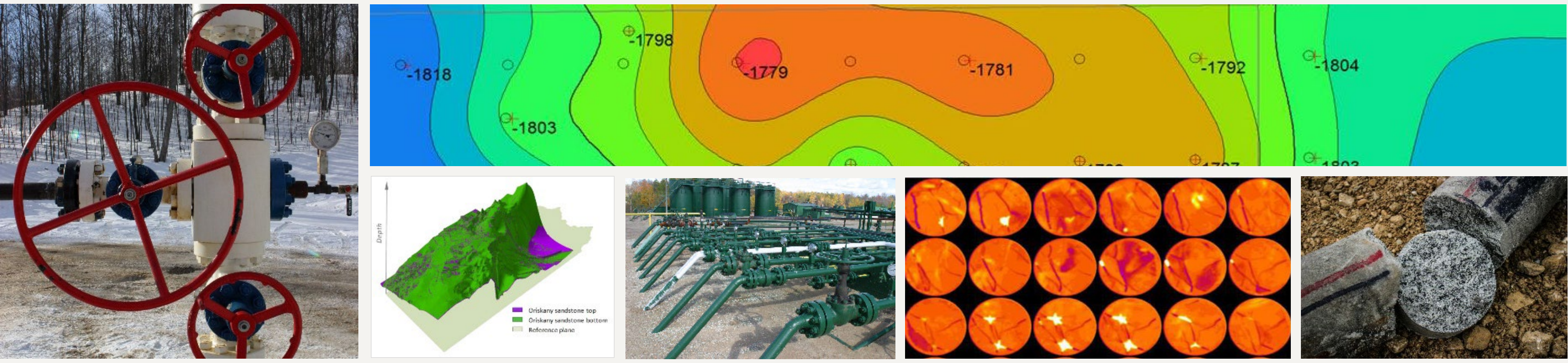

FECM/NETL Natural Gas with Hydrogen Pipeline Cost Model (2024): Model Results and Comparative Analysis

June 28, 2024
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EXHIBITS

EQUATIONS

ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
bscf	Billion standard cubic feet
CAPEX	Capital expenditure
d	Day
DO	Design option
DOE	Department of Energy
FECM	Fossil Energy and Carbon Management
FYBE	First-year break-even
H_2	Hydrogen
HDSAM	Hydrogen Delivery Scenario Analysis Model
in.	Inch
LCOT	Levelized cost of transport
mi	Mile
MMBtu	Million British thermal units
MPa-g	Megapascal gauge
MW	Megawatt
NETL	National Energy Technology Laboratory
NG	Natural gas
NPV	Net present value
NREL	National Renewable Energy Laboratory
OPEX	Operation expenditure
ProFAST	Production Financial Analysis Scenario Tool
psig	Pounds per square inch gauge
SAInt	Scenario Analysis Interface for Energy Systems
tonne	Metric ton (1,000 kilograms)
U.S.	United States
yr	Year

EXECUTIVE SUMMARY

Transporting a blend of hydrogen (H_2) and natural gas (NG) within existing NG pipelines is an achievable approach to reducing the carbon emissions of NG pipeline projects in the United States (U.S.). Additionally, blending H_2 into existing NG streams along existing NG pipeline routes could reduce H_2 transportation costs relative to greenfield H_2 pipeline construction by leveraging existing infrastructure and avoiding negative public perceptions associated with new pipeline development. In this way, blended H_2 and NG transmission could provide relatively quick, early-market access for H_2 transmission that could encourage needed growth of both upstream H_2 supply and end-use H_2 demand in the United States, enabling quicker implementation of a low-carbon H_2 economy.

The potential benefits of H_2-NG blended pipeline transmission led the U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) National Energy Technology Laboratory (NETL) to develop the FECM/NETL Natural Gas with Hydrogen Pipeline Cost Model (NG-H2_P_COM) [1]. The NG-H2_P_COM is an Excel-based model that estimates revenues and capital, operating, and financing costs for transporting gaseous phase NG with up to 25 percent H_2 for a single point-to-point pipeline, which may have compressors along the pipeline to boost the pressure [2].

This report contains two studies using NG-H2_P_COM:

- The first study, “General Results Study,” provides transport cost results for two case studies that demonstrate and compare the impact of variability of several cost drivers including pipeline length, H_2 blend percentage, pipeline and compressor reuse percentages, and pipeline retrofit cost factors. The two case studies are differentiated by whether their pipeline reuse parameters were held constant or not as H_2 volume percentage increased; the case studies are named “Constant Reuse Parameters” and “Variable Reuse Parameters.”
- The second study, “BlendPATH Comparison Study,” compares the transport cost result from a case study performed by the National Renewable Energy Laboratory (NREL) using the NREL Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) with NG-H_2 transport cost output from NG-H2_P_COM using similar scenario inputs.

Using NG-H2_P_COM, the General Results Study’s Constant Reuse Parameters case study demonstrated 1) that at a fixed pipeline length, fixed percentage of pipeline reuse, and fixed reuse cost factor, increasing H_2 volume alone has little effect on the first year break-even (FYBE) price of pipeline transportation beyond slight annual operational cost increase associated with additional compression needed, and 2) as pipeline lengths increase, transport costs also increase due mostly to the increased number of compressor stations and compression costs. The Variable Reuse Parameters case study demonstrated 1) replacing compressors for NG-H_2 blends above 5 percent H_2 by volume represents a significant capital expense relative to reusing compressors, and 2) FYBE prices are sensitive to higher percentages of pipeline needing replaced at a higher replacement cost factors, all of which might be necessary at higher H_2 volume percent blends.

The BlendPATH Comparison Study demonstrated that 1) NG-H2_P_COM was capable of closely replicating an NG–H_2 blend transportation cost case study scenario performed by another transportation techno-economic model (BlendPATH) despite the two models having somewhat different inputs and analytical workflows, and 2) the transportation cost estimated by NG-H2_P_COM was similar the transportation cost estimated by BlendPATH (as shown in Exhibit ES-1). The BlendPATH Comparison Study validates to an extent NG-H2_P_COM's modeling approach.

