HYDRAULIC ANALYSIS
REPORT 8143-M-002

HYDROGEN PIPELINE STUDY
TRANSPORTATION SYSTEM

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1. Executive Summary

1.1 Background

In support of the Southern California Gas Company's (SCG) feasibility study of introducing a large-scale, green hydrogen pipeline system to supply the Los Angeles basin and Southern California energy needs. SPEC Services has been commissioned to develop a system concept that can produce, transport, and deliver hydrogen gas at-scale to the LA Basin. Five potential production locations were selected by SCG representing five individual systems to feed select power plants, transportation fueling centers, refineries, and natural gas blending applications. A sixth system was also considered which uses production in California with seasonal storage in Utah. This report details the hydraulic basis of design for the gas pipeline system that would receive hydrogen production, flow at transmission pressure, deliver to demand centers, and balance daily and seasonal production cycles with a potential mass storage facility.

Hydraulic modeling methodology and conclusions are documented in this report, including pipeline sizing, annual storage requirements, and expected process conditions during operation. Modeled hydrogen production rates, storage viability, and demand rates were critical inputs to this study but are beyond the scope of this report. Annual throughputs were based on the "Low Case" Scenario 7 provided by SCG. Development of "Medium" and "High" cases will be provided in future studies.

1.2 Summary of System Results

Delivery of [redacted] of hydrogen gas per year results in an average flow of approximately [redacted] standard cubic feet per hour (MMscfh). Peak production rates from the various sites considered varied from [redacted] MMscfh [redacted]. A solar-only system was also considered with a peak production rate of [redacted] MMscfh. The hydrogen production rate was calculated for every hour by Technip and that data used in this initial low case analysis. See Section 3 of this report for details on each production site.

Downstream demand varied from [redacted] to [redacted] MMscfh based on power plant output. Power plants, however, only represent a [redacted] of the projected annual throughput. See Section 4 for details on each demand site.

The pipeline transmission system from the production site will have to accommodate the highest hydrogen production rates, which could [redacted] times the average production rate. The pipeline transmission system from storage to the LA basin demand centers will be closer to the average production rate, depending on the demand profiles of the users. These ranges can be accommodated by the five system configurations described in Section 5 of this report. A sixth system configuration utilizes high-pressure storage near the production site in combination with seasonal storage at Delta to balance the daily solar-only production case.

This hydraulic analysis includes California-based geological storage and production for Systems 1 – 4, Utah-based geological storage (salt caverns) and production for System 5, and a combination of California-based production (Mojave) and Utah-based seasonal storage for System 6. Geologic storage in oil/gas reservoirs [redacted] is included for the first four systems as an alternative to the Delta salt caverns. Large-scale hydrogen storage was a critical component to system functionality for both daily variations between peak production times and peak demand times as well as seasonal changes. Calculated hydrogen storage requirements were as high as [redacted] of the annual throughput of the system and required design rates similar to the hydrogen production source. Despite the significant volume of the proposed pipeline systems considered, daily movements in and out of storage were common and continuous controls were required to stabilize overall system pressure. (Hydraulic analysis for Systems 1-5 did not include high-pressure storage near the production site, but it has been added to the Systems 1-4 summaries and estimates, as described for System 6 below.)

System 6 was developed to economize the use of seasonal storage in Utah by minimizing the daily cycling of the caverns with additional pipeline volume. This system was modeled with [redacted] miles of [redacted] pipe looped within the proposed Mojave production site to act as local high-pressure storage, a [redacted] pipeline connection to Delta, and a pressure regulating junction to balance gas flow from the two sources. A simplified flow diagram of this configuration is attached to the end of this report.

