/

[79] DOE, 2023b, Education, Office of EERE webpage, https://www.hydrogen.energy.gov/program-areas/education

[80] GTI Energy, 2024, Hydrogen Training, webpage, https://www.gti.energy/training-events/training-overview/hydrogen-training/

Refer to the “Workforce Planning & Training Evaluation” study for additional considerations for a workforce trained and qualified with appropriate skills to operate and maintain hydrogen infrastructure.

4.4.3 Maintenance and Repair

Studies have shown that many different mechanisms can affect the need for maintenance or contribute to the failure of an equipment part, such as packing wear on a valve in place.[81] Having a regular maintenance program offers opportunities to minimize the potential for leakage from infrastructure. For example, a predictive or condition-based maintenance approach is one in which operating conditions are monitored and maintenance decisions are based on either performance or defined conditions. Leak detection and repair programs are used across the natural gas industry and result in reductions in overall system leakage. These same practices can be adopted by the hydrogen industry to increase the likelihood that valves and other components are maintained and tightened to prevent leaks. Plans for Integrity Management are discussed in the Future Considerations section of the Draft Pipeline Sizing and Design Study Report.

- Timely repair in conjunction with timely leak detection can minimize leakage by reducing the leak duration. Traditional leak detection methodologies include conducting regular screening of components using sensors or optical imaging instruments. Sensors can be used for regular/frequent/continuous screening of potential sources of leakage.

- High-performance hydrogen gas sensors with low-concentration detection limits, wide measurement ranges, and fast responses can be used to monitor potential for leakage and facilitate timely repairs to minimize potential for leakage to the atmosphere. The reductions potential is estimated to range from 89%[82] to 96%.[83]

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[81] INGAA, 2018, Improving Methane Emissions from Natural Gas Transmission and Storage, August, https://ingaa.org/wp-content/uploads/2018/08/34990.pdf

[82] California State University, Fullerton, 2012, Estimation of Methane Emissions from the California Natural Gas System (California Energy Commission), https://doi.org/10.1080/10962247.2015.1025924

[83] Pacific Gas and Electric Company’s Comments on the Revised Draft Regulation Proposal for Greenhouse Gas Emission Standards for Crude Oil and Natural Gas Facilities, https://ww2.arb.ca.gov/sites/default/files/classic/isd/cc/oil-gas/meetings/pge_02262016.pdf

5.0 RESULTS

This Study summarizes potential sources of leakage, leakage estimation methodologies, and opportunities to mitigate and minimize the potential for leakage. Data reported in literature that was reviewed from the last two decades shows large variation in estimates for potential hydrogen leakage. This indicates that additional research and investigation of hydrogen leakage is required for more detailed predictions.

With further development of leakage sensor detection and direct measurement technologies, more accurate measurements of hydrogen leakage and more refined evaluation of the effectiveness of implementation of mitigation strategies can be performed. Mitigation measures to minimize leakage may include design parameters, operating and maintenance procedures, and leak detection and repair processes. With successful implementation of mitigation strategies, the likelihood of infrastructure with the potential for leakage can be minimized.[84] [85] [86] Based on the potential mitigation measures identified, the overall reductions can be more than 90%.

SoCalGas recognizes comments from stakeholders, such as EDF, CBE, Food and Water Watch, Protect Playa Now, and Physicians for Social Responsibility – Los Angeles, that have expressed concerns that the Preliminary Data and Findings document for the this Study did not include detailed estimates of the volumetric potential for leakage and have incorporated a preliminary high-level top-down estimate using a methodology that was based on the values available in the literature. More data and information based on detailed design and engineering of the infrastructure would be needed to use the bottom-up component-level methodology.

Limitations

The limitations related to the results presented is primarily due to the limitations of the quantity and quality of information currently available regarding actual leak measurement data for hydrogen. With infrastructure design development, project refinements, and detailed information from technological data measurement and collection advancements, the estimates of the potential for hydrogen leakage could be further refined.

