ANGELES LINK PHASE 1
PIPELINE SIZING & DESIGN CRITERIA
FINAL REPORT – DECEMBER 2024

SoCalGas commissioned this Pipeline Sizing & Design Criteria from Burns & McDonnell. The analysis was conducted, and this report was prepared, collaboratively.

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LIST OF ABBREVIATIONS

Abbreviation	Term/Phrase/Name
AACE	Association for the Advancement of Cost Engineering
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Bscfd	Billion standard cubic feet per day
CBOSG	Community Based Organizations Stakeholder Group
CPUC	California Public Utilities Commission
DOT	Department of Transportation
GIS	Geographic Information Systems
ksi	1,000 pounds per square inch (psig)
ID	Inside Diameter
ILI	Inline Inspection
LEL	Lower Explosive Limit
M&R	Metering & Regulation
MAOP	Maximum Allowable Operating Pressure
MAWP	Maximum Allowable Working Pressure
MDMT	Minimum Design Metal Temperature
MMscfd	Million standard cubic feet per day
MMTPY	Million metric tons (tonnes) per year
NACE	National Association of Corrosion Engineers
NDE	Non-Destructive Examination
NFPA	National Fire Protection Association
NPS	Nominal Pipe Size
OD	Outside Diameter
P&ID	Piping & Instrumentation Diagram
PAG	Planning Advisory Group
PHMSA	Pipeline and Hazardous Materials Safety Administration
psig	Pounds per square inch (gauge)
scf	Standard Cubic Foot
SJV	San Joaquin Valley
SMYS	Specified Minimum Yield Strength
Tonne	Metric ton (1,000 kg)
TPD	Tonnes per day
TPY	Tonnes per year
WT	Wall Thickness

EXECUTIVE SUMMARY

Southern California Gas Company (SoCalGas) is proposing to develop a clean renewable hydrogen[1] pipeline system to facilitate transportation of clean renewable hydrogen from multiple regional third-party production sources and storage sites to various delivery points and end users in Central and Southern California, including in the Los Angeles Basin. The CPUC's Phase 1 Decision, approving the Memorandum Account for SoCalGas's proposed Angeles Link, requires SoCalGas to identify and compare routes and configurations for Angeles Link. The Pipeline Sizing and Design Criteria Study (Design Study) establishes a preliminary engineering and design basis that supports the consideration of cost estimates, reliability, and resiliency. The Design Study is focused on the transport of clean renewable hydrogen via pipeline and includes evaluation of compression and ancillary equipment.

The objective of this Design Study is to evaluate and determine a preliminary range of pipeline diameters and pressure profiles. Additionally, technical specifications such as operating parameters, suitable equipment, logistics, and materials of construction were considered to support an efficient and reliable pipeline system. This evaluation was completed through literature review, hydraulic modeling, and data from other Phase 1 Studies, including the Production Planning & Assessment (Production Study), the Demand Study, the Preliminary Routing/Configuration Analysis (Routing Analysis), and the Evaluation of Applicable Safety Requirements (Safety Study). Data from this study was utilized in the High-Level Economic Analysis & Cost Effectiveness (Cost Effectiveness Study), the Project Options & Alternatives (Alternatives Study), and the Workforce Planning & Training Evaluation (Workforce Study).

Information from the Production Study, the Demand Study, and the Routing Analysis were integrated to identify eight operational scenarios for initial hydraulic evaluation. The costs from these various scenarios are part of the basis of analysis in the Cost Effectiveness Study and Workforce Study. Additional hydraulic evaluation was completed for the four potential preferred routes identified in the Routing Analysis. Multiple sizing options were considered, with a focus on maintaining reasonable pressure loss and providing operational resiliency.

The key findings are presented below for potential preferred routes and are discussed further within this document. These findings are based on analysis and information

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[1] In the California Public Utilities Commission (CPUC)'s 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 (CO_2e) 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.

available during Angeles Link Phase 1 development and may be subject to change. Future considerations to advance engineering design, project requirements, and execution are also discussed in this document.

- **Preliminary Design Criteria**
  - The appropriate pipe sizes could range from 16-inch up to 36-inch in nominal diameter.
  - Two to three compressor stations will likely be necessary for maximum 1.5 MMTPY throughput, based on the potential configurations considered.
  - The lowest delivery pressure to the Ports of Los Angeles and Long Beach was assumed to be approximately 200 pounds per square inch gauge (psig) while the upper bounds of the modeled system did not go above 1200 psig.[2]
  - Select pipelines were modeled and assessed as single run and dual run (e.g., two parallel lines) for functional flexibility, and system resiliency and capacity considerations.
  - American Petroleum Institute (API) 5L X52 pipe is recommended based on preliminary calculations and operating parameters.

Stakeholder Feedback

The input and feedback from stakeholders including the Planning Advisory Group (PAG) and Community Based Organization Stakeholder Group (CBOSG) has been helpful to the development of this Design Study. For example, in response to stakeholder comments, the Design Study examined preliminary material specifications, design considerations such as repurposing existing pipelines, and an electric reliability review The thematic feedback that was incorporated through development of this study is summarized in Chapter 7. All feedback received is included, in its original form, in the quarterly reports submitted to the CPUC and published on SoCalGas's website.[3]

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[2] Refer to Design Pressure Section 3.2. The system modeled may be effective for MAOP of 1200 psig however, this is subject to change depending on actual operating parameters, and material selections.
[3] Angeles Link: SoCalGas, (n.d.-a). https://www.socalgas.com/sustainability/hydrogen/angeles-link

1. INTRODUCTION – PIPELINE SIZING & DESIGN

Pipeline systems are designed to operate using a variety of different facilities to transport gas from sources of supply to sources of demand. This includes the point where gas enters the system, its transfer to areas of high demand, and eventual utilization by end users. Today, SoCalGas owns and operates a natural gas system of over 3,000 miles of transmission pipelines, over 100,000 miles of distribution and service pipelines, nine compressor stations, and four underground natural gas storage facilities.[4] Compressor stations increase pressure in pipelines that operate over long distances to keep gas flowing. Underground storage facilities are used to help meet demand by balancing load between supply and demand and maintaining a stable gas flow throughout the pipeline system.

A hydrogen gas pipeline system would have a similar architecture to a natural gas pipeline system, whereby similar facilities and pipeline system operation parameters would be employed. Operational differences may also drive design choices with regard to supply and offtake. For example, load balancing on a clean renewable hydrogen system may require consideration of the fluctuations in production of clean renewable hydrogen generated via electrolysis paired with solar driven by daily and seasonal photovoltaic impacts. Load balancing on the natural gas system today requires considerations of a similar manner. Gas supply and demand can vary based on weather conditions such as disruptions to supply during severe weather events, and increases in demand during winter (to heat residential and commercial buildings) and summer months (to meet increased electric power demand for natural gas).[5]

1.1 Components of a Pipeline System

A pipeline system design includes a variety of components. Additional features may be necessary on a case-by-case basis. The following is a list of the components that may be part of a clean renewable hydrogen pipeline system:

1. **Pipelines:** Tubular sections made from materials compatible with hydrogen to transport the gas from one point to another. They must be designed to resist hydrogen embrittlement[6] and withstand the specific pressures and temperatures of hydrogen gas.

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[4] Form 10-K for Sempra filed 02/27/2024. (n.d.). https://investor.sempra.com/static-files/fd1dd362-92ec-42a9-a1e1-009866e4a413

[5] U.S. Energy Information Administration - EIA - independent statistics and analysis. Factors affecting natural gas prices - U.S. Energy Information Administration (EIA). (n.d.). https://www.eia.gov/energyexplained/natural-gas/factors-affecting-natural-gas-prices.php

[6] Refer to Hydrogen Embrittlement Section 5.2.

2. **Compressors:** Mechanical equipment, typically found in transmission stations, used to increase the pressure of the hydrogen gas to adequate levels for transmission through the pipeline. They are essential for maintaining flow and overcoming frictional losses along the pipeline length.
3. **Air Cooled Heat Exchangers:** Heat transfer equipment, typically found in transmission stations, used to cool the hot discharge gas from compressors to acceptable temperatures conducive to pipeline transportation.
4. **Valves:** Including isolation valves, control valves, and safety valves; these components regulate, direct, or control the flow of hydrogen by opening, closing, or partially obstructing various passageways.
5. **Pressure Relief Valves (PRVs):** Safety devices designed to open at a predetermined pressure to prevent an excess pressure build-up that could jeopardize the pipeline's structural integrity.
6. **Emergency Shutdown Systems (ESDs):** Systems designed to rapidly shut down compressor station equipment and/or facilities under certain conditions in the event of a detected leak or other hazardous situations that will isolate sections of the pipeline to minimize risks.
7. **Pressure Limiting Station (PLS):** Devices that regulate or limit the flow of gas at a specific set point to achieve or maintain a certain pressure to keep pipeline operations within the determined pressure limits.
8. **Pig Launchers & Receivers:** Facilities used for the insertion and retrieval of in-line inspection tools used to clean and inspect the pipeline.
9. **Metering Stations:** These stations measure the flow rate of hydrogen through the pipeline and are utilized for operational control and billing purposes.
10. **Corrosion Protection Systems:** Includes cathodic protection and protective coatings that are designed to prevent internal and external corrosion.
11. **Leak Detection Systems:** Technologies deployed along the pipeline to detect and locate leaks based on pressure, acoustic signals, or chemical sensors. These are components essential for the early detection of failures or breaches in pipeline integrity.
12. **Control & Monitoring Systems:** Centralized systems that use field technology, sensors and communication methods to monitor and control the physical parameters of the pipeline.

The final design of a system and the selection of the above components will take into account federal, state, and industry codes and standards. The system will be designed to meet operational requirements, account for facility locations, and to support construction, operations, and integrity management objectives. As such, during the feasibility analysis, pipeline design activities occur at a high-level and identify a basis for further evaluation. Pipeline materials, pipeline diameter, anticipated compression requirements, and ability for pipeline cleaning and inspections (piggability) are evaluated at a feasibility level within this report. Ancillary components in addition to the pipeline system may include third-party production and storage facilities, offtake equipment specific to individual applications, and potentially equipment specific to gas purification or scrubbing.

1.2 Pipeline Sizing Process

In gas distribution and transmission systems, the sizing of pipelines is a critical engineering task that influences efficiency, safety, and operational viability. This section of the report introduces the key concepts and considerations involved in pipeline sizing that are applied in this report to Angeles Link.

Pipeline sizing is the process of determining the optimal diameter and wall thickness of a pipeline so that it can safely and efficiently transport the required volume of gas under given operating conditions.

Effective pipeline sizing requires a thorough understanding of the physical and chemical properties of hydrogen as well as the dynamics of gas flow through pipelines. These include considerations of the gas's compressibility which affects how its volume changes with pressure; the type of flow – whether laminar or turbulent – which influences the pressure losses in the pipe; and the Reynolds number, a dimensionless quantity that helps determine the flow regime based on pipe dimensions, flow velocity, and gas viscosity.

Hydrogen is the lightest of all gases, which can significantly influence its behavior within a pipeline system. It has a low molecular weight, which can lead to higher flow rates while its low viscosity leads to a higher Reynolds number at comparable conditions, which could result in turbulent flow. Due to hydrogen's small molecule size and high diffusivity, pipelines must be constructed with materials that minimize permeation.

Temperature and pressure conditions, both environmental and operational, must also be carefully evaluated. Additionally, the required flow rate – dictated by consumer demand and production capacities – plays a fundamental role in determining the appropriate pipe diameter. By understanding and applying these considerations, the pipeline can be sized to meet current demand while also maintaining scalability for future needs without significant reengineering.

Sizing and design features identified within this report are subject to change as additional information and analysis of the system is completed. The Future Considerations Chapter of this report includes discussion on the next steps that progress the degree of certainty for pipeline sizing and design.

1.3 Study Approach

The Design Study allows for the integration of data from several related Angeles Link Phase 1 studies, including the Production, Demand, and Safety studies. This information is used to build the basis of the system evaluation from where the design parameters can be established to support hydraulic modeling. Hydraulic modeling is then used to evaluate Scenarios 1-8, which consider different potential routing pathways (Routing Analysis), production capacities and total system volumes (Production Study) from a hydraulic standpoint. Additional modeling is then completed for four potential preferred routes (as identified in the Routing Analysis) to evaluate pipeline configuration to determine preliminary sizing and material recommendations. These sizing and material recommendations are utilized for the purposes of cost estimation for Scenarios 1-8, which are then used to inform the Cost Effectiveness and Alternatives Study.

The following steps illustrate the activities completed within this Study and are explored in greater detail in the subsequent chapters.

1) Study Integration – System Description
2) Assumptions – Design Parameters
3) Scenario Evaluation – Hydraulic Analysis and System Resiliency
4) Material Review & Cost

2. SYSTEM DESCRIPTION

2.1. System Overview

The objective of Angeles Link is to transport clean renewable hydrogen, likely from multiple local and longer term regional clean hydrogen production sources to various delivery points in Central and Southern California, including the Los Angeles Basin (including the concentrated commercial and industrial area in and around the Ports of Los Angeles and Long Beach). Therefore, the Angeles Link Phase 1 Production Study and Demand Study provide information that is critical to the pipeline system sizing and design. These studies identify characteristics of the potential hydrogen supply to the pipeline along with the potential offtake from the pipeline.

The system is evaluated at varying levels of total system capacity, illustrative of possible temporal growth. This allows for evaluation considering the potential for short-term versus long-term sizing, with a total system capacity used for evaluation of the Angeles Link Phase 1 potential preferred routes.

2.2. Hydrogen Production

The Production Study identified three primary areas within SoCalGas's service territory for potential hydrogen production sites. The three potential Production Areas are referred to as San Joaquin Valley (SJV), Lancaster, and Blythe. Although these areas were identified as locations with a higher likelihood for large-scale production, hydrogen production facilities may also be located outside of these identified areas. Under Scenarios 1-8, production was modeled within pipeline routing as a supply that ranged from 500,000 – 750,000 tonnes per year (TPY) from various combinations of production areas.

As the location of the conceptual production facilities was not identified beyond the general areas illustrated below in Figure 1, the lateral, or secondary pipeline(s) that would connect to the main pipeline to transport hydrogen from individual production facilities to the larger system were excluded from the hydraulic model. See the Production Study for further detail.

2.3. Hydrogen Demand

The Demand Study projected potential demand for clean renewable hydrogen across the mobility, power generation, and industrial sectors in SoCalGas' service territory through 2045. See the Demand Study for further detail.

The Angeles Link system proposes to transport a portion of the projected demand under three cases, using the 2045 throughput sector ratios interpolated to approximately 0.5, 1.0, and 1.5 million tonnes per year (MMTPY). See Production Study for further detail. These Angeles Link specific throughput assumptions were used in this Design Study. Table 1 illustrates these various assumed annual throughputs.

Table 1 - Angeles Link Demand Cases

Angeles Link Phase 1 Study	Case 1	Case 2	Case 3
Sizing & Design Study	0.5 MMTPY	1.0 MMTPY	1.5 MMTPY

The Demand Study identified potential users and off-takers across Central and Southern California. Demand locations significantly influence the operational conditions of the system, including pressures and flow rates. For the purposes of hydraulic modeling and sizing for maximum throughput, it was assumed that all demand was concentrated at a single point within the Los Angeles Basin (LA Basin). This is a conservative assumption as potential off-takes were identified in the Demand Study located upstream of the LA Basin, where hydrogen may be withdrawn by off-takers located in Central and Southern California.

2.4. Hydrogen Storage

As noted in the Production Study, the storage of hydrogen can be used to balance fluctuations in supply and demand. Storage would hold excess hydrogen during production periods when supply exceeds demand, and provide hydrogen when demand exceeds supply. The volume of storage needed is in direct correlation to the operating and usage characteristics of the production and offtake facilities. Hydrogen may be stored and accessed within the pipeline system as well as in aboveground or underground hydrogen storage facilities discussed in the Production Study. Clean hydrogen production and aboveground and underground storage is not currently part of Angeles Link. As Angeles Link is further designed and, in alignment with the development of system requirements, the role of storage to support regional hydrogen producers and end users should be considered. Distributed storage equipment located at third-party production and end user sites, along with system line-pack, can provide storage capacity while at-scale storage technologies are developed over time to support regional requirements.

2.5. Pipeline Routes

The Routing Analysis identified a variety of different conceptual pipeline routes. The pipeline distances and elevation along the selected routes were modeled in ProMax[7], the hydraulic simulation software utilized in this study. Combinations of the conceptual Production Areas and pipeline routes shown in Figure 1 were evaluated, along with the preferred routes identified by the Routing Analysis. The pipeline routes will be evaluated in further detail in subsequent Phases and are subject to change based on additional information and continued developments in the hydrogen economy in Central and Southern California. See the Routing Analysis for further detail on conceptual route evaluation process, routing analysis, and resulting preferred routes.

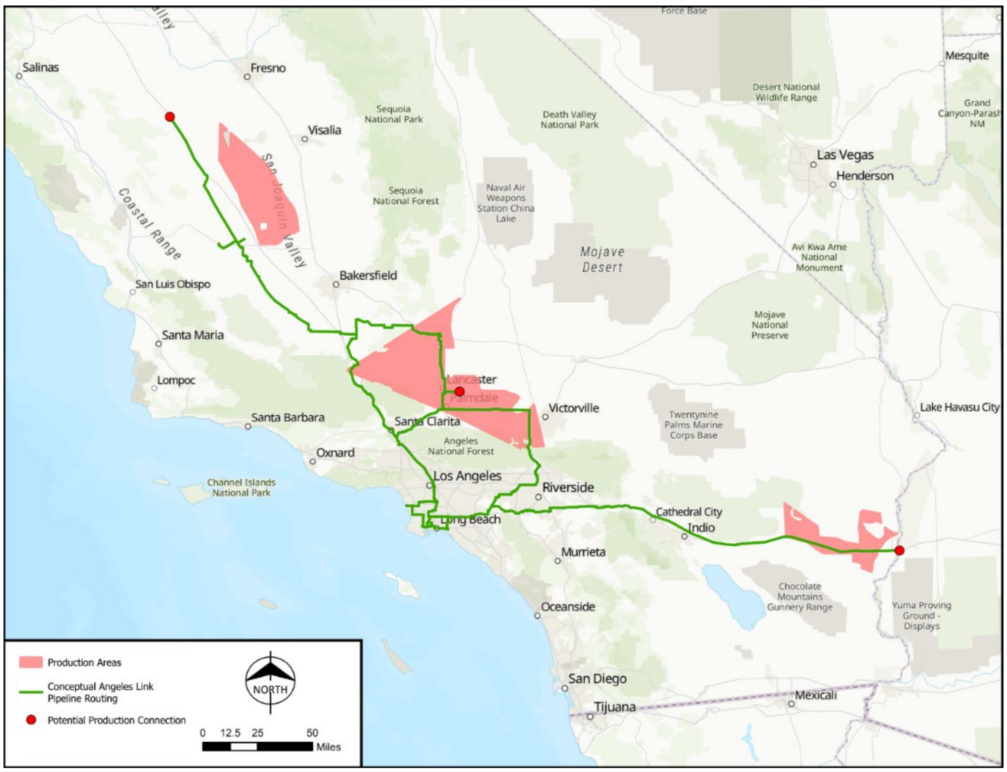

Figure 1 - Conceptual Production Areas and Pipeline Routing

[7] Refer to Section 4.1 for Pipe Modeling Software details.

3. DESIGN PARAMETERS

Specific criteria were used to conduct the preliminary engineering and design evaluation described in this document. These criteria form the design parameters for pipeline sizing, to guide engineering calculations and simulations. This chapter discusses the various criteria that were taken into consideration, and their impact on the study's results.

3.1. Industry Codes, Standards, and Best Practices

Transmission of clean renewable hydrogen across the value chain must prioritize safety and leverage applicable industry experience and best practice, regulations, codes, and standards. For example, the Pipeline and Hazardous Materials Safety Administration (PHMSA) sets pipeline safety regulations (Title 49 Code of Federal Regulations (CFR) Parts 190-199), which include specific requirements for the design, construction, operation, and maintenance of hydrogen pipelines. Industry specific requirements may be set by other agencies such as the American Petroleum Institute (API) and the American Society of Mechanical Engineers (ASME). States may have additional regulations, particularly concerning environmental impacts and safety measures. Refer to the Safety Study for details on applicable state codes and regulations.

ASME has developed a consensus design standard for hydrogen pipelines and plant piping in a document called ASME B31.12[8], "*Hydrogen Piping and Pipelines*" which covers the transportation of hydrogen, detailing requirements for materials, design, fabrication, and testing to ensure safety and efficiency. ASME B31.8, "*Gas Transmission and Distribution Piping Systems*" is another key design standard. Incorporating these standards by reference into federal regulations allows PHMSA to enforce industry standards and guidelines set by organizations like API or ASME. However, even when industry codes are not specifically incorporated by reference, they may offer relevant guidance and best practices for consideration. As compliance with codes and regulations are incorporated into the pipeline design, design governance will prioritize the more stringent requirements to increase safety.

As stated in the Evaluation of Applicable Safety Requirements, industry best practices for hydrogen pipelines emphasize the importance of integrating safety management systems, risk assessments, and the adoption of new technologies for leak detection and emergency response. The industry also focuses on ongoing research and development

[8] The latest edition of ASME B31.12 was published in 2019. As hydrogen pipelines have been recognized as a critical part of the energy transition, ASME members recently voted to update ASME B31.8 to address hydrogen pipelines and retire B31.12. This would include Hydrogen Industrial Piping in this project, currently be covered by ASME B31.12, which will be incorporated into ASME B31.8.

to address the challenges of hydrogen embrittlement and the unique properties of hydrogen.

These guidelines and regulations are designed to confirm that hydrogen pipelines are built and operated safely, efficiently, and sustainably, aligning with the broader goals of federal energy policies and environmental protection standards.

The following is a list of several key codes and standards applicable to hydrogen pipelines and related facilities:

- API 617, 618, 619, ISO 13631 for Compressors
- API 661 for Air Coolers
- API 1104, *Welding Pipelines and Related Facilities*
- ASME B31.3, *Process Piping*
- ASME B31.8, *Gas Transmission and Distribution Piping Systems*
- ASME B31.12, *Hydrogen Piping and Pipelines*
- ASME BPVC (Boiled and Pressure Vessel Code) Section VIII, *Rules for Construction of Pressure Vessels*
- ASME BPVC Section IX, *Welding, Brazing, and Fusing Qualifications*
- ASME BPVC Section XIII, *Rules for Overpressure Protection*
- 49 CFR Part 191 (Code of Federal Regulations), *Transportation of Natural and Other Gas By Pipeline; Annual, Incident, and Other Reporting*
- 49 CFR Part 192 (Code of Federal Regulations), *Transportation of Natural and Other Gas By Pipeline: Minimum Federal Safety Standards*
- CGA G-5.5 (Compressed Gas Association), *Standard for Hydrogen Vent Systems*
- NFPA 54 National Fuel Gas Code

3.2. Design Pressure

An initial discharge pressure from each pipeline compressor station was assumed to be the maximum allowable operating pressure (MAOP) of 1,200 psig. Based on system requirements to achieve the annual throughput of 1.5 MMTPY discussed in Section 2.3, the MAOP of 1,200 psig was selected to stay within a pressure rating of Class 600, as defined by American National Standards Institute (ANSI). The efficacy of 1,200 psig as the maximum pressure was later confirmed through the various hydraulic calculations performed in this study. At lower MAOP, the available pressure drop becomes a limiting factor to reach the desired pressure at the destination. Maintaining a higher system pressure allows greater pipeline flow rates with less pressure drop from the pipeline inlet to the pipeline outlet. Minimum delivery pressure within the LA Basin was assumed to be 200 psig.

For purposes of modeling, the initial inlet pressure (suction pressure) to the compressor stations was determined to be 500 psig. It is assumed that third-party hydrogen production facilities will provide adequate pressure via their equipment to successfully connect to the Angeles Link system. Electrolyzer technologies produce hydrogen at an outlet pressure typically between 430 and 580 psig.[9] In addition, the intake pressure will ultimately be contingent upon the location of the third-party producer with respect to the broader system; intake pressure for third-party connections may vary between station inlet pressure and pipeline MAOP. The actual compressor station inlet pressure may vary depending on system requirements, operating parameters, and equipment selection, which will be further evaluated in a future phase of the project.

3.3. Design Flow Rates

The Production Study included calculations that estimate the average annual flow rates for the clean renewable hydrogen transported through the Angeles Link system. Calculations from this study were used to apply the average annual flow rate for a total system capacity of 1.5 MMTPY to the steady-state hydraulics within this Study for the sizing of Angeles Link. This flow rate results in approximately 4,110 TPD. Average annual flow rates based on total system capacity of 0.5 MMTPY and 1.0 MMTPY were also applied within the scenarios evaluated and discussed further in Section 4.5.

The hydrogen supply follows a solar (without battery storage) energy hourly profile, which varies by the hour and season. The Production Study concluded that the maximum hourly flow injection rates from production may be 2.8 times the average annual injection flow rates. Furthermore, the peak demand may be highly driven by the power generation sector with potential hourly demand data indicating peak flow rates may exceed 3.8 times the average production rate from storage to the demand locations.

Application of higher flow rates representative of a single event in a steady-state model, such as a maximum hourly flow rate, increase the probability of overestimating the system requirements to accommodate a single factor, without considering other system conditions. The variations in flow rate that are expected due to the mismatch between supply production and demand requirements must be further evaluated using transient modeling, as discussed in the Future Considerations Chapter. This may affect future system pipeline sizing recommendations.

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[9] Ikhmal Salehmin , M. N., Husaini, T., Goh, J., & Sulong, A. B. (2022, July 14). High-pressure PEM water electrolyser: A review on challenges and mitigation strategies towards green and low-cost hydrogen production. Energy Conversion and Management. https://www.sciencedirect.com/science/article/abs/pii/S0196890422007786; 30-40bar to PSI by 1 bar = 14.5038 PSI

3.4. Gas Composition for Modeling

Electrolyzers produce hydrogen at purity levels ranging from 99.9% to 99.999%.[10] The purity of hydrogen impacts its application. For fuel cells, particularly those used in transportation and portable applications, high-purity hydrogen (above 99.99%) is crucial to prevent catalyst poisoning and operate efficiently.[11] In contrast, hydrogen combustion engines are less sensitive to lower purity levels, as they can tolerate certain impurities without significant performance degradation.[12] For the purposes of modeling, a gas composition of pure hydrogen (100%) was assumed.