Exhibit ES-1. BlendPATH Comparison Study's NG–H_2 blend transport cost comparison

Model	NG–H_2 Blend Transportation Cost (2020$/MMBtu)	Difference Between Costs (%, relative to BlendPATH)
NG-H2_P_COM	$0.25	19%
BlendPATH	$0.21	-

1 INTRODUCTION

Incorporating clean hydrogen (H_2) into the United States (U.S.) energy economy provides an opportunity to contribute to U.S. greenhouse gas emission reduction goals. The United States has approximately 300,000 miles (mi) of natural gas (NG) transmission pipelines [3], representing an opportunity for blending H_2 with NG and transporting the blend in existing pipelines. Transporting a blend of NG and H_2 within existing pipelines could reduce the costs and enable quicker implementation relative to greenfield H_2 pipeline construction by leveraging existing infrastructure like rights-of-way, compressor stations, metering equipment, and pipelines, as well as by avoiding negative public perceptions associated with new pipeline development like eminent domain. Blended NG and H_2 transmission could also lower the carbon intensity of the NG pipeline projects, and provide needed early-market access for H_2 transmission that could encourage growth of both upstream H_2 supply and end-use H_2 demand.

The U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) National Energy Technology Laboratory (NETL) developed the FECM/NETL Natural Gas with Hydrogen Pipeline Cost Model (NG-H2_P_COM) [1] to estimate the cost of blended NG–H_2 pipeline transmission. The NG-H2_P_COM is an Excel-based model that estimates revenues and capital, operating, and financing costs for transporting gaseous phase NG with up to 25 percent H_2 for a single point-to-point pipeline, which may have compressors along the pipeline to boost the pressure [2].

General NG-H2_P_COM results using model defaults have not yet been published to demonstrate the impact of key cost drivers on NG–H_2 blend pipeline transport costs, nor has NG-H2_P_COM cost results been compared to those generated by other similar models or modeling efforts. This report contains two studies using NG-H2_P_COM to address these deficits:

- The "General Results Study" used NG-H2_P_COM to provide transport cost results for a variety of pipeline transport scenarios to demonstrate and compare the impacts of several cost drivers including pipeline length, H_2 blend percentage, pipeline and compressor reuse percentages, and pipeline retrofit cost factors.
- The "BlendPATH Comparison Study" compared the transport cost result from a case study performed by the National Renewable Energy Laboratory (NREL) using the NREL Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) (referred to as the "NREL Study") with NG-H2_P_COM results using similar inputs.

This report is organized into the following sections:

Section 2 describes the methodologies used to perform the General Results Study, and the BlendPATH Comparison Study. The section includes a short description of NG-H2_P_COM and the scenario matrices for the General Results Study's two case studies. The section also includes a short description of NREL's BlendPATH model, and crosswalks the relevant input parameters used in the NREL Study with those used to replicate the case study in NG-H2_P_COM.

Section 3 reports and discusses key results for the General Results Study and the BlendPATH Comparison Study.

2 METHODOLOGY

This section provides methodology used for the General Results Study and the BlendPATH Comparison Study.

This section is organized into the following subsections:

Section 2.1 describes the methodology for the General Results Study by first describing the basic functionality of NG-H2_P_COM, emphasizing its key inputs, in Section 2.1.1, and then outlining the design of the two case studies with the matrix of inputs used for scenarios assessed in Section 2.1.2.

Section 2.2 describes the methodology for the BlendPATH Comparison Study by first describing the basic functionality of NREL's BlendPATH model in Section 2.2.1, and then crosswalking the NREL Study's inputs with inputs used in NG-H2_P_COM to closely replicate the case study in Section 2.2.2.

2.1 GENERAL RESULTS STUDY METHODOLOGY

The General Results Study assessed the impacts of NG–H_2 pipeline transport project design parameter variability on first-year break-even (FYBE) transport price over a range of H_2 volumes in the NG–H_2 blend, as estimated by NG-H2_P_COM. The General Results Study included two case studies. The first case study, "Constant Reuse Parameters," had scenarios that varied pipeline distance, and consequently the number of compressor stations, for a range of H_2 volume percentages, and held all pipeline reuse parameters constant. The second case study, "Variable Reuse Parameters," had scenarios that varied pipeline reuse parameters as H_2 volume percent changed, while holding the pipeline distance constant.

2.1.1 NG-H2_P_COM Description

The NG-H2_P_COM is a screening level Excel-based model that estimates costs for transporting gaseous phase NG and H_2 blends by pipeline. Costs are estimated for a single point-to-point pipeline, which may include compressors along the pipeline to boost the pressure. There are 160 inputs that can be changed by the user, allowing the user to generate project specific results. Of the 160 available inputs, 48 are considered key and are most likely to be changed by the user. Some of these key inputs are described in Section 2.1.1.1 and Section 2.1.1.2 for NG-H2_P_COM's Main Module and Engineering Module, respectively. Major outputs generated by NG-H2_P_COM include FYBE price, given in both $/million British thermal units (MMBtu) and $/metric ton (tonne) for the NG–H_2 blend. Additional information on NG-H2_P_COM can be found within the FECM/NETL Natural Gas with Hydrogen Pipeline Cost Model (2024): Description and User's Manual ("User's Manual") [2] [4].

The FYBE price is the price a pipeline owner would need to charge its customers (to generate revenues that offset costs, including capital costs, operating and maintenance costs, taxes, and financing costs [principal and interest on debt and the minimum desired internal rate of return on equity]) that makes the net present value (NPV) of the project nearly equal to zero. In other words, the FYBE price is the lowest price the pipeline operator can charge for transporting a

NG–H_2 blend and still have, at minimum, a viable project. In this report, FYBE price and transportation cost are used interchangeably, since the FYBE price charged by a pipeline owner is the transportation cost borne by its customer(s).

As described in the User's Manual, there are four main operational parameters that can be adjusted to accommodate an increased H_2 content in a NG stream: 1) operating pressure, 2) compressor station frequency, 3) compression power, 4) transport capacity (flow rate or energy output), or 5) the nominal diameter of the pipeline. Since the purpose of NG-H2_P_COM is to determine the cost of adding H_2 to an existing NG pipeline, the operating pressure, compressor station frequency, and pipe diameter are fixed parameters, leaving transport capacity or compression power available to be adjusted. To determine a FYBE price, NG-H2_P_COM maintains the energy output being transported prior to blending by increasing the compression power required to accommodate the increased volumetric flow rate needed to maintain the energy output.

H_2 has a lower density and energy content per unit of volume than NG. To compensate for the lower energy and density of H_2, the volumetric flow rate of the pipeline needs to be increased, directly increasing the flow velocity, to maintain the same energy output as the NG stream prior to the addition of H_2. The increased velocity results in a frictional pressure drop along the pipeline segment that must be managed by increasing the compression power [5]. The NG-H2_P_COM determines the new transport capacity to accommodate the addition of H_2 to the NG stream to maintain the same energy output. The compression power required to transport the increased volumetric flow rate of the NG–H_2 blend is then calculated at the fixed operating pressure, compressor station frequency, and pipeline diameter. As the H_2 blending ratio increases, the required compression power increases, which increases the yearly operating expenses of the pipeline [6].