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[84] Hauglustaine, D., F. Paulot, W. Collins, R. Derwent, M. Sand and O. Boucher, 2022, Climate benefit of a future hydrogen economy, Comm. in Earth & Environment, 3 Article 295, https://doi.org/10.1038/s43247-022-00626-z

[85] Ocko, I. and S. Hamburg, 2022, For hydrogen to be a climate solution, leaks must be tackled, Environmental Defense Fund blog, March, https://www.edf.org/blog/2022/03/07/hydrogen-climate-solution-leaks-must-be-tackled

[86] Warwick, N.J., A.T. Archibald, P.T. Griffiths, J. Keeble, F.M. O'Connor, J.A. Pyle, and K.P. Shine, 2023, Atmospheric composition and climate impacts of a future hydrogen economy, Atmospheric Chemistry and Physics 23(20) 12451-13467, https://doi.org/10.5194/acp-23-13451-2023

6.0 CONCLUSION

Results regarding the potential for leakage and mitigation opportunities related to Angeles Link, as well as third-party production and third-party storage, as set forth in this Study are to inform Phase 1 of Angeles Link.

As described in the literature reviewed for this Study, potential sources of leakage associated with potential hydrogen infrastructure include production equipment such as electrolyzers, compression equipment such as reciprocating and centrifugal compressors, storage equipment such as aboveground vessels and underground salt caverns, and transmission infrastructure such as pipelines. Based on the information gathered, the total value chain approach (top-down) leakage estimation methodology was selected as the preferred approach given that insufficient data was available regarding direct measurements of hydrogen leaks to perform accurate leak estimates. The component-level approach could be evaluated in the future with more detailed information and development of hydrogen leakage factors.

Some studies consulted provided preliminary leak estimates using the total value chain approach.[87] Leakage estimation methodologies include direct measurement such as leak detection sensors, as well as published estimates based on a variety of methodologies including calculations via proxies such as natural gas, laboratory experiments, and theory-based models or simulations. The reviewed publications show agreement on the necessity of performing additional research and investigation on hydrogen leakage to generate more accurate data.

The magnitude of the potential for hydrogen leakage depends on the quantity and type of equipment that is used for production, compression, and storage, how the infrastructure is designed and engineered, whether the pipelines are above ground or below ground, the sizing and routing of the pipelines, and how the infrastructure is operated and maintained, amongst other factors.

A preliminary high-level estimate of the potential for leakage associated with both general hydrogen infrastructure and Angeles Link infrastructure was prepared as described in Section 4.3. As shown in Table 2A, the estimate of potential for leakage for general hydrogen infrastructure ranges from 1,200 MT per year for the low throughput scenario (using the median of the leakage estimates) to 13,800 MT per year for the high throughput scenario, based on the mean or the average of the leakage estimates found in the literature. As shown in Table 2B, the estimate of potential for leakage for Angeles Link infrastructure ranges from 850 MT per year for the low throughput scenario (using the median of the leakage estimates) to 4,065 MT per year for the high throughput scenario, based on the mean or the average of the leakage estimates found in the literature.

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[87] Arrigoni, Alessandro and Laura Bravo Diaz, 2022, Ibid.

Mitigations and opportunities to minimize the potential for leakage from various processes are available in design and engineering of new infrastructure, operation of equipment and systems, as well as maintenance procedures. In addition to design and engineering, the use of existing and emerging sensor technologies support early identification of leaks and facilitate timely repairs, thereby mitigating leaks. The selection of available mitigation measures for equipment and systems that comprise Angeles Link infrastructure will determine the overall reductions. Based on the potential mitigation measures identified, the overall reductions can be more than 90%.

This Study acknowledges that while limited data exists in the literature for actual measurements of hydrogen for production, compression, storage, and transmission of clean renewable hydrogen, measurement technologies and calculation methodologies related to hydrogen are anticipated to develop further over time. As significant enhancements have been made for natural gas leak detection and mitigation over the past decades, it is anticipated that those measures to reduce gas leakage in general will be employed and new developments will similarly be made for hydrogen to minimize the potential for leakage. The design details of the Angeles Link infrastructure, as well as further project refinements, will allow future refinements of the evaluation of the potential for leakage and opportunities to minimize leakage of hydrogen.

