Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) Documentation and User Manual

Jamie Kee, Evan Reznicek, Mark Chung and Kevin Topolski

National Renewable Energy Laboratory

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15013 Denver West Parkway
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List of Acronyms and Abbreviations

AC	additional compressors
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BlendPATH	Blending Pipeline Analysis Tool for Hydrogen
bool	boolean
CA	California
CapEx	capital expenditures
CSV	comma-separated values
depr	depreciation
DN	Diametre Nominal
DOE	Department of Energy
DR	direct replacement
EOS	equation of state
GL	Great Lakes
GP	Great Plains
H2FAST	Hydrogen Financial Analysis Scenario Tool
int	integer
json	javascript object notation
kg	kilogram
km	kilometer
kW	kilowatt
LCOT	levelized cost of transport
m	meter
MA	Mid-Atlantic
MAOP	maximum allowable operating pressure
mi	mile
mm	millimeter
MACRS	modified accelerated cost recovery system
MJ	megajoule
MMBTU	metric million British thermal units
MPa-g	megapascal-gauge
MW	megawatt
NE	New England
nfc	no fracture criterion
NREL	National Renewable Energy Laboratory
OpEx	operating expenditures
O&M	operations and maintenance
Pa-g	pascal-gauge
PL	parallel looping
PN	Pacific Northwest
ProFAST	Production Financial Analysis Scenario Tool
rk	Redlich-Kwong
RM	Rocky Mountains
s	second
SE	Southeast
SMYS	specific minimum yield strength
str	string
SW	Southwest
TOPC	take or pay contract
vol.	volume

Executive Summary

The Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) is a flexible, open-source Python tool designed to provide users with case-by-case analysis capabilities to identify the necessary modifications to repurpose existing natural gas transmission pipeline networks to transport hydrogen as a blend of a user-specified volume fraction of hydrogen or as a pure stream and to estimate the associated capital and operating expenditures resulting from those modifications. This tool is intended to be applied during the initial screening stage of a prospective project when pipeline developers compile transmission pipeline technical documentation and history but prior to performing detailed pipeline inspections. Performing analysis with BlendPATH during this initial screening stage can provide the user with an understanding of promising opportunities and probable economic outcomes of repurposing their pipeline network for hydrogen before proceeding with detailed pipeline materials testing and pipeline inspections.

BlendPATH consists of multiple modules to simulate, assess, and modify existing natural gas transmission pipeline network designs to be compatible with hydrogen as a blend or pure stream. The tool employs an open-source gas network hydraulic model to simulate existing, user-specified transmission pipeline networks, and it applies ASME B31.12 to assess the pipe segments within these networks for compatibility with hydrogen and to modify the networks to achieve compatibility where the existing infrastructure is inadequate. Users can specify ASME B31.12 design options for pipeline assessment and can select from multiple methods for pipeline modification.

This report details the functionalities of BlendPATH Version 2.0 and demonstrates an example of applying BlendPATH to a case study. Potential and intended users of this framework include natural gas pipeline developers and operators and researchers at both public and private institutions. BlendPATH is publicly available at https://github.com/NREL/BlendPATH.

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1 Introduction

There is increasing interest from natural gas transmission pipeline operators, researchers, and their associated governments to blend hydrogen into existing natural gas transmission pipeline networks for potential low-cost energy transportation. But blending hydrogen into existing natural gas transmission pipeline infrastructure involves a number of technical challenges that should be addressed before implementation. These challenges include, but are not limited to, gaseous hydrogen's material degradation effect on line pipe steels, the additional power required to compress hydrogen due to its lower molecular weight, and the compatibility of existing pipeline network equipment with hydrogen blended in pipeline gas or as a pure stream. Further, the extent to which these technical challenges are present depends on the transmission pipeline network system design and operation, wherein the equipment model, equipment condition, and material of construction play significant roles in determining the cost to transport pipeline gas in a given network. A case-by-case approach is necessary to evaluate an existing pipeline network's appropriateness for hydrogen blending or for pure hydrogen transport.

The Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) model is designed to identify the required transmission pipeline network modifications and estimate the capital expenditures (CapEx) and operating expenditures (OpEx) that are likely to be incurred when repurposing the existing pipeline network infrastructure for the transport of hydrogen as a natural gas blend or as a pure stream. This model applies ASME B31.12 (American Society of Mechanical Engineers 2023) and existing equipment constraints to determine what pipeline network modifications are necessary for a pipeline operator to inject a user-specified amount of hydrogen into the network. High-level CapEx and OpEx are aggregated into a levelized cost of service to transport natural gas and/or hydrogen while maintaining end-use energy demand. The intent of BlendPATH is to provide users with case-by-case techno-economic analysis capabilities to screen promising opportunities to transport hydrogen within their pipeline assets and to identify potential pipeline network modifications and probable economic outcomes prior to investing in higher-cost assessments, such as pipeline inspections and materials testing, to qualify a transmission pipeline network to handle hydrogen.

The technical documentation presented here describes BlendPATH Version 2.0, its limitations, program installation, how to use the program, and an example case study. BlendPATH is available to install as a Python package from the National Renewable Energy Laboratory (NREL) on GitHub at https://github.com/NREL/BlendPATH.

2 Model Description

BlendPATH is an NREL-developed Python package that estimates the required pipeline design modifications and levelized cost associated with transporting a specified volume fraction of hydrogen in the pipeline gas through a natural gas transmission pipeline. BlendPATH determines the pipeline design modifications and the associated costs by incorporating both physics-based hydraulic modeling and generally accepted accounting principles-based financial analysis to provide users with a thorough techno-economic analysis of repurposing existing natural gas transmission networks for hydrogen blending or pure hydrogen transport. Figure 1 illustrates the structure of BlendPATH and the inputs available to users to customize their analysis for a specific case study. BlendPATH accepts a variety of user-defined inputs relating to pipeline design and operation, equipment costs, and project financial structure to define a given pipeline network case study of interest for blending analysis. Further, BlendPATH users can specify the targeted hydrogen content for blending into the pipeline gas, the ASME B31.12 design option, and the BlendPATH modification method that is appropriate for their blending analysis. BlendPATH offers three predefined methods (discussed in greater detail in Section 2.3) that modify the user-specified network to enable operation with a desired hydrogen content. These modification methods rely on both an internal hydraulic network model and ProFAST (Kee and Penev 2024) to identify designs that minimize the levelized cost of transport (LCOT) for the blended gas using the selected modification method while satisfying the user-specified constraints. The last stage of the BlendPATH assessment involves a final financial assessment and reports the techno-economic analysis results. The following sections describe the BlendPATH modeling in more detail.

2.1 Pipeline Network Hydraulic Model

BlendPATH includes an isothermal pipeline network hydraulic model to estimate the steady-state operating conditions for user-specified pipeline case studies. The theory for simulating steady-state pipeline network operating conditions is well established (Osiadacz 1987; Srinivasan et al. 2023), and a couple open-source, steady-state pipeline network models—such as Lohmeier et al. (2020) and Lu, Pesch, and Benigni (2022)—have been published in recent years. Although several open-source options are available, BlendPATH employs a custom open-source pipeline network model developed for ease of integration into the overarching BlendPATH framework.

Pipeline networks are represented in BlendPATH as a collection of nodes connected by branches. Nodes can be classified as supply or demand nodes where hydrogen and/or natural gas are injected into or extracted from the network, respectively. Branches are classified as either pipes or compressor stations that condition gas streams from one node to another. With this representation, users can flexibly model a pipeline network structure of interest within BlendPATH. Further, both nodes and branches possess user-specified attributes to characterize network component design and operation. Key user inputs describing operation include the following pipeline network