3.5. Pipe Sizing Philosophy

Pipelines are safe, efficient and because most are buried underground, largely unseen.[13] PHMSA acknowledges that the efficiency of volumes transported by pipeline are beyond the capacity of other forms of transportation[14], and furthermore DOE concludes that dedicated hydrogen pipelines moving large volumes over long distances are critical to achieving economies of scale.[15] To transport the total annual throughput of 1.5 MMTPY, it would take approximately 12,700 gaseous trucks at 1 ton per load capacity and 3,400 loading bays dispatching four trucks per day to deliver hydrogen from production to potential off-takers in Central and Southern California, including the LA Basin.[16] The current SoCalGas system has pipelines sized from 2-inch to 36-inch in diameter, and pipelines throughout the country range in size from 2-inch to 42-inch. While existing

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[10] International Energy Agency (IEA). (2020). The Future of Hydrogen. https://www.iea.org/reports/the-future-of-hydrogen

[11] Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2JU). (2016). Hydrogen roadmap Europe – A sustainable pathway for the European energy transition. Publications Office. https://data.europa.eu/doi/10.2843/341510

[12] Wróbel, K., Wróbel, J., Tokarz, W., Lach, J., Podsadni, K., & Czerwiński, A. (2022). Hydrogen Internal Combustion Engine vehicles: a review. *Energies*, *15*(23), 8937. https://doi.org/10.3390/en15238937

[13] Where are the pipelines?. Energy API. (n.d.-c). https://www.api.org/oil-and-natural-gas/wells-to-consumer/transporting-oil-natural-gas/pipeline/where-are-the-pipelines

[14] General Pipeline Faqs. PHMSA. (n.d.-a). https://www.phmsa.dot.gov/faqs/general-pipeline-faqs

[15] Office of Technology Transitions, Office of Clean Energy Demonstrations, Hydrogen & Fuel Cell Technologies Office, Elgowainy, A., Penev, M., Crane, D., Cummins, K., Klembara, M., Chan, V., Tian, L., Shah, J., & Wagner, J. (2023). Pathways to commercial liftoff: Clean hydrogen. https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf

[16] See Angeles Link Phase 1 Cost Effectiveness Study, Table 22

hydrogen pipelines in the United States range in size from 10-inch to 24-inch, there are global initiatives such as the European Hydrogen Backbone[17] that propose a dedicated hydrogen pipeline transport network spanning tens of thousands of kilometers with diameters up to 48-inch.

Utilizing commonly manufactured pipe sizes and minimizing variation can provide benefits. These benefits include more predictable and consistent flow characteristics as well as interchangeability of piping components such as fittings, flanges, and valves, and cost-efficiency when procuring, manufacturing, operating, and inspecting materials in bulk. In general, the hydraulic analysis sought to utilize a set of common pipe sizes that range from 12-inch to 36-inch.

Proposed pipeline routes that aim to connect areas of clean renewable hydrogen production with areas of demand tend to originate closer to or within areas of rural land and travel to serve demand in more concentrated urban centers. The population density, proximity to, and occupancy of buildings tend to increase as pipelines travel from rural to urban areas. These factors are considered for pipeline design and generally result in smaller pipe sizes due to requirements for operating conditions and constructability.

As gas flows through a pipeline, it experiences friction against the pipe walls leading to pressure loss, or “drop”. The pressure drop available in the system impacts the selection of pipe size, as it will determine the power and flow requirements to maintain the operating pressure. Smaller pipe sizes result in larger pressure drop, while larger pipe sizes result in lower pressure drop. Balancing pipe size and power requirements is essential to overcome pressure losses while maintaining system efficiency and economic feasibility.

Pipelines are sized in terms of their internal and outer diameter. These two measurements will be different as they account for the wall thickness of the pipe material. Material specifications and requirements for different sizes are governed by standards.

While pipelines themselves transport energy efficiently, pipeline size affects the efficiency of supply chain and logistics components during siting, construction, and operation. Pipeline diameters and wall thickness area affected by a variety of logistic components:

Commercial Availability – While pipes can be milled in any size needed, using commercially available standard pipe sizes can maximize cost effectiveness. Specifications of custom pipe may result in a limitation on the manufacturers available, decrease availability and increase cost, and there may also be a mismatch between the

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[17] Jens, J., Wang, A., Van Der Leun, K., Peters, D., Buseman, M., & Guidehouse. (2021). Extending the European hydrogen backbone. In A European Hydrogen Infrastructure Vision Covering 21 Countries. https://ehb.eu/files/downloads/European-Hydrogen-Backbone-April-2021-V3.pdf

pipeline and appurtenances or fixtures needed to operate and connect. Custom pipe can therefore result in additional customization to the fittings, other pipeline fixtures, and the equipment needed to construct and operate. Standard sizes result in an increase in the availability of materials and therefore, lower cost.

Materials Storage – Pipeline diameter also affects the maximum allowable stacking heights for the material from a storage standpoint, adding additional logistic elements for consideration.[18] This is typically due to the weight and the ease of handling.

Handling – The weight and size of loads during loading and unloading in transportation is important to the evaluation of the potential challenges it may present both in terms of equipment used in the process and the risks to job personnel. In general, smaller and lighter loads result in simpler handling.

3.6. Compressor Assumptions

3.6.1. Compression at Production Sites

It is assumed that compression at third-party hydrogen production facilities and storage locations will be third-party owned and operated. Production facilities should provide the pressure to transport hydrogen to an Angeles Link system. It is expected that storage locations will provide the pressure to store hydrogen at the appropriate conditions for the selected storage technology. Refer to the Production Study Appendix B for more information on storage technology requirements.

3.6.2. Compression into Angeles Link Pipeline

Compression from the point of injection from third-party producers to the demand centers or point of injection from third-party storage to the demand centers, is expected to be operated by SoCalGas. The various assumed compressor location(s) for purposes of this analysis include:

- San Joaquin Valley (SJV)
- Lancaster
- Blythe
- Wheeler Ridge (Preferred Route Configuration D, with intermediate compression)

[18] American Ductile Iron Pipe Stacking. (n.d.-a). https://liberty.american-usa.com/SubmittalsPDF/ADIP/PDF/OtherTopics/Loading_and_Stacking.pdf

Intermediate compression was considered to reduce operating near MAOP and to potentially increase pack and draft capabilities to provide daily operational buffer capacity and longer-term hydrogen storage.

3.6.3. Compressor Types

Three compressor types that may be used to transport clean renewable hydrogen are centrifugal, diaphragm, and reciprocating. The different compressors' varying functions and benefits are described below.

Centrifugal compressors increase the pressure by using the rotation of impeller blades to increase kinetic energy. The kinetic energy will then increase the potential energy in the form of pressure through the compressor diffuser. Although centrifugal compressors work well in high-flow environments, high pressures may cause the machinery to stall and cause impacts to hydrogen supply downstream. Additionally, hydrogen gas has a low molecular weight which results in low operating density and pressure. This low pressure may increase operating speeds that would require custom impeller material and design to withstand the resulting forces.

Diaphragm compressors are driven by a reciprocating piston-crankshaft mechanism that separates hydraulic fluid/oil from process gas. Since these two fluids remain separated, diaphragm compressors are typically used for hydrogen service end-use where hydrogen purity can be crucial to the safe and reliable operation of equipment. This type of compressor is typical in hydrogen fueling stations. Diaphragm compressors may not be ideal for Angeles Link due to their relatively low flow capacity on an individual unit basis (necessitating many compressors operating in parallel) and their mechanical complexity relative to the other compressor types discussed in this section.

Reciprocating compressors utilize a piston and crankshaft to drive gases at varying flow rates in high-pressure environments. To reduce potential issues arising from hydrogen embrittlement, reciprocating compressors are customizable, allowing specific choices of materials that will be in contact with hydrogen. Therefore, the adaptability and durability of reciprocating compressors compared to their counterparts proves advantageous in situations for varying pressures and flow rates.[19]

After consulting vendors and reviewing compressor options, the reciprocating compressor is recommended on a preliminary basis due to its material adaptability,

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[19] Sdanghi, G., Maranzana, G., Celzard, A., & Fierro, V. (2019). Review the current technologies and performances of hydrogen compression for stationary and automotive applications. Renewable and Sustainable Energy Reviews, 102, 150–170. https://doi.org/10.1016/j.rser.2018.11.028

resiliency, and favorable turn-down ratios[20] that provide versatility in dynamic flow and pressure conditions, which are anticipated for the proposed Angeles Link system. This study assumed reciprocating compressors for cost estimate development purposes and will select a compatible compressor type in a future phase of the project.

3.6.3.1 Compressor Drives

The compressor drive should consider renewable sources of energy to align with the objective of Angeles Link to develop a clean renewable hydrogen transport system. Compressor drives refer to the mechanism or system responsible for powering the operation of a compressor, like an engine in an automobile. The two main types of compressor drives use electricity or gas as the fuel source. In natural gas applications, typically a share of the gas stream is used as fuel in an engine to drive an attached compressor. For hydrogen applications, a gas driven compressor would utilize a portion of the hydrogen fuel stream to power the compression, and the engine itself functions similarly to a standard automobile engine. The geometry of the pistons and combustion timing must be altered to fit the profile of hydrogen gas as it has a different composition.

Industry leaders and manufacturers are researching dual-drive setup where both electricity and gas are utilized in the compressor drive. There are emerging technologies that would develop 100% hydrogen-driven reciprocating compressors capable of outputting 1,000 kW (1,340 hp), 3,000 kW (4,020 hp), and even 10,000 kW (13,400 hp) power at 50 Hz in the future. The existing hydrogen-driven engines are currently smaller than those needed to efficiently run the compressors required for the Angeles Link system and are primarily designed for generators, which have different operational demands compared to compressors.

Based on available information as of the date of this publication, one known company has a patent for a dual hydrogen driven compression technology[21], and the use of the technology is approved for two compressor packagers for use on natural gas engines available from two manufacturers. Neither of these manufacturers has an existing engine

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[20] Turn-down is the ratio of maximum capacity to minimum capacity.
[21] There are commercially available compressors that can operate and accommodate up to a 25% hydrogen-natural gas blend, with continuous ratings ranging from 1,515 kW to 2,519 kW (2,030 hp to 3,380 hp). Using blended natural gas and hydrogen fuels in an engine can lower emissions compared to using pure natural gas and can improve overall fuel flexibility and resilience by utilizing hydrogen directly from the pipeline. However, the requirement for two fuel sources means that if the externally sourced natural gas supply is disrupted, the engine cannot run. Managing the blend ratio also adds operational complexity, potentially increasing maintenance and monitoring requirements.

designed to drive a compressor that can run on pure hydrogen. Both manufacturers are developing such an engine for a dual-drive setup.

Energy system resiliency in the context of hydrogen or electric-driven compression is another consideration for maintaining reliable pipeline operations while managing emissions. While compressors powered by hydrogen or renewable electricity offer benefits, the interconnected nature of using hydrogen to power electric compression requires a robust backup system to help mitigate risks. This could involve integrating renewable energy sources (e.g., solar with battery storage) or using a hybrid approach (e.g., combining hydrogen and grid electricity) which supports resiliency by helping prevent energy vulnerabilities in one area from impacting another.

Fully hydrogen gas driven engines are commercially available but not at the specifications required for this study's preliminary results. This study assumed electric-driven compressors for cost estimate development purposes and will analyze available technologies in development for hydrogen-fueled engines in a future phase of the project.

3.6.3.2 Compressor Assumptions for Pipe Sizing

The compressor efficiency was assumed to be 80% after consultation with hydrogen compressor vendors and manufacturers. The temperature and pressure of the fluid in the pipeline are used by the equation of state to calculate physical properties of the fluid, including the density and viscosity which affect the pressure drop throughout the pipeline. The ground type, which affects the pipeline heat transfer rate to the surrounding soils, was based on engineering judgment from existing pipeline hydraulic analyses performed in Southern California.

In future project phases, specific soil parameters should be based on soils reports developed from soil samples along the potential pipeline routes. For the purposes of this study, the heat exchanger pressure drop was assumed to be 0.25 psi based on API 661 Air-Cooled Heat Exchangers. An air-cooled heat exchanger has a pressure drop due to frictional losses and flow resistance as the gas moves through many small tubes, which are used to transfer heat from the gas to the atmosphere. This pressure drop reduces the downstream pressure and can decrease the flow rate. The heat exchanger outlet temperature of 120 °F is based on requirements for Department of Transportation (DOT) pipelines and can be found in CFR 192.112.[22] The parameters in Table 2 were assumed

[22] 49 CFR 192.112 -- Additional design requirements for steel pipe using alternative maximum allowable operating pressure. (n.d.). https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-D/part-192/subpart-C/section-192.112

for the Phase 1 hydraulic analysis and will be updated in a future phase of the project when a preferred route is selected.

Table 2 - Compressor Assumptions

Parameter	Value
Compressor Polytropic Efficiencies	80%
Heat Exchanger Pressure Drop	0.25 psi
Compressor Discharge Temperature out of Cooler	120 °F
Centerline of Buried Pipe	48 Inches
Ground Type	Clay, Moist
Pipeline Ambient Temperature	65 °F

3.6.3.3 Heat Exchangers

When hydrogen gas is compressed, the gas temperature rises from the operating equipment, and a heat exchanger is required downstream from the compressor to lower the stream temperature. This also prevents the compressor from seeing high inlet temperatures in subsequent stages, which can lead to high-temperature upsets and derating piping. Operating with a pressure drop of 0.25 psig, the heat exchangers used in the hydraulic model prevent the hydrogen stream from exceeding 120 °F within the pipeline. The pressure drop of 0.25 psig, as specified in the basis of design, was chosen as a conservative number for gas compression based on engineering experience and this value or a lower one can be specified as the maximum allowable pressure drop during procurement.

3.7. Design Basis

The design parameters discussed in this Chapter were used as the basis for hydraulic analysis and are summarized in Table 3.

Table 3 - Pipeline Design Information Summary

Parameter	Value
Case 1 Flow Rate	0.5 MMTPY
Case 2 Flow Rate	1 MMTPY
Case 3 Flow Rate	1.5 MMTPY
Compressor Station Inlet Pressure	500 psig
LA Basin Demand Pressure	200 psig
Maximum Allowable Operating Pressure	1,200 psig

4. HYDRAULIC ANALYSIS

For the purposes of this study, steady-state average flows were used to develop pipeline size criteria, and the location and operation of third-party storage were excluded from the hydraulic model. In a pipeline system, a steady-state condition occurs when the flow rates entering and leaving the system are equal, maintaining a constant pressure at any given point in time. Conversely, a transient model represents conditions where the flow rates entering and leaving the system can change and be unequal, resulting in fluctuating pressure at any given point in time.

The following additional assumptions and methodologies were applied in the hydraulic study:

a. Hydraulics calculations were performed in ProMax Version 6.0.
b. The hydraulic analysis is based on steady-state calculations.
c. Transient calculations were not performed in this phase of the project.
d. The property package for calculations was GERG-2008 equation of state.
e. Beggs and Brill correlation was used to model the pipeline flow.

4.1. Pipe Modeling Software

ProMax software, a process simulator used for gas processing, refining, and chemical facilities, was used to simulate hydrogen flow through pipeline sections. At the time of this evaluation, ProMax was the only software capable of using GERG-2008[23] and therefore the preferred software to model hydrogen hydraulics with high accuracy. ProMax is a steady-state modeling software and does not have transient modeling capabilities. Flow was modeled by balancing through the system such that the delivery pressures at the LA Basin demand centers were sufficient for intended use (minimum pressure was assumed to be 200 psig at the LA Basin).

4.2. Steady State Analysis

A steady-state model using average annual flow rates was used to determine the preliminary design and evaluate overall system feasibility.

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[23] ProMax hydraulic analysis include GERG-2008. GERG-2008, a multi-parameter equation of state developed by The Groupe Européen de Recherches Gazières (GERG), is recognized as an equation of state capable of representing the behavior of hydrogen gas in a complex system. The second equation used in the simulation environment is known as the Beggs and Briggs correlation and allows the model to identify multiphase flow behavior subject to various inclination angles, elevations, and directions.

The variability in the production and demand profiles as discussed in Section 3.3 will require further transient hydraulic modeling to understand the time-dependent system response. Transient modeling will require input and information that is currently unknown in Angeles Link Phase 1 such as definitive initial and final operating conditions (flow rates, pressures, and temperatures), detailed pipeline routing and geometry, and distinct location of customers, third-party producers, and third-party storage operators. Transient modeling should be considered in the future, upon further determination of storage site(s), demand sector locations, and pipeline routing selection. The additional modeling should reflect both high-demand/low-production and low-demand/high-production scenarios to fully assess system sizing requirements.

4.3. Pipeline Resiliency

The pipeline system was modeled with select portions as two parallel lines (or dual run) with identical specifications, operating conditions, and routing from one point to another. The dual run configuration acts as a backup if one of the parallel lines is temporarily removed from service, such as during maintenance, inspections, or emergency situations. This pipeline configuration can improve system resiliency during potential disruptions, minimize downtime, and allow for continuous operation.

Another approach to increase operational resiliency is to design a pipeline loop, where multiple pipelines combine and split at various points to form a “loop”. A pipeline loop can provide additional backup capability if a portion of that system becomes unavailable; the other pipelines forming the loop could supply flow to maintain operation, sometimes in a bidirectional manner.

Both dual run and pipeline loop configurations can also provide increased storage capacity within the system to meet demands during peak usage periods.

4.4. Model Schematic Overview

The GIS data for the pipeline routes identified in the Routing Analysis was imported into ProMax and used as the basis for the hydraulic simulations. A schematic overview of the main system components and location evaluated are shown in Figure 2. The hydraulic models represent different combinations of these system components based on varying factors such as production and demand locations, target throughput, and pipeline routing configurations.

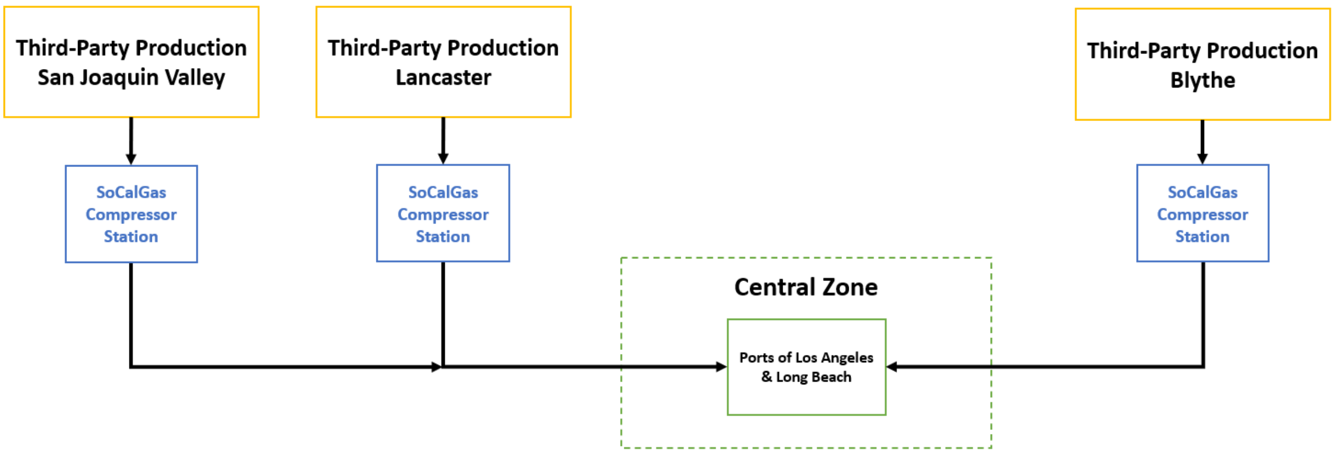


Figure 2 - Schematic Overview of System Components Evaluated

4.5. Scenarios

Results from the Production Study were used as the basis of hydraulic analysis where the following were modeled:

- Scenarios 1 – 3: Case 1 throughput of 0.5 MMTPY
- Scenarios 4 – 6: Case 2 throughput of 1.0 MMTPY
- Scenarios 7 – 8: Case 3 throughput of 1.5 MMTPY

4.5.1. Modeling Hydrogen Storage

While storage is not currently part of Angeles Link and was excluded from the hydraulic analysis, connections to potential storage locations were modeled to evaluate potential pipeline requirements and to develop estimates for the Cost Effectiveness study. For the Lancaster and SJV production locations, it is assumed the pipeline passes by potential underground storage between production and the demand centers in the LA Basin. For the Blythe production location, it is assumed the pipeline can connect to potential salt cavern storage in both Arizona and Utah. To the extent that regional underground storage is developed, such underground storage, including compression into storage and associated hydrogen purification processes after withdrawal from storage, is assumed to be operated by a third party. The compression required for storage is separate from the system hydraulics and is not included in the model. It is assumed that the underground storage cavern is pre-charged with hydrogen such that any additional hydrogen stored by the operation can be fully retrieved by the system.

Storage was not considered in the model to balance the flow between production, storage, and the demand centers. As gas storage systems serve as a buffer to smooth out fluctuations between production and demand, modeling a system that can handle the required throughput without considering storage is a conservative assumption. This approach simplifies the analysis by focusing on the pipeline's capability to meet demand directly, without relying on storage to balance the flows. Storage can also be achieved within a pipeline system through a network of distributed above-ground equipment and utilization of line packing, which refers to storing and then withdrawing gas supplies from the pipeline. For more information on hydrogen storage technologies, see Production Study Appendix B.

4.5.2. Scenario Results

Eight scenarios were evaluated as potential systems to deliver clean renewable hydrogen from the primary production locations identified to potential demand centers in Central and Southern California. For conservative modeling purposes, it was assumed that most demand centers were concentrated in the LA Basin. Single-run and mixed-run configurations were evaluated for Scenarios 1-8 to provide a range of preliminary pipe and compressor sizes. Select pipelines were modeled as two-parallel pipes in the mixed-run configuration to provide operational flexibility. The single-run configuration results are summarized in Table 4 and were used to develop cost estimates for the Cost Effectiveness study to determine the potential levelized cost of clean renewable hydrogen to be delivered to end-users. The cost estimates were also provided to the Workforce Evaluation as the basis for the employment and economic impact analysis. Refer to Chapter 6 for Cost Estimate details.

Table 4 - Scenario 1-8 Single-Run Configuration Results

Scenario	Total Throughput MMTPY	Primary Production Location(s)	Total Route Mileage	Range of Nominal Pipe Sizes	Total Compressor Station(s)	Compressor Station*
1	0.5	San Joaquin Valley (SJV)	355	12-in to 30-in	1	33,000 hp
2	0.5	Lancaster	314	12-in to 24-in	1	33,000 hp
3	0.5	Blythe	303	12-in to 30-in	1	33,000 hp
4	1.0	SJV, Lancaster	392	12-in to 36-in	2	33,000 hp (each)
5	1.0	Lancaster, Blythe	537	12-in to 30-in	2	33,000 hp (each)
6	1.0	SJV, Blythe	578	12-in to 30-in	2	33,000 hp (each)

7	1.5	SJV, Lancaster	390	16-in to 36-in	2	50,000 hp (each)
8	1.5	SJV, Lancaster, Blythe	616	12-in to 36-in	3	33,000 hp (each)

*Compressor station size specified for line packing operation.

In Scenario 1, the SJV production location was assumed to produce 0.5 MMTPY. The main pipeline from the SJV production location to the LA Basin was estimated to be 24-inch and 30-inch under a single-run configuration, and 16-inch and 20-inch under a mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 20-inch, and 24-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near the SJV production area.

In Scenario 2, the Lancaster production location was assumed to produce 0.5 MMTPY. The main pipeline from the Lancaster production location to the LA Basin was estimated to be 24-inch under a single-run configuration, and 16-inch under a mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 16-inch, and 24-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near the Lancaster production area.

In Scenario 3, the Blythe production location was assumed to produce 0.5 MMTPY. The main pipeline from the Blythe production location to the LA Basin was estimated to be 30-inch under a single-run configuration, and 20-inch under a mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 16-inch, and 24-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near the Blythe production area.

Figure 3 illustrates where potential third-party production could be as well as potential storage locations which may be developed in the future to support regional hydrogen producers and end users. These are the assumptions for Scenarios 1 through 3. Scenario 1 has the highest total route mileage of the 0.5 MMTPY throughput scenarios evaluated and allows for the most direct access to potential depleted oil and gas fields for underground storage in Central California. Scenario 2 presents the closest distance from a potential production location (Lancaster) to the LA Basin and is also relatively close to potential Central California underground storage access. Scenario 3 has the lowest total route mileage of the 0.5 MMTPY throughput scenarios and is closest to potential salt basin underground storage outside of California.

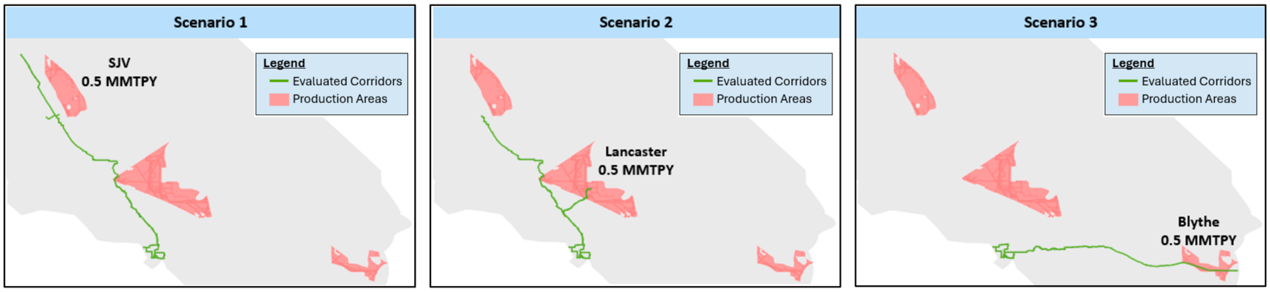


Figure 3 - Scenario 1-3

In Scenario 4, the SJV and Lancaster production locations were assumed to produce 0.5 MMTPY each resulting in a total of 1.0 MMTPY throughput. The main pipeline from the SJV production location to the junction combining with the pipeline from Lancaster was estimated to be 24-inch and 30-inch under the single-run configuration, and 16-inch and 20-inch under mixed-run configuration. The main pipeline from the Lancaster production location to the junction combining with pipeline from SJV was estimated to be 24-inch under the single-run configuration, and 16-inch under mixed-run configuration. The pipeline from the SJV and Lancaster junction to the LA Basin was estimated to be 36-inch under the single-run configuration, and 24-inch under the mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch and 20-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near each of the SJV and Lancaster production areas.