7.0 STAKEHOLDER FEEDBACK

SoCalGas presented opportunities for the PAG and CBOSG to provide feedback at four key milestones in the course of conducting this study: (1) the draft description of the Scope of Work, (2) the draft Technical Approach, (3) Preliminary Data and Findings, and (4) the Draft Report. These milestones shown in Table 4 below were selected because they are critical points at which relevant feedback can meaningfully influence the study.

Table 4: Key Milestone Dates

Milestone	Date Provided to PAG/CBOSG	PAG/CBOSG Comment Due Date	Responses to Comments in Quarterly Report
1. Scope of Work	June 6, 2023	July 31, 2023	Q3 2023
2. Technical Approach	September 7, 2023	October 20, 2023	Q4 2023
3. Preliminary Data and Findings	February 27, 2024	March 29, 2024	Q1 2024
4. Draft Report	May 29, 2024	June 26, 2024	Q2 2024

Feedback provided at the PAG/CBOSG meetings is memorialized in the transcripts of the meeting. Written feedback received is included in the quarterly reports, along with responses. Meeting transcripts are also included in the quarterly reports. The quarterly reports are submitted to the CPUC and are published on SoCalGas's website.

Feedback was incorporated as applicable at each milestone throughout the progression of the study. Some feedback was not incorporated for various reasons including feedback that was outside the scope of the Phase 1 Decision or study, and feedback that raises issues better suited for third parties to address.

A summary of stakeholder input that was incorporated throughout the development of the Leakage Study and into this Final Report is provided in Table 5: Summary of Stakeholder Feedback. All feedback received, whether incorporated into the study or not as described above, has been recorded in the quarterly reports, along with SoCalGas's responses. Additionally, some administrative and other minor corrections were made to the Final Leakage Study Report for clarity.

Table 5: Summary of Incorporated Stakeholder Feedback	
Thematic Comments from PAG/CBOSG Members	**Incorporation of and Response to Feedback**
Volumetric Estimate of Leakage Stakeholders requested that the Leakage Study include a volumetric estimate of the potential for leakage.	In response to stakeholder comments, the Study includes a preliminary high-level volumetric estimate of the potential for leakage from hydrogen infrastructure. Specifically, a range of preliminary high-level volumetric estimates of the potential for leakage was developed based on the range of values derived from the literature review. This analysis was developed using the conservative, moderate, and ambitious Demand scenarios, as well as by using the low, medium, and high Angeles Link throughput scenarios.
Climate Impact Several stakeholders requested impacts to climate change associated with volumetric leakage estimates be discussed and included in the Greenhouse Gas Study Report.	In response to stakeholder comments, the range of high-level volumetric leakage estimates was used in the parallel Greenhouse Gas (GHG) Study to estimate a range of potential impacts associated with potential leakage. That potential leakage is accounted for when considering the overall expected GHG reductions associated with general hydrogen infrastructure and with Angeles Link infrastructure.
Leakage at End Users Stakeholders included a request to analyze the potential for leakage associated with end users of hydrogen.	Acknowledgement of this issue has been added to Section 4.1.1. While requested by stakeholders, additional information would be required to expand the scope of the Leakage Study to project hydrogen leakage rates for each sub-sector within the three primary sectors of potential end-users (mobility, power generation, and hard-to-electrify industrial). The Phase 1 analysis was conducted using a top-down approach, at a high level rather than at a granular facility level and equipment