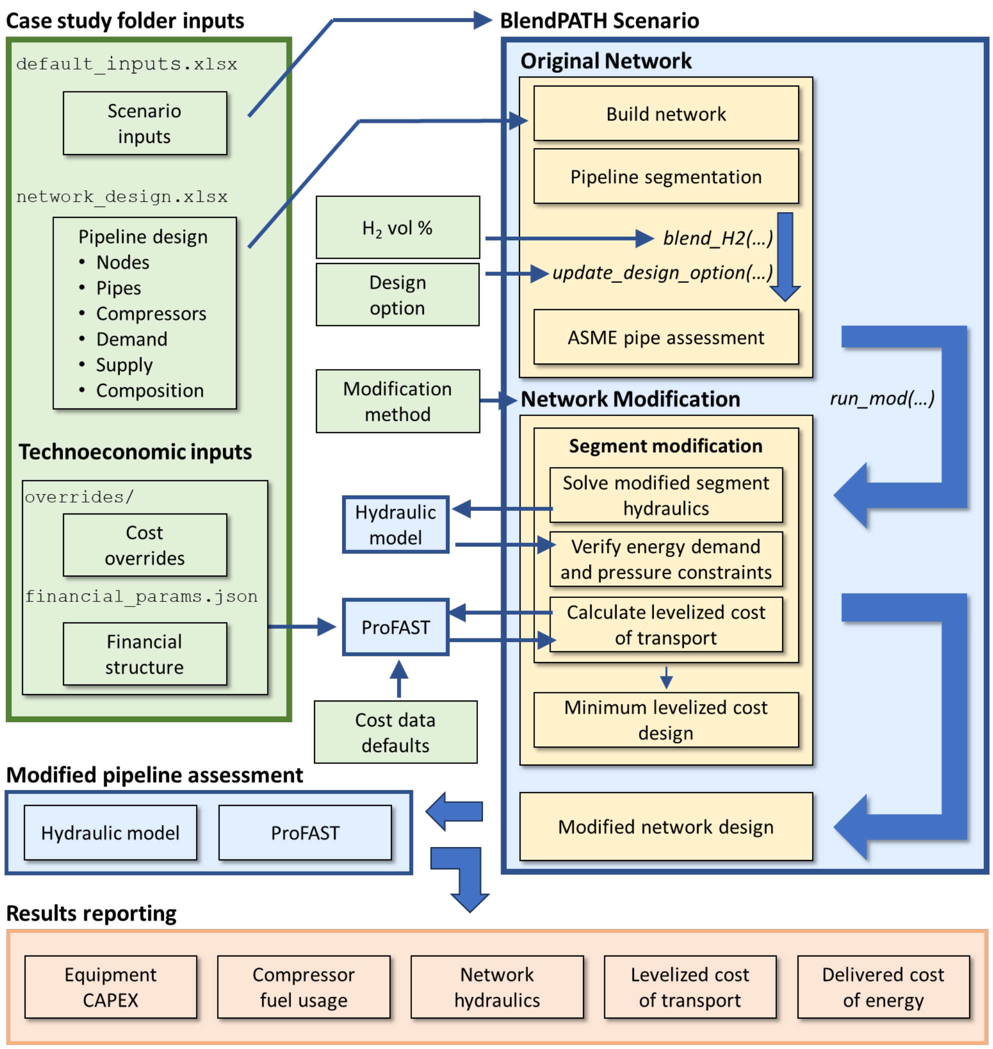

Figure 1. BlendPATH package code structure. Green boxes indicate user input, blue boxes indicate high-level modules within BlendPATH, yellow boxes indicate internal computations to BlendPATH, and orange boxes indicate model outputs.

boundary conditions: supply node pressure, demand node energy demand, and compressor outlet pressure. These boundary conditions are required inputs for BlendPATH's pipeline hydraulic model to solve for steady-state pipeline network pressures and flow rates. Users can provide network design information to BlendPATH through an Excel file; Section 5.1.1 discusses these input parameters in detail and provides user guidance to specify the pipeline network designs via the Excel file.

2.1.1 Physical Modeling of Pipes

The hydraulics within the pipeline network, and more specifically the pressures, are determined by evaluating the momentum balance for a given pipe:

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{f}{2D}\rho\upsilon|\upsilon| - \rho\upsilon\frac{\mathrm{d}\upsilon}{\mathrm{d}x} \tag{2.1}$$

where p is the pressure, x is the length along a pipe, f is the wall friction factor, D is the pipe inner diameter, ρ is the fluid density, and υ is the fluid velocity. BlendPATH calculates the friction factor using the explicit Hofer approximation of the Colebrook-White formula (Hofer 1973):

$$f = \left(-2\log_{10}\left[\frac{4.518}{Re}\log_{10}\left(\frac{Re}{7}\right)+\frac{k}{3.71D}\right]\right)^{-2} \tag{2.2}$$

where Re is the fluid Reynolds number, and k is the pipe roughness. BlendPATH employs several simplifications when solving the momentum equation. First, it assumes one-dimensional plug flow and that the kinetic energy term is negligible (Osiadacz 1987). Given that BlendPATH solves for the steady-state pressure profile, the mass flow rate is constant in any singular pipe. Based on these simplifications, the mass flow rate through a pipe, $\dot{m}$, can be modeled as:

$$\dot{m} = A\left(\frac{M_\mathrm{w}}{ZRT}\frac{D}{fL}\right)^{0.5}\sqrt{p_2^2 - p_1^2} \tag{2.3}$$

where A is the pipe cross-sectional area; M_w is the fluid's molecular weight; R is the gas constant; T is the temperature; L is the pipe length; and p_2 and p_1 are the absolute pressures at the pipe inlet and outlet, respectively. The gas compressibility, Z, is calculated using the average fluid properties in the pipe as:

$$Z_\mathrm{avg} = \frac{p_\mathrm{avg}M_\mathrm{w}}{RT_\mathrm{avg}\rho_\mathrm{avg}} \tag{2.4}$$

where the average temperature, pressure, and density are calculated as follows:

$$p_\mathrm{avg} = \frac{2}{3}\left(p_1 + p_2 - \frac{p_1 p_2}{p_1 + p_2}\right) \tag{2.5}$$

$$T_\mathrm{avg} = \frac{T_1 + T_2}{2} \tag{2.6}$$

$$\rho_\mathrm{avg} = \rho\left(p_\mathrm{avg}, T_\mathrm{avg}\right) \tag{2.7}$$

and where T_1 and T_2 are the fluid temperatures at the pipe inlet and outlet, respectively. Note that the density calculation in Equation 2.7 depends on which equation of state (EOS) is applied. BlendPATH allows users to choose between the Papay EOS or the Redlich-Kwong EOS. The former EOS is programmed within BlendPATH's hydraulic model whereas the latter EOS is accessed through Cantera, an open-source python package (Goodwin et al. 2023). The Papay EOS is not recommended for use with high hydrogen blends at elevated pressures in which the calculated compressibility asymptotes to $Z = 1$ with respect to hydrogen content. The compressibility correlation for the Papay EOS (Papay 1968) is as follows:

$$Z = 1 - \frac{3.53p_\mathrm{r}}{10^{0.9813T_\mathrm{r}}} + \frac{0.274p_\mathrm{r}^2}{10^{0.8157T_\mathrm{r}}} \tag{2.8}$$

where p_r is the ratio of pressure to critical pressure, and T_r is the ratio of temperature to critical temperature. In contrast, the Redlich-Kwong EOS more accurately captures the compressibility of hydrogen at pressures that deviate from ideal gas properties. The Redlich-Kwong EOS (Redlich and Kwong 1949) is represented as:

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T} V_m (V_m + b)} \tag{2.9}$$

where a and b are corrective constants specified as:

$$a = 0.42748 \frac{R^2 T_c^{2.5}}{p_c} \tag{2.10}$$

$$b = 0.08664 \frac{R T_c}{p_c} \tag{2.11}$$

where V_m is the fluid molar volume. The critical temperature, T_c, and pressure, p_c, are calculated for a given gas mixture, weighted by the composition. The Redlich-Kwong EOS requires an implicit numerical method to estimate density (or molar volume as in Equation 2.9) at a given pressure and temperature. This calculation is handled within BlendPATH by the Cantera Python package (Goodwin et al. 2023).