1.3 Conversion Factors

1 kilogram of hydrogen	= 423.3 standard cubic feet of gas
1,516,445 metric tons per year	= 6,419 billion standard cubic feet per year
	= 1,759 million standard cubic feet per day
	= 73.277 million standard cubic feet per hour

2. System Description and Approach

2.1 System Options

Five potential production sites were considered for creating green hydrogen to feed the LA Basin via pipeline. In order to balance the difference between daily and seasonal production against daily and seasonal demand changes, each production site requires unique features to function within the parameters documented in this report. Six systems were modeled and analyzed:

System 1 – Five Points Production with Storage at [redacted]

System 2 – Mojave Production with Storage at [redacted]

System 3 – Whitewater Production with Storage at [redacted]

System 4 – Blythe Production with Storage at [redacted]

System 5 – Delta Production with Storage in the adjacent caverns

System 6 – Mojave Production with Seasonal Storage in the Delta caverns

Systems 1 through 4 were based on an optimized combination of solar and wind energy sources to normalize green hydrogen production. A hypothetical underground storage facility was modeled in the [redacted] area to receive daily hydrogen production from these sites and provide continuous supply to the demand centers.

System 5 assumes that all hydrogen production would be stored in the Delta caverns with a continuous feed to the LA Basin via pipeline. An intermediate booster compressor was modeled in the Las Vegas area to facilitate an adequate flow of gas from this distance.

System 6 was based on an all-solar energy source to produce hydrogen at Mojave with integrated high-pressure storage to normalize production. A pipeline was modeled to Delta for seasonal storage. Excess hydrogen produced during the summer was diverted toward Delta while hydrogen production during the winter was subsidized by Delta. This system also included an intermediate booster compressor at Las Vegas.

2.2 Pipeline Routing and Lengths

Pipelines were routed using desktop Geographic Information System (GIS) data to develop a feasible path from each production location to the selected demand center locations within the LA Basin. Each develop route consists of a trunk line to the Port of LA / Port of Long Beach area with laterals to pick-up demand locations along the way. Methods for determining individual pipeline routes are beyond the scope of this report.

Distances from this database were used in the hydraulic model of each system route. The following figure shows the pipeline distances from each significant feature. [redacted] All lengths are in miles.

[redacted]

2.3 Design Pressures and Temperatures

The proposed system was modeled with a pressure rating of [redacted] Discharge pressures from each production locations were limited to [redacted] psig. Delivery pressures to each demand location were maintained at a minimum of [redacted] psig. A discharge temperature of [redacted] was used at each production facility.

2.4 Pipeline Hydraulic Properties

The Colebrook equation was used to calculate friction loss for each pipeline segment using an absolute roughness value of 0.0018" for steel pipe. The majority of trunk line was modeled as [redacted] pipe with laterals consisting of [redacted] and [redacted] pipe. The following table lists the nominal pipe sizes, wall thickness, and inner diameters used in the model. Actual pipeline wall may be thinner depending the selected steel grade in the final design.

Table 2.4 – Modeled Pipeline Sizes and Inner Diameters

Nominal Pipe Size	Wall Thickness	Inner Diameter
[redacted]	[redacted]	[redacted]

The system was modeled to transition from Class 2 to Class 3 upon entering the greater urban area surrounding the LA Basin. Pipeline diameters and number of parallel "looped" pipes were selected to keep the simulation running within the design pressures discussed in Section 2.3.

2.5 Hydrogen Storage Solutions

For Systems 1 – 4, a potential underground storage facility near [redacted] was modeled as fixed pressure to absorb excess gas at peak production periods or provide uninterrupted gas supply back to the system during low production periods. Compression would be provided at this storage facility to raise the pressure for injection/storage, and to assist with withdrawal as necessary. This compression is separate from the system hydraulics and not included in the model. A pressure of [redacted] psig was used to model [redacted] to balance flow between the production, storage, and the demand centers. It is assumed that the storage cavern is pre-charged with hydrogen such that any additional hydrogen stored by the operation can be fully retrieved by the system.

For the northern production locations (Five Points and Mojave), the main trunk line passes near this location, so flow through the LA Basin trunk line is continuous in one direction. For the eastern production locations (Whitewater and Blythe), [redacted] is beyond the demand centers, so flow alternates through the LA Basin trunk line depending on whether hydrogen is feeding or pulling from storage.

For System 5, the Delta production location did not utilize the proposed storage at [redacted] as this option is assumed to provide hydrogen to the pipeline at a constant rate with ample gas storage at the production site.