Table 5: Summary of Incorporated Stakeholder Feedback	
Thematic Comments from PAG/CBOSG Members	**Incorporation of and Response to Feedback**
	specific level. The limited information concerning end users that has been found includes the following: The anticipated ranges of the potential for leakage from hydrogen liquefaction and refueling stations are approximately 0.15% to 10% and 2% to 15%, respectively.[88] Regarding the power generation end use sector, the potential for leakage from power generation is identified as 0.01% to 3%.[89] These values have been added to Section 4.1.1. Further investigation would be needed to evaluate whether any of these estimated values amongst these wide ranges would be appropriate predictors for Angeles Link end users.
Last Mile Delivery Stakeholders requested that leakage associated with last-mile delivery of hydrogen beyond the Angeles Link project which may potentially be in the form of hydrogen liquefaction and delivery to heavy-duty truck refueling stations be evaluated.	Acknowledgement of this issue has been added to Section 4.1.1. Analysis of last mile delivery was not included in any of the Phase 1 studies because the preferred route has not yet been selected and end user details have not been finalized. Uncertainty and insufficient data regarding potential leakage sources precluded preparation of estimates of potential leakage for last mile delivery.
Leakage Estimates Several stakeholders expressed concerns that the Leakage Study underestimates the potential for leakage and does not account for the potential difference between methane and hydrogen leakage.	In response to stakeholder feedback, numerous articles cited in comment letters have been included in the Study references section. Specific literature provided by stakeholders speaks to the lack of detailed information about the

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[88] Esquivel-Elizondo, et. al., 2023, Ibid.
[89] Esquivel-Elizondo, et. al., 2023, Ibid.

Table 5: Summary of Incorporated Stakeholder Feedback	
Thematic Comments from PAG/CBOSG Members	**Incorporation of and Response to Feedback**
Stakeholders stressed the importance of examining all possible research and literature around hydrogen leakage including articles provided by stakeholders. Comments also suggested examining all possible sources of hydrogen including venting and purging and including this information in the study calculations.	potential for hydrogen leakage currently available. For example, "Wide Range in Estimates of Hydrogen Emissions from Infrastructure,"[90] states "It is virtually unknown how much H_2 is emitted intentionally and unintentionally from hydrogen systems since, to date, these emissions have not been measured, mainly because the instrumentation to measure H_2 emissions at low-level concentrations has been lacking." The article goes on to state: "Over the past two decades, several studies have attempted to estimate total value chain and component-level H2 emissions to assess the risk of large-scale hydrogen use on the climate." The article explains that "estimation methods are heavily dependent on assumptions, calculations via proxies, laboratory experiments, or theoretically-based models or simulations." The article concludes that "more robust data is required to have confidence in the H2 emissions rates for each value chain or its components". The Leakage Study has summarized the information that is available, which is limited as highlighted by this article. Another article referenced in stakeholder comments on the Draft Report entitled, "Hydrogen emissions from the hydrogen value chain-emissions profile and impact to global warming"[91] concludes that if hydrogen is used and traded the way natural gas is then emissions are

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[90] Esquivel-Elizondo, et. al., 2023, Ibid.

[91] Cooper, et. al., 2022, Ibid.

Table 5: Summary of Incorporated Stakeholder Feedback	
Thematic Comments from PAG/CBOSG Members	**Incorporation of and Response to Feedback**
	considerably smaller when comparing the two. This is because “H2 has a significantly smaller global warming potential (GWP), and a higher mass energy density meaning a smaller mass needs to be transferred for the same end use and any emissions that do occur have a lesser effect.”
Measurement of Leakage Stakeholders indicated that the Study should identify available sensors and emerging leak detection methodologies including the availability of technology for measuring hydrogen leakage. Concerns were raised regarding the difficulty of measuring hydrogen leakage rate at low levels indicating that studies have shown that leak detection and prevention at parts per billion level is needed to evaluate climate benefits from use of hydrogen.	Consistent with stakeholder feedback, information regarding available and emerging direct measurement tools and leakage sensors is included in the Leakage Study. Existing and emerging technologies regarding hydrogen leak detection sensors and direct measurement tools are presented in Section 4.2. Additional information regarding measurement tools is also available in Section 8 of the Safety Study Report.
Minimization and Mitigation of Leakage Stakeholders requested that the Study should identify potential mitigation opportunities and proposed leak prevention measures, as well as availability of technology for measuring and mitigating hydrogen leakage.	Consistent with stakeholder feedback, minimization of leakage is discussed in Section 4.4 with a summary in Table 3. Specifically, details with respect to mitigation opportunities during design and engineering are provided in Section 4.4.1, mitigation options during operations are discussed in Section 4.4.2, and discussion of mitigation options related to maintenance and repair are discussed in Section 4.4.3. Sources of potential hydrogen leakage including venting and purging are anticipated to be mitigated via leakage capture mechanisms.