2.1.2 Compressor Stations

Within BlendPATH's pipeline network model, compressor stations are represented as a branch connecting the compressor's inlet and outlet nodes. BlendPATH models compressors to estimate compressor shaft work and to determine compression station capacity. Inputs to this model include the gas mixture's thermodynamic properties at the compressor inlet and outlet and the mass flow rate of the gas being compressed. The mass-basis enthalpy, h_1, and entropy, s_1, at the inlet of the compressor are estimated via Cantera as functions of the temperature, pressure, and composition:

$$h_1 = f(T_1, p_1, X_1) \tag{2.12}$$

$$s_1 = f(T_1, p_1, X_1) \tag{2.13}$$

where f denotes the thermodynamic property evaluation within Cantera; and T_1, p_1, and X_1 are the temperature, pressure, and molar composition at the compressor inlet. Conversely, the enthalpy at the compressor outlet, $h_{2,s}$, for an isentropic process is given as:

$$h_{2,\mathrm{s}} = f\left(s_1, p_2, X_2\right) \tag{2.14}$$

The adiabatic head of the compressor, $\Delta h_{\text{isentropic}}$, is calculated as the change in enthalpy between the compressor's inlet and a theoretic isentropic outlet:

$$\Delta h_{\text{isentropic}} = h_{2,\mathrm{s}} - h_1 \tag{2.15}$$

The real change in enthalpy, Δh_{real}, is calculated by dividing the compressor's adiabatic head with an isentropic efficiency:

$$\Delta h_{\text{real}} = \frac{\Delta h_{\text{isentropic}}}{\eta_{\text{compressor}}} \tag{2.16}$$

where $\eta_{\text{compressor}}$ is the isentropic efficiency for compression. Compressor stations in BlendPATH by default assume an isentropic efficiency of 0.78 for gas-driven compressors (Interstate Natural Gas Association of America 2010) and 0.88 (Nexant, Inc et al. 2008) for electricity-driven compressors. Compressor shaft power, $\dot{W}_{\text{shaft}}$, is calculated as:

$$\dot{W}_{\text{shaft}} = \Delta h_{\text{real}} \dot{m}_{\text{compressor}} \tag{2.17}$$

where $\dot{m}_{\text{compressor}}$ is the mass flow rate of fluid exiting the compressor. This assumes that any gas fueling the compression station is extracted prior to the gas entering the compressor. Last, the driver fuel rate W_{fuel} is given as:

$$\dot{W}_{\text{fuel}} = \frac{\dot{W}_{\text{shaft}}}{\eta_{\text{driver}}} \tag{2.18}$$

where η_{driver} is the driver efficiency for a gas-driven compressor. By default, BlendPATH assumes a driver efficiency of 0.357 (Interstate Natural Gas Association of America 2010) for gas-driven compressor stations. For electricity-driven compressor stations, the default driver efficiency is calculated as:

$$\eta_{\text{driver}} = 8\text{E-}5x^4 - 0.0015x^3 + 0.0061x^2 + 0.0311x + 0.7617 \tag{2.19}$$

where $x = \ln\left(\dot{W}_{\text{shaft}}\right)$, and $\dot{W}_{\text{shaft}}$ is in units of kilowatts (Nexant, Inc et al. 2008). BlendPATH users can override the default isentropic and driver efficiencies if more appropriate values are available. Sections 5.1.1 and 5.1.2 describe how to override these values for existing and new compressor stations, respectively.

2.1.3 Higher Heating Value

Higher heating value is applied in BlendPATH for estimating the compressor fuel utilization and for converting the energy demand at demand nodes from energy flow rates to mass flow rates. BlendPATH estimates the higher heating value of a gas mixture by considering the mixture's fuel components, which exclude N_2 and CO_2, and it assumes that a stoichiometric amount of oxygen is mixed into the gas mixture. BlendPATH applies Cantera to estimate the enthalpy of the gas mixture pre-combustion. Assuming full combustion, the post-combustion gas mixture enthalpy is also calculated. The higher heating value, HHV_{blend}, of the gas mixture is calculated as follows:

$$HHV_{\text{blend}} = -\frac{h_2 - h_1 + \Delta h_{\text{H}_2\text{O}} Y_{\text{H}_2\text{O}}}{Y_{\text{stoich\_fuel}}} Y_{\text{combustibles}} \tag{2.20}$$

where h_2 is the post-combustion mass-basis enthalpy, h_1 is the mass-basis enthalpy of the stoichiometric combustible mixture, $\Delta h_{\text{H}_2\text{O}}$ is the change in mass-basis enthalpy associated with water evaporation, $Y_{\text{H}_2\text{O}}$ is the mass fraction of water in the post-combustion mixture, $Y_{\text{stoich\_fuel}}$ is the mass fraction of fuel in the pre-combustion mixture that has stoichiometric oxygen added, and $Y_{\text{combustibles}}$ is the mass fraction of fuel in the pipeline gas mixture.