In Scenario 5, the Lancaster and Blythe production locations were assumed to produce 0.5 MMTPY each, resulting in a total of 1.0 MMTPY throughput. The main pipeline from the Lancaster production location to the LA Basin was estimated to be 24-inch under the single-run configuration, and 16-inch under the mixed-run configuration. The main pipeline from the Blythe production location to the LA Basin was estimated to be 24-inch and 30-inch under the single-run configuration, and 16-inch and 20-inch under mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 16-inch, 20-inch, and 24-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near each of the Lancaster and Blythe production areas.

In Scenario 6, the SJV and Blythe production locations were assumed to produce 0.5 MMTPY each, resulting in a total of 1.0 MMTPY throughput. The main pipeline from the SJV production location to the LA Basin was estimated to be 30-inch under the single-run configuration, and 20-inch under the mixed-run configuration. The main pipeline from the Blythe production location to the LA Basin was estimated to be 30-inch under the single-run configuration, and 20-inch under mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 20-inch, and 30-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near each of the SJV and Blythe production areas.

Figure 4 illustrates where potential third-party production could be as well as potential storage locations which may be developed in the future to support regional hydrogen producers and end users. These are the assumptions for Scenarios 4 through 6, which are also evaluated in the Cost Effectiveness Study. Scenario 4 has the lowest total route mileage of the 1.0 MMTPY throughput scenarios evaluated with potential depleted oil and gas fields for underground storage located approximately in the middle between the SJV and Lancaster production locations. Scenario 5 assumed Central California storage access for the Lancaster production location, and storage access outside of California for the Blythe production location. Scenario 6 has the highest total route mileage of the 1.0 MMTPY throughput scenarios and assumed Central California storage access for the SJV production location, and storage access outside of California for the Blythe production location.

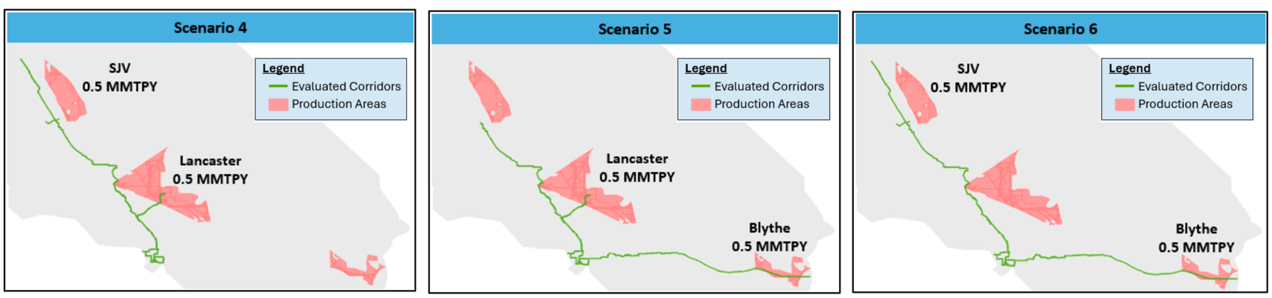


Figure 4 - Scenario 4-6

In Scenario 7, the SJV and Lancaster production locations were assumed to produce 0.75 MMTPY each resulting in a total of 1.5 MMTPY throughput, based on the availability of land identified within the Production Study. The main pipeline from the SJV production location to the junction combining with the pipeline from Lancaster was estimated to be 30-inch under the single-run configuration, and 20-inch under mixed-run configuration. The main pipeline from the Lancaster production location to the junction combining with pipeline from SJV was estimated to be 24-inch under the single-run configuration, and 16-inch under mixed-run configuration. The pipeline from the SJV and Lancaster junction to the LA Basin was estimated to be 36-inch under the single-run configuration, and 24-inch under the mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 16-inch, 20-inch, 24-inch, and 36-inch. For both configurations, a 50,000 hp compressor station was calculated and assumed to be located near each of the SJV and Lancaster production areas.

In Scenario 8, all three SJV, Lancaster, and Blythe production locations were assumed to produce 0.5 MMTPY each resulting in a total of 1.5 MMTPY throughput. The main pipeline from the SJV production location to the junction combining with the pipeline from Lancaster was estimated to be 30-inch under the single-run configuration, and 20-inch under mixed-run configuration. The main pipeline from the Lancaster production location to the junction combining with pipeline from SJV was estimated to be 24-inch under the single-run configuration, and 16-inch under mixed-run configuration. The pipeline from the SJV and Lancaster junction to the LA Basin was estimated to be 36-inch under the single-run configuration, and 24-inch under the mixed-run configuration. The main pipeline from the Blythe production location to the LA Basin was estimated to be 24-inch and 30-inch under the single-run configuration, and 16-inch and 20-inch under mixed-run configuration. Under both single- and mixed-run configurations, the pipelines within the LA Basin were estimated to be 12-inch, 20-inch, 24-inch, and 30-inch. For both configurations, a 33,000 hp compressor station was calculated and assumed to be located near each of the SJV, Lancaster, and Blythe production areas.

Figure 5 illustrates where potential third-party production could be as well as potential storage locations which may be developed to support regional hydrogen producers and end users. These are the assumptions for Scenarios 7 and 8, which are also evaluated in the Cost Effectiveness Study. Scenario 7 has the lower total route mileage of the 1.5 MMTPY throughput scenarios evaluated, and access to potential depleted oil and gas fields for underground storage located approximately in the middle between the SJV and Lancaster production locations. Scenario 8 has the highest total route mileage of the 1.5 MMTPY throughput scenarios and assumed Central California storage access for the SJV and Lancaster production locations, and storage access outside of California for the Blythe production location.

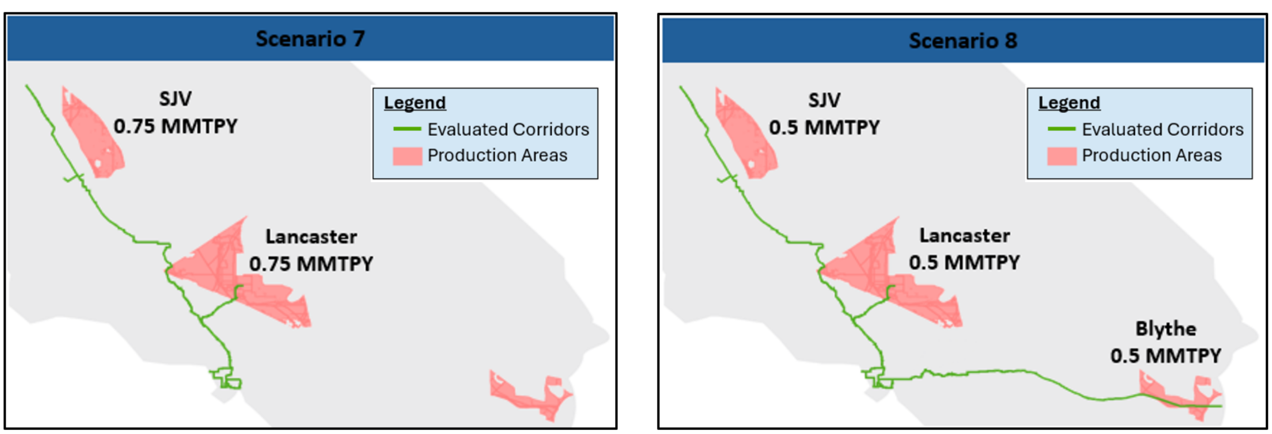


Figure 5 - Scenario 7 and 8

In all scenarios, the Central Zone (the area near the Ports of Los Angeles and Long Beach) has pipeline loops, allowing most of the lines in this area to be single lines. The Central Zone is represented in Figure 6. Once the main pipelines reach the Central Zone, the main pipeline(s) split, allowing them to cover more geographic areas that can serve as future demand takeoff points as hydrogen demand increases. Each side of the loop provides additional capacity, so if a portion of one pipeline becomes unavailable, flow could be supplied by the other pipeline sections forming the loop. This looping approach also allows for smaller pipe diameters that require less space for construction, which may be necessary in areas with high density of subsurface utilities and other congestion found within more populated and urban areas.

Figure 6 - Conceptual Central Zone Pipelines Modeled

4.6. Preferred Route Configurations

After evaluation of the routes, the Routing Analysis identified four Preferred Routes – A, B, C, and D – to be modeled and evaluated for preliminary sizing and system design. Scenario 7 reflects Preferred Route A. These configurations represent high-level preliminary pathways of highest potential to connect clean renewable hydrogen production with concentrated areas of demand at the time the analysis was conducted. The routes and variation will be evaluated in further detail in subsequent Phases and are subject to change based on additional information and continued developments in the hydrogen economy in Central and Southern California.

4.6.1. Preferred Route Configuration Results

The following sections summarize the results for the Preferred Routes A, B, C, and D. In Table 5, the term "Normal" refers to the normal operating conditions the compressor station will experience based on the modeled throughput (or flow rate), and "Max" refers to operating compressor at MAOP of 1,200 psig during line packing operation.

Table 5 - Preferred Routes: Single and Mixed Run Result Comparison

	Configuration A		Configuration B		Configuration C		Configuration D*	
	Single Run	**Mixed Run**	**Single Run**	**Mixed Run**	**Single Run**	**Mixed Run**	**Single Run**	**Mixed Run**
Throughput	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY	1.5 MMTPY
Mileage of Land Traversed	390 miles		406 miles		472 miles		481 miles	
Installed Pipe	390 miles	699 miles	406 miles	730 miles	472 miles	715 miles	481 miles	880 miles
Pipe Sizes	16", 20", 24", 30", 36"	16", 20", 24"	20", 36"	20", 24"	20", 24", 30", 36"	20", 24"	24", 36"	24"
SJV Compressor Station								
Normal Outlet Pressure	725 psig	1,000 psig	815 psig	1,065 psig	825 psig	1,010 psig	950 psig	1,180 psig
Normal Power	19,500	38,000 hp	26,000	44,000 hp	26,500	39,000 hp	35,000	49,000 hp
Max Power	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp
Lancaster Compressor Station								
Normal Outlet Pressure	800 psig	1,020 psig	700 psig	950 psig	700 psig	885 psig	775 psig	1,015 psig
Normal Power	25,000	39,500 hp	17,500	36,000 hp	17,500	30,500 hp	23,000	39,000 hp
Max Power	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp	50,000 hp

*Configuration D results does not include intermediate compression. Refer to Section 4.6.1.4 for intermediate compression results.

4.6.1.1 Preferred Route Configuration A (Route A)

Route A is the lowest mileage of all preferred route configurations and provides the most direct path to connect third-party production areas of SJV and Lancaster with the demand centers in Central California and Los Angeles Basin. The flow within the pipeline was modeled to split within the Los Angeles Basin as displayed in Figure 6. Locations along Route A are presented in Figure 7 with results from the hydraulic calculations shown in Figure 8. A summary of the labeled locations follows:

- Point 1 is the connection point modeled for SJV production location
- Point 2 is the connection point modeled for Lancaster production location
- Point 3 is the junction point where SJV and Lancaster flow combine
- Point 4 is the entry point to the Central Zone (beginning of the LA Basin)
- Point 5 is the Los Angeles Basin Demand Pressure location

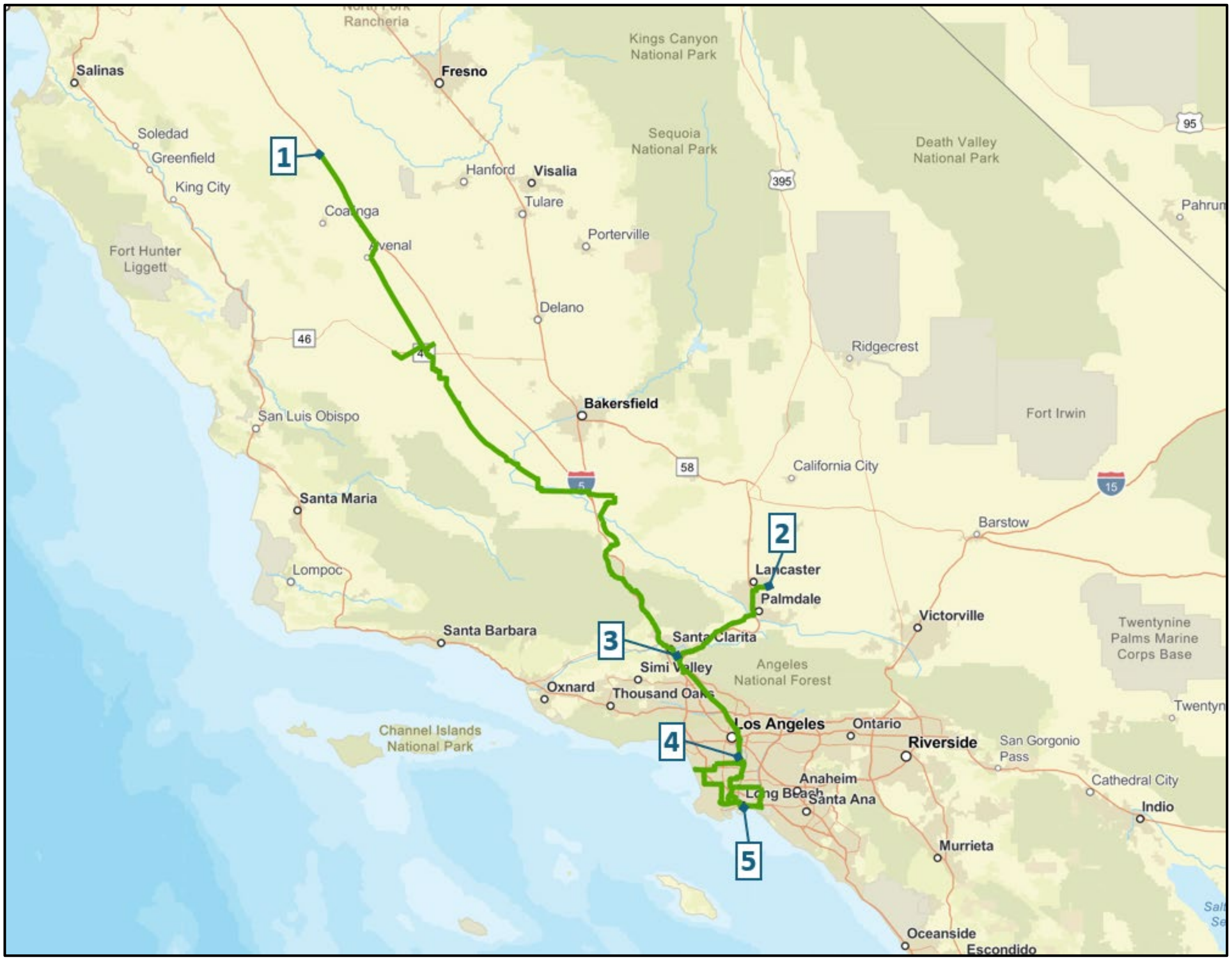
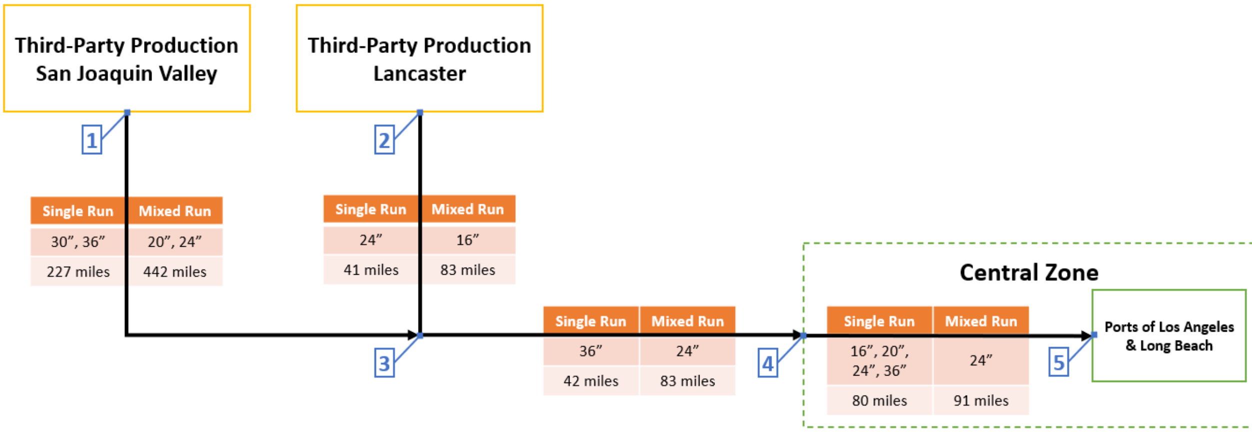


Figure 7 - Route A Map

Route A explores the most direct route from hydrogen production sites to the Los Angeles Basin demand center with the shortest overall pipeline distance. The pipeline from SJV to the junction (Point 1 to 3) was calculated to require 227 miles of 30- and 36-inch pipe for the single run configuration, and 442 miles of 20- and 24-inch for the mixed run configuration. The pipeline from Lancaster to the junction (Point 2 to 3) was calculated to require 41 miles of 24-inch pipe for the single run configuration, and 83 miles of 16-inch pipe for the mixed run configuration. The pipeline from the junction to the Central Zone (Point 3 to 4) was calculated to require 42 miles of 36-inch pipe for the single run configuration, and 83 miles of 24-inch pipe for the mixed run configuration. The pipelines within Central Zone to the Ports of Los Angeles and Long Beach (Point 4 to 5) was calculated to require 80 miles of 16-inch, 20-inch, 24-inch, and 36-inch pipe for the single run configuration, and 91 miles of 24-inch pipe for the mixed run configuration. Figure 8 displays the flow rates and pressure results at various locations, including the range of potential pipeline sizes estimated using ProMax.



Normal Operating Data	1	2	3	4	5
Single Run Pressure (psig)	725	800	487	307	215
Mixed Run Pressure (psig)	1,000	1,020	614	325	218
Flowrate (MMTPY)	0.75	0.75	1.5	1.5	1.5

Figure 8 - Route A Hydraulic Results

Compressor discharge pressure affects the required pipe size and line packing capabilities. The normal operating horsepower is based on modeled flowrate, and the max horsepower is sized at MAOP of 1,200 psig to be used when line packing.

For the single run configuration, the normal outlet pressure at the SJV compressor station is 725 psig and 800 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 475 psig at the SJV compressor station and 400 psig buffer at the Lancaster station to each compressor’s MAOP.

For the mixed run configuration, the normal outlet pressure at the SJV compressor station is 1,000 psig and 1,020 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 200 psig at the SJV compressor station and 180 psig buffer at the Lancaster station to each compressor’s MAOP.

For both configurations, the max outlet pressure at the SJV and Lancaster compressor stations is 1,200 psig to allow for line packing operation. The system was designed to reduce compressor horsepower while maximizing the volume that can be gained from line packing. Table 6 displays the calculated compressor information for the normal and the maximum operations.

Table 6 - Route A Compressor Information

Route A - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	19,500	50,000	500	725	1,200	0.75
	Lancaster	25,000	50,000	500	800	1,200	0.75
Mixed Run	SJV	38,000	50,000	500	1,000	1,200	0.75
	Lancaster	39,500	50,000	500	1,020	1,200	0.75

4.6.1.2 Preferred Route Configuration B (Route B)

Route B connects production sites in SJV and Lancaster with a single route without major laterals (or secondary pipelines branching from the main line) and continues onto the Los Angeles Basin with a single route and right-of-way. The overall pipeline distance is higher than Route A, but lower than Routes C and D. The flow within the pipeline was modeled to split within the Los Angeles Basin as displayed in **Error! Reference source not found.**6. Locations along Route B are presented in **Error! Reference source not found.**9 with results from the hydraulics calculations shown in Figure 10. A summary of the labeled locations follows:

- Point 1 is the connection point modeled for SJV production location
- Point 2 is the connection point modeled for Lancaster production location
- Point 3 is the entry point to the Central Zone (beginning of the LA Basin)
- Point 4 is the Los Angeles Basin Demand Pressure location

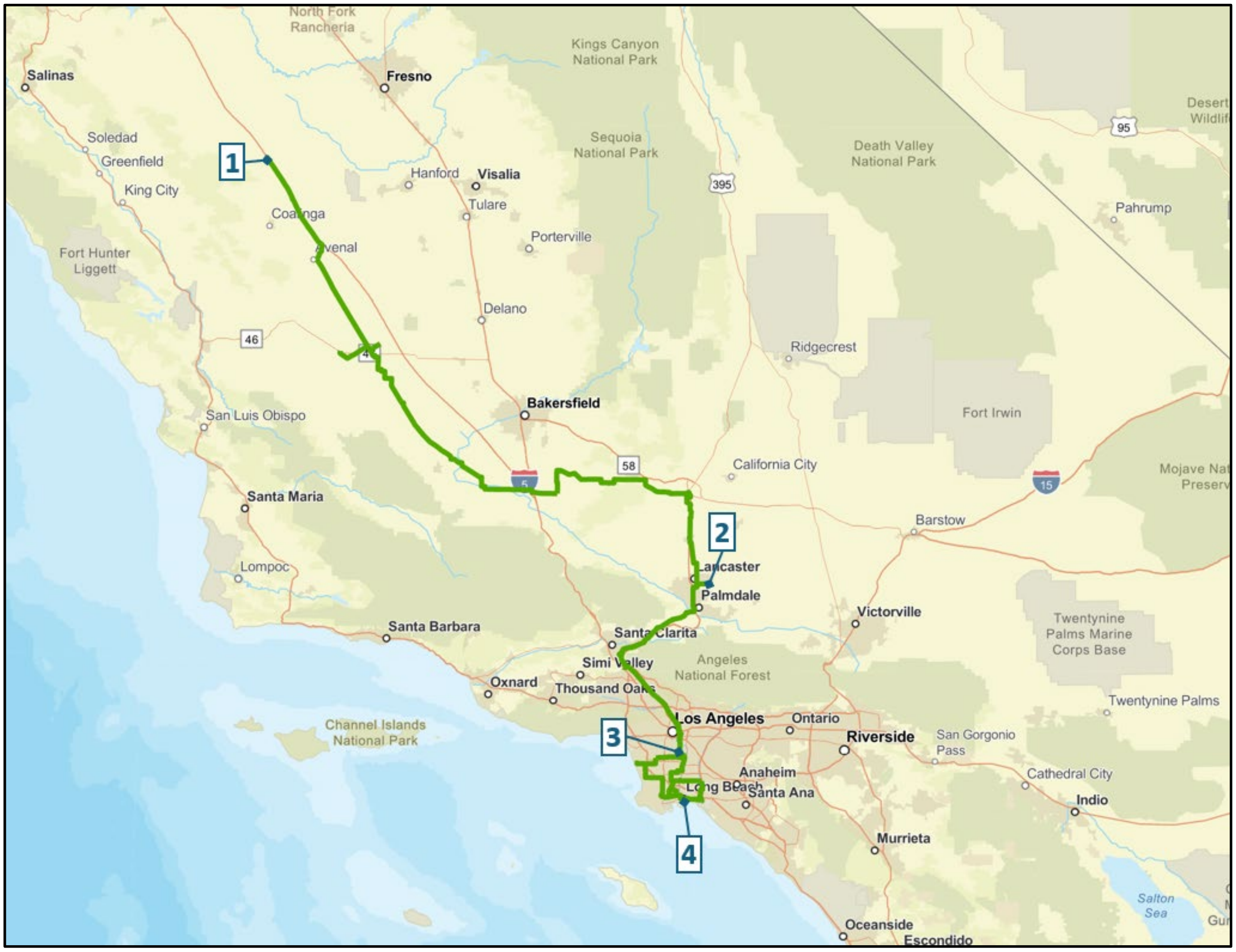
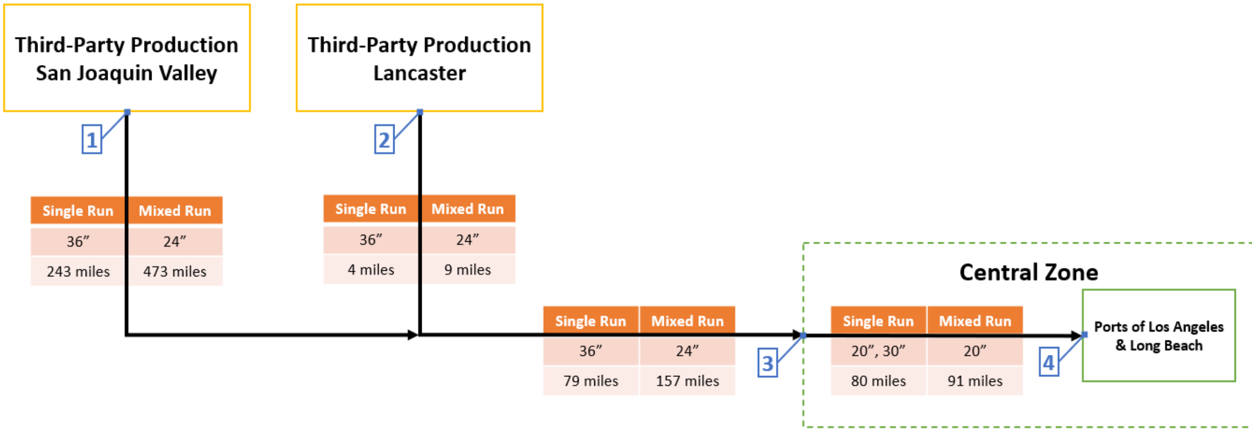


Figure 9 - Route B Map

Route B connects SJV and Lancaster production locations with a single route without major branching and continues onto the Los Angeles Basin with a single route. The pipeline from SJV to the Lancaster production connection (Point 1 to 2) was calculated to require 243 miles of 36-inch pipe for the single run configuration, and 473 miles of 24-inch for the mixed run configuration. The connection to the Lancaster production location (Point 2) was calculated to require 4 miles of 36-inch pipe for the single run configuration, and 9 miles of 24-inch pipe for the mixed run configuration. The combined SJV and Lancaster production pipeline (Point 2 to 3) was calculated to require 79 miles of 36-inch pipe for the single run configuration, and 154 miles of 24-inch pipe for the mixed run configuration. The pipelines within Central Zone to the Ports of Los Angeles and Long Beach (Point 3 to 4) were calculated to require 80 miles of 20-inch and 30-inch pipe for the single run configuration, and 91 miles of 20-inch pipe for the mixed run configuration. Figure 10 displays the flow rates and pressure results at various locations, including the range of potential pipeline sizes estimated using ProMax.