2.1.1.1 Key Inputs for the Main Module

Several operational and financial inputs can be changed by the user within the "Main" sheet of NG-H2_P_COM, which is where the majority of the key inputs are located. Exhibit 2-1 lists a simplified version of the key inputs that are most relevant to the NG-H2_P_COM inputs and outputs discussed in this report. An important input is the average daily volumetric flow rate, which is the flow rate in the existing NG pipeline. This input is used to determine the energy output of the current NG stream, which is then used by the model to determine the volumetric flow rate of the blended gas stream needed to maintain the same energy output at the specified percentage of H_2. Another important parameter is the percentage of pipeline that can be reused, which will vary depending on the condition of the existing pipeline. For a recently installed pipeline, 100 percent of the pipeline could likely be used to transport NG–H_2 blends. However, an older pipeline, after years of environmental and erosional degradation, may require a 50 percent replacement of the existing pipeline, especially at higher H_2 concentrations. The input "BROWN" is the default method used to calculate capital costs for both new and reused portions of the pipeline—based on NG pipeline capital cost equations published by Brown et al. [7]. Additional information on capital cost calculations is provided in Section 2.1.1.2.

Other key input parameters in NG-H2_P_COM include the number of compressor stations along the pipeline route and how many of those stations will reuse the existing compressors. Literature varies on best practices when it comes to compressor replacement versus reuse. Some studies recommend replacing all compressors with new, built-for-purpose compressors, while others suggest that replacement may not be necessary until the H_2 concentration reaches 10 percent [8] [9] [10]. Since the default H_2 percentage is 15 percent, the default value for the number of compressor stations reusing existing compressors is zero. Many, if not all, of the operational default values for each parameter listed in Exhibit 2-1 will vary from pipeline to pipeline and can be adjusted accordingly within NG-H2_P_COM.

For financial-related key inputs, NG-H2_P_COM can provide costs in real or nominal dollars, which is why some financial parameters in Exhibit 2-1 provide defaults for both real and nominal dollars. The financial default values in the model are for real dollar calculations, but defaults for performing a nominal dollar methodology, where appropriate, are also given. A full list of the key inputs that are located on the “Main” sheet can be found in Exhibit 2-1 of the User’s Manual [2]. Default values were used to generate all NG-H2_P_COM outputs discussed in this report unless otherwise stated.

Exhibit 2-1. Key inputs on the "Main" sheet in NG-H2_P_COM

	Parameter	Default Value	Location in "Main" Sheet	Note	
Operational	Average daily volumetric flow of NG transported (bscf/d)	0.2	Cell E50	This is a placeholder default value.	
	Length of pipeline (mi)	200	Cell E55		
	Percentage of pipeline being reused (%)	75	Cell E56		
	Nominal diameter of pipeline	24	Cell E59		
	Percentage of H_2 by volume (%)	15	Cell E65	≤ 25%	
	Number of compressor stations	1	Cell E90		
	Number of compressor stations being reused	0	Cell E91		
	Duration of construction (yr)	1	Cell E109	Can be up to five years	
	Duration of operation (yr)	30	Cell E110	Must be less than 95 years	
	Equation to use for calculating capital costs for pipeline (specify one)	BROWN	Cell E115	PARKER for the equations from Parker [11]	
				MCCOY for the equations from McCoy and Rubin [12]	
				RUI for the equations from Rui et al. [13]	
				BROWN for the equations from Brown et al. [7]	
	Region of U.S. for Brown et al. equations (specify one region) [7]	Avg	Cell E118	NE (New England)	This cell will be light orange when the BROWN option is selected.
				MA (Mid-Atlantic)	
				SE (Southeast)	
				GL (Great Lakes)	
				GP (Great Plains)	
				RM (Rocky Mountains)	
				PN (Pacific Northwest)	
				SW (Southwest)	
				CA (California)	
				Avg (Average of all U.S. Regions)	

Parameter		Default Value	Location in “Main” Sheet	Note
Financial	Cost of equity or $IRROE_{min}$ (%/yr)	10.77 (real) 13.3 (nominal)	Cell E96	See Appendix A: Rationale Behind Key Financial Parameters in NG-H2_P_COM User’s Manual [2]
	Cost of debt or interest rate on debt (%/yr)	3.91 (real) 6.3 (nominal)	Cell E97	See Appendix A: Rationale Behind Key Financial Parameters in NG-H2_P_COM User’s Manual [2]
	Escalation rate beyond project start year (%/yr)	0 (real) 2.3 (nominal)	Cell E101	See Appendix A: Rationale Behind Key Financial Parameters in NG-H2_P_COM User’s Manual [2]
	Project contingency factor (%)	15	Cell E102	Applied to all capital costs (a project contingency in the range of 15–30% is recommended for the level of detail provided by the cost equations used in the model since the miscellaneous cost category in the pipeline capital costs includes contingency [and some taxes]) [14]

2.1.1.2 Key Inputs for the Engineering Module

The remaining key inputs are located within the "Eng Mod" sheet of NG-H2_P_COM. The key inputs on this sheet are related to engineering calculations, capital cost estimates, and operating cost estimates. Exhibit 2-2 lists a pared-down version of the key inputs and includes parameters that are most relevant to the NG-H2_P_COM inputs and outputs discussed in this report. A full list of the key inputs that are located on the "Eng Mod" sheet can be found in the User's Manual [2].