Table 5: Summary of Incorporated Stakeholder Feedback	
Thematic Comments from PAG/CBOSG Members	**Incorporation of and Response to Feedback**
Infrastructure Commentors inquired whether the study will consider research on existing hydrogen pipelines and research at existing hydrogen facilities. Stakeholders indicated that different leakage rates for liquid and gaseous storage should be considered when assessing potential environmental impacts.	Consistent with stakeholder feedback, a literature review of leakage rates was conducted for various elements of infrastructure. Estimated leakage rates were evaluated for the anticipated Angeles Link infrastructure, in addition to third-party production and third-party storage (underground and aboveground), as described in Section 4.2.1. Gaseous storage was evaluated whereas liquid storage as not based on the Angeles Link project description, as discussed in Section 4.1.
Literature Review Several stakeholders provided reports and literature to review and incorporate into the Leakage Study.	In response to stakeholder feedback, the Study includes a review of relevant literature provided by stakeholders.

Summary of Literature Provided by Stakeholders

- Specific literature provided by PAG/CBOSG stakeholders has been evaluated and relevant information has been incorporated, as appropriate, including, but not limited to:
    - Environmental Defense Fund, March 2023, As Climate Concerns About Hydrogen Energy Grow, New Tech Unveiled at CERAWeek Delivers Unprecedented Results Measuring Leaks, Other Emissions. https://www.edf.org/media/climate-concerns-about-hydrogen-energy-grow-new-tech-unveiled-ceraweek-delivers-unprecedented
    - Esquivel-Elizondo, Sofia, Alejandra Hormaza Mejia, Tianyi Sun, Eriko Shrestha, Steven P. Hamburg and Ilissa B. Ocko, 2023, Wide Range in Estimates of Hydrogen Emissions from Infrastructure, Frontiers in Energy Research Vol. 11: 1207208, https://www.frontiersin.org/articles/10.3389/fenrg.2023.1207208/full

- Hauglustaine, D., F. Paulot, W. Collins, R. Derwent, M. Sand and O. Boucher, 2022, Climate benefit of a future hydrogen economy, Comm. in Earth & Environment, 3 Article 295, https://doi.org/10.1038/s43247-022-00626-z
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8.0 GLOSSARY

Biomass Gasification - Biomass is a renewable organic resource that includes agriculture crop residues (such as corn stover or wheat straw), forest residues, special crops grown specifically for energy use (such as switchgrass or willow trees), organic municipal solid waste, and animal wastes. This renewable resource can be used to produce hydrogen, along with other byproducts, by gasification.

Caprock - Caprock or cap rock is a more resistant rock type overlying a less resistant rock type, analogous to an upper crust on a cake that is harder than the underlying layer.

Centrifugal Compressors - These are the compressors of choice for pipeline applications due to their high flowrate and moderate compression ratio. Centrifugal compressors rotate a turbine at very high speeds to compress the gas. Hydrogen centrifugal compressors must operate at top speeds three times faster than that of natural gas compressors to achieve the same compression ratio because of the low molecular weight of hydrogen.

Clean renewable hydrogen - hydrogen that does not exceed 4 kilograms of carbon dioxide equivalent (CO2e) produced on a lifecycle basis per kilogram of hydrogen produced and does not use fossil fuel in the hydrogen production process where fossil fuel is defined as a mixture of hydrocarbons including coal, petroleum, or natural gas, occurring in and extracted from underground deposits.[92]

Component-level leaks - A component-level leak is a leak in a component of the overall transmission system, such as a valve. A leak in a valve is characterized by a leak rate, which is often given as a volumetric flow rate at a standard temperature and pressure (e.g., standard cubic meters per minute).