Normal Operating Data	1	2	3	4
Single Run Pressure (psig)	815	700	411	208
Mixed Run Pressure (psig)	1,065	950	447	207
Flowrate (MMTPY)	0.75	0.75	1.5	1.5

Figure 10 - Route B Hydraulic Results

For the single run configuration, the normal outlet pressure at the SJV compressor station is 815 psig and 700 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 385 psig at the SJV compressor station and 500 psig buffer at the Lancaster station to each compressor's MAOP.

For the mixed run configuration, the normal outlet pressure at the SJV compressor station is 1,065 psig and 950 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 135 psig at the SJV compressor station and 250 psig buffer at the Lancaster station to each compressor's MAOP.

For both configurations, the max outlet pressure at the SJV and Lancaster compressor stations is 1,200 psig to allow for line packing operation. Table 7 displays the calculated compressor information for the normal and the maximum operations.

Table 7 - Route B Compressor Information

Route B - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	26,000	50,000	500	815	1,200	0.75
	Lancaster	17,500	50,000	500	700	1,200	0.75
Mixed Run	SJV	44,000	50,000	500	1,065	1,200	0.75
	Lancaster	36,000	50,000	500	950	1,200	0.75

4.6.1.3 Preferred Route Configuration C (Route C)

Route C includes a loop, which provides multiple flow paths. This allows fluid to follow the path of least resistance which can lower the overall pressure drop of the system. The flow within the pipeline was modeled to split within the Los Angeles Basin as displayed in Figure 6. Locations along Route C are presented in Figure 11 with results from the hydraulics calculations shown on a diagrammatic layout in Figure 12. A summary of the labeled locations follows:

- Point 1 is the connection point modeled for SJV production location
- Point 2 is the connection point modeled for Lancaster production location
- Point 3 is the north end of the pipeline loop where flow first splits from the main line(s)
- Point 4 is the south end of the pipeline loop where the flow combines to the main line(s).
- Point 5 is the entry point to the Central Zone (beginning of the LA Basin)
- Point 6 is the Los Angeles Basin Demand Pressure location

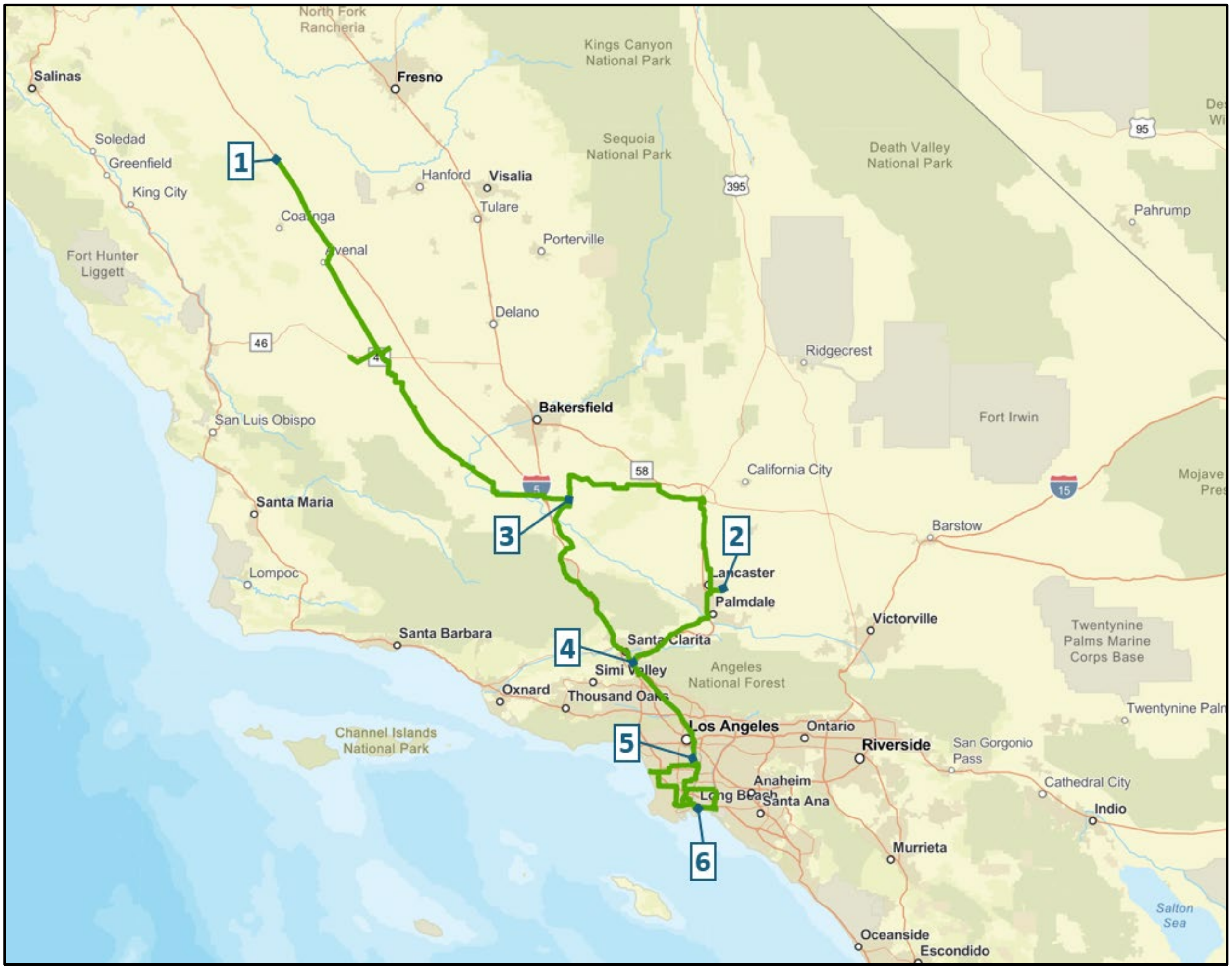
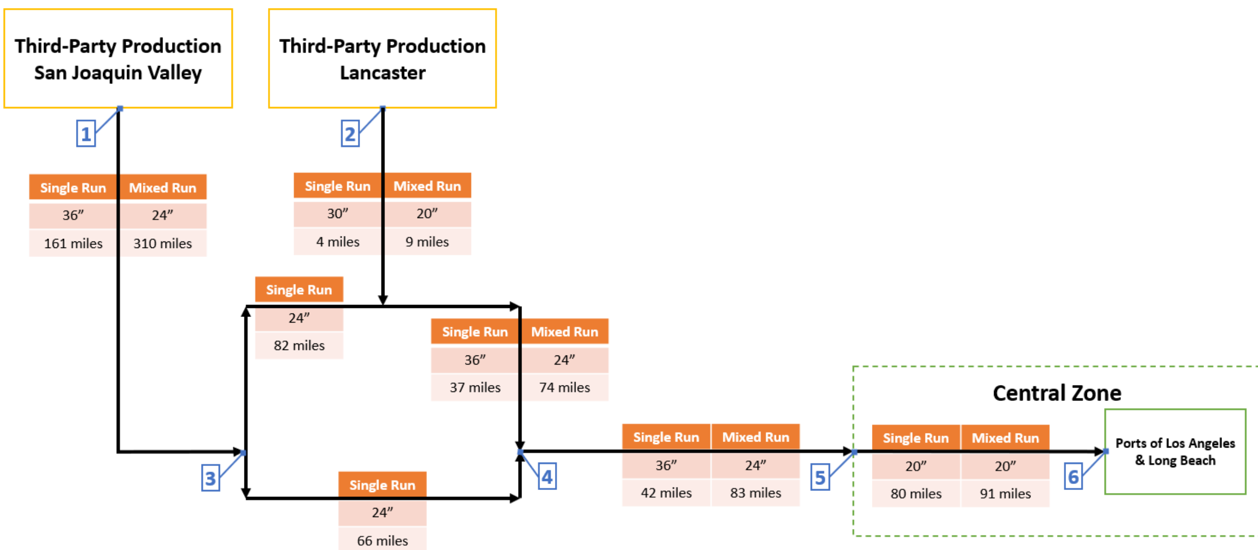


Figure 11 - Route C Map

Route C examines the impacts of having a pipeline loop between the production facilities and the Los Angeles Basin. This allows for flow to travel in both directions around the loop, offering greater system resiliency. Additionally, splitting flows within the pipeline loop results in lower flowrates in certain portions of the loop, therefore lowering the corresponding pressure drop in that specific portion.

The pipeline from SJV production location to the north end of the pipeline loop (Point 1 to 3) was calculated to require 161 miles of 36-inch pipe for the single run configuration, and 310 miles of 24-inch for the mixed run configuration. Due to the pipeline loop, a single 82 miles of 24-inch pipe was calculated from the point at which the SJV flow splits and combines with Lancaster production on the northern side of the loop (Point 3 to 2), and a single 66 miles of 24-inch pipe was calculated from the point that SJV flow splits and combined with Lancaster production on the southern side of the loop (Point 3 to 4). The pipeline from the Lancaster production to the loop was calculated to require 4 miles of 30-

inch pipe for the single run configuration, and 9 miles of 20-inch pipe for the mixed run configuration. The point where Lancaster production enters the loop and combines with the flow split from the SJV production (Point 2 to 4) was calculated to require 37 miles of 36-inch pipe for the single run configuration, and 74 miles of 24-inch pipe for the mixed run configuration. The combined SJV and Lancaster production pipeline (Point 4 to 5) was calculated to require 42 miles of 36-inch pipe for the single run configuration, and 83 miles of 24-inch pipe for the mixed run configuration. The pipelines within Central Zone to the Ports of Los Angeles and Long Beach (Point 5 to 6) were calculated to require 80 miles of 20-inch pipe for the single run configuration, and 91 miles of 20-inch pipe for the mixed run configuration. The pipeline loop in Route C allowed for flow splitting and subsequently lower pressure drop, which resulted in smaller 20-inch diameter pipes within the Central Zone as compared to Routes A and B. Figure 12 displays the flow rates and pressure results at various locations, including the range of potential pipeline sizes estimated using ProMax.



Normal Operating Data	1	2	3	4	5	6
Single Run Pressure (psig)	825	700	870	560	412	215
Mixed Run Pressure (psig)	1,010	885	737	686	444	201
Flowrate (MMTPY)	0.75	0.75	0.75	1.5	1.5	1.5

Figure 12 - Route C Hydraulic Results

For the single run configuration, the normal outlet pressure at the SJV compressor station is 825 psig and 700 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 375 psig at the SJV compressor station and 500 psig buffer at the Lancaster station to each compressor's MAOP.

For the mixed run configuration, the normal outlet pressure at the SJV compressor station is 1,010 psig and 885 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 190 psig at the SJV compressor station and 315 psig buffer at the Lancaster station to each compressor's MAOP.

For both configurations, the max outlet pressure at the SJV and Lancaster compressor stations is 1,200 psig to allow for line packing operation. Table 8 displays the calculated compressor information for the normal and the maximum operations.

Table 8 - Route C Compressor Information

Route C - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	26,500	50,000	500	825	1,200	0.75
	Lancaster	17,500	50,000	500	700	1,200	0.75
Mixed Run	SJV	39,000	50,000	500	1,010	1,200	0.75
	Lancaster	30,500	50,000	500	885	1,200	0.75

4.6.1.4 Preferred Route Configuration D (Route D)

Similar to Route B, Route D connects production sites in SJV and Lancaster with a single route without major branching and continues onto the Los Angeles Basin with a single route and right-of-way. Route D explored extending the Angeles Link system for potential connection with demand centers located in Riverside and San Bernardino counties. The overall pipeline distance for Route D is highest of all the preferred route configurations, which required evaluating an intermediate compressor station (also known as a booster compressor). As gas flows through pipelines, it experiences friction against the pipe walls leading to pressure loss. Intermediate compression helps maintain the pressure high enough to allow gas to continue moving efficiently across long distances.

Route D – Without Intermediate Compression

The flow within the pipeline was modeled to split within the Los Angeles Basin as displayed in Figure 6. Locations along Route D without intermediate compression are presented in Figure 13 with results from the hydraulics calculations shown in Figure 14. A summary of the labeled locations follows:

- Point 1 is the connection point modeled for SJV production location
- Point 2 is the connection point modeled for Lancaster production location
- Point 5 is the entry point to the Central Zone (beginning of the LA Basin)
- Point 6 is the Los Angeles Basin Demand Pressure location

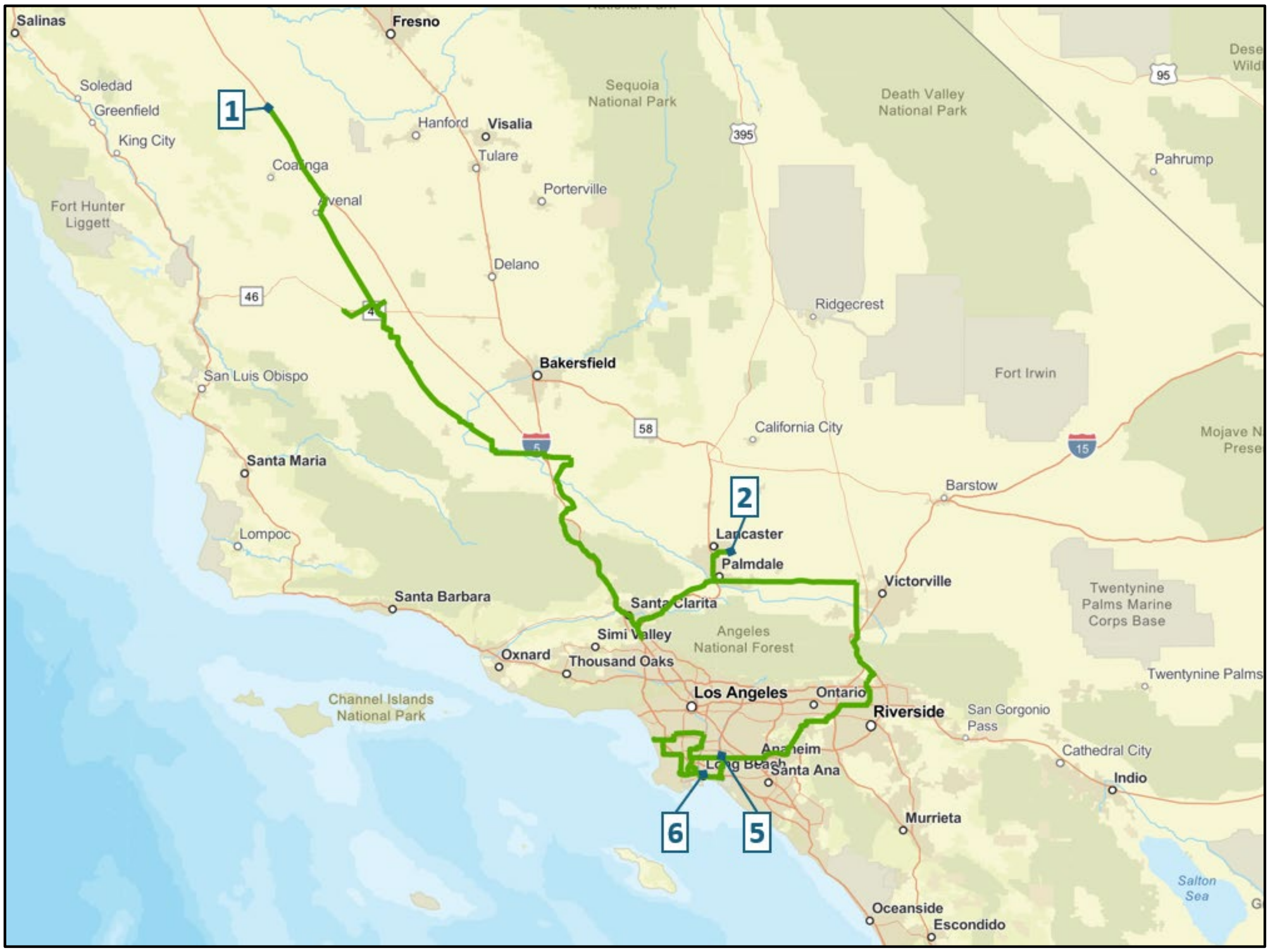
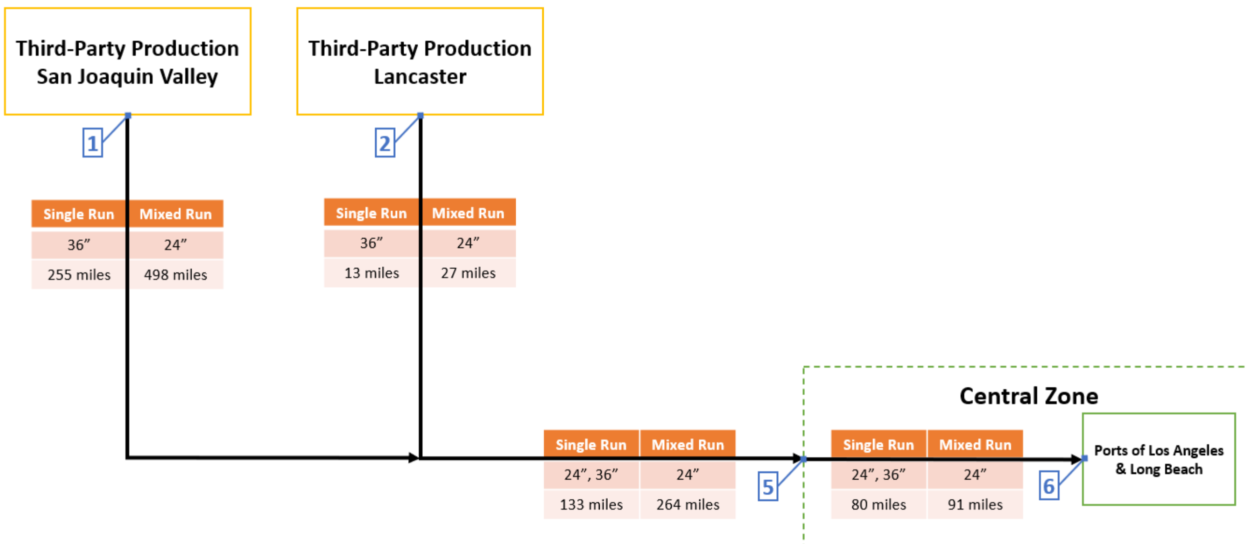


Figure 13 - Route D (Without Intermediate Compression) Map

Route D connects SJV and Lancaster production locations with a single route without major branching and continues onto the Los Angeles Basin with a single route. The pipeline from SJV to the Lancaster production connection (Point 1 to 2) was calculated to require 255 miles of 36-inch pipe for the single run configuration, and 498 miles of 24-inch for the mixed run configuration. The connection to the Lancaster production location (Point 2) was calculated to require 13 miles of 36-inch pipe for the single run configuration, and 27 miles of 24-inch pipe for the mixed run configuration. The combined

SJV and Lancaster production pipeline (downstream of Point 2 to 5) was calculated to require 133 miles of 24-inch and 36-inch pipe for the single run configuration, and 264 miles of 24-inch pipe for the mixed run configuration. The pipelines within Central Zone to the Ports of Los Angeles and Long Beach (Point 5 to 6) were calculated to require 80 miles of 24-inch and 36-inch pipe for the single run configuration, and 91 miles of 24-inch pipe for the mixed run configuration. Figure 14 displays the flow rates and pressure results at various locations, including the range of potential pipeline sizes estimated using ProMax.



Normal Operating Data	1	2	5	6
Single Run Pressure (psig)	950	775	356	231
Mixed Run Pressure (psig)	1,180	1,015	328	202
Flowrate (MMTPY)	0.75	0.75	1.5	1.5

Figure 14 - Route D (without Intermediate Compression) Hydraulic Results

For the single run configuration, the normal outlet pressure at the SJV compressor station is 950 psig and 775 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 250 psig at the SJV compressor station and 425 psig buffer at the Lancaster station to each compressor’s MAOP.

For the mixed run configuration, the normal outlet pressure at the SJV compressor station is 1,180 psig and 1,015 psig at the Lancaster compressor station outlet. This allows for an operating buffer of 20 psig at the SJV compressor station and 185 psig buffer at the Lancaster station to each compressor’s MAOP.

For both configurations, the max outlet pressure at the SJV and Lancaster compressor stations is 1,200 psig to allow for line packing operation. Table 9 displays the calculated compressor information for the normal and the maximum operations.

Table 9 - Route D (without intermediate compression) Compressor Information

Route D - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	35,000	50,000	500	950	1,200	0.75
	Lancaster	23,000	50,000	500	775	1,200	0.75
Mixed Run	SJV	49,000	50,000	500	1,180	1,200	0.75
	Lancaster	39,000	50,000	500	1,015	1,200	0.75

Route D – With Intermediate Compression

For the mixed run configuration without intermediate compression, the SJV compressor must operate at nearly the MAOP of 1,200 psig to deliver hydrogen to the Central Zone demand centers. Adding an intermediate compressor station will allow the SJV compressor station to operate at a relatively lower operating pressure, which can potentially decrease strain on equipment and materials, provide margin for pressure and flow rate fluctuations, and increase the capacity for line packing. Therefore, an intermediate compressor configuration was modeled and evaluated for Route D with Figure 15 depicting locations and hydraulic results shown in Figure 16. A summary of the labeled locations follows:

- Point 1 is the connection point modeled for SJV production location
- Point 2 is the connection point modeled for Lancaster production location
- Point 3 is suction (inlet) modeled for the intermediate compression station
- Point 4 is discharge (outlet) modeled for the intermediate compression station
- Point 5 is the entry point to the Central Zone (beginning of the LA Basin)
- Point 6 is the Los Angeles Basin Demand Pressure location

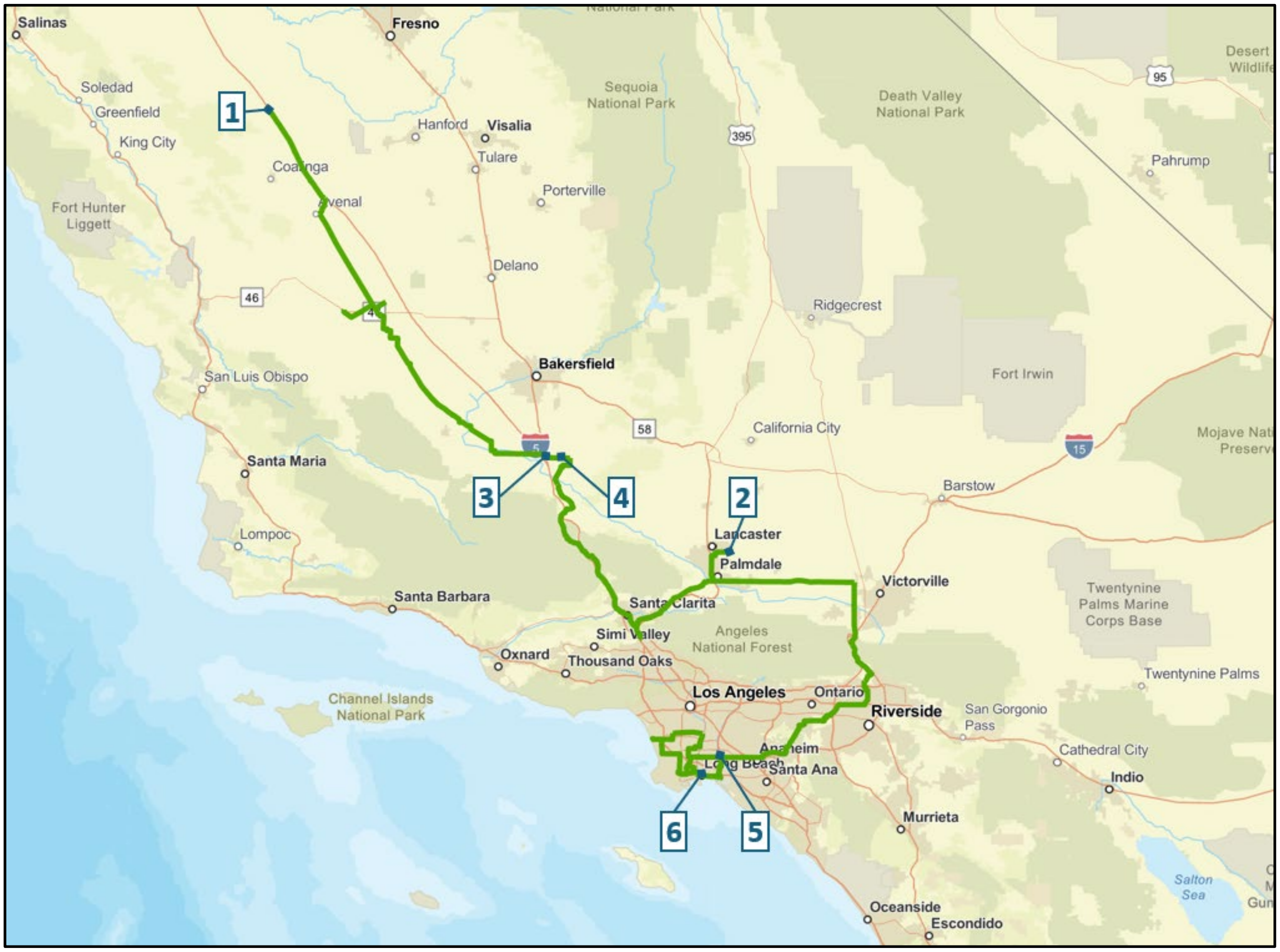
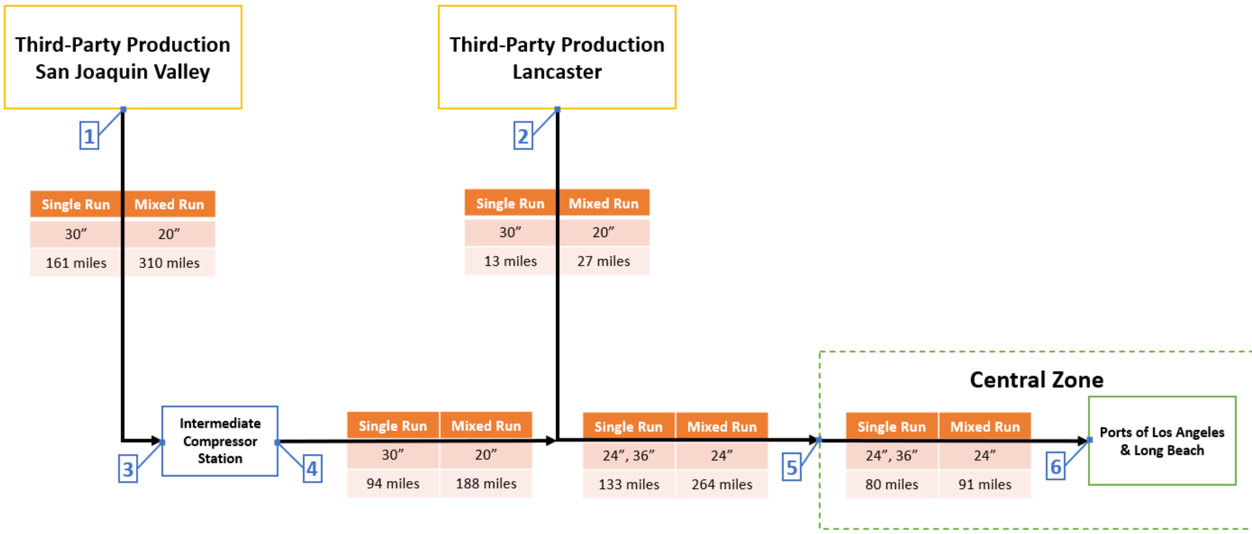


Figure 15 - Route D (With Intermediate Compression) Map

The pipeline from SJV to the intermediate compressor station inlet (Point 1 to 3) was calculated to require 161 miles of 30-inch pipe for the single run configuration, and 310 miles of 20-inch for the mixed run configuration. From the intermediate compressor outlet to the connection with the Lancaster production location (Point 4 to 2) was calculated to require 94 miles of 30-inch pipe for the single run configuration, and 188 miles of 20-inch pipe for the mixed run configuration. The connection to the Lancaster production location (Point 2) was calculated to require 13 miles of 30-inch pipe for the single run configuration, and 27 miles of 20-inch pipe for the mixed run configuration. The combined SJV and Lancaster production pipeline (downstream of Point 2 to 5) was calculated to require 133 miles of 24-inch and 36-inch pipe for the single run configuration, and 264 miles of 24-inch pipe for the mixed run configuration. The pipelines within Central Zone to the Ports of Los Angeles and Long Beach (Point 5 to 6) were calculated to require 80 miles of 24-inch and 36-inch pipe for the single run configuration, and 91 miles of 24-inch pipe for the mixed run configuration. Figure 16 displays the flow rates and pressure results at various locations, including the range of potential pipeline sizes estimated using ProMax.