Exhibit 2-2. Key inputs on the "Eng Mod" sheet in NG-H2_P_COM

Parameter	Default Value	Location in "Eng Mod" Sheet	Note
Number of Active Compressors in Each Compressor Station	2	Cell D25	Value from "H2 Compressor" sheet in HDSAM [15]
Steel Grade of Pipeline	X70	Cell D141	Steel grade X52 is only available for an inlet pressure ≤ 1,000 psig and for class location 1
First Pipeline Class Location	1	Cell D142	Class Location 1 is any 1-mi section with 10 or fewer occupied dwellings (i.e., sparsely populated areas) [7] Class Location 3 is any 1-mi section with 46 or more occupied dwellings (i.e., outskirts of a city) [7]
Percentage of Pipeline Length in Class Location (%)	100	Cell D143	100% = Entire pipeline located in a single class location <100% = Pipeline is located in two different class locations
Cost Factor for Reuse of NG Pipeline	0.3	Cell D180	Best professional judgment

There are two steel grade options within NG-H2_P_COM, X52 and X70. There is no clear consensus among literature on which steel grade is less likely to be affected by H_2 embrittlement. Some studies suggest lower-grade steels (X52) are better for H_2 transportation, while other studies suggest a higher grade steel (X70) is better [16]. As previously mentioned, capital costs for replacing portions of the existing pipeline with new pipe are based on the capital costs for building new NG pipelines as described in Brown et al. [7]. Capital costs are calculated for the reused portions of the pipeline by applying a reuse cost factor to the capital costs for a newly constructed pipeline. The default cost factor is 30 percent but could range 10–35 percent depending on multiple factors, such as pipeline length, pipeline diameter, the condition of the pipeline, H_2 concentration, number of compressor stations, and operating pressure [17]. The calculated cost of capital for reuse covers minor retrofitting costs for the pipeline to ensure safe transportation of the blended gas stream, which includes inspections, pressure testing, fittings and valve replacement, metering and regulating station modifications, and upgraded leak detection and monitoring systems [16] [18] [10]. As previously mentioned, default values were used for all NG-H2_P_COM outputs discussed in this report unless otherwise stated.

2.1.2 General Results Study: Case Studies

The General Results Study has two separate case studies that compare scenarios to demonstrate the impact of specific cost drivers, as modeled by NG-H2_P_COM, while holding other parameters constant:

- The Constant Reuse Parameters case study varies H_2 blend 5–25 percent for 200-mi and 500-mi pipeline lengths, keeping pipeline reuse and reuse cost factors constant at 75 percent and 30 percent, respectively. The scenario matrix for the Constant Reuse Parameters case study is discussed in Section 2.1.2.1.
- The Variable Reuse Parameters case study varies pipeline reuse percentage, reuse cost factor, and compressor reuse percentage more realistically as H_2 percentage varies 5–25 percent, keeping pipeline length and diameter constant at 200 mi and 24 inches (in.), respectively. The scenario matrix for the Variable Reuse Parameters case study is discussed in Section 2.1.2.2.

The General Results Study case study analyses were performed using NG-H2_P_COM default values except for the parameters and values specified in the scenario matrices presented in the next sections (Exhibit 2-3 and Exhibit 2-4).

2.1.2.1 Constant Reuse Parameters Case Study Scenario Matrix

The Constant Reuse Parameters case study was designed to demonstrate the impacts of variations in H_2 volume percent and pipeline lengths on NG–H_2 transport costs. Exhibit 2-3 shows the scenario input matrix for the Constant Reuse Parameters case study. Pipeline diameter, pipeline reuse percentage, pipeline reuse cost factor, distance between compressors stations, and NG–H_2 blend energy content transported remained constant for all scenarios. Note in Exhibit 2-3 the number of compressor stations increases with pipeline length since the distance between compressor stations remains constant.

The Constant Reuse Parameters case study results are provided in Section 3.1.1.

Exhibit 2-3. Constant Reuse Parameters case study scenario matrix

Pipeline Length	Pipeline Diameter	Pipeline Reuse	Pipeline Reuse Cost Factor	Distance Between Compressor Stations	Compressor Stations	H_2 Volume		NG–H_2 Blend Energy Content (Pipeline Transport Capacity)
mi	in.	%	%	mi	#	%	MMBtu/d	bscf/d
200	24	75	30	100	1	5	209,000	0.2071
						10		0.2148
						15		0.2231
						20		0.2320
						25		0.2417
500	24	75	30	100	4	5	209,000	0.2071
						10		0.2148
						15		0.2231
						20		0.2320
						25		0.2417

2.1.2.2 Variable Reuse Parameters Case Study Scenario Matrix

The Constant Reuse Parameters case study fixed pipeline reuse percentage and the cost factor associated with reuse (Exhibit 2-3). Literature studies suggest, however, retrofitting costs would likely increase with increasing H_2 volume because some of the existing infrastructure could handle low concentrations of H_2 (i.e., less than 10 percent), with little to no modifications. Many studies cite compressors being the limiting factor for reuse at 10 percent H_2 by volume, while others suggest all compressors should be replaced with new built-for-purpose compressors even for H_2 volumes as low as 1 percent [8] [9] [10]. The consensus within literature is a relatively small amount of capital would be required at or below 10 percent H_2, with more significant investments required at concentrations of 20–30 percent H_2 for transmission pipelines [19].

The Variable Reuse Parameters case study demonstrates the impact of retrofitting parameters varying, more in alignment with literature consensus, as the H_2 volume increases, keeping pipeline length, pipeline diameter, and pipeline transport capacity constant. These reuse input parameters in NG-H2_P_COM that can be varied include compressor reuse percentage, pipeline reuse percentage, and the pipeline reuse cost factor. Exhibit 2-4 shows the scenario input matrix for the Variable Reuse Parameters case study.

Exhibit 2-4. Variable Reuse Parameters case study scenario matrix

Pipeline Length	Pipeline Diameter	H_2 by Volume	Cost Factor for Pipeline Reuse	Pipeline Reuse	Number of Compressor Stations	Number of Compressor Stations Being Reused	NG–H_2 Blend Energy Content (Pipeline Transport Capacity)	
mi	in.	%	%	%	#	#	MMBtu/d	bscf/d
200	24	5	10	100	1	1	209,000	0.2071
		10	20	90	1	0		0.2148
		15	20	90	1	0		0.2231
		20	30	75	1	0		0.2320
		25	30	75	1	0		0.2417

The 5 percent H_2 scenario, for example, represents a pipeline where 100 percent of the pipeline can be reused along with the compressors at the compressor station and a 10 percent reuse cost factor. The reuse cost factor represents the percentage of new-build NG pipeline capital costs. The 10 percent reuse cost factor may be representative of costs associated with pipeline inspection and testing, and minor retrofitting to the pipeline as well as to meter and regulator stations.

The 10 percent and 15 percent H_2 scenarios represent minor pipe replacement (10 percent replacement; 90 percent reuse), as well as replacement of old compressors with new built-for-purpose compressors at the compressor station, and a reuse cost factor of 20 percent.

The 20 percent and 25 percent H_2 scenarios are representative of more significant pipe replacement (25 percent replacement; 75 percent reuse), as well as replacement of old compressors with new built-for-purpose compressors, and a reuse cost factor of 30 percent.