2.1.4 Pipeline Network Representation as a System of Nonlinear Equations

To represent a pipeline network as a system of nonlinear equations, BlendPATH applies mass balances for every node (Osiadacz 1987):

$$L_i + \dot{W}_{\text{fuel},i} = \sum_{p=1}^{N_{\text{Pipes}}} a_{i,p}\dot{m}_p \qquad \forall i \in N_{\text{Nodes}} \tag{2.21}$$

where $\dot{m}_{\text{p}}$ is the mass flow rate through pipe p; and $a_{i,p}$ is a branch-node incident value of 1, 0, or -1; denoting the connection of pipe p to node i with 0 denotes no connections, and 1 or -1 denotes flow into or out of the node, respectively. The summation of the mass flow rates representing external supplies or demands at node i is denoted as L_{i}. Likewise, fuel consumption at node i is represented as $\dot{W}_{\text{fuel},i}$ if the node represents a compressor station inlet. Equation 2.21 is alternatively presented in matrix form as:

$$\mathbf{A}\dot{\mathbf{m}} = \mathbf{L} + \dot{\mathbf{W}}_{\mathbf{fuel}} \tag{2.22}$$

where $\mathbf{A}$ is the branch-nodal incidence matrix of $a_{i,p}$ values, $\mathbf{m}$ is the vector of mass flows through pipes in dimension N_{Pipes}, $\mathbf{L}$ is the vector of mass flows representing external supplies or demands at nodes in dimension N_{Nodes}, and $\dot{\mathbf{W}}_{\mathbf{fuel}}$ is the fuel consumption at nodes where gas-driven compressor stations are modeled.

Pipe pressures are also represented as:

$$\sum_{i=1}^{N_{\text{Nodes}}} -a_{i,p} P_i = \Delta P_p \qquad \forall p \in N_{\text{Pipes}} \tag{2.23}$$

where P_i is the square of pressure at node i, and ΔP_p is the difference of the squared nodal pressures through pipe p. Likewise, Equation 2.23 is presented in matrix form as:

$$-\mathbf{A}^{\mathsf{T}}\mathbf{P} = \Delta\mathbf{P} \tag{2.24}$$

where $\mathbf{P}$ is the vector of the squared nodal pressures in dimension N_{Nodes}, and $\Delta\mathbf{P}$ is the vector form of ΔP_p in dimension N_{Pipes}. Note that $\mathbf{A}^{\mathsf{T}}$ is the transpose of the branch-nodal incidence matrix in Equation 2.22.

Equation 2.1.5 can be expressed in vector form in dimension of N_{Pipes} as:

$$\dot{\mathbf{m}} = \Phi(\Delta\mathbf{P}) \tag{2.25}$$

where $\Phi(\Delta\mathbf{P})$ is the vector of functions relating the pipe pressure drop to the mass flow rate. Equation 2.24 can be substituted into Equation 2.25 for $\Delta\mathbf{P}$:

$$\dot{\mathbf{m}} = \Phi(-\mathbf{A}^{\mathsf{T}}\mathbf{P}) \tag{2.26}$$

Further, Equation 2.26 can be substituted into Equation 2.22 to relate the nodal pressures to the external mass flow rates at nodes representing supplies or demands:

$$\mathbf{A}\left[\Phi\left(-\mathbf{A}^{\mathsf{T}}\mathbf{P}\right)\right] = \mathbf{L} + \dot{\mathbf{W}}_{\mathbf{fuel}} \tag{2.27}$$