Normal Operating Data	1	2	3	4	5	6
Single Run Pressure (psig)	775	780	475	900	341	208
Mixed Run Pressure (psig)	1,000	1,050	522	1,165	342	223
Flowrate (MMTPY)	0.75	0.75	0.75	0.75	1.5	1.5

Figure 16 - Route D (With Intermediate Compression) Hydraulic Results

For the single run configuration, the normal outlet pressure at the SJV compressor station is 780 psig, the Lancaster compressor station normal outlet pressure is 1,050 psig, and the intermediate compressor station outlet pressure is 900 psig. This allows for an operating buffer of 420 psig at the SJV compressor station and 150 psig buffer at the Lancaster station to each compressor’s MAOP.

For the mixed run configuration, the normal outlet pressure at the SJV compressor station is 1,000 psig, the Lancaster compressor station normal outlet pressure is 1,050 psig, and the intermediate compressor station outlet pressure is 1,165 psig. This allows for an operating buffer of 200 psig at the SJV compressor station and 150 psig buffer at the Lancaster station to each compressor’s MAOP.

For both configurations, the max outlet pressure at the SJV and Lancaster compressor stations is 1,200 psig to allow for line packing operation. Table 10 displays the calculated compressor information for the normal and the maximum operations.

Table 10 - Route D (with intermediate compression) Compressor Information

Route D - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	23,000	50,000	500	775	1,200	0.75
	Lancaster	23,500	50,000	500	780	1,200	0.75
	Intermediate Compressor	35,000	53,500	475	900	1,200	0.75
Mixed Run	SJV	38,000	50,000	500	1,000	1,200	0.75
	Lancaster	41,000	50,000	500	1,050	1,200	0.75
	Intermediate Compressor	45,500	47,500	522	1,165	1,200	0.75

For the mixed run configuration, the intermediate compressor reduced the normal operating pressure of the SJV compressor station from 1,180 psig to 1,000 psig. The addition of the intermediate compressor for Route D can also decrease the required pipe sizes as the pressure drop will decrease, however this will result in increasing capital and operating expenses for installing and maintaining another compressor station with a maximum operating requirement of 47,500 horsepower. The benefits of reducing the SJV compressor station operating pressure were offset by the increased capital, maintenance, and utility costs of a third compressor station for Route D. Therefore, Route D with intermediate compression was not included in further analysis or cost estimate development.

5. MATERIALS REVIEW

Given hydrogen's unique properties, selecting appropriate materials is vital to mitigate potential issues such as hydrogen embrittlement. This section explores a range of potential material specifications based on hydraulic analyses, addressing key aspects such as pipeline wall thickness and pipe composition and physical properties (pipe grade) comparison. It also considers construction logistics and maintenance practices to improve pipeline longevity and reliability. Considerations to be explored in future phases of the Angeles Link project will include evaluation of material selection based on established operating parameters and integrity management technologies to further optimize the Angeles Link system.

5.1. Material Specification

The material specifications in this section are based on the latest edition of ASME B31.12 including applicable design factors. Preliminary calculations indicate that API 5L Grade X52 pipe appears to be suitable for the Angeles Link system based on the Hydraulic Analysis discussed in Chapter 4.

5.1.1. Pipeline Wall Thickness Calculation

The selection of pipeline sizes, pressures, and design factors directly influences the calculation of wall thickness and the resultant overall integrity of the system. Required pipeline sizes are determined through hydraulic calculations to meet operating parameters defined in the Design Parameters, Chapter 3. Temperature is controlled throughout the system by employing heat exchangers where necessary, as determined through hydraulic calculations.

Pipeline wall thicknesses are calculated and provided in Table **11** 11, Table 12, and Table 13 using the "Steel Pipe Design Formula" in ASME B31.12, PL-3.7.1 and the following assumed inputs:

- Design pressure (P) is 1,200 psig (Refer to Design Pressure, Section 3.2)
- Nominal outside diameter (D) is 16 to 36 inches (Refer to Hydraulic Analysis, Chapter 4)
- Temperature derating factor (T) is 1.000, for pipe up to 250 °F
- Quality Factor (E) is 1.00 based on using API 5L pipe, incorporated by reference into 49 CFR 192
- Design Factor (F) is 0.40 and is based on a Location Class 4
- These calculations do not include a corrosion allowance

The Design Factor (F) of 0.40 corresponds to a Location Class 4, which is defined by ASME B31.12, PL-3.2.2(d) to include areas where multistory buildings are prevalent, where traffic is heavy or dense, and where there may be numerous other utilities underground. Assuming Location Class 4 for the pipeline wall thickness calculation is consistent with ASME B31.12, GR-5.2.1 recommendations for any piping with a SMYS greater than 52,000 psi. This is a conservative assumption, as the Routing Analysis identified approximately 2 miles of initial corridors are within Location Class 4. Furthermore, ASME B31.12 allows pipelines operating less than or equal to 2,200 psig using materials with a SMYS of less than or equal to 52,000 psi to be considered in a Location Class 3 unless they are operating in Location Class 4 areas.

Other factors used to calculate potential wall thickness include the pipe grade and the resulting Material Performance Factor shown in Figure 17 and discussed below:

- Material stress value (S) is based on the SMYS for the chosen pipe grade. The values from Table IX-1B of ASME B31.12 follow:
    a. APL 5L Grade X52 has a SMYS of 52,000 psi (52 ksi)
    b. APL 5L Grade X60 has a SMYS of 60,000 psi (60 ksi)
    c. APL 5L Grade X70 has a SMYS of 70,000 psi (70 ksi)
- Material Performance Factor (H_f) is based on system design pressure and SMYS

Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652	0.606
Over 82 through 90	≤80	0.694	0.694	0.662	0.632	0.610	0.584	0.542

Figure 17 - Carbon Steel Pipeline Materials Performance Factor, H_f

The following tables provide the calculated wall thickness at varying diameters for different grades of pipe. The pipe grades used in these calculations conform to API 5L and are distinguished by their specified minimum yield strength (SMYS), measured in psi (pounds-force per square inch).

Using API 5L Grade X52 pipe does not derate the pipe, the lower SMYS results in the greatest calculated wall thickness when compared to the higher grades. With the ability in ASME B31.12, GR-5.2.1 to apply a Location Class 3 to pipeline outside of Location Class 4, API 5L Grade X52 pipe offers the greatest flexibility in the latest edition of ASME B31.12.

Table 11 - Pipeline Wall Thickness Calculation (X52)

OD, NPS (in)	OD, Actual Pipe Size (in)	Calculated Wall Thickness (in), Class 4	Calculated Wall Thickness (in), Class 3
16	16.00	0.462	0.370
20	20.00	0.577	0.462
24	24.00	0.693	0.554
30	30.00	0.866	0.693
36	36.00	1.039	0.831

Using API 5L Grade X60 applies a derating factor of 0.874 resulting in a pipe wall thickness less than 1% lower than those calculated for API 5L Grade X52 despite the higher SMYS, when comparing Location Class 4 areas. Based on the guidance in ASME B31.12, GR-5.2.1, 36-inch pipe using API 5L Grade X60 would require a wall thickness greater than 1-inch. API 5L Grade X60 offers derating capability and slightly lower calculated wall thickness compared to API 5L Grade X52.

Table 12 - Pipeline Wall Thickness Calculation (X60)

OD, NPS (in)	OD, Actual Pipe Size (in)	Calculated Wall Thickness (in) Class 4
16	16.00	0.458
20	20.00	0.573
24	24.00	0.687
30	30.00	0.859
36	36.00	1.030

Using API 5L Grade X70 applies a derating factor of 0.776 resulting in a pipe wall thickness about 4% lower than those calculated for API 5L Grade X52 despite the higher SMYS, when comparing Location Class 4 areas. Based on ASME B31.12, API 5L Grade X70 is the only pipe grade reviewed in this study that resulted in a pipe wall thickness less than 1-inch when operating in a Location Class 4.

Table 13 - Pipeline Wall Thickness Calculation (X70)

OD, NPS (in)	OD, Actual Pipe Size (in)	Calculated Wall Thickness (in) Class 4
16	16.00	0.442
20	20.00	0.553
24	24.00	0.663
30	30.00	0.829
36	36.00	0.995

This study used recommendations in the latest edition of ASME B31.12, which was issued on December 29, 2023. Pipe manufacturers continue to test pipe to meet the stringent requirements of ASME B31.12. Manufacturers have qualified API 5L X65 per existing standards with testing of X70 grade occurring in various labs for conformance with ASME B31.12 and other standards to achieve full qualification for higher grades. Trial plans for heavy gauge up to 1-inch thickness have been developed based on pilot-scale trials to finalize alloy design and processing. A challenge for higher-grade line pipes in hydrogen applications is the Vickers hardness limitation (235 HV), which is being revised with standard committees. Higher grades of steel, like X70 and above, tend to have greater hardness and there is concern of embrittlement with these higher hardness steels. Finally, a new version ASME B31.12 is scheduled for publication in 2026 and "material performance factors will be reevaluated as materials research data are developed and understanding of hydrogen embrittlement of carbon and low alloy steels increases". ASME has published five editions of ASME B31.12 since December 2008 and has reduced derating and/or performance factors with each publication of ASME B31.12. In a future phase of the project, the Angeles Link pipeline system design will consider changes in publications from ASME, API, the CFR, and other codes and standards to remain current on the latest requirements and recommended practices.

5.2. Hydrogen Embrittlement

Hydrogen lowers the stress required to cause crack initiation and propagation. The related cracking is often referred to as hydrogen induced cracking (HIC). There are various mechanisms by which this occurs, including hydrogen enhanced decohesion (HEDE), hydrogen enhanced localized plasticity (HELP) and formation of brittle hydrides although hydride formation is uncommon in steel. Hydrogen embrittlement also reduces tensile ductility (reduced elongation in a tensile test) and the tensile strength of notched specimens.

In some steels, especially those with laminations or elongated nonmetallic inclusions, hydrogen atoms can collect at those features and recombine to form hydrogen molecules. Formation of hydrogen molecules from hydrogen atoms causes a large increase in hydrogen gas volume and a related increase of internal pressure of hydrogen gas within the wall of the steel until bulging ("hydrogen blistering") and related extension of the blister occurs via crack formation and growth at the edges of the blister. Hydrogen blistering can occur in low strength steels, whereas hydrogen embrittlement is more frequently found in higher strength steels.

The rate at which hydrogen embrittlement occurs is closely related to how quickly hydrogen dissociates and enters the steel surface as H+. In severe conditions, such as electrochemical charging in a laboratory or, to a lesser extent, exposure to excessively negative cathodic protection potentials, detectable hydrogen embrittlement can occur within a day. In most hydrogen pipeline service, hydrogen embrittlement occurs much more slowly, if at all.[24] If a material is embrittled, it will remain that way regardless of time or exposure to more or less hydrogen. Angeles Link is planned to be a new pipeline system and mitigation of embrittlement will be considered as part of the primary design, monitoring, and development of future operations and maintenance procedures.

5.2.1. Effect of Gas Composition, Temperature, and Pressure

Susceptibility to hydrogen embrittlement and the rate of embrittlement are both related to the service conditions and to the metallurgical characteristics of the pipe. From the standpoint of the environment, the extent of the embrittlement is related to the partial pressure of hydrogen and, to a much lesser extent, the temperature. Hydrogen embrittlement is reduced at elevated temperatures (until at least 200°C when high temperature hydrogen attack[25] occurs) but is not greatly affected by the typical range of pipeline operating temperatures. Measurable reductions in toughness and related effects on fatigue life occur at partial pressures as low as 15 psia. However, embrittlement requires that some of the hydrogen molecules (H_2) dissociate to H^+ at the pipe surface so

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[24] DOE Hydrogen Program FY 2005 Progress Report 449, Contract Number: DE-FC36-04GO14229, Start Date: 9/1/04, Projected End Date: 3/31/2006. See also Xiao Xing, Mengshan Yu, Olayinka Tehinse, Weixing Chen, Hao Zhang "The Effects of Pressure Fluctuations on Hydrogen Embrittlement in Pipeline Steels" Proc. ASME. IPC2016, Volume 1: Pipelines and Facilities Integrity, V001T03A025, September 26–30, 2016 Paper No: IPC2016-64478

[25] Hydrogen attack is the degradation of steel at elevated temperature due to atomic hydrogen travelling through the material and impacting impurities and defects.

that the hydrogen can enter ("adsorption") and diffuse through the pipe wall. Active corrosion, especially in the presence of hydrogen sulfide (H_2S), and unoxidized (actively growing) crack tips promote the entry of H^+.

5.2.2. Effect of Pipe Grade and Steel Metallurgy

There is broad consensus that susceptibility to embrittlement increases as pipe strength increases. However, the relationship is complicated by the interrelated effects of variations in metallurgical characteristics, including chemical composition and thermomechanical processing (i.e., details of the plate rolling procedure). ASME B31.12 notes that for a given pipe grade, susceptibility to embrittlement generally increases as carbon, manganese, sulfur, phosphorous, and chromium contents increase. Microalloying generally results in lower susceptibility to embrittlement.

ASME B31.12 recommends that steel pipe not have a grade greater than X52, even though higher strengths are permitted. However, for grades stronger than X52 the Materials Performance Factor (H_f) used for calculation of maximum allowable pressure for a given wall thickness decreases as strength increases. As a result, an increase in pipe strength is much greater than the corresponding decrease in required wall thickness when using grades stronger than X52 for pipe thickness determinations using ASMB B31.12 Option A. Table 14 illustrates that effect of increasing pipe strength on the required minimum wall thickness.

Table 14 - Effect of Hf on Required Wall Thickness for Pipelines Using B31.12 Option A

SMYS (ksi)	% Increase in SMYS vs. X52	% Decrease in H_f vs. X52	% Reduction in Required Wall Thickness vs. X52
52	0.0	0.0	0.0
56	7.7	12.6	- 4.9*
60	15.4	12.6	2.8
65	25.0	22.4	2.6
70	34.6	22.4	12.2
80	53.8	30.6	23.2

* 4.9% *greater* wall thickness is required compared to X52

5.3. Pipeline Integrity & Maintenance

Fitness for service is an important consideration as it is determined based on the ability of different types of facilities or individual components to satisfactorily perform their intended function, which is to safely and reliably deliver gas to customers.[26] In the absence of cracking or crack-like planar flaws, hydrogen embrittlement has little to no effect on long-term pipeline integrity. Fitness for service assessments need to account for the decrease in toughness that is expected to be associated with hydrogen embrittlement. The challenge is to accurately estimate the expected amount of toughness decrease resulting from exposure to hydrogen. The severity of embrittlement has been shown to be mostly related to hydrogen partial pressure, rather than to merely the percent of hydrogen present or to the total system pressure. The effect of hydrogen embrittlement on critical crack size can be illustrated by comparing flaw size versus failure pressure curves for a range of toughness values on a hypothetical pipeline.

Because critical crack sizes are smaller and cracks subjected to fluctuating stresses grow more quickly for steel exposed to pressurized hydrogen, inspection practices, including in-line inspection tools (ILI – aka smart pigs) need to be capable of reliably detecting and sizing planar flaws. Some elastomers and polymers used in ILI tools may not be compatible with high pressure hydrogen, so there may be a subset of existing inspection devices that are not suitable unless modified for hydrogen service. ILI service providers are aware of the increasing interest in inspections of hydrogen pipelines.

Simultaneously, design choices that minimize material stress will reduce the likelihood of cracks and reliance on inspection.

5.4. Repurposing Review

In alignment with stakeholder comments, a high-level literature review of repurposing existing natural gas pipelines for 100% hydrogen gas service was conducted. The potential advantages and disadvantages of converting natural gas pipeline versus building new pipelines intended for hydrogen service are summarized below:

Advantages of conversion:

- Lower cost relative to building new pipelines
- Potential use of existing easements and rights of way
- Time required for conversion of existing pipelines can be less than installation of new pipelines

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[26] Report to America on Pipeline Safety. (2011). Determining natural gas distribution fitness for service. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/FFS-%20Distribution%20Technical%20Note%20Proposal%20Final%20%282%29.pdf

Disadvantages of conversion:

- Existing steel pipe may not match ideal properties (also, some existing pipelines may not have all of the preferred property data available, especially regarding toughness); uncertain properties of welds, especially pre-existing repairs and hot taps.
- Integrity of existing assets may be imperfect, i.e., pre-existing corrosion, pre-existing mechanical damage, stress corrosion cracking (SCC), fatigue, surface imperfections from manufacturing that would not exist in new pipe
- Some existing wall thickness may not be recommended by ASME B31.12. For example, for pipe greater than 4-inch diameter, the minimum wall thickness allowed in hydrogen service is 0.25-inch. That limit precludes the conversion of pipelines that may only be 0.156-inch, 0.188-inch, or 0.219-inch thick.
- Allowable MAOP in hydrogen service may be lower, depending upon location class, seam type, pipe grade, etc. The effect of pipe grade was previously described and illustrated in Table 14. The difference in design factor for Location Class 1 and 2 are shown in Table 15. While Table 15 shows the design factors applicable to ASME B31.12 Option B are the same as for ASME B31.8, ASME B31.12 Option B requires rigorous analysis of fatigue cycles and determination of embrittled toughness to determine the wall thickness required for a desired MAOP. As a result, the wall thickness could be significantly different than the thickness determined using ASME B31.8 for the same MAOP, or the MAOP may have to be reduced to achieve the desired fatigue life with the available or existing wall thickness.
- ASME B31.12 does not allow the use of pipe having butt welded longitudinal seams. Butt welded seam pipe (either furnace butt weld or continuous butt weld) is common in pipe sizes up to and including NPS 4.

Table 15 - Comparison of Design Factors from ASME B31.8 and ASME B31.12

Location Class	B31.8 Design Factor	B31.12 Option A Design Factor	B31.12 Option B Design Factor
1, Div. 1	0.80	NA	NA
1, Div. 2	0.72	0.50	0.72
2	0.60	0.50	0.60
3	0.50	0.50	0.50
4	0.40	0.40	0.40

5.4.1. Case Study of Retrofit Projects

In 2005 Air Liquide presented a summary of their experience converting two crude oil pipelines to hydrogen service[27] including:

- Corpus Christi Pipeline: An 8-inch diameter, Grade B pipe built in 1940-1950 was converted to hydrogen service at 700 psig for 6 months. It ruptured due to an unspecified form of corrosion in 1998, and then was derated to 350 psig. Currently, 65 miles of this retrofitted pipeline are still in service.
- Freeport to Texas City Pipeline: A 14-inch diameter pipeline built in 1979 with various grades and wall thickness, including X60, was converted to hydrogen service at 740 psig in 1996. No issues were reported, including the use of existing ball valves previously used for crude oil service.

A comparison of the specifications used in the Air Liquide retrofitted pipelines to a new pipeline suitable for 100% hydrogen service is shown in Table 16.

Table 16 - Air Liquide New and Converted Pipeline Characteristics[28]

Specification	New Pipeline	Retrofitted Freeport to Texas City Pipeline	Retrofitted Corpus Cristi Pipeline
Hardness	<250 HB	225 HB	178 HB
Carbon Equivalent	<0.43	0.63	0.325
Grade	<X52	X60	Grade B
Sulfur	<0.015%	0.015	0.036
Phosphorus	<0.015%	0.017	0.011
Charpy Impact	>35 J	>27 J	6 J
Heat Treatment	Normalized	N/A	N/A

There are several studies regarding the feasibility of converting existing pipelines to either 100% hydrogen service or to natural gas and hydrogen blends. For example, APA group (an Australian company) is studying the feasibility of converting a 0.219-inch and 0.312-inch thick API 5L X52 pipeline built in 1970 to ASME B31.8 code to 100%

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[27] Campbell, J. & Air Liquide. (2005, August 31). DOE Hydrogen Pipeline Working Group Meeting - Questions and issues on hydrogen pipelines. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/articles/questions-and-issues-hydrogen-pipelines-pipeline-transmission-hydrogen

[28] Ibid.

hydrogen service.[29] In the United Kingdom, the H21 Programme is studying conversion of existing natural gas distribution pipelines to 100% hydrogen.[30]

[29] APA Group. (2023, May). Parmelia Gas Pipeline: Hydrogen Conversion Technical Feasibility Study. https://www.apa.com.au/globalassets/our-services/gas-transmission/west-coast-grid/parmelia-gas-pipeline/3419_apa_public-pipeline-conversion_v6.pdf

[30] *UK hydrogen strategy (accessible HTML version)*. (2023, December 14). GOV.UK. https://www.gov.uk/government/publications/uk-hydrogen-strategy/uk-hydrogen-strategy-accessible-html-version

6. COST ESTIMATES

SoCalGas developed cost estimates for the Scenarios and Preferred Route options using common practices associated with projects in development. SoCalGas utilized historical project information of constructed natural gas pipelines and compressor stations as the basis for developing unit costs for pipeline system features. The applicable project data was reviewed and selected based on certain variables such as common project types, pipeline installation length, geography, and right-of-way area. The estimate was organized into a standard project work breakdown structure where each category (e.g., Company Labor, Project Services, Environmental) was calculated using historical averages while also incorporating the estimating team's judgment. Contingency was also calculated incorporating the estimating team's judgment based on the level of design and known project uncertainties.

6.1. Basis of Estimate

SoCalGas utilized the recommended practices from Association for the Advancement of Cost Engineering International (AACEi) as guidelines for estimate development. AACEi is an internationally recognized organization that provides a structured framework, industry-specific guidance, and a focus on lifecycle costs—all of which contribute to enhancing cost and risk management for pipeline infrastructure projects. The Angeles Link project utilized the AACEi recommended practices (RP) of "Cost Estimate Classification Systems" to classify project cost estimates based on their purpose (e.g., evaluation, approval, funding). The following were adopted for Angeles Link preliminary cost estimates:

- "97R-18: Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Pipeline Transportation Infrastructure Industries" for pipeline costs
- "18R-97 Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries" for compressor station costs

For the Angeles Link Phase 1 feasibility study, Class 5 estimates were developed according to AACEi Recommended Practice 97R-18 and 18R-97 listed above.[31] Class 5 estimates are generally prepared based on limited information (typically 0-2% project scope definition) and have wide accuracy ranges. Typical accuracy ranges for Class 5

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[31] Class 5 estimates are the most preliminary class of estimate addressed in the AACEi classification system and are followed by Class 4 and Class 3 estimates as the project scope matures; the latter is considered the most appropriate for budget authorization, appropriation, and/or funding.

estimates are -20% to -50% on the low side, and +30% to +100% on the high side, depending on technological and system complexity, and appropriate reference information and other risks (after inclusion of an appropriate contingency determination). Ranges could exceed those shown if there are unusual factors including volatile commodity markets and escalation (i.e., because of the proportion of commodity material content such as steel). The intended end use for Class 5 estimates is to inform any number of strategic business purposes, including, but not limited to, market studies, engineering design, assessment of initial viability, evaluation of alternate schemes, project screening, routing studies, evaluation of resource needs and budgeting, and long-term capital planning.

6.2. Scope of Estimate

The Class 5 estimates completed for the preliminary sizing results are based on historic SoCalGas construction project unit costs in SoCalGas service territory normalized to 2024 dollars, and include direct costs of the following:

- Contractor Costs for Construction
- SoCalGas Company Management, Union Labor and Non-Labor Costs, and Outreach & Public Affairs
- Engineering and Design Services
- Project Management and Project Services
- Material Procurement and Management
- Survey / As-Builts
- Pressure Test Certification Services
- X-Ray and Non-Destructive Examination
- Environmental Planning, Management, Monitoring, and Abatement Support
- Construction Management
- Inspection
- District Personnel (Management, Operations Manager, Union Labor, Instrumentation and Facilities Operation Supervisor)
- M&R (Meters and Regulation)
- Pipeline Integrity
- Water Storage
- Miscellaneous Services associated with hydrogen systems
- Outreach & Public Affairs
- Land Services
- City Permits
- Other Non-Labor Costs

The Class 5 estimates exclude the following:

- Future escalation (all costs are normalized to 2024 dollars)
- Indirect costs (overhead, administrative, insurance, taxes, etc.)
- New land purchasing and acquisition costs
- Point of Receipt costs
- Night work except for pipeline Tie-Ins / Isolations
- Weekend or Holiday Work
- Cultural resources (e.g., costs to remove, preserve, and/or handle unexpected discoveries)
- Dewatering
- Producer or customer connection costs
- Expected environmental remediation costs
- Any unexpected constructability costs

6.3. Scenarios 1-8 Cost Estimates

Class 5 estimates were completed for each of the scenarios based on the results described in Section 4.5. These estimates were developed for the Cost Effectiveness Study to determine the potential levelized cost of clean renewable hydrogen to be delivered to end-users. The cost estimates were also provided to the Workforce Evaluation as the basis for the employment and economic impact analysis.