The Variable Reuse Parameters case study transport cost results are provided in Section 3.1.2, and include breakouts of transport costs by major cost category: capital expenditure (CAPEX), operational expenditure (OPEX) excluding electricity, and electricity expenditure.

2.2 BLENDPATH COMPARISON STUDY METHODOLOGY

The BlendPATH Comparison Study was designed to compare the levelized cost of transport (LCOT) reported in nominal 2020$/MMBtu of blended NG–$H_2$ for a specific pipeline scenario from a case study performed by NREL (referred to throughout this report as the “NREL Study”) using BlendPATH [20] with the FYBE price of NG–H_2 transport in nominal 2020$/MMBtu from a similar scenario modeled using NG-H2_P_COM. A description of NREL’s BlendPATH model is provided in Section 2.2.1. To recreate the NREL Study, NG-H2_P_COM inputs had to be matched as closely as possible to those assumed for the NREL Study. The crosswalk of the inputs in both models is described in Section 2.2.2.

2.2.1 BlendPATH Description

BlendPATH is a Python tool developed by NREL that estimates the LCOT for blends of H_2 and NG along existing NG pipelines and, therefore, represents an ideal tool to compare NG-H2_P_COM analysis with. BlendPATH is a screening-level model designed to evaluate opportunities at the initial project assessment stage [20]. BlendPATH uses the Scenario Analysis Interface for Energy Systems (SAInt) integrated energy system modeling platform [21] to perform gas pipeline hydraulic modeling and the Production Financial Analysis Scenario Tool (ProFAST) economic analysis package [22] to perform financial analysis.

BlendPATH determines default pipeline material costs based on weight of common steel grades reported by Savoy Piping, Inc. [23]. NG pipeline construction (labor, rights-of-way, and miscellaneous) default costs are based on region-specific NG pipeline cost equations published by Brown et al. [7]. NG compressor station default costs (material, labor, rights-of-way, and miscellaneous) are from methods published by Rui et al. [13]. Costs can be directly input in BlendPATH [20].

BlendPATH has three options for modifying an existing NG pipeline:

1. **Direct Replacement** of existing pipeline segments with new pipe of the same diameter but different thickness and steel grade to accommodate the new NG–H_2 blend at the original operating pressure
2. **Parallel Looping** of new pipeline segments parallel to existing pipeline to reduce overall operating pressure in each segment while increasing volumetric capacity to accommodate the new NG–H_2 blend
3. **Additional Compressors** at shorter spacing intervals along the pipeline pathway to reduce overall operating pressure in the existing segments while increasing volumetric capacity to accommodate the new NG–H_2 blend

2.2.2 BlendPATH Comparison Study Input Crosswalk

The NREL Study referenced in this study is the "DO – no fracture control" [20], which was based on a modified version of a case study from Wang et al. [24], and performed by NREL using BlendPATH. "DO – no fracture control" refers to the design option (DO) approach used to determine the maximum pipeline pressure (i.e., the design pressure) used in the NREL Study, where the design pressure was fixed, as opposed to calculated using pipeline fracture control equations to determine the maximum pipeline operating pressure. Pipeline fracture control equation options are built into BlendPATH, and are defined in American Society of Mechanical Engineers (ASME) B31.12 "Standard on Hydrogen Piping and Pipelines" [25]. ASME B31.12 standards were developed for H_2 pipelines, and so may not be appropriate for low H_2 percentage NG–H_2 blends (<10 percent) [26].

The NREL Study modeled the cost of replacing a 248.5-mi-long NG pipeline in the Great Plains region with 26-in. diameter X60 grade steel pipeline with a design pressure of 8.7 megapascals gauge (MPa-g). The NREL Study assumed 3 years of construction to replace the existing pipeline, and 50 operating years, transporting an existing NG stream blended with 20 percent H_2. Key parameters in the NREL Study are provided in Exhibit 2-5 where they are crosswalked with parameters input into NG-H2_P_COM for the purpose of the comparison study.

Exhibit 2-5. Crosswalk of NREL Study scenario inputs with comparable NG-H2_P_COM inputs

Parameter Type	Parameter	NREL Study	NG-H2_P_COM
Pipeline Capacity	Total off-take demand (MW)	6442 (equivalent to 527,545 MMBtu/d)	-
	Average current pipeline transport capacity of NG (bscf/d)	-	0.5050 (equivalent to 527,619 MMBtu/d)
	Capacity factor (%)	100	100
Pipeline Route	Region	Great Plains	Great Plains
	Length (mi)	248.5	248
	Change in elevation (ft)	-	0
	Percentage of pipeline being reused (%)	-	0
	Right-of-way costs ($)	0	0
Pipeline Specifications	Diameter (in.)	26	30
	Steel Grade	X60	X70
	Compression ratio	1.55	-
	Inlet pressure (psig)	-	755
	Outlet pressure (psig)	482	482
Compressor Stations	Compressor stations	3	3
	Power requirement per station (MW)	12.5	11.5
	Total compressors per station	-	2
	New compressors per station	0	0
Project Stages	Project/analysis start year	2020	2020
	Duration of construction (yr)	3	3
	Duration of operations (yr)	50	50
Financial Parameters	Percent equity (%)	40	40
	Interest rate on debt (%)	3.7	3.7
	Income tax rate (%)	25.74	25.74
	Escalation rate (%)	1.9	1.9
	Project contingency factor (%)	-	0

An input to both BlendPATH and NG-H2_P_COM is the energy content of the original transported gas stream, as this value needs to be maintained by the blended NG–H_2 steam if the pipeline's customers' energy demand remains unchanged. BlendPATH uses offtake demand as this input, in megawatt (MW) units. NG-H2_P_COM uses pipeline volumetric capacity, in units of billions of standard cubic feet (bscf)/day (d). Both models report these capacity inputs in units of MMBtu/d for purposes of reporting transport costs in dollars per MMBtu. The NREL Study assumed a pipeline offtake demand that totaled 6,442 MW (154,608 megawatt hours) [20], which is equivalent to 527,545 MMBtu/d [18]. To match a similar energy output, the volumetric transport capacity of the original NG stream input into NG-H2_P_COM was 0.5050 bscf/d (equivalent to 527,619 MMBtu/d). To maintain the transport energetic capacity after blending NG with 20 percent H_2 by volume, the pipeline transport volumetric capacity of the blended stream increases to 0.586 bscf/d of NG–H_2.

A long-term utilization parameter input of 1 was used in the NREL Study [18], which was assumed to be equivalent to a pipeline capacity factor of 100 percent, input in NG-H2_P_COM. Capacity factor is equal to the ratio of the average annual flow rate to the annualized maximum flow rate.