Diaphragm compressors - A diaphragm compressor is a variant of the classic reciprocating compressor with backup and piston rings and rod seal. The compression of gas occurs by means of a flexible membrane, instead of an intake element. The back and forth moving membrane is driven by a rod and a crankshaft mechanism. Only the membrane and the compressor box come in contact with compressed gas. Diaphragm compressors are an option for high pressure, low volume situations such as filling aboveground storage tanks.

Electrochemical Sensors - Electrochemical gas sensors are gas detectors that measure the concentration of a target gas by oxidizing or reducing the target gas at an electrode and measuring the resulting current.

Electrolysis - Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer that can range in size from small, appliance-sized equipment that is well-suited for small-scale distributed

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[92] California Public Utilities Commission (CPUC) adopted Decision 22-12-055, Ibid.

hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

Embrittlement – Embrittlement is a decrease of ductility of a material, which makes the material brittle. Embrittlement happens when the environment compromises a stressed material's mechanical performance, such as temperature or environmental composition. Various materials have different mechanisms of embrittlement; therefore, it can manifest in a variety of ways, from slow crack growth to a reduction of ductility and toughness.

Emissions – Emissions are substances that are released into the air, water, or soil by various sources, such as vehicles, factories, or animals.

End User – An end user uses the good or service provided, in this case clean renewable hydrogen.

Feasibility study – A feasibility study is an assessment of the practicality of a proposed project plan or method. For example, asking “Is this feasible?” by analyzing factors such as technical, economic, legal, and operational feasibility.

Hydrocarbons – Hydrocarbons are organic compounds that contain carbon and hydrogen atoms, forming the backbone of fossil fuels and many other substances. Hydrocarbons can have different shapes and structures, depending on how the carbon atoms bond with each other and with the hydrogen atoms.

Impermeability - Impermeability is a measure of the difficulty of passage for liquids, gases, or specific chemicals through a material.

Infrastructure – Infrastructure is the resources (such as buildings or equipment) required for an activity, in this case the transmission pipeline and associated support equipment such as compressors and otherwise.

Leak or leakage – Leak or leakage means any unexpected, accidental, and/or unintended gas or liquid flows through an object because of anthropogenic activities through an imperfection or production defect such as a hole, crack, or weak seal.

Methodology – A methodology is a system of methods and principles for doing something, for example for teaching or for carrying out research.

Mitigation/Mitigating factors – Mitigation means implementing actions to reduce impacts.

Raman scattering – Raman scattering is inelastic light scattering, is the only common optical technique suitable for hydrogen, as it is specific to hydrogen and accessible. (Inelastic scattering from different molecules gives each component a spectral fingerprint).

Reciprocating Compressors - A reciprocating compressor uses a motor with a linear drive to move a piston back and forth. This motion compresses the hydrogen by reducing the volume it occupies. Reciprocating compressors are the most used compressors for applications that require a very high compression ratio (compression ratio is the ratio of the pressure at the outlet of the compressor over the pressure at the inlet of the compressor).

Sensors - A sensor is a device that detects and responds to some type of input from the physical environment. The input can be light, heat, motion, moisture, pressure, or any number of other environmental phenomena.

Steam methane reforming – Steam methane reforming (SMR) is a process that commercial hydrogen producers and petroleum refineries use to separate hydrogen atoms from carbon atoms in methane and primarily use natural gas as the methane source.

Underground hydrogen storage – Underground hydrogen storage is the practice of hydrogen storage in caverns, salt domes and depleted oil/gas fields.

Value chain – A value chain is a series of consecutive steps that go into the creation of a finished product, from its initial design to its arrival at a customer's domicile or place of use.

Viscosity – Viscosity is the resistance of a fluid (liquid or gas) to a change in shape, or movement of neighboring portions relative to one another. Viscosity denotes opposition to flow.

Work Function-Based Sensors - This type of hydrogen sensor is based on the variation of work function induced by hydrogen. Features of these gas sensors' operation and the various materials, such as metallic films, inorganic and organic layers, which can be used in these devices as a sensing element.

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