For System 6, the Mojave production location was modified with an additional [redacted] miles of [redacted] looped pipeline to model a high-pressure storage volume. This resulted in a fixed volume of over [redacted]. Excess production was allowed to fill high-pressure storage up to [redacted] psig and supply the downstream pipeline system to a minimum storage pressure of [redacted] psig, providing a net working capacity of approximately [redacted] hours of the average production rate). A control system was modeled to also allow production to be diverted towards the Delta pipeline for another [redacted] cubic feet of fixed volume. However, the pressures within the pipeline were maintained within a narrower range to facilitate movements to and from the Delta caverns, so the effective working capacity was approximately [redacted] scf (another [redacted] hours). During the summer, the daily solar production typically lasts ten hours (10 + 10 + 5.5 = 25.5 hours per day) so the excess volume goes towards seasonal cavern storage. During the winter, the daily solar production typically lasts seven hours (7 + 10 + 5.5 = 22.5 hours per day) so the volume is subsidized by seasonal storage.

Underground reservoir, cavern, and high-pressure pipeline storage were all assumed to have a 100% recovery factor for hydrogen. Initial charge volumes and geological formation losses are beyond the scope of this report.

2.6 Transient Gas Pipeline Modeling

DNV GL Synergi Pipeline Simulator version 10.7 was used to model and simulate each pipeline network. A complete model was built of the LA Basin demand centers and interconnections from the various trunk lines upstream (see Figure 1). This software simulates the transient effects of the pipeline, including changes to line pack as gas pressure fluctuates and the resulting changes to flow in the overall system.

Valves were inserted for modeling purposes to segregate the proposed systems so each production location could be analyzed with the same model for consistency.

The BWRS equation of state was selected to model pure hydrogen with a base viscosity of 0.0084 centipoise.

The transthermal mode was used in order to track temperature on the pipeline from the production compressor discharge to the demand centers. All pipe was modeled as buried with a soil conductivity of 0.3 BTU/hr·ft·dF with an ambient temperature of 70 °F. This resulted in a delivery temperature between 100 and 120 °F, depending on the distance downstream of the production site. Friction of high velocity hydrogen gas also contributes to the operating temperature. Using transthermal modeling was found to have small impact to the overall hydraulics with about a 3% deviation from an isothermal model at 70 °F.

3. Hydrogen Production Locations

SCG has requested five production locations to be considered for five separate pipeline systems. The following figure shows the locations of these production sites and the main trunk lines routed to the LA Basin.