BlendPATH assumed the case study pipeline was built and operated within the Great Plains region of the United States [18], and used capital costs for NG pipeline construction derived from Brown et al. [7]. BlendPATH assumed pipeline material costs based on Savoy Piping, Inc. [23]. NG-H2_P_COM used regional capital cost equations for NG pipeline materials and construction from Brown et al. [7], and the Great Plains region was selected to recreate the NREL Study pipeline scenario.

The NREL Study assumed a 248.5-mi existing pipeline length [18], which was rounded to 248 mi in NG-H2_P_COM.

The elevation change in the NREL Study was assumed to be negligible [18], so the change in elevation between the pipeline inlet and outlet was set to 0 feet in NG-H2_P_COM. The NREL Study used BlendPATH's direct replacement modeling option for modifying the existing pipeline, described in Section 2.2, and so assumes all (100 percent) of the original pipeline was replaced. Therefore, the user input percentage of the pipeline being reused in NG-H2_P_COM was set to 0 percent.

Despite the BlendPATH model using NG pipeline construction default costs based on region-specific NG pipeline cost equations published by Brown et al. [7], which incorporate the costs of right-of-way, the NREL Study's right-of-way costs were listed as zero [18]. NG-H2_P_COM's right-of-way costs, therefore, were manually zeroed for the comparison modeling.

NG-H2_P_COM was developed to estimate costs for pipelines with common nominal diameters, in inches, of 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, 30, 36, 42, and 48. The NREL Study's 26-in. pipeline [18] could, therefore, not be identically modeled in NG-H2_P_COM; a 30-in.-diameter pipeline was selected for this comparative analysis as it is the closest diameter pipeline available in the model that still maintains its integrity at the capacity and pressures modeled in the NREL Study.

The NREL Study assumed the replacement pipeline material was X60 grade steel [18]. NG-H2_P_COM has options for X52 and X70 grade steel. X70 grade steel has higher minimum yield strength relative to X52 (and X60) [27]; therefore, X70 was selected in NG-H2_P_COM to maintain a yield strength equal to or greater to the reference NREL Study's X60 assumption.

The NREL Study used a compression ratio of 1.55 and a pipeline outlet pressure (i.e., the pressure of the gas stream at the pipeline outlet and compressor inlet) of 3.325 MPa-g [18], equivalent to 482 pounds per square inch gauge (psig). The pipeline inlet pressure (i.e., the pressure of the gas stream at the pipeline inlet and compressor outlet) is a required input in NG-H2_P_COM, and can be determined using the following compression ratio equation (Equation 1):

$$CR = \frac{P_1 + P_{atm}}{P_2 + P_{atm}}$$

Equation 1: Compression ratio equation

Where:

CR is the compression ratio

P_1 is the pipeline inlet pressure

P_2 is the pipeline outlet pressure

P_{atm} is atmospheric pressure of 14.7 psi

The inlet pressure is 755 psig at a compression ratio of 1.55 and pipeline outlet pressure of 482 psig.

The NREL Study assumed reuse of all compressors located at three distinct compressor stations [18], but the case study did not specify the number of compressors per station. The NREL Study did specify the power of each compressor station as 12.5 MW. The NG-H2_P_COM assumed two compressors per compressor station; based on compressor sizing equations, NG-H2_P_COM calculated the required power per compressor station to be 11.5 MW.

The NREL Study used built-in compressor station costs based on equations from Rui et al. [13]. NG-H2_P_COM used built-in compressor costs based on compressor cost equations in Argonne National Laboratory's Hydrogen Analysis Project (H2A) Hydrogen Delivery Scenario Analysis Model (HDSAM) [28], which are based on data provided by compressor manufacturers.

The pipeline project modeled in the NREL Study assumed a start year of 2020, 3 years of construction (to replace the existing pipeline) and 50 years of operations [18]; this date and stage durations were used in NG-H2_P_COM.

Key financial parameters used in the NREL Study that can be directly input into NG-H2_P_COM included a 3.7 percent interest rate on debt (i.e., cost of debt), a 1.5 debt equity ratio (i.e., debt is 150 percent of equity; 60 percent debt and 40 percent equity), a 25.74 percent effective income tax rate, and a 1.9 percent inflation rate (effectively a 1.9 percent escalation rate) [18]. The NREL Study assumed assets were depreciated linearly over 30 years [18]; the depreciation method in NG-H2_P_COM was selected to be a 150 percent declining balance over 15 years. Financial parameters assumed in the NREL Study that were not inputs in NG-H2_P_COM included property tax and insurance (0.9 percent), administrative expenses (0.5 percent, presumably of capital costs), capital gains tax rate of 15 percent, and leverage after tax nominal discount rate (10 percent) [18]. Financial parameters assumed in NG-H2_P_COM that are not accounted for in the NREL Study include annual cost of equity (13.3 percent), and project contingency factor (0 percent). NG-H2_P_COM's default contingency factor is 15 percent, but 0 percent was selected for the comparison since contingency was not defined in the NREL Study [18].

3 RESULTS

The results section reports and discusses key results for the General Results Study in Section 2.1, and for the BlendPATH Comparison Study in Section 2.2.

3.1 GENERAL RESULTS STUDY: RESULTS

The General Results Study's Constant Reuse Parameters and Variable Reuse Parameters case studies, outlined in Section 2.1.2.1 and Section 2.1.2.2, respectively, were designed to demonstrate the impact of key cost drivers on transport price. The FYBE price outputs associated with each scenario in these case studies are presented by case study in the next two sections.

3.1.1 Constant Reuse Parameters Case Study: Results

Exhibit 3-1 shows the model outputs for the FYBE price (in real 2023$/MMBtu), volumetric flow rate, and the increased electricity costs associated with transporting blended NG with H_2 at varying H_2 percentages. The scenarios' input parameters are provided in Exhibit 2-3. The results show that at a fixed percentage of pipeline reuse (e.g., 75 percent default value) and reuse cost factor (e.g., 30 percent default value), H_2 volume has little effect on the FYBE price. However, the addition of H_2 to a NG stream increases the amount of compression needed, increasing yearly operating costs. For a 200-mi pipeline with only one compressor station, electricity costs could increase to over $1 million/year (yr) to maintain the same energy transport capacity as the original NG stream. As the pipeline length increases, the number of compressor stations along the pipeline route increases, resulting in a slight change in the FYBE as the H_2 volume increases. For example, a 500-mi pipeline with four compressor stations could increase electricity costs by over $5 million/yr at 25 percent H_2 by volume.