6.3.1. Results/Discussion

Table 17 summarizes the Class 5 estimates for Scenarios 1 through 8. The costs developed are based on several factors such as land types (e.g. rural lands, urban areas, and mountainous terrain), and preliminary system design specifications. For estimating purposes, land types were assumed to be rural if greater than 75% of the pipeline were in Class 1 locations, and urban if greater than 75% of the pipeline were in Class 2, 3, or 4 locations as defined by Code of Federal Regulations, Title 49 CFR 192.5(b). The pipeline estimates assumed unit costs for valve stations, cathodic protection, launcher and receivers, fiber optic monitoring and SCADA (Supervisory Control and Data Acquisition) systems based on preliminary routing configurations. Preliminary pipeline material specifications were based on guidance from ASME B31.12, § PL-3.7.1 with corresponding hydraulic model sizing results and parameters. The compressor stations were estimated based on historic SoCalGas project estimates for reciprocating compressors at various operating requirements (horsepower).

The pipeline and compressor costs were combined to produce the total cost per scenario, which represents the estimated capital expenditures (CapEx). The annual operating expenditure (OpEx) was estimated to be 1% of the capital costs for fixed operation and maintenance activities.[32] Variable operating costs were developed by the Cost Effectiveness Study based on anticipated utility costs to operate the compressor stations.

Table 17 –Scenario Cost Estimate Summary

	Installed Pipe, miles	Range of Nominal Pipe Sizes	Approx Total Pipeline Cost*	No. of Compressor Station(s)	Approx Total Compressor Cost*	Approx Total Cost* (CapEx)
Scenario 1	355	12-in to 30-in	$5 B	1 @ 33,000 hp	$1B	$6 B
Scenario 2	314	12-in to 24-in	$4 B	1 @ 33,000 hp	$1 B	$5 B
Scenario 3	303	12-in to 30-in	$5 B	1 @ 33,000 hp	$1 B	$6 B
Scenario 4	390	12-in to 36-in	$4 B	2 @ 33,000 hp (each)	$2 B	$6 B
Scenario 5	537	12-in to 24-in	$6 B	2 @ 33,000 hp (each)	$2 B	$8 B
Scenario 6	578	12-in to 30-in	$7 B	2 @ 33,000 hp (each)	$2 B	$9 B
Scenario 7	390	16-in to 36-in	$6 B	2 @ 50,000 hp (each)	$3 B	$9 B
Scenario 8	616	12-in to 36-in	$9 B	3 @ 33,000 hp (each)	$3 B	$12 B

*Cost based on Class 5 estimates, which have accuracy ranges of -20% to -50% on the low side, and +30% to +100% on the high side. See Section 6.1 for details.

6.4. Preferred Route Cost Estimates

Class 5 estimates were completed for each of the Preferred Route Configurations based on the results described in Section 4.6. This section supports the Routing Analysis by including cost as an additional factor for consideration and comparison for the Preferred Route Configurations.

[32] Khan, M.A., Young, C. and Layzell, D.B. (2021). The Techno-Economics of Hydrogen Pipelines. Transition Accelerator Technical Briefs Vol. 1, Issue 2, Pg. 1-40. ISSN 2564-1379.

6.4.1. Results/Discussion

Table 18 summarizes the Class 5 estimates for the single-run configuration for Preferred Routes A through D, which assumed the same preliminary land, pipeline, and compressor specifications as the Scenario 1-8 estimates.

Table 18 - Preferred Route Single-Run Configuration Cost Estimate Summary

Single-Run Configuration	Installed Pipe, miles	Pipe Sizes, inches	Approx Total Pipeline Cost*	No. of Compressor Station(s)	Approx Total Compressor Cost*	Approx Total Cost* (CapEx)
Route A	390	16”, 20”, 24”, 30”, 36”	$6 B	2 @ 50,000 hp (each)	$3 B	$9 B
Route B	406	20”, 36”	$7 B	2 @ 50,000 hp (each)	$3 B	$10 B
Route C	472	20”, 24”, 30”, 36”	$6B	2 @ 50,000 hp (each)	$3 B	$9 B
Route D	481	24”, 36”	$8 B	2 @ 50,000 hp (each)	$3 B	$11 B

*Cost based on Class 5 estimates, which have accuracy ranges of -20% to -50% on the low side, and +30% to +100% on the high side. See Section 6.1 for details.

As described in Section 4.6, single- and mixed-run configurations were modeled for the Preferred Routes to evaluate the system performance, operability, and resiliency, if portions of the system were temporarily removed from service for maintenance and other activities. The dual-run sections have smaller pipe diameters compared to the single-run equivalent, which is an important consideration since pipeline size impacts overall cost due to the increased material, weight, transportation, and constructability requirements associated with larger diameter pipes.

The single- and mixed-run Preferred Route Configuration cost comparison is presented in Table 19. The cost difference between the single- and mixed-run configurations ranges from 23% to 32%. The mixed-run configuration did not double the total installed pipe mileage, since only pipelines that were not part of a “looped” configuration were modeled as two-parallel lines (dual-run) to improve system resiliency, allow for continuous operation during potential disruptions, and increase storage capacity during peak usage periods.

Table 19 - Preferred Route Configuration: Single and Mixed Run Cost Estimate Comparison

	Approx. Total Cost*, Single-Run	Approx. Total Cost*, Mixed Run	Approx. Cost Difference	% Cost Difference
Route A	$9 B	$11 B	$2 B	23%
Route B	$10 B	$13 B	$3 B	27%
Route C	$9 B	$12 B	$3 B	31%
Route D	$11 B	$14 B	$3 B	32%

*Cost based on Class 5 estimates, which have accuracy ranges of -20% to -50% on the low side, and +30% to +100% on the high side. See Section 6.1 for details.

7. 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 20 below were selected because they are critical points at which relevant feedback can meaningfully influence the study.

Table 20: Key Milestone Dates

Milestone	Date Provided to PAG/CBOSG	PAG/CBOSG Comment Due Date	Responses to Comments in Quarterly Report[33]
1. Scope of Work	July 6, 2023	July 31, 2023	Q3 2023
2. Technical Approach	September 7, 2023	November 3, 2023	Q4 2023
3. Preliminary Data and Findings	May 21, 2024	June 4, 2024	Q2 2024
4. Draft Report	July 19, 2024	August 30, 2024	Q3 2024

Written feedback received is included in the quarterly reports, along with responses. Feedback provided at the PAG and CBOSG meetings is memorialized in the transcripts of the meeting which 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 or feedback that would be addressed in future phases. A summary of stakeholder input that was incorporated throughout the development of the Design Study and into this Final Report is provided in Table 21: Summary of Incorporated Stakeholder Feedback. All feedback received, whether incorporated into the study or not as

[33] Each Quarterly Report can be found on SoCalGas's website. (SoCalGas Angeles Link website, https://www.socalgas.com/sustainability/hydrogen/angeles-link)

described above, has been recorded in the quarterly reports, along with SoCalGas's responses.

Table 21: Summary of Incorporated Stakeholder Feedback

Thematic Comments from PAG/CBOSG Members	Incorporation of and Response to Feedback
Multiple Routing Scenarios Stakeholders requested multiple scenarios for pipeline routing to be examined that include a hub model and different ways of disaggregating production. Stakeholders also requested inter-state options evaluated to be marked distinctly from intra-state options, and assumptions to be identified.	In alignment with stakeholder comments, the potential design requirements for eight scenarios and four preferred routes as identified by the Routing Analysis were evaluated and findings are provided in Section 4.5 and Section 4.6, respectively. Refer to the Routing Analysis for details on the preliminary routing scenarios. Refer to the Production Study for details on assumptions on production locations. Refer to the Alternatives Study for details on the localized hub evaluation.
Repurposing Existing Pipelines Stakeholders requested as assessment of repurposing existing gas pipelines for material comparability and risk associated with repurposed pipelines.	In response to stakeholder comments, a high-level literature review of repurposing existing natural gas pipelines for hydrogen gas service was conducted and added to the Design Study. The potential advantages and disadvantages of converting natural gas pipelines compared to building new pipelines intended for hydrogen service was reviewed and presented in Section 5.4 "Repurposing Review."
Leakage Consideration Stakeholders requested emphasis to be placed on safety and leak prevention with regard to materials, monitoring technologies, proposed retrofits, siting, notification, and safety protocols.	In response to stakeholder comments, discussion of leak prevention and minimization opportunities was added to the "Design Development," Section 8.2.6, for future consideration. Leak prevention and minimization measures will be evaluated in detail when a preferred route is selected, operating conditions are established, and detailed engineering and design work commences in future project

Thematic Comments from PAG/CBOSG Members	Incorporation of and Response to Feedback
	phases. Refer to Section 4.4 of the Hydrogen Leakage Assessment (Leakage Study) for details on leak minimization methods, and Chapter 8 of the Safety Study for details on leak mitigation and repair.
Potential Impact Radius Stakeholders are interested in the differences between the potential impact radius (PIR) calculations for hydrogen and natural gas.	In response to stakeholder comments, PIR was added to the "Design Development," Section 8.2.2 for future consideration. Refer to Chapter 8 of the Safety Study for additional information on regulations, requirements, and calculations related to PIR.
Seismic Concerns Stakeholders requested earthquakes and seismic events to be addressed in pipeline routing and design.	In response to stakeholder comments, Section 8.2.3 "Geohazards" was added for future consideration. This section includes seismic concerns and other potential geohazards such as earthquakes, landslides, flooding, wildfire, and subsidence, to be considered when a preferred route is selected and detailed engineering and design work commences in future project phases.
Electric Reliability Stakeholders expressed concerns regarding increased reliance on electricity for end-use demand resulting in potentially greater criticality of disruptions to electricity. Stakeholders requested an assessment of proposed hydrogen infrastructure with regard to power system reliability and resiliency.	In response to stakeholder comments, a literature review of electric reliability was conducted and added to the Design Study to understand existing challenges, the planning process and outlook, and the integration between the electric and gas systems, with the purpose of informing the technical feasibility of Angeles Link as facilitating the provision of clean firm power in support of electrification and electric reliability. Refer to Appendix B "Electric Reliability" for literature review details and analysis.

Summary of Literature Provided by Stakeholders

- Literature provided by PAG/CBOSG stakeholders was evaluated and incorporated, where relevant and as appropriate, including, but not limited to:

- Martin, P., Ocko, I. B., Esquivel-Elizondo, S., Kupers, R., Cebon, D., Baxter, T., & Hamburg, S. P. (2024). A review of challenges with using the natural gas system for hydrogen. Energy Science & Engineering. https://doi.org/10.1002/ese3.1861

8. FUTURE CONSIDERATIONS

Angeles Link Phase 1 studies, including the Pipeline Sizing and Design Criteria (Design Study), address the feasibility aspects of and establish a foundation for the Angeles Link project. These feasibility studies serve as a precursor to more detailed analysis and refinement that underpin the subsequent stages of preliminary and Front End-Engineering Design (FEED) activities. FEED represents a detailed approach through which the project's specifications will be further defined to a 30% design. The future considerations identified within this chapter will be necessary to safely advance the engineering design, identify specific project requirements, safety and design factors, and support efficient project execution in the future. These following considerations are important to the advancement of Angeles Link but were not considered part of the feasibility evaluation.

8.1. Hydraulic Performance and Modeling

8.1.1. Transient Hydraulic Analysis

A transient or dynamic hydraulic model focuses on studying the changes in flow conditions within a pipeline system over time. Analysis can be performed to examine the dynamic behavior of fluid flow within a pipeline when the flow conditions change rapidly. These changes can occur due to valve operations, changes in demand, or changes in supply. The analysis helps predict pressures exceeding normal operational levels and allows for a pipeline to be designed to the appropriate specifications for the characteristics of connected loads.

A hydraulic model of the pipeline will include all relevant pipeline system components like compression, valves, fittings, reservoirs, and pipeline geometries. Modeling software is then used to simulate different transient or dynamic scenarios. These tools use the method of characteristics or other numerical methods to solve the transient flow equations. This differs from static modeling where the models evaluate steady-state conditions where the flow parameters such as pressure, velocity, and flow rate are assumed to remain constant over time (as completed in Phase 1 of this study). The primary goal of static modeling is to evaluate the system under a normal operational state without considering changes over time. It is focused on efficiency and feasibility. By contrast, a dynamic analysis considers the time-dependent changes in the flow conditions caused by operations or disturbances. These models can capture how an event will affect variables such as pressure and flow rate over time. They are more complex and computationally intensive due to the need to solve the equations of motion and continuity for fluid dynamics, considering the elasticity of the fluid and the pipe wall. Transient modeling is used for understanding the pipeline's behavior under non-standard and emergency conditions, focusing on system integrity and how the system responds to changes.

Transient modeling allows for a variety of safety considerations to be made. First, as noted above, material selection requires transient modeling. It is additionally important in the development of design for protective measures such as pressure relief valves or the development of operational standards, monitoring thresholds, and system maximums/minimums.

In subsequent phases of Angeles Link, additional specific details regarding the pipeline connections can be determined as the route selection and material choice is narrowed. This additional detail will allow for the complexities of transient modeling to be performed.

8.1.2. System Requirements

The development of system requirements is also supported via transient hydraulic modeling and is an important component of system design on its own. The term “system requirements” for a pipeline refers to the specific operational and performance criteria that the pipeline must meet to function effectively and safely under various conditions, including extreme scenarios. These requirements are typically defined during the design phase of the pipeline and are crucial to the design process for adequacy during typical operating conditions but also during rare and challenging circumstances.

System requirements mandate that the design accounts for the most severe conditions anticipated during the pipeline’s lifetime. For example, designing for a 1/35-year condition means that the pipeline must be able to withstand and operate during events that have a 2.86% chance of occurring in a given year. Operational margins are included to maintain the system’s receipt and delivery objectives are achieved within a relatively wide variety of circumstances.

Materials must be chosen for their performance under normal conditions including for durability and resiliency under the specified extreme conditions. This might include selection of materials with higher corrosion resistance, greater mechanical strength, or enhanced flexibility. Engineering specifications such as wall thickness, diameter, and the type of joints and seals might be adjusted to cope with additional pressures or movements caused by extreme conditions.

Operational flexibility and performance standards are also defined via system requirements. This could include the amount of time expected for the system to quickly adjust operations in response to fluctuating demands, supply, or emergency events. Conversely, they may define the amount of time the system is expected to be operational and available for use without interruption, also known as “system up time”. This metric allows for evaluation of the reliability and efficiency of the system and is part of the overall performance standards. It is typically expressed as a percentage of the total time over a specific period, often annually. For example, an expected up time of 99% annually means the system is expected to be operational for 99% of the time throughout the year, which translates to being "down", or non-operational, for no more than 3.65 days in a year. High up time requirements may necessitate redundancy in critical parts of the system architecture to support continuous operation and/or affect integrity maintenance planning strategies in order to prioritize performance of predictive maintenance with up time requirements in mind.

Service Level Agreements (SLAs) in a commercial context illustrate the expectations between service providers and customers. These SLAs stipulate the performance criteria, including up time, that must be met, and the penalties for failing to meet these criteria. As details of the project are developed, including hydrogen receipt and offtake, agreements such as SLAs would reflect corresponding system requirement features that allow for connection to the Angeles Link system.

8.1.3. Storage and Scalability

Hydraulic modeling is essential to the design of a system that is scalable and integrates storage solutions. The ability to evaluate changes over transient periods of time allows for evaluation of how to scale the system to meet current and future demands efficiently.

Long term planning options are developed as dynamic modeling simulates fluid flow over time, considering variations in supply and demand, compression operations, and other factors that affect flow and pressure in the system. Capacity planning, predicting how the pipeline will perform as demand increases or as new sources or sinks are integrated into the system, is essential in large infrastructure projects. Dynamic modeling allows for a simulation of what types of system changes may be adequate including installation of larger diameter pipes, adding parallel lines, or increasing the number and capacity of compressors. It also creates the capability to evaluate how an initial system may cope with future increases or decreases in flow to support informed decision making about system staging and growth.

By modeling different operational scenarios, it is possible to identify periods when the system may face excess supply or demand shortfalls. Storage facilities can be strategically located and sized to support regional hydrogen producers and end users to buffer these fluctuations, creating a steady supply and preventing system overload or underutilization. During periods of low demand, excess gas can be stored rather than reducing the pipeline's throughput drastically, which might be less efficient. Clean renewable hydrogen production and above ground and underground storage is not currently proposed as part of Angeles Link. As Angeles Link is further designed and, in alignment with the development of system requirements, the role of storage to support regional hydrogen producers and end users should be considered. Distributed storage equipment located at third-party production and end user sites, along with line packing, which refers to storing and then withdrawing gas supplies from the pipeline, can provide storage capacity while scale storage technologies are developed overtime to support regional requirements.

The scalability of a pipeline system is another important mechanism in design given that the ability to respond to the growth of the supply and offtake, for which the pipeline acts as a transportation mechanism, is key. Clean renewable hydrogen production is currently not widespread but is anticipated to significantly increase as the shift toward sustainable energy sources gains momentum. Similarly, the demand for hydrogen is expected to rise as it becomes more integral to various industries seeking to decarbonize and meet State and Federal targets. See the Demand Study and the Production Study for further information on projected growth. In response to this emerging market, the development of a dedicated pipeline system for hydrogen transport is critical. Such a system must not only cater to current demands but must also be designed to accommodate future increases in production and consumption volumes. The time required to plan for installation of infrastructure necessitates that pipeline system components are anticipated in advance of when they may then be needed. This supports a smooth energy transition and a supply chain that is robust and responsive to the evolution of the energy landscape.

8.2. Design Development

Pipeline design is significantly influenced by the physical location of the pipeline as well as operational and maintenance considerations. These considerations are discussed below.

8.2.1. Material Selection & Corrosion Protection

Material selection is part of the design process and is heavily influenced by the route. Compatibility with environmental factors, such as soil and groundwater chemistry, can play a role in the material selected. Selection of materials that are robust and appropriate for the specific conditions of the pipeline's operation will minimize the risk of material degradation and failure due to corrosion. Corrosion is a natural process where materials made from metals deteriorate through an electrochemical reaction known as oxidation (rusting),[34] and can occur both internally and externally on a pipeline. It is critical to

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[34] Pipeline Safety Stakeholder Communications. PHMSA. (n.d.-b). https://primis.phmsa.dot.gov/comm/FactSheets/FSCorrosion.htm

employ protection strategies and make material choices that are tailored to specific local geological and hydrological conditions as the rate of corrosion and susceptibility to it is influenced by these factors.

Corrosion – Different transported substances can have varying impacts on materials, potentially leading to corrosion or wear. Including integrity management involves the selection of materials that resist such degradation processes, thus maintaining the structural and functional integrity of the pipeline. This includes choosing corrosion-resistant alloys or applying protective coatings and linings both internally and externally.

Corrosion can be characterized by where and/or how it occurs. For example:

External corrosion occurs due to environmental conditions on the exterior surface of the steel pipe that can cause an electrochemical interaction between the exterior of the pipeline and the soil, air, or water surrounding it. Galvanic and atmospheric corrosion are common types of external corrosion.

Internal corrosion occurs due to a chemical attack on the interior surface of a steel pipe from the products transported in the pipe. This can be from either the commodity transported, or from other materials carried along with the commodity, such as water, hydrogen sulfide, and carbon dioxide.

Other types of corrosion can occur due to specific material defects or environments. These include stress corrosion cracking (SCC), microbiologically-influenced corrosion (MIC), stray current interference corrosion, and selective seam corrosion. These types of corrosion problems can be exacerbated by environmental conditions, manufacturing processes, pipe wall erosion from the transported commodity, physical location with respect to other structures, and applied stresses resulting from routine and normal pipeline operations.

Simultaneously, pipelines must also be designed for the fuel being carried. See the Materials Review Chapter of this Study for further detail into pipeline integrity (with regard to materials), hydrogen embrittlement, maintenance, and repurposing.

In subsequent phases of Angeles Link, more details will be available that will inform the development of specific integrity management practices for hydrogen infrastructure. Iteratively, integrity management needs will also drive material selection in the following ways.

Technology – Tools and equipment used to evaluate pipeline integrity, including devices such as smart in-line-inspection tools and others used to appropriately monitor and check pipeline health over time, are an important consideration in material selection. Part of the design process is to select materials that can be effectively inspected using commercially available equipment, and opting for standard sizes can enhance the availability of these tools and simplify integrity management practices. Materials that are compatible with advanced inspection and monitoring techniques, such as smart pigging and ultrasonic testing, enable more effective and less intrusive integrity checks.

Maintenance Practices – Material selection can also facilitate the ease of monitoring and maintenance of the pipeline. It may be more practical to select certain materials in areas that are challenging or difficult to physically access versus materials that require more frequent or invasive inspection.

Cost-Effectiveness – Initial cost of materials is an important factor in the material selection process. Additionally, consideration must be given to the lifecycle cost of the pipeline. Selecting materials that require less maintenance, have longer lifespans, and have lower risk of failure can significantly reduce operational and repair costs over time.

Flow Velocity - Gas movement within a pipeline can be measured by its velocity. Pipeline erosion occurs when a fluid flowing within a pipeline gradually degrades small amounts of the inner pipeline surface through surface collisions with greater effect at higher fluid velocities. Gas velocities can be calculated to determine at what operating conditions erosion may occur in a pipeline using the Erosional Velocity Equation per ASME B31.12. The erosional velocity is a function of temperature and pressure and fluctuates throughout the system based on operating conditions. The fluid velocity is an important consideration for selecting pipe size and will be further analyzed in future phases when operating parameters throughout the Angeles Link system are established.

I-3.4.5 Hydrogen gas velocities in piping should not exceed the erosional velocity at peak conditions. Lower velocities are recommended. The erosional velocity, u_e, is calculated by:[1]

$$u_e = \frac{100}{\sqrt{\frac{29GP}{ZRT}}}$$

where

G = gas gravity (0.0695)
P = minimum pipeline pressure, psia
R = universal gas constant
= 10.73 $ft^3 \cdot psia/(lb\text{-}mol \cdot °R)$
T = flowing gas temperature, °R
u_e = erosional velocity, ft/sec
Z = compressibility factor at specified temperature and pressure, dimensionless

Figure 18 - Erosional Velocity Equation (ASME, 2024)

Sourcing Logistics – The availability of specific materials can vary greatly depending on geographic location, manufacturing capacity, and market demand. Materials that are readily available or can be delivered quickly from nearby suppliers may reduce lead times and assist in adherence to project schedules. Conversely, opting for materials that require long lead times or are subject to supply chain uncertainties can delay project timelines. The distance, means, and cost of transportation from the supplier to the project site can affect the total cost of the project. Heavy or bulky materials such as large-diameter pipes or heavy steel sections, might require special transportation arrangements. Additionally, some materials may have storage or handling constraints that complicate logistics.

As pipeline route, system needs, and design are further refined for Angeles Link, the selection of materials and corrosion protection features can be further developed. Due to the integration between these components, it is advisable to develop them after the project feasibility stage to allow for a more informed, accurate, and compliant approach. This creates a basis that is solid and founded on detailed project specifications to make them capable of addressing all operational and environmental requirements effectively.

8.2.2. Pipeline Routing[35], Construction & Maintenance

Pipeline routing influences the material selection of a pipeline as well as the overall design. Plans for construction and maintenance may also influence the design beyond the selection of materials. Cost, efficiency, weather, seismicity, and infrastructure proximity are all considerations that impact pipeline sizing and materials.

Cost – Routes that avoid natural obstacles like rivers, mountains, and protected ecosystems, sensitive habitats and potential wildlife habitats help to minimize environmental disruption, thereby reducing the amount of earth moved during construction and potential environmental mitigation requirements. Cost reductions or savings may result, which is also a key consideration achieved by shortening the overall length of the pipeline and the selection of routes that allow for easier construction and lower material costs. For example, construction within mountainous terrain can pose disadvantages due to potential for land movement, extreme or unpredictable weather, complexities in design, and ease of access for both installation and transportation of materials. These characteristics can result in higher design and installation costs.

Efficiency – Operational efficiency is another significant factor in route selection. The chosen route should consider facilitation of maintenance and surveillance to maximize ease of access in all seasons and conditions. This includes not only the construction timeframe when the ingress and egress of equipment to a work location will be important, but also includes consideration of future needs for pipeline inspection and repairs (e.g. potential rights-of-way or specific routing needs to accommodate maintenance equipment). The ability to surveil pipeline sites for safety and security must be

[35] Refer to Routing Analysis for additional considerations not described in this chapter such as engineering, environmental, social, and geographic elements.

incorporated into the route planning such that monitoring systems like patrol routes for aerial surveillance are effective and efficient.

Piggability – Designing pipelines to accommodate pipeline inspection gauges, or "pigs", is an important consideration for anticipated cleaning, inspection, and maintenance activities. General factors to consider include pipeline operating conditions, configuration, diameter changes, entry and exit points for the pig such as launchers and receivers, and fittings that include valves, bends, and elbows. Piggability also considers the materials specification depending on the type of pigging activity. Pigs that are equipped with sensors and data recording devices may only be compatible with certain material and pipe specifications. A variety of factors will need to be considered in subsequent design and project development to facilitate routine integrity management and maintenance activities.

Transportation – Material weight is increased as pipe diameter and wall thickness increases. This, in turn, affects how the pipe can be safely transported from the location where the steel is milled to the location where it will be stored or used for construction. Guidelines set forth by the U.S. Department of Transportation Federal Highway Administration for Freight Management and Operations[36] govern weight limitations for transportation by vehicle.