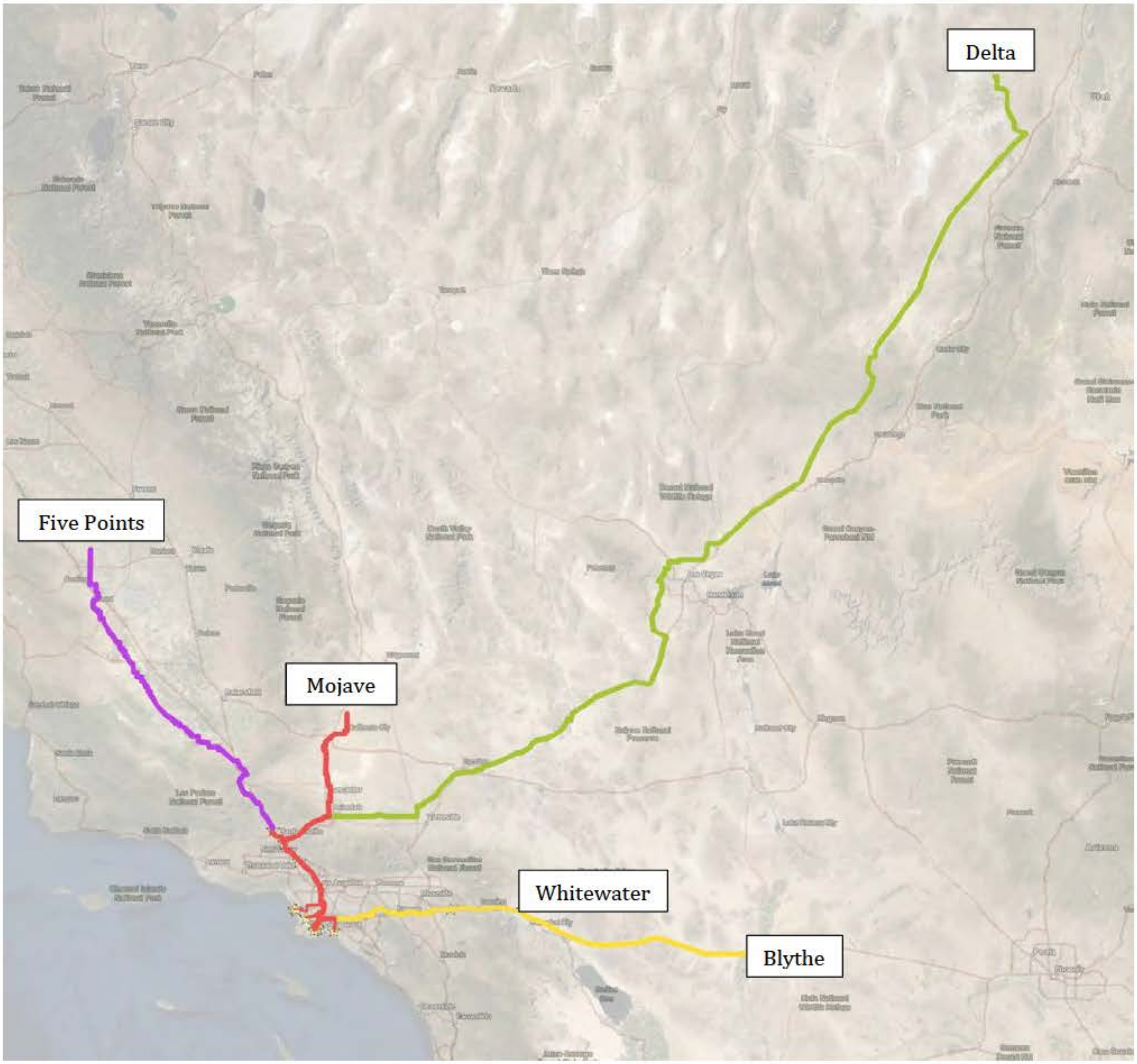

Figure 3 – Proposed Hydrogen Production Sites and Trunk Line Routes

3.1 Basis and Approach

Development, research, and modeling of conceptual large-scale hydrogen production facilities was performed by Technip Energies. Their model considered solar and wind renewable energy sources at each of the five production sites and optimized a theoretical hydrogen generation output trend for a 365-day period. A total production of approximately [redacted] metric tons per year was calculated for each site, [redacted] The production rates were scaled by [redacted] to model the system hydraulics. After applying this factor, the production rate data was fed directly in to the transient hydraulic model (at one-hour intervals) to select and validate the functionality of the pipeline system and determine the gas storage parameters for each system configuration.

After review of the optimized solar/wind production, a solar-only model was developed for application with System 6. A similar data set was provided by Technip and was also scaled to match the SCG demand.

The following sections provide details for each production site as relevant to the hydraulic model. The basis of this data is by Technip and is beyond the scope of this report.

3.2 Peak Rates and Performance for California Production Sites

Based on the data provided by Technip, the following tables compare the maximum rates for Systems 1 – 4.

Table 3.2.1 – Comparative Production Parameters for Five Points

Rates (MMscfh)	Minimum	Maximum	Statistical Mode
	[redacted]	[redacted]	[redacted]
% of Max	5%	100%	67%
% of Average	9%	187%	126%

Table 3.2.2 – Comparative Production Parameters for Mojave

Rates (MMscfh)	Minimum	Maximum	Statistical Mode
	[redacted]	[redacted]	[redacted]
% of Max	5%	100%	71%
% of Average	9%	179%	126%

Table 3.2.3 – Comparative Production Parameters for Whitewater

Rates (MMscfh)	Minimum	Maximum	Statistical Mode
	[redacted]	[redacted]	[redacted]
% of Max	5%	100%	79%
% of Average	8%	160%	126%

Table 3.2.4 – Comparative Production Parameters for Blythe

Rates (MMscfh)	Minimum	Maximum	Statistical Mode
	[redacted]	[redacted]	[redacted]
% of Max	17%	100%	59%
% of Average	37%	215%	126%

[redacted]

Production varies daily and seasonally. During the winter months, available green power is less consistent than the summer. This results in a higher average rate during the summer time. This excess production [redacted] during the summer and withdrawn during the winter.