Exhibit 3-1. Transport cost results for the Constant Reuse Parameters case study scenarios

Pipeline Length	Number of Compressor Stations	H_2 Volume	Transport Capacity	FYBE Price	Increase in Electricity Costs Compared to Original NG
mi	#	%	bscf/d	2023$/MMBtu	2023$/yr
200	1	5	0.2071	0.37	239,372
		10	0.2148	0.37	491,821
		15	0.2231	0.37	759,206
		20	0.2320	0.37	1,043,614
		25	0.2417	0.39	1,347,440
500	4	5	0.2071	0.98	957,489
		10	0.2148	1.00	1,967,286
		15	0.2231	1.02	3,036,825
		20	0.2320	1.04	4,174,455

Pipeline Length	Number of Compressor Stations	H_2 Volume	Transport Capacity	FYBE Price	Increase in Electricity Costs Compared to Original NG
		25	0.2417	1.05	5,389,758

3.1.2 Variable Reuse Parameters Case Study: Results

Exhibit 3-2 demonstrates how varying retrofitting parameters to align more realistically with infrastructural requirements likely to change as H_2 volume increases impacts the price of NG–H_2 transportation. As discussed in Section 2.1.2.2, the Variable Reuse Parameters case study varied compressor reuse, pipeline reuse, and the pipeline reuse cost factor inputs to adjust with H_2 volume percent changes to be more in line with literature consensus.

Exhibit 3-2. Transport cost results for the Variable Reuse Parameters case study scenarios

H_2 by Volume	Cost Factor for Pipeline Reuse	Percentage of Pipeline Being Reused	Number of Compressor Stations	Number of Compressor Stations Being Reused	FYBE Transport Price of NG–H_2 Blend
%	%	%	#	#	2023$/MMBtu
5	10	100	1	1	0.14
10	20	90	1	0	0.26
15	20	90	1	0	0.28
20	30	75	1	0	0.39
25	30	75	1	0	0.39

Exhibit 3-2 demonstrates a substantial increase in FYBE transport price (from $0.14/MMBtu to $0.26/MMBtu) for 5–10 percent H_2, due in large part to the change in compressor reuse assumptions from complete reuse at 5 percent H_2 to complete replacement at 10 percent H_2 and higher volumes. A second significant increase in FYBE price (from $0.28/MMBtu to $0.39/MMBtu[a]) occurs for the 15–20 percent H_2 volume scenarios, respectively, where the percent of pipeline reused drops from 90 percent to 75 percent, and the cost factor of that reused pipeline increases from 20 percent to 30 percent. Note there is no appreciable difference in FYBE price for 20–25 percent H_2 volume scenarios, indicative of H_2 volume percent increases having little effect (i.e., less than a penny in this case) on transport price beyond a slightly higher compression operations cost (as discussed in Section 3.1.1). The FYBE price results from Exhibit 3-2 are shown graphically, broken out by major cost category (capital expenditure [CAPEX], operations and maintenance costs [OPEX] excluding electricity, and electricity costs), in Exhibit 3-3.

[a] FYBE price is $0.02 higher than in the Constant Reuse Parameter case study (20 percent scenario) due to rounding the FYBE price of each cost category to the nearest cent.

Exhibit 3-3. Transport cost results for the Variable Reuse Parameters case study scenarios, broken out by major cost category