Weather – Weather related challenges significantly impact both the construction schedule and methodology of pipeline projects. Seasonal extremes must be considered, such as heavy rainfall or intense heat, which can influence when and how construction proceeds. Additionally, regions prone to freeze thaw cycles may require specific engineering solutions to manage soil instability that could involve deeper burial of the pipeline or the use of certain pipe materials. Areas prone to other transient environmental conditions like flooding may also require additional design considerations, which could include elevated structures or reinforced embankments to prevent erosion during heavy rains.

Infrastructure Proximity – Additional infrastructure within close proximity to the pipeline may have design implications. It is necessary to consider multiple components when siting an underground hydrogen pipeline with regard to other substructures, such as content carried, pressure, diameter, size, setback, and depth requirements, etc.[37] For

[36] Compilation of existing State Truck Size and Weight Limit Laws - Appendix A: State Truck Size and Weight Laws - FHWA Freight Management and Operations. (n.d.). https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/app_a.htm

[37] Global Designing Cities Initiative. (2022a, September 13). Underground Utilities Design Guidance - Global Designing Cities Initiative. https://globaldesigningcities.org/publication/global-street-design-guide/utilities-and-infrastructure/utilities/underground-utilities-design-guidance/

aboveground infrastructure, proximity to other energy infrastructure, such as overhead electrical lines, is a site-specific consideration that may require rerouting or design adjustments. Design choices may be further affected by location with regard to zoning and land use. It is preferred to install operations and maintenance facilities in areas where noise and ingress or egress due to construction and operations will minimize disruption to local communities as feasible.

Potential Impact Radius – As discussed in the Safety Study, the potential impact radius (PIR) is utilized to determine high and moderate consequence areas along a pipeline that will inform the development of an integrity management program, as required by 49 CFR Part 192 Subpart O - Gas Transmission Pipeline Integrity Management. The PIR will be calculated in future project phases after a preferred route is selected and the pipeline nominal diameter and MAOP are finalized. Refer to "Integrity Management" section in Chapter 8 of the Safety Study for additional information on PIR and consequence areas.

8.2.3. Geohazards[38]

Pipeline design and routing should consider geohazards, which can impact pipelines and related infrastructure. Frameworks typically consider the physical characteristics of geohazards and how the pipeline reacts to these hazards. A geohazard management program (GMP) incorporates methods and processes to systematically identify, evaluate, and manage geohazards, aiming to minimize the risk of pipeline damage and failure.[39] After establishing a pipeline route, it becomes possible to identify specific geohazards that need to be included in the GMP. The GMP can then be developed during detailed stages of the design process. Typical geohazard design considerations are as follows:

8.2.3.1. Seismic Fault

Pipeline design and routing should also consider the potential impacts of seismic activity or crossing of a fault. While many steps can be taken in response to a seismic event, proactive measures can also be engineered into the design. The installation of automatic valves on either side of known earthquake faults presents a proactive opportunity for real-time control should a pipeline failure occur. Valve set-back distance is conservatively determined through calculations that include the distance from the fault crossing where

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[38] Wang, Y. (2019). *PR-350-164501-R01 Guidance for Assessing Buried Pipelines after a Ground Movement Event*. https://doi.org/10.55274/r0011582
[39] Miller, A. (2023, November 6). IMCI 2.0 2023 framework for Geohazard Management. INGAA. https://ingaa.org/imci-2-0-2023-framework-for-geohazard-management/https://ingaa.org/wp-content/uploads/2023/11/2023_Framework-For-Geohazard-Management_Public.pdf

pipeline force is reduced to an acceptable level. Pipeline characteristics such as material and external site-specific conditions such as soil strength parameters assist in the valve-siting process. SoCalGas has designed and mitigated pipeline fault crossings on its existing natural gas system through different measures such as geo foams, shallow trenches, increased wall thickness, and proper crossing design angles. As done today, the implementation of Finite Element Analysis to model the soil and pipe interaction can also be used to mitigate fault ruptures. In addition, both deterministic and probabilistic fault rapture analysis[40] can be used to further evaluate the proposed lines to make proactive design choices.

8.2.3.2. **Liquefaction and Lateral Spreading**

Soil conditions such as liquefaction and lateral spreading present another geohazard. SoCalGas manages this risk today in a way that can be leveraged for hydrogen pipelines through the use of California Geological Survey maps as well as historical operating data to identify areas where this geohazard may exist. Finite Element Models and mitigation measures such as piles can be used to mitigate against these geohazards.

8.2.3.3. **Landslides**

Proactive mitigation and monitoring are two main strategies to minimize landslide risk.[41] Publicly available maps and historical data used by SoCalGas today can be leveraged to identify areas of land movement; and to mitigate the hazard by either avoiding the hazard areas, using deeper burial depths, creating Best Management Practice measures that take this hazard into consideration, re-grading and benching the area, and/or using other civil engineering and geotechnical techniques and technologies to stabilize land movement.

8.2.3.4. **Flooding and Debris Load**

Hydrologic Engineering Center's River Analysis System (HEC-RAS) software, issued by the US Army Corps of Engineers, is used by SoCalGas today and can be further leveraged to calculate scour depth, flood height, and the velocity of flood events and

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[40] Nicee. (n.d.-b). https://www.wcee.nicee.org/wcee/article/16WCEE/WCEE2017-4570.pdf
[41] Guidelines for Management of Landslide Hazards for Pipelines. (n.d.-b). https://ingaa.org/wp-content/uploads/2020/08/38070.pdf

associated debris loading. Deeper burial depths, deep foundation construction, and increasing the elevation of the pipe above the flood level are all methods currently employed to properly address potential flooding and debris loading. In addition, other techniques such as horizontal directional drilling, jack and bore, and/or the use of River-X software can be leveraged to design pipeline crossings over bodies of water.

8.2.3.5. **Wildfire**

SoCalGas utilizes post-wildfire data from USGS and CalFire. Once it's safe, geologists and/or geotechnical engineers perform field reconnaissance of the burnt area, followed by debris flow susceptibility analysis. This data could be utilized to minimize routing through wildfire prone areas, where feasible, and to inform pipeline design considerations such as soil conditions.

8.2.3.6. **Subsidence, Expansive Soil and Other Geohazard Issues**

SoCalGas will review the proposed pipeline route and design against other geohazards issues such as subsidence or expansive soil and provide different potential ways to mitigate these issues based on detailed geotechnical investigations, as needed.

8.2.4. Pressure & Flow Management

Design and pipeline route selection can also consider the potential effects of varying temperature and elevation on the chemical properties of the commodity being transported.

Topography - Pipeline design is impacted by the topography of the pipeline route. Elevation and temperature changes affect gas density.[42] If a pipeline passes through higher elevations, these factors must be considered to plan for necessary pressure and flow rates at other points along the pipeline which affect the size of the pipeline and MAOP.

Compression - In subsequent phases of Angeles Link, sites and design specifications will be developed for compressor stations. Compressor stations are essential for maintaining the pressure and flow of gas necessary for efficient transportation over long

[42] Hydrogen density at different temperatures and pressures: H2tools: Hydrogen tools. H2tools. (n.d.). https://h2tools.org/hyarc/hydrogen-data/hydrogen-density-different-temperatures-and-pressures

distances. Their size, location, and operational characteristics are inherently linked with route, materials, and system requirements.

The siting of compressor stations considers the pipeline route at intervals determined by the pressure drop in the pipeline. As discussed in previous chapters of this report, pressure drop in the pipeline is influenced by factors like pipeline diameter, roughness of the pipe interior, and the elevation changes along the route. There is an accessibility component for compression siting, specifically with regard to commercial power and utilities (water), construction, operation, and maintenance. While there are remote compressor stations the site must be accessible for construction equipment and emergency response. In addition, hydrogen compressor stations would be manned facilities requiring the necessary on-site accommodations such as an office building, operations room, maintenance shop and warehouse. Consideration of existing roads and the need for new road construction is crucial.

Valving – Valve stations manage operational conditions such as pressure and flow rate and allow for adjustments to be made based on system demand or operational conditions. Valve stations would be leveraged to perform an isolation of pipeline segments during routine maintenance or emergencies.

The size, pressure rating, and type of product being transported influence where valves are placed. Regulations often dictate minimum safety requirements, including the placement of valves at critical points such as populated areas, or near other infrastructure. The need for operational flexibility in terms of managing gas within the system also determines the design choices for the number, placement and type of valves selected. Design and siting of valve stations is also contingent upon geography and environmental elements identified over the course of the route. This could include water crossings or other natural barriers, seismic faults, ease of access for maintenance, or elevation changes. Environmental sensitivities of an area may further affect valve station placement because during emergencies or maintenance operations, valves may need to be physically reached quickly and safely. Lastly, the cost of the valve station, including installation and maintenance, is an important consideration. Station placement seeks to optimally balance safety and functionality with cost-efficiency.

In subsequent phases of Angeles Link, additional design components will be identified and sited as appropriate for efficient and safe operation of the pipeline system.

8.2.5. Control System Design & Technology Integration

Integration of digitization, technology and controls are important for the reliable and efficient operation of a system and create the ability to manage and monitor a pipeline's operation. Control system design involves developing the automation and control mechanisms that enable the centralized monitoring and management of the pipeline.

Control systems design includes SCADA (Supervisory Control and Data Acquisition) systems, PLCs (Programmable Logic Controllers), communication infrastructure such as fiberoptics, safety systems such as ESDs (Emergency Shutdown systems), and Human-Machine Interfaces (HMIs). These will be critical components to the detailed design of a pipeline system. These control applications are currently used and integrated with existing infrastructure at SoCalGas and play a crucial role in leak detection and repair.

Technology integration involves the seamless incorporation of various technologies into the pipeline system to enhance performance, safety, and reliability. This may include sensors and instrumentation, data analytics, cybersecurity measures, and integration with other systems.

8.2.6. Leakage Consideration

Opportunities to minimize and prevent hydrogen leakage will be further considered in future phases to enhance system safety and operations, and to reduce potential indirect climate impacts, as discussed in the Greenhouse Gas (GHG) Emissions Evaluation (GHG Study). Future project phases will consider engineering and design, operations, maintenance and repair, and other methods to minimize potential leakage in the Angeles Link pipeline transmission system. Furthermore, future project phases will also monitor the development of regulations and design standards that may impact hydrogen leakage and incorporate them into the system design, material selection, integrity management program, and safety plan considerations where applicable. Refer to Section 4.4 of the Hydrogen Leakage Assessment (Leakage Study) for details on leak minimization methods, and Chapter 8 of the Safety Study for details on leak mitigation and repair.

9. GLOSSARY

Air Cooled Heat Exchangers - Heat transfer equipment typically found in transmission stations, used to cool the hot discharge gas from compressors to acceptable temperatures conducive to pipeline transportation.

American National Standards Institute (ANSI) – A private, non-profit organization that administers and coordinates the U.S. voluntary standards and conformity assessment system.[43]

[43] American National Standards Institute. (n.d.). ANSI introduction. ANSI. https://www.ansi.org/about/introduction

American Petroleum Institute (API) - Formed in 1919 as a standards-setting organization and has developed more than 800 standards to enhance operational and environmental safety, efficiency and sustainability.[44]

American Society for Testing and Materials (ASTM) - A nonprofit organization that develops and publishes approximately 12,000 technical standards, covering the procedures for testing and classification of materials of every sort.[45]

American Society of Mechanical Engineers (ASME) - A nonprofit professional organization that enables collaboration, knowledge sharing, and skill development across all engineering disciplines, while promoting the vital role of the engineer in society.[46]

Association for the Advancement of Cost Engineering (AACE) - Advocates for its Body of Knowledge and the people who employ it through iteration and innovation of trusted technical guidance and meaningful collaboration.[47]

Butt Welding Steam Pipes - A joint where two pieces of metal are placed together in the same plane, and the side of each metal is joined by welding.[48]

California Public Utilities Commission (CPUC) – Regulates services and utilities, protects consumers, safeguards the environment, and assures Californians' access to safe and reliable utility infrastructure and services.[49]

Catalyst Poisoning - Metals like iron and potassium that are inherent in certain biomass feedstocks interact with the catalyst, poisoning it and causing loss of catalyst function.[50]

Centrifugal Compressors - Compressors increase the pressure by using the rotation of impeller blades to increase kinetic energy.

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[44] About API. Energy API. (n.d.). https://www.api.org/about

[45] ASTM International. ANSI Webstore. (n.d.). https://webstore.ansi.org/sdo/astm?msclkid=b5145c8e3c9110b215d53ac1f2f86bb8&utm_source=bing&utm_medium=cpc&utm_campaign=Standards-US&utm_term=ASTM+standards+store&utm_content=ASTM

[46] About ASME. ASME. (n.d.). https://www.asme.org/about-asme#:~:text=Founded%20in%201880%20as%20the%20American%20Society%20of,the%20vital%20role%20of%20the%20engineer%20in%20society.

[47] About Aace. (n.d.). https://web.aacei.org/about

[48] Welding joint types: Butt, lap, tee, Edge Joints & More: UTI. UTI Corporate. (n.d.). https://www.uti.edu/blog/welding/joint-types

[49] California Public Utilities Commission. (n.d.). What industries does the CPUC regulate? In California Public Utilities Commission. https://www.cpuc.ca.gov/-/media/cpuc-website/about-cpuc/documents/transparency-and-reporting/fact_sheets/cpuc_overview_english_030122.pdf

[50] Unlocking the mystery of Catalyst Poisoning | Department of Energy. (n.d.-g). https://www.energy.gov/eere/bioenergy/articles/unlocking-mystery-catalyst-poisoning

Compressor Drives - The mechanism or system responsible for powering the operation of a compressor, like an engine in an automobile.

Compressor Stations - facilities that maintain the flow and pressure of a gas by receiving gas from the pipeline, re-pressurizing it, and sending it back into the pipeline system.

Compressors - Mechanical equipment, typically found in transmission stations used to increase the pressure of the hydrogen gas to adequate levels for transmission through the pipeline. They are essential for maintaining flow and overcoming frictional losses along the pipeline length.

Control & Monitoring Systems - Centralized systems that use field technology, sensors and communication methods to monitor and control the physical parameters of the pipeline.

Corrosion - A natural process where materials made from metals deteriorate through an electrochemical reaction known as oxidation (rusting).

Corrosion Protection Systems - Includes cathodic protection and protective coatings that are designed to prevent internal and external corrosion.

Derate - Also known as pipeline derating, is the process of reducing a pipeline's maximum allowable operating pressure (MAOP), allowable stress, or capacity under certain conditions.

Diaphragm Compressors - Driven by a reciprocating piston-crankshaft mechanism that separates hydraulic fluid/oil from process gas.

Electrolyzers - Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer.[51]

Emergency Shutdown Systems (ESDs) - Systems designed to rapidly shut down the pipeline operation in the event of a detected leak or other hazardous situations that will isolate sections of the pipeline to minimize risks.

Geographic Information System (GIS) - Geographic Information Systems (GIS) are systems that capture, store, analyze, and display spatial or geographic data. GIS can be used to create maps, models, and simulations that show the patterns, relationships, and trends of various phenomena that occur on the Earth's surface or in the atmosphere.

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[51] Hydrogen production: Electrolysis | Department of Energy. (n.d.-a). https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Hot Tapping - A procedure used to make a new pipeline connection while the pipeline remains in service, flowing natural gas under pressure.[52]

Hydrogen Embrittlement - A process resulting in a decrease in the fracture toughness or ductility of a metal due to the presence of atomic hydrogen.[53]

Inflation Reduction Act of 2022 (IRA) - Enhanced or created more than 20 tax incentives for clean energy and manufacturing.[54]

Inline Inspection (ILI) - A technique used to assess the integrity of natural gas transmission pipelines from the inside of the pipe and is used by Southern California Gas Company (SoCalGas) as part of its ongoing pipeline integrity program.[55]

Inside Diameter (ID) - Measured from top to bottom or left to right from the inside hole of the pipe. This measurement is important when calculating the flow of liquid.[56]

Intermediate Compressor/Booster - Maintains the pressure of natural gas as it flows through a pipeline.[57]

Leak Detection Systems - Technologies deployed along the pipeline to detect and locate leaks based on pressure, acoustic signals, or chemical sensors. These are components essential for the early detection of failures or breaches in pipeline integrity.

Line Packing - A method used for providing short-term gas storage in which natural gas is compressed in transmission lines, providing additional amounts of gas to meet limited peak demand.[58]

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[52] Environmental Protection Agency. (n.d.). EPA. https://www.epa.gov/natural-gas-star-program/pipeline-hot-taps
[53] Hydrogen embrittlement. (n.d.-d). https://ntrs.nasa.gov/api/citations/20160005654/downloads/20160005654.pdf
[54] Inflation reduction act. U.S. Department of the Treasury. (2024, May 8). https://home.treasury.gov/policy-issues/inflation-reduction-act
[55] In-line inspection of pipelines - SoCalGas. (n.d.-f). https://www.socalgas.com/documents/news-room/fact-sheets/In-LinePipelineInspection.pdf
[56] Simple guide to pipe size terminology. (n.d.-j). https://pandfglobal.com/wp-content/uploads/PFG-pipe-size-terminology-whitepaper-FA4.pdf
[57] UMN. (n.d.-k). https://mwc.umn.edu/wp-content/uploads/2021/01/compressor-station-pages1and2.11302020.pdf
[58] *Line pack · Energy KnowledgeBase*. (n.d.). https://energyknowledgebase.com/topics/line-pack.asp#:~:text=Line%20pack%20is%20natural%20gas,day%20does%20not%20match%20consumption.

Location Class 1 - Any 1.6km (1 mile) section that has ten or fewer buildings intended for human occupancy. A Location Class 1 is intended to reflect areas such as wasteland, deserts, wetlands, mountains, grazing land, farmland and sparsely populated areas.[59]

Location Class 1, Division 1 - Not applicable to hydrogen service and not recognized in this Code.[60]

Location Class 1, Division 2 - Class 1 where the design factor of the pipe is equal to or less than .72 and has been tested to 1.1 times the maximum-operating pressure (ASME B31.12, PL-3.7.1-6 provides exceptions to design factor).[61]

Location Class 2 - Any 1.6 km (1 mile) section that has more than 10 but fewer than 46 buildings intended for human occupancy. A Location Class 2 is intended to reflect areas where the degree of the population is intermediate between Location Class 1 and Location Class 3, such as fringe areas around cities and towns, industrial areas, ranch or country estates, etc.[62]

Location Class 3 - Any 1.6 km (1 mile) section that has 46 or more buildings intended for human occupancy, except when a Location Class 4 prevails. A Location Class 3 is intended to reflect areas such as suburban housing developments, shopping centers, residential areas, industrial areas, and other populated areas not meeting Class 4 requirements.[63]

Location Class 4 - Includes areas where multistory buildings are prevalent, where traffic is heavy or dense, and where there may be numerous other utilities underground. Multistory means four or more floors above ground, including the first or ground floor. The depth of basements or number of basement floors is immaterial.[64]

Lower Explosive Limit (LEL) - The minimum concentration of vapor in air below which propagation of a flame does not occur in the presence of an ignition source.[65]

Maximum Allowing Operating Pressure (MAOP) - maximum pressure at which the equipment may be operated

Metering & Regulation (M&R) - Track the volume of natural gas as it is transported and distributed. M&R stations use different meters and other equipment to continuously

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[59] ASME B31.12, PL-3.2.2
[60] ASME B31.8
[61] ASME B31.12, PL-3.2.2
[62] ASME B31.12, PL-3.2.2
[63] ASME B31.12, PL-3.2.2
[64] ASME B31.12, PL-3.2.2
[65] 1915.11 - scope, application, and definitions applicable to this subpart. Occupational Safety and Health Administration. (n.d.). https://www.osha.gov/laws-regs/regulations/standardnumber/1915/1915.11

measure the flow and, if needed, reduce the pressure of gas as it moves through the station.[66]

Metering Stations - These stations measure the flow rate of hydrogen through the pipeline and are utilized for operational control and billing purposes.

Microalloying - Used in wrought steels to refine grain size during thermo-mechanical controlled processing.[67]

National Association of Corrosion Engineers (NACE) - Has become the global leader in developing corrosion prevention and control standards, certification and education.[68]

National Fire Protection Association (NFDPA) - Started as a Boston-based organization for fire sprinkler codes has grown to become the leading global advocate for the elimination of death, injury, property, and economic loss due to fire, electrical, and related hazards.[69]

Nominal Pipe Size Diameter (NPS) - Related to the inside diameter in inches, and NPS 12 and smaller pipe has outside diameter greater than the designated size.[70]

Non-Destructive Examination (NDE) - Used to inspect and evaluate materials, components, or assemblies without destroying their serviceability.[71]

Outside Diameter (OD) - Measured from top to bottom or left to right from the outside edges of the pipe – not the collar or socket end. The OD is often critical for joining pipes or getting the correct fitting that will fit over the pipe.[72]

Pipeline Draft (drafting) – condition in a pipeline when the demand is greater than the supply resulting outflow of gas.

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[66] Metering and regulating (M&R) stations. Earthworks. (n.d.). https://earthworks.org/issues/metering_and_regulating_mr_stations/
[67] Khalid, P. (2016, January 6). Overview of microalloying in steel. Academia.edu. https://www.academia.edu/20055864/6._Overview_of_Microalloying_in_Steel
[68] History. AMPP. (n.d.). https://www.ampp.org/about/nace-history
[69] Learn more about NFPA: The National Fire Protection Association. nfpa.org. (n.d.). https://www.nfpa.org/About-NFPA
[70] PI-21-0008. PHMSA. (2021, September 1). https://www.phmsa.dot.gov/regulations/title49/interp/pi-21-0008
[71] *What is nondestructive testing? Discover the world of NDT*. (n.d.). https://www.asnt.org/what-is-nondestructive-testing
[72] Simple guide to pipe size terminology. (n.d.-j). https://pandfglobal.com/wp-content/uploads/PFG-pipe-size-terminology-whitepaper-FA4.pdf

Pig Launchers & Receivers - Facilities used for the insertion and retrieval of pipeline inspection gauges (pigs) also known as in-line-inspection tools used to clean and inspect the pipeline.

Piggability - a pipeline or segment that has been constructed (or modified) to permit free passage of in-line inspection tools.[73]

Pipeline and Hazardous Materials Safety Administration (PHSMA) - Mission is to protect people and the environment by advancing the safe transportation of energy and other hazardous materials that are essential to our daily lives.[74]

Pipeline Erosion - Occurs when a fluid flowing within a pipeline gradually degrades small amounts of the inner pipeline surface through surface collisions with greater effect at higher fluid velocities.

Pipeline Pack (packing) - condition in a pipeline when supply is greater than demand resulting in excess gas accumulation.

Pressure Limiting Station (PLS) - Devices that regulate or limit the flow of gas at a specific set point to achieve or maintain a certain pressure to keep pipeline operations within the determined pressure limits.

Pressure Relief Valves (PRVs) - Safety devices designed to open at a predetermined pressure to prevent an excess pressure build-up that could jeopardize the pipeline's structural integrity.

Pressure Swing Adsorption - Used for separation of gases or vapors from air based upon their adsorption isotherms being a function of total pressure, as well as vapor pressure, and temperature. It is also used to separate pollutants from flue gases.[75]

Reciprocating Compressors - Utilize a piston and crankshaft to increase gas pressure at varying flow rates in high-pressure environments.

Reynolds Number - A dimensionless quantity that helps determine the flow regime based on pipe dimensions.

Service Level Agreements - Illustrate the expectations between service providers and customers.

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[73] Clark, T., Nestleroth, B., & Battelle. (2004). Topical report on gas pipeline pigability (DE-FC26-03NT41881). Battelle. https://netl.doe.gov/sites/default/files/2018-03/DE-FC26-03NT41881-topicalreport.pdf
[74] PHMSA's mission. PHMSA. (n.d.-a). https://www.phmsa.dot.gov/about-phmsa/phmsas-mission
[75] Choosing an adsorption system for VOC: Carbon, zeolite, ... (n.d.-b). https://www3.epa.gov/ttn/catc/dir1/fadsorb.pdf

Specified Minimum Yield Strength (SMYS) - SMYS is the minimum yield strength, expressed in pounds per square inch (psi) gage, prescribed by the specification under which pipe material is purchased from the manufacturer.[76]

Storage Facilities - Locations identified where quantities of gas are contained. Gas may be added or withdrawn from these facilities in a controlled manner.

System Requirements (for a Pipeline) - The specific operational and performance criteria that the pipeline must meet to function effectively and safely under various conditions, including extreme scenarios.

Transient Modeling - Model focuses on studying the changes in flow conditions within a pipeline system over time. Analysis can be performed to examine the dynamic behavior of fluid flow within a pipeline when the flow conditions change rapidly.

Valves - Including isolation valves, control valves, and safety valves, these components regulate, direct, or control the flow of hydrogen by opening, closing, or partially obstructing various passageways.

Viscosity - A measure of a fluid's resistance to flow.[77]

Wall Thickness (WT) - The distance between one surface of an object and its opposite surface.

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[76] Pipeline Safety Stakeholder Communications. PHMSA. (n.d.-b). https://primis.phmsa.dot.gov/comm/glossary/index.htm?nocache=5217#SpecifiedMinimumYieldStrength

[77] Viscosity basics: What every engineer should know. AIChE. (2016, March 2). https://www.aiche.org/resources/publications/cep/editorial-calendar/viscosity-basics-what-every-engineer-should-know#:~:text=Viscosity%20%E2%80%94%20a%20measure%20of%20a%20fluid%E2%80%99s%20resistance,be%20used%20for%20both%20process%20and%20product-quality%20control.