Each production site had a different maximum rate [redacted]. A higher maximum also correlated with less consistent daily production. Minimum production did not fall below 5% of the maximum value for each site due to electrolyzer turndown. [redacted] Despite the minimum flow provisions and substantial length of the modeled pipelines, each of these system required daily use of the modeled bulk gas storage site at [redacted].

All four sites maintained a nominal production rate of about [redacted] hydrogen gas. [redacted] solar-only production trend [redacted] was generated by Technip which was used to model System 6. The following table and charts illustrate the data used for this system.

Table 3.2.5 – Solar-Only Production Parameters for System 6

Rates (MMscfh)	Minimum	Maximum
	[redacted]	[redacted]
% of Max	5%	100%
% of Average	13%	267%

[redacted]

Figure 3.2.5 – Modeled Hydrogen Production Rate for System 6

The optimized solar-only system achieved the same peak production rate nearly every day with only the duration of production changing seasonally. Excess electrical capacity was included to maintain battery charge to meet the 5% electrolyzer turndown requirements. Summer solar capacity was curtailed based on optimizationof [redacted]. The following figure shows a sample of production to compare typical days.

[redacted]

Figure 3.2.6 – Comparison of Daily Production Curves by Season

The maximum hydrogen output was limited by the modeled electrolyzer capacity. Typical summer days exceed ten hours of production while winter days were less than eight and had more frequent weather-related reductions. During peak solar performance, excess capacity is used to charge batteries which provide for the continuous minimum 5% output.

[redacted]

Figure 3.2.7 – Annual Production Trends per Day

Seasonal changes of daily hydrogen production followed an overall consistent curve with some intermediate drops due to projected weather events.

3.3 Modeled Performance of Delta, Utah Production Site

Large-scale cavernous hydrogen gas storage is available at the selected site in Utah. Because the production site is assumed to be near or colocated with this storage, the performance of the Delta location was modeled as a fixed discharge pressure of [redacted] psig. An intermediate compressor station was modeled near Las Vegas, Nevada to boost the pressure to [redacted] psig toward the LA Basin. These pressures were used to calculate the required flow from the Delta location and the differential pressure required by the intermediate compressor station.

[redacted]

4. Hydrogen Demand Locations

SCG has requested four Los Angeles Department of Water and Power (LADWP) power generation plants be fed by the proposed hydrogen systems. Development and research of other large-scale hydrogen consumers was performed by Strategen, including vehicle fueling in the ports, refineries, and blending with existing natural gas assets. The following figure shows the locations of these demand centers and the pipeline laterals routed from the main trunk lines.

[redacted]

Figure 4 – Proposed Hydrogen Demand Locations

Annual demand totals for each market sector were provided by SCG (Scenario 7). The following sections provide the demand data modeled for each demand type.

4.1 Power Generation Plants

Four LADWP plants are being considered as demand centers for hydrogen. Hourly power output for these facilities were provided by Strategen for 2019. This data was scaled proportionately to match the annual hydrogen demand data provided in Scenario 7. The following table lists the conversion factors used to determine hourly hydrogen demand.

Table 4.1.1 – Power Plant Annual Demand Factors for Hydrogen

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Note that this factor does not represent an energy value for hydrogen, but just a conversion from the 2019 power demand data to future hydrogen demand by the proposed system. This method keeps the modeled annual demand consistent with the Scenario 7 values while incorporating the variability of power generation plant demand. The following table and figures summarize the modeled conditions for each power plant.

Table 4.1.2 – Modeled Parameters for Power Plants

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Peak power demand was calculated as [redacted] scfh and was maintained for a [redacted]. Combined with the demand rates at other locations (see the following report sections), a maximum system demand rate of [redacted] scfh is required.