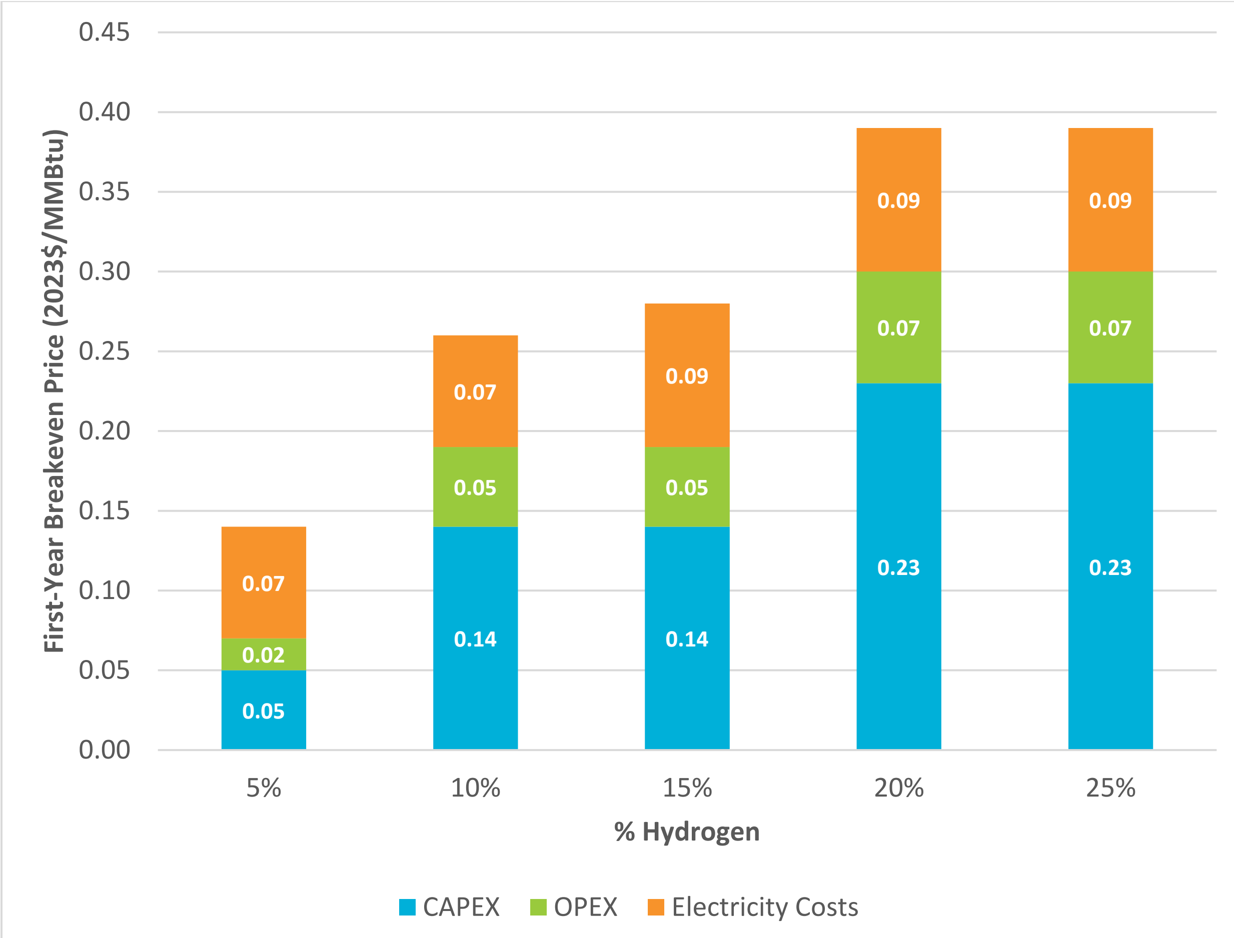

Exhibit 3-3 demonstrates the first significant increase in FYBE price for 5–10 percent H_2 as being mostly related to an increase in CAPEX, due to replacing compressors instead of reusing them. The CAPEX again increases for 15–20 percent H_2, due to the additional costs associated with higher pipeline replacement percentages and higher pipeline replacement cost factors assumed between these two scenarios.

When pipeline reuse, compressor reuse, and the pipeline reuse cost factors are varied to better align with H_2 percentages by volume, based on literature assumptions, a FYBE price of $0.14/MMBtu may better represent costs for transporting a NG–H_2 blend with 5 percent H_2, relative to the $0.37/MMBtu FYBE price reported for the similar 5 percent H_2 200-mi scenario in the Constant Reuse Parameters case study (Exhibit 3-1).

3.2 BlendPATH Comparison Study: Results and Discussion

The NREL Study reported a LCOT of $0.21/MMBtu of NG–$H_2$ blend. The LCOT assumed a NPV close to zero [20]. NG-H2_P_COM reported in analogous (i.e., NPV near zero) FYBE cost of transport of $0.25/MMBtu of NG–$H_2$ blend for the same (as close as possible given the model input options) scenario. NG-H2_P_COM's costs are 19 percent higher.

Differences in the transport costs are likely due to the following modeling assumptions in the NREL Study that could not be recreated identically in NG-H2_P_COM:

- Compressor cost equations (NG-H2_P_COM's costs were based on costs reported in a 2015 H_2 cost model [28]; the NREL Study's costs were based on equations from a 2011 study built into BlendPATH [13])
- Pipeline material costs (NG-H2_P_COM's costs were based on regional equations from 2022 [7]; the NREL's Study's costs were based on per weight steel prices from an industry supplier built into BlendPATH [23])
- Pipeline steel grade (NG-H2_P_COM assumed a higher strength X70 steel than the NREL Study's modeled X60 steel)
- Pipeline diameter (NG-H2_P_COM assumed a larger diameter 30-in. pipeline than the NREL Study's modeled 26-in. pipeline)

The two models also have different solutions for modeling pipeline hydraulics and performing financial analysis, which likely contribute to the differences in transportation cost results. BlendPATH uses SAint [21] and ProFAST [22], while NG-H2_P_COM uses built-in engineering equations (e.g., defaults include the American Gas Association-8 method for calculating blend density and compressibility [29], the Lee gas viscosity correlation [30], the McCoy compressible fluid flow equations [31], and the Colebrook-White fanning friction equation [32]) and a built-in cash flow module for financial analysis (refer to the User's Manual [2] for more detail).

BlendPATH reports a NG price, which may allude to the composition of the original NG blend prior to H_2 blending but does not explicitly describe the composition of the original NG blend. NG-H2_P_COM requires the original NG blend composition to be input as a volume percentage per component (e.g., methane, nitrogen, carbon dioxide, ethane, propane, isobutane, butane). Both models use defaults that are within normal NG pipeline specifications.

Both models are useful depending on the modeling use case(s). Relative to BlendPATH, which requires the user to have background knowledge in Python as well as having Anaconda and SAInt installed [33], NG-H2_P_COM has a somewhat more user-friendly Excel format with no additional software. However, BlendPATH offers additional pipeline infrastructure scenario analysis options, like parallel looping and adding additional compressor stations.

For future work, it would be valuable to collaborate with NREL's BlendPATH team to develop and assess additional scenarios for various inputs and configurations in both BlendPATH and NG-H2_P_COM. In such way, the outcomes will be cross-benchmarked.

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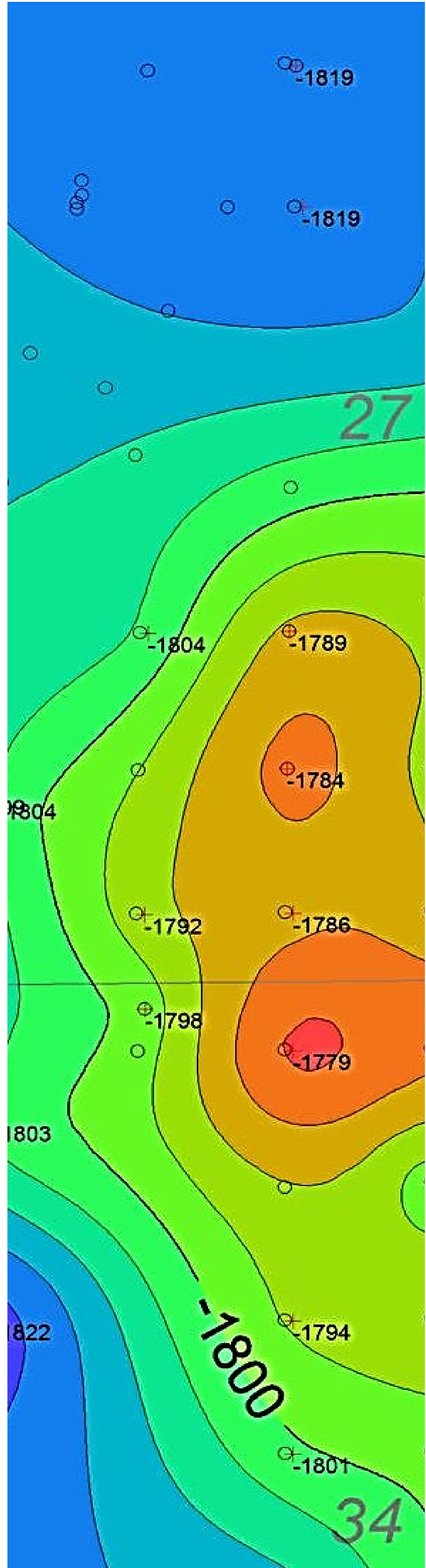

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