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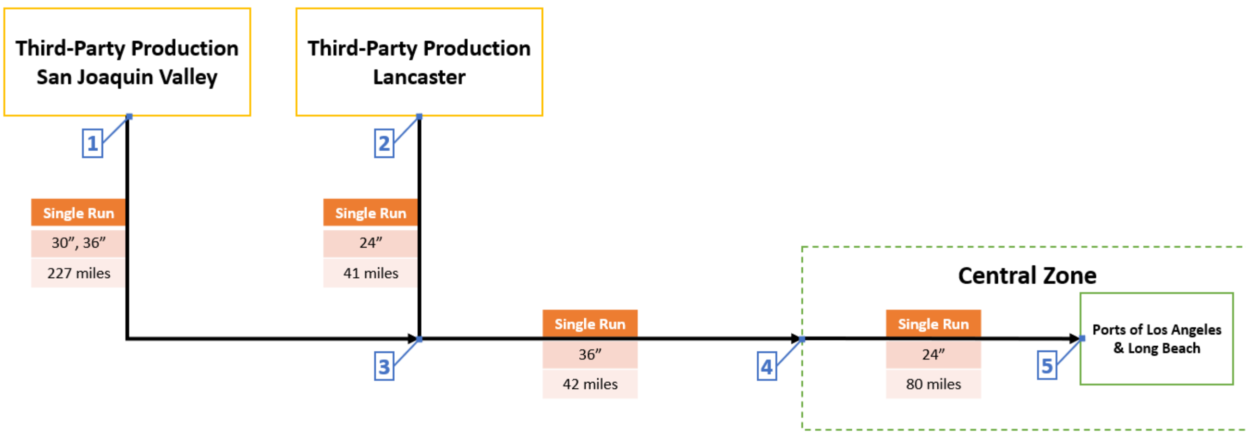
11. APPENDIX

11.1. Appendix A: Maximum Daily Production and Demand Rates

Steady-state hydraulic calculations were performed for Route A using the single-run configuration and daily maximum flowrates from the Production Study to support the Cost Effectiveness study sensitivity analysis. The flowrate at both SJV and Lancaster increased to 1.08 MMTPY, resulting in total throughput of 2.16 MMTPY to the Los Angeles Basin. The daily maximum flowrate is an approximately 44% increase from the average annual flowrate of 1.5 MMTPY.



Normal Operating Data	1	2	3	4	5
Single Run Pressure (psig)	1,035	1,060	685	405	215
Flowrate (MMTPY)	1.08	1.08	2.16	2.16	2.16

Figure 19 - Route A Maximum Daily Production Hydraulic Results

The pipeline sizes remained the same as the Preferred Routing Configuration A discussed in Section 4.6.1.1 at 1.5 MMTPY flowrate. The compression requirements at SJV and Lancaster increased by approximately 44%, which is proportional to the flowrate increase to 2.16 MMTPY. Table 22 displays the calculated compressor information for the normal and the maximum operations.

Table 22 - Maximum Daily Production Compressor Information

Maximum Daily Production - Compressors							
Configuration	Location	Normal (hp)	Max (hp)	Inlet Pressure (psig)	Normal Outlet Pressure (psig)	Max Outlet Pressure (psig)	Flowrate (MMTPY)
Single Run	SJV	58,000	72,000	500	1,035	1,200	1.08
	Lancaster	60,000	72,000	500	1,060	1,200	1.08

The preliminary results demonstrate a robust system capable of accommodating the maximum daily flowrates with increased compression and minimal piping adjustments. In a future phase of the project, transient modeling will be performed to thoroughly assess the Angeles Link system sizing requirements to accommodate variable production and demand flowrates.

11.2. Appendix B: Electric Reliability

In alignment with stakeholder comments,[78] a literature review of electric reliability was conducted to understand existing challenges, the planning process and outlook, and the integration between the electric and gas systems, with the purpose of informing the technical feasibility of Angeles Link facilitating the provision of as clean firm power in support of electrification and electric reliability.

11.2.1. Electric System Reliability Background

California's climate policy requires reducing statewide greenhouse gas (GHG) emissions to 40% of 1990 levels by 2030[79] and achieving carbon neutrality by 2045.[80] More recently, the California Air Resources Board's (CARB) 2022 Scoping Plan set a more aggressive trajectory of emission reductions to 48% by 2030.[81] Given the important role electrification will play in California's ability to achieve these goals, decarbonizing California's electric grid will be necessary and agencies and utilities across the State are

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[78] Appendix 1 - SoCalGas Responses to Comments Link: ALP1_Quarterly_Report_Appendices_Q3-2023.pdf (socalgas.com)
[79] Assembly Bill (SB) 32 (Ch. 249, 2016).
[80] Assembly Bill (AB) 1279 requires statewide carbon neutrality as soon as possible, but no later than 2045.
[81] California Air Resources Board (CARB). *2022 Scoping Plan*, dated November 16, 2022 at 116.

working to achieve this objective. Meanwhile, statewide policies seek to electrify many sectors of the economy, expanding dependency on the electric grid. Advancements in technology, such as Artificial Intelligence (AI) and data centers, are anticipated to place even greater strain on electric demand. The increased adoption of electrification for critical activities such as light duty transportation is just one example of how the delivery of power to meet demand 24/7, 365 days a year will become increasingly critical. Thus, the collaboration of simultaneous electric grid decarbonization and electrification will need to prioritize electric reliability.

Existing reliability studies and analysis[82] largely estimate the reliability of proposed electric portfolios using less rigorous reliability screens as opposed to more robust analysis such as hourly loss of load modeling.

More recent awareness of the grid's increased sensitivity to reliability risks (e.g. blackouts, heatwaves, and higher penetration of intermittent resources) has resulted in utilization of more robust reliability analysis. These more recent studies, such as LA100,[83] SoCalGas Clean Fuels and Evolution of Clean Fuels studies, [84] and SDG&E's Path to Net Zero,[85] anticipate that higher amounts of "clean firm power,"[86] such as clean renewable hydrogen, will be required to support the State's reliability needs.

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[82] For example: Energy and Environmental Economics' *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board* and the *2021 SB 100 Joint Agency Report*.

[83] Cochran, Jaquelin, and Paul Denholm, eds. 2021. *The Los Angeles 100% Renewable Energy Study*. Prepared by National Renewable Energy Laboratory (NREL) for Los Angeles Department of Power and Water (LADWP).

[84] Southern California Gas. 2021. *The Role of Clean Fuels and Gas Infrastructure in Achieving California's Net Zero Climate Goal.* https://www.socalgas.com/sites/default/files/2021-10/Roles_Clean_Fuels_Full_Report.pdf. And Southern California Gas. 2023. *The Evolution of Clean Fuels in California.* *https://issuu.com/stfrd/docs/cleanfuelsreliabilityreportjuly23?fr=sNDA4OTYwNzQ4NTk*

[85] San Diego Gas & Electric. 2022. *The Path to Net Zero: A Decarbonization Roadmap for California*. Prepared by Boston Consulting Group and Black & Veatch. https://www.sdge.com/sites/default/files/documents/netzero2.pdf

[86] "Clean firm power" is defined as zero-carbon power that can be relied on whenever needed for as long as
it's needed. As defined by Long, J. (n.d.). Also see, EDF: *California needs clean firm power, and so does the rest of the world*https://www.edf.org/sites/default/files/documents/SB100 clean firm power report plus SI.pdf

11.2.2. Electric Reliability Challenges

Increased Renewables and the Evolution of California's Electric Grid

Today's electric grid meets real-time energy needs by dispatching, increasing, or decreasing the generation of relatively quick-responding resources. These electric or power generation plants typically utilize natural gas generation[87] and can be called on to meet increased demand quickly for short to long periods of time, from a few hours to many days, depending on the electric grid's needs.

As the electric grid continues to increase capacity with intermittent renewable resources such as solar or wind, firm, dispatchable power such as that generated with clean renewable hydrogen will be necessary to maintain electric reliability. To illustrate, as the renewable electricity percentage from solar increases, the grid becomes more variable, challenging load growth, and necessitating flexible load following resources to balance the system. The increasing integration of solar is resulting in a growing number of days where daytime solar production is higher than electric load, resulting in mid-day excess energy. Later, as solar generation drops, dispatchable resources such as gas generation and battery energy storage systems (BESS) are called upon to quickly ramp up to balance the electric grid to maintain reliability. The operational characteristics of BESS form limitations on their duration and capacity, highlighting the essential need for firm, dispatchable gaseous generation.

The build-out of the future decarbonized electricity portfolio is expected to be comprised primarily of solar, wind, and BESS resources.[88] These resources along with firm and dispatchable resources are needed to meet peak demand. Additionally, future import availability may be constrained as neighboring states may require increased firm, dispatchable resources to address their own reliability needs and decarbonization efforts. The anticipated growth in electric demand, an increasingly intermittent electric supply portfolio, and aggressive decarbonization targets, will require clean firm and dispatchable resources that operate with critical system attributes such as load following and quick start capabilities.

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[87] Quick responding generation usually comes from peakers or simple cycle plants but can also be from increasing the output of larger steam plants that are not operating at full capacity. However, larger resources cannot typically go from cold start to generating at full capacity within a few minutes like a gas- or oil-fired simple cycle turbine.
[88] California Air Resources Board (CARB). 2022. *2022 Scoping Plan for Achieving Carbon Neutrality*. Prepared by the California Air Resources Board (CARB), https://ww2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf Page 203

Climate-Related Changes Present Grid Reliability and Resiliency Threats

The increasing impacts of climate change and natural disasters present challenges to California meeting its clean energy goals, particularly during severe weather events. Increasingly high temperatures contribute to droughts, wildfires, earthquakes, and heat waves that pose threats to humans, the environment, and reliability. Events such as extreme heat and wildfires, floods, jeopardize existing electric transmission and generation infrastructure, including those feeding the Los Angeles Basin.

2020 Extreme Heat Wave

In August 2020, an extreme heat wave across the West caused Californians to experience two days of rotating outages. Following the event, the California Independent System Operator (CAISO), California Public Utilities Commission (CPUC), and California Energy Commission (CEC) identified the following three main causes:

- The extended extreme heat wave—identified as being climate change-induced—created greater electricity demand on the electric grid than what was available or planned.
- Resource planning targets were not fully adapted to the grid's ongoing transition to clean energy resources and did not ensure sufficient capacity was available when needed, particularly in the evening hours.
- Market conditions in the day-ahead energy market magnified supply issues.[89]

The potential risks of having insufficient electric resources to meet demand were realized during this event, causing California to implement changes across the electric sector focused on planning, coordination, tracking, and greater attention to the changing needs of the grid as more variable resources are added in pursuit of climate goals.[90]

2022 Extreme Heat Wave

While reliability planning was enhanced following the 2020 heat wave, in late August and early September of 2022, California faced another 10-day extreme heat wave

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[89] California Independent System Operator (CAISO), California Public Utilities Commission (CPUC), and California Energy Commission (CEC). Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave (caiso.com) (January 2021), 1.
[90] Kootstra, M., and N. Barcic. 2023. *Joint Agency Reliability Planning Assessment.* Prepared by California Energy Commission (CEC) and California Public Utility Commission (CPUC), 1.

with record-setting temperatures and peak demand.[91] On August 31, 2022, Governor Gavin Newsom issued a Proclamation of a State of Emergency to increase energy supply and reduce demand as a result of the extreme heat and forecasting supply deficiencies.[92] On September 6, 2022, the State experienced the highest level of demand during the heatwave, prompting CAISO to issue a level 3 energy emergency alert (EEA), warning Californians of imminent blackouts.[93] Following this warning, CAISO sent an emergency text alert requesting Californians to conserve power. To increase supply, energy suppliers resorted to using backup gas generators.[94] While blackouts were avoided due to the actions taken by energy users, the need to rely on voluntary demand reductions and backup generation to maintain reliability may not always prove to be effective. The future for reliability points to the need for the electric grid to examine and address the planning and operational needs in light of expected future extreme weather events. As California moves toward its net GHG neutrality goal in 2045, reliability and resiliency risk management, implementing planning, forecasting, and tracking measures will need to continue to evolve with the transition.

11.2.3. Reliability and Hydrogen Decarbonization Studies

The existing electric resource planning of California's highly renewable grid may not fully address reliability and resiliency risks, as noted by the 2020 outages. Comprehensive reliability assessments should also include hourly modeling of multiple years for every iteration of each scenario examined. As a result, existing decarbonization studies may improperly account for renewable penetration and the growing impacts of climate change.

After the 2020 heatwaves, planners and modelers began more thoroughly analyzing reliability and resiliency risks when charting California's decarbonized future. Specifically, some more recent studies include robust reliability testing and some are using the industry-approved North American Electric Reliability Corporation (NERC)

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[91] Q1 2022 Report on Market Issues and Performance. (n.d.-d). http://www.caiso.com/Documents/2022-First-Quarter-Report-on-Market-Issues-and-Performance-Sep-6-2022.pdf

[92] https://www.gov.ca.gov/wp-content/uploads/2022/08/8.31.22-Heat-Proclamation.pdf?emrc=78e3fc

[93] A level 3 EEA is issued when the grid operator is unable to meet minimum reliability reserve requirements. See https://www.caiso.com/Documents/Emergency-Notifications-Fact-Sheet.pdf

[94] CAISO September 6, 2022 generation data

"one day in ten years" loss of load expectation (LOLE) testing.[95] The studies[96] that include this type of detailed reliability testing generally require or conclude the need for higher resource capacities across all technologies, including more clean, firm, dispatchable resources like clean renewable hydrogen. While most of the published studies listed below applied the higher-level reliability screenings, the increased focus on reliability issues will likely result in some level of additional LOLE testing in the next iteration of these studies.

As future decarbonization studies further examine electric reliability issues and acknowledge the need for clean firm resources, it is expected that clean dispatchable resources like clean renewable hydrogen will play a key role.

2020 PATHWAYS Scenarios Developed for the California Air Resources Board (CARB) [97]

This CARB study is a high-level exploration of plausible PATHWAYS to economy-wide carbon neutrality. The report focuses on electrification and sector-wide carbon dioxide removal but does not specifically address how the electric sector could reliably support a decarbonized economy other than to acknowledge that some form of dispatchable generation is needed to maintain system reliability.

The study's Balanced Scenario and Zero-Carbon Scenario reduce the 2045 electric sector emissions to zero by maximizing variable renewables at 80-85% and **requiring 15-20% of firm resources, namely hydroelectric, geothermal and dispatchable clean fuels – either biomethane or hydrogen**.

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[95] LOLE is defined as the expected number of days per time period (usually a year) for which the available generation capacity is insufficient to serve the demand at least once per day. LOLE counts the days having loss of load events, regardless of the number of consecutive or nonconsecutive loss of load hours in the day. The study applies the industry standard of 0.1 days per year, or one day in ten years.
[96] LA100, SoCalGas Clean Fuels and Evolution of Clean Fuels studies, and SDG&E's Path to Net Zero, anticipate requiring higher amounts of "clean firm power" to support the State's reliability needs, one of which is the use of clean renewable hydrogen.
[97] Energy and Environmental Economics, Inc. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*. Prepared by Energy and Environmental Economics, Inc (E3) for the California Air Resources Board (CARB) https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf

2021 SB 100 Joint Agency Report, Achieving 100 Percent Clean Electricity in California: An Initial Assessment[98]

The 2021 SB 100 Report assumes much of the existing natural gas capacity is retained through 2045 to meet reliability and also agrees with the 2020 CARB PATHWAYS study on the importance of emerging technologies, noting that "(E)nergy storage technologies — including batteries, pumped hydro, **hydrogen**, and other emerging technologies — are expected to play a significant role in helping balance the grid as the state implements SB 100."[99]

Despite alignment with the CARB PATHWAYS study, the SB 100 report's list of modeled technologies for their Core Scenario excludes many emerging firm clean dispatchable generation, including "green" hydrogen[100] combustion. However, the 2021 SB 100 report included the clean "generic dispatchable" and "generic baseload" resource categories in its additional Study Scenarios. These categories include a wide variety of emerging technologies such as green hydrogen combustion. The SB 100 report notes inadequate supply and cost data, and/or lack of commercial availability of green hydrogen in California at the time of the report publication. The Report concludes that reaching 100% carbon-free retail sales by 2045 is technically achievable but provides that additional work is needed, including modeling to "ensure reliability for all hours of the year in line with state planning requirements while meeting clean energy and climate goals."

At the 2025 SB 100 Inputs and Assumptions Workshop, CEC staff noted the Investment Reduction Act's (IRA) federal incentives on clean hydrogen production and listed hydrogen technologies that are available in California as proposed eligible resources for 2025 SB100 report modeling.[101]

The CEC has committed to complete a LOLE reliability analysis,[102] which is expected to result in the need for higher amounts of clean firm power resources. If hydrogen resources become SB100-eligible, the upcoming modeling would be able to analyze

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[98] Liz Gill, Aleecia Gutierrez, Terra Weeks. 2021. *2021 SB 100 Joint Agency Report, Achieving 100 Percent Clean Electricity in California: An Initial Assessment*. Prepared by the California Air Resources Board (CARB), the California Energy Commission (CEC), and the California Public Utilities Commission (CPUC), https://www.energy.ca.gov/publications/2021/2021-sb-100-joint-agency-report-achieving-100-percent-clean-electricity

[99] Page 108 2021 SB 100 Report

[100] Page B-8 2021 SB 100 Report; the 2021 SB100 Report defined green hydrogen as "hydrogen gas that is not produced from fossil fuel feedstock sources and does not produce incremental carbon emissions during its primary production process."

[101] Mark Koostra of the CEC at the February 16, 2024 SB 100 Input and Assumptions Workshop

[102] Ibid.

how clean hydrogen resources can help meet clean firm power needs. Further, federal incentives can also lower the cost of hydrogen, increasing the likelihood that SB100 portfolios would include hydrogen resources.

2022 CARB Scoping Plan for Achieving Carbon Neutrality[103]

The 2022 Scoping Plan updates prior statewide plans to reach California's economy-wide greenhouse gas (GHG) reduction targets. It also outlines a path to achieving the State's 2045 carbon neutrality goals. However, like the SB 100 Report, the 2022 Scoping Plan does not include sensitivities, such as loss of load evaluations in its reliability modeling, which may lead to implementation differences from the plan.

The final Scoping Plan modeling assumed retention of existing natural gas capacity and added 9 GW of hydrogen combustion for reliability purposes.

2021 EDF and CATF: California needs clean firm power, and so does the rest of the world[104]

The Environmental Defense Fund (EDF) and the Clean Air Task Force (CATF) commissioned three distinct and independent modeling efforts, each producing distinct pathways for California to achieve carbon neutrality by 2045. These models relied on prior analyses to estimate the loss of load of each portfolio. Each model produced similar conclusions, indicating that the most feasible and cost-effective pathway involves sustained investment in wind and solar energy, complemented by a diverse mix of clean firm power sources. The study stated: "Our modeling concludes an ambitious but achievable investment in clean firm power capacity, essentially replacing the gas fleet with 25-40 gigawatts of clean firm power will minimize costs while maintaining reliability and substantially and reduce the amount of renewable energy capacity that must be deployed."[105] While the study does not select a specific clean firm power mix, clean fuels such as clean renewable hydrogen are listed as potential technologies.

At the time of this study's modeling, the lower cost scenario primarily consisted of clean firm power technologies such as carbon capture and sequestration and

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103 California Air Resources Board (CARB). 2022. *2022 Scoping Plan for Achieving Carbon Neutrality*. Prepared by the California Air Resources Board (CARB), https://ww2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf

104 Long, JCS, et al. 2021. *California needs clean firm power, and so does the rest of the world*. Prepared for EDF and CATF. https://www.edf.org/sites/default/files/documents/SB100%20clean%20firm%20power%20report%20plus%20SI.pdf

105 Ibid

nuclear, with relatively smaller amounts of clean fuel generation.[106] However, at the August 22, 2023, SB 100 Kick-Off workshop, EDF indicated that potential future modeling would select more clean fuel generation such as hydrogen due to expected reductions in hydrogen costs from IRA incentives.[107]

2021 NREL: The Los Angeles 100% Renewable Energy Study for LADWP (LA100)[108]

The LA100 is a comprehensive analysis of a clean electricity future for Los Angeles that focused particular attention on the potential for climate change risks affecting the Los Angeles Basin, specifically elevated wildfire risks that can result in de-energization of critical transmission lines coupled with energy demand increases from increased use of air conditioning.[109] The National Renewable Energy Laboratory (NREL) modeled Los Angeles Department of Water and Power's (LADWP) customer electricity demand, local solar adoption, power system generation, and transmission and distribution networks. The LA100 explores these options through four scenarios, each assessed under varying levels of load electrification and with robust reliability testing that assesses all hours of the year for five years. The LA100 Study notes challenges upgrading the city's local electric transmission infrastructure, which would be needed to help import utility scale renewable energy to some areas of Los Angeles, and thus the LA100 scenarios require in-basin renewably fueled generation. The study shows that pathways to 100% decarbonization diverge on how to meet the last 10%–20% of energy demand that cannot be met by existing renewable and conventional storage technologies, and that the main solution currently available to maintain a reliable system that can withstand extreme events is to store and use renewable fuels, with hydrogen and biofuels being the key alternatives. The LA100 also emphasizes the need for research and development in hydrogen power, alongside the development of renewable firm capacity resources.

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106 Ibid

107 08-22-23; EDF's comments during their presentation at the SB 100 Kickoff Workshop

108 Cochran, Jaquelin, and Paul Denholm, eds. 2021. *The Los Angeles 100% Renewable Energy Study*. Prepared by National Renewable Energy Laboratory (NREL) for Los Angeles Department of Power and Water (LADWP). https://maps.nrel.gov/la100/.

109 Cochran, *The Los Angeles 100%*, NREL, Ch 12, 24.

2022 SDG&E: The Path to Net Zero: A Decarbonized Roadmap for California[110]

This study investigates decarbonization pathways for California and includes how San Diego Gas & Electric (SDG&E) can expand on technologies and approaches to encourage decarbonization. The roadmap utilizes economy-wide modeling of the State with LOLE reliability modeling of the electric sector. Several priority areas are highlighted in this study, notably electric sector reliability. A three-pronged approach for achieving decarbonization in California focuses on clean electricity, carbon removal, and clean fuels.

The study notes that, "Clean dispatchable electric generators are most critical for keeping the electricity grid reliable while meeting emissions reduction goals. They can both quickly provide electricity to meet customer needs and use a clean fuel source such as green hydrogen."[111] The study also acknowledges current barriers and the need for clean fuels infrastructure to enable clean dispatchable resources.

This study's focus on reliability highlighted a need for flexible and dispatchable generation for which the study includes 20 GW of dispatchable clean hydrogen generation by 2045.

2021 and 2023 SoCalGas: The Role of Clean Fuels and Gas Infrastructure in Achieving California's Net-Zero Climate Goal and The Evolution of Clean Fuels in California[112]

SoCalGas's Clean Fuels Study (CFS) is a technical analysis that explores achieving decarbonization in California, examining the potential role that clean fuels and a supporting clean fuels network could play in achieving carbon neutrality. The study examined cross-sector optimization across electric, fuels, and transport. With

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110 San Diego Gas & Electric. 2022. *The Path to Net Zero: A Decarbonization Roadmap for California*. Prepared by Boston Consulting Group and Black & Veatch. https://www.sdge.com/sites/default/files/documents/netzero2.pdf

111 SDG&E's *The Path to Net Zero: A Decarbonization Roadmap for California*, p. 11, available at: https://www.sdge.com/sites/default/files/documents/netzero2.pdf

112 Southern California Gas. 2021. *The Role of Clean Fuels and Gas Infrastructure in Achieving California's Net Zero Climate Goal.* https://www.socalgas.com/sites/default/files/2021-10/Roles_Clean_Fuels_Full_Report.pdf. And Southern California Gas. 2023. *The Evolution of Clean Fuels in California.* *https://issuu.com/stfrd/docs/cleanfuelsreliabilityreportjuly23?fr=sNDA4OTYwNzQ4NTk*

electricity demand expected to double by 2045,[113] there is no established blueprint for widescale decarbonization. Thus, the study examined four corner case scenarios designed to pull different decarbonization levers to different degrees and highlight distinctions for evaluation as no one scenario can reliably predict and forecast future developments. Three of the scenarios assume that fuels are delivered to end uses. All four scenarios were evaluated against a set of criteria that support public welfare, including energy system reliability and resiliency. The analysis found that the scenarios that met the criteria of reliability and resiliency retain the fuels network with approximately 35 – 50 GW of thermal generation capacity. This thermal generation was supported by a blend of clean fuels including biogas and hydrogen.

In 2023, SoCalGas published a supplemental analysis to the CFS, The Evolution of Clean Fuels in California. This updated analysis utilized an hourly LOLE reliability evaluation to model the potential for electric system outages, producing more refined results that led to concluding the need for incremental capacity for all resource types: batteries, wind, solar, and clean hydrogen generation as a clean firm power resource. The impact of this additional reliability testing found that up to 10 GW of incremental clean hydrogen generation capacity was needed to meet the LOLE reliability requirement.

11.2.4. Conclusion - Reliability

Reliability and resiliency are essential components of a dependable energy system and must include consideration of future decarbonization goals. Clean firm power resources will play a key role in overcoming strains from climate-induced weather events and the growing number of intermittent resources to meet the growing demands of electricity users whose dependence on grid reliability will grow over time.

The most widely used firm power resource in California is currently natural gas generation, which has the capability to ramp up or down when called upon, enabling the integration of renewables, and providing both short duration and seasonal long duration storage supported by a network of gas pipelines. Pipelines provide reliable and resilient underground infrastructure that is shielded from many extreme weather conditions. The resiliency, reliability, and local resource adequacy provided by the existing natural gas generation fleet can be transitioned to clean firm power by replacing natural gas with clean fuels such as clean renewable hydrogen, retaining the local reliability and resiliency attributes.

[113] Southern California Gas. 2021. *The Role of Clean Fuels and Gas Infrastructure in Achieving California's Net Zero Climate Goal.* https://www.socalgas.com/sites/default/files/2021-10/Roles_Clean_Fuels_Full_Report.pdf at 3.

Many of the decarbonization studies described herein identified clean renewable hydrogen as a clean firm power resource that could help decarbonize California while supporting grid reliability. Moreover, as noted by ARCHES, "renewable clean hydrogen is also the most scalable zero-carbon alternative to natural gas for use in gas power plants required by state planning to remain operational to ensure reliability."[114] Similarly, the Biden-Harris Administration recognized that "Achieving commercial-scale hydrogen deployment is a key component of President Biden's Investing in America agenda, and critical to building a strong clean energy economy while enabling our long-term decarbonization objectives."[115]

A hydrogen pipeline system such as Angeles Link would provide the connective infrastructure to enable the use of clean renewable hydrogen at the bulk scale to support the decarbonization of the power generation sector, among others.

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[114] ARCHES H2, Frequently Asked Questions (March 2024) at 2, available at: https://archesh2.org/wp-content/uploads/2024/03/ARCHES-FAQ-Basic-1.pdf.

[115] DOE, Biden-Harris Administration Releases First-Ever National Clean Hydrogen Strategy and Roadmap to Build a Clean Energy Future, Accelerate American Manufacturing Boom (June 5, 2023), available at: https://www.energy.gov/articles/biden-harris-administration-releases-first-ever-national-clean-hydrogen-strategy-and.