A [redacted] pipeline lateral was modeled for the connection to each power plant.

[redacted]

4.2 Transportation Fueling Centers

Two vehicular loading centers are being considered for fueling trucks in the Port of Los Angeles (POLA) and Port of Long Beach (POLB). Annual demand for this operation was provided by the SCG Scenario 7. This demand was assumed to be split evenly between POLA and POLB and flow continuously to these sites. The following table lists the factors used to determine hourly hydrogen demand.

[redacted]

4.3 Refineries

Refineries are major consumers of hydrogen with natural gas steam reformation being the primary process source. [redacted] Annual demand for these locations was provided in aggregate in the SCG Scenario 7 as [redacted] metric tons per year. This value was divided between the refineries in proportion to their reported capacity to the California Energy Commission. The following table lists the factors used to determine hourly hydrogen demand.

[redacted]

Hydrogen flow to refineries was also considered to be continuous. A [redacted] pipeline lateral was modeled for each refinery connection.

4.4 Residential and Commercial Natural Gas Blending

Scenario 7 provided demands for residential and commercial blending of hydrogen as [redacted] Mt/year and [redacted] Mt/year, respectively. A continuous rate of [redacted] and [redacted] scfh were modeled for residential and commercial blending, respectively.

Residential blending was modeled to occur at a point upstream of the Los Angeles urban area as the trunk line transitions from Class 2 to Class 3. Commercial blending was modeled at the end of the trunk line in the LA Basin.

4.5 Combined Daily Demand Trend

The proposed systems are required to supply the total demand all year. The following figure shows the daily demand volumes.

[redacted]

Figure 4.5 – Annual Demand Trends per Day

Since the majority of demand centers were assumed to flow continuously at the average annual rate, there isn't as much seasonal variation to demand as there is seasonal hydrogen production. Although power plants represent about [redacted] of the total figure, they are the only demand centers that were modeled to vary and result in a [redacted] swing of total demand.

5. Results

Each system was modeled and simulated to operate with the year of production and demand data provided by SCG, Technip, and Strategen. The truck line from each production center was increased until the pipeline system was able to meet the design requirements. For Systems 1 – 4, a common piping node was used to connect all the demand centers and the storage facility at [redacted]. The following figure shows the modeled portion common these systems.

[redacted]

For System 6, a more complex control system was necessary to account for the lack of regional storage [redacted] the larger flux of hydrogen production with the solar-only data, and the distant connection to the Delta cavernous storage. The following figure shows these controls.

[redacted]

The figure above shows hydrogen generation at Mojave (G_MOJAVE), initial compression into either high-pressure storage (SH_MOJAVE) or the pipeline system (MELA.M000.00). A junction between the Mojave supply line and the Delta trunk line splits flow between supply, demand, and seasonal storage. The following table

The following sections describe the additional pipe calculated for each specific system configuration and the resulting pressure ranges from these sources.

5.1 Five Points – System 1

[redacted] were modeled from Five Points to the storage site lateral connection. The pipeline route for this segment required [redacted] miles, or [redacted] miles of installed [redacted] pipe.

The following figure shows the operating envelop required by the compressors at Five Points.

[redacted]

5.2 Mojave System 2

[redacted] was modeled from Mojave to the LA Basin trunk line. The pipeline route for this segment required [redacted] miles of installed [redacted] pipe. Additionally, [redacted] miles of [redacted] pipe was needed to connect the [redacted] storage site to the rest of the pipeline system.

The following figure shows the operating envelop required by the compressors at Mojave.

[redacted]

5.3 Whitewater System 3

[redacted] were modeled from Whitewater to the [redacted]. The pipeline route for this segment required [redacted] miles, or [redacted] miles of installed [redacted] pipe. With production coming from the east, the pipeline extended [redacted] where flow through the LA Basin changed direction daily as excess volume was pushed to and pulled from storage.

The following figure shows the operating envelop required by the compressors at Whitewater.

[redacted]

5.4 Blythe System 4

[redacted] were modeled from Blythe to Whitewater (extending the pipeline system described for System 3 in the previous section). The pipeline route for this segment required [redacted] miles, or [redacted] miles of installed [redacted] pipe.

The following figure shows the operating envelop required by the compressors at Blythe.

[redacted]

5.5 Storage Requirements (Systems 1 – 4)

To make up for the daily and seasonal variations of production from the four California-based systems, a bulk hydrogen storage facility is required. Each system had different peak production, daily averages, and seasonal rates that resulted in different amounts of storage. The following graph overlays the quantity of stored hydrogen throughout the modeled year.

[redacted]

The production trends of Five Points required the most storage at [redacted] metric tons of hydrogen ([redacted]) or about [redacted] of the annual throughput. For the northern production locations (Five Points and Mojave), storage peaked in late September, while in eastern production locations (Whitewater and Blythe) storage peaked in early August. Blythe had the least storage requirement ([redacted] metric tons) since production was seasonally more consistent, however daily production was more erratic.

The application of [redacted] as a hydrogen storage field is a significant assumption to these hydraulic results. [redacted] The Delta, Utah site can be used for long term storage for seasonal changes to production and demand. The added pipeline length to this site would also help to absorb daily variations in pressure. This is the basis for Systems 5 and 6.

5.6 Delta, Utah System 5

[redacted] was modeled from Delta, Utah to the LA Basin trunk line. The pipeline route for this segment required [redacted] miles of installed [redacted] pipe. [redacted] storage site was not used for this system, so the additional [redacted]-mile segment was not required, however, an intermediate compressor station was required to boost pressure back to [redacted] psig to provide the for the required flow rates. The following shows the performance required by a compressor station modeled in the Las Vegas area.

[redacted]

A minimum system pressure of [redacted] psig occurred during the maximum demand event described in Section 4.1. For the modeled year, the delivery pressure to Haynes (most distant demand location) dropped below [redacted] psig for a total of [redacted] non-consecutive hours. It is assumed that accommodations can be made during these peak summer events to receive hydrogen at reduced pressure as it represents only [redacted] of the total operation of the system.

5.7 Mojave All-Solar Production with Delta Storage – System 6

[redacted] was modeled from Delta, Utah to the LA Basin trunk line. The pipeline route for this segment required [redacted] miles of installed [redacted] pipe including an intermediate compressor station. This line was larger than the [redacted] line modeled for System 5 since it was bi-directional and acted as a buffer between the production at Mojave and seasonal movement into the Delta cavern. The intermediate compressor station (B-1 and B-2) was also bi-directional and maintained available pressure in the segment between Las Vegas and Los Angeles. The segment pressure between Las Vegas and Delta was maintained by compressors at Delta (S-1 and S-2).

At Mojave, [redacted] miles of [redacted] high-pressure storage line was modeled on-site to receive excess hydrogen production. A bank of compressors were modeled to discharge at [redacted] psig at the full production rate and draw from high-pressure storage after daily production finishes (P-1 and P-2). [redacted] was modeled to connect the Mojave site to the trunk line. The pipeline route required [redacted] miles of installed [redacted] pipe.

[redacted]

Note that separate compressors were modeled for each direction of flow, however these units do not operate simultaneously and may represent the same physical units with appropriately manifolded valves. The following descriptions provide the parameters applied to the controlling elements modeled to facilitate System 6. These parameters are sufficient to model the system and confirm feasibility, and not intended to be an optimization of the operation and control of this system.

[redacted]

[redacted]

Larger flow ratios were required during the summer season to prevent the high-pressure storage at Mojave from becoming too full. Smaller flow ratios were required during the winter season to prevent excess flow from being diverted towards Delta and cause oscillations into and out of the cavern.

The following figures show a representative sample of the System 6 operation.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Peak Delta storage reach approximately [redacted] metric tons of hydrogen, or about [redacted] of the total annual capacity. A working cavern capacity of [redacted] scf would need to be reserved at Delta storage to facilitate this system.

6. Attachments

6.1 Flow Diagram for Hydraulic Model (System 6)

6.2 SPS Master Model (Systems 1 –5) Screenshot

6.3 SPS System 6 Model Screenshot