Equation 2.27 could be rearranged into a vector of nodal error functions, $\mathbf{F}(\mathbf{P})$, of dimension N_{Nodes} as:

$$\mathbf{F}(\mathbf{P}) = \mathbf{A}\left[\Phi\left(-\mathbf{A}^{\mathsf{T}}\mathbf{P}\right)\right] - \mathbf{L} - \dot{\mathbf{W}}_{\mathbf{fuel}} \tag{2.28}$$

where $\mathbf{F}(\mathbf{P}^*) = 0$ when BlendPATH's simulation solution method determines the vector of nodal pressures $\mathbf{P}^*$ that satisfies Equation 2.27. Equation 2.28 can be expressed in an alternate algebraic format as:

$$f(P_i) = -L_i - \dot{W}_{\mathrm{fuel},i} + \sum_{j=1}^{N_{\mathrm{Nodes}}} a_{i,j}\left(A\left(\frac{M_{\mathrm{w}}}{ZRT}\frac{D}{fL}\right)^{0.5}\sqrt{a_{i,j}(P_i - P_j)}\right) \qquad \forall i \in N_{\mathrm{Nodes}} \tag{2.29}$$

where $f(P_i)$ is the element-wise expression for Equation 2.28, and j is an index representing an adjacent node connected by pipe p to node i. Note that pipe p represents a branch connecting two nodes, i and j. In Equation 2.29, the pipe index, p, is substituted with j, another node index of dimension N_{Nodes}, to represent an adjacent node connected by pipe p. More formally, $p \Leftrightarrow (i, j)$ and $(i, j) \in N_{\mathrm{Pipes}}$ within this nodal model representation of a pipeline network.

2.1.5 Steady-State Simulation Solution Process

BlendPATH applies the Newton-Raphson method on Equation 2.28 to determine a solution to Equation 2.27 (Osiadacz 1987). This approach is adapted from Lu, Pesch, and Benigni (2022) to simulate the steady-state solution. The Newton-Raphson method is a stationary iterative method that approximates a nonlinear system of equations into a linear system to determine an iterative solution. The Newton-Raphson method solves the system of equations for new sets of solutions until a convergence criteria is attained (i.e., $\mathbf{F}(\mathbf{P}) \Rightarrow 0$). This method involves an iterative process in which the dependent variable being solved for is updated until convergence. For Equation 2.28, the dependent variables being iterated are the nodal pressures $\mathbf{P}^k$ as:

$$\mathbf{P}^{k+1} = \mathbf{P}^k + (\delta\mathbf{P})^k \tag{2.30}$$

where k is the number of Newton-Raphson iterations to solve Equation 2.28, and $\delta\mathbf{P}$ is the pressure correction computed from iteration k to $k+1$. The pressure correction is computed with the following:

$$\mathbf{J}^k(\delta\mathbf{P})^k = -\left[\mathbf{F}(\mathbf{P})\right]^k \tag{2.31}$$

where $\mathbf{J}^k$ is a square Jacobian matrix of dimensions N_{Nodes} by N_{Nodes} at iteration k. The Jacobian is given as:

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f_i}{\partial p_n} & \frac{\partial f_i}{\partial p_{n+1}} & \cdots & \frac{\partial f_i}{\partial p_{N_{\text{Nodes}}}} \\ \frac{\partial f_{i+1}}{\partial p_n} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \frac{\partial f_{N_{\text{Nodes}}}}{\partial p_n} & \cdots & \cdots & \frac{\partial f_{N_{\text{Nodes}}}}{\partial p_{N_{\text{Nodes}}}} \end{bmatrix} \tag{2.32}$$

where $\frac{\partial f_i}{\partial p_n}$ is the partial derivative of Equation 2.29, expressed as:

$$\frac{\partial f_i}{\partial p_n} = \sum_{j=1}^{N_{\text{Nodes}}} a_{i,j} \left(A \left(\frac{M_{\text{w}}}{ZRT} \frac{D}{fL} \right)^{0.5} \frac{a_{i,j} p_i}{\sqrt{p_i^2 - p_j^2}} \right) \qquad \forall i, n \in N_{\text{Nodes}} \tag{2.33}$$

and n is an additional index for all nodes described in the pipeline network. Note that Equation 2.31 is expressed as a linear system of equations, and therefore $(\delta \mathbf{P})^k$ could be solved for with linear algebraic numerical methods.

Figure 2 shows a flowchart of BlendPATH's pipeline network hydraulic solver to illustrate the solver algorithm computation with Equations 2.24, 2.28, 2.30, 2.31, and 2.32. As shown in Figure 2, BlendPATH requires an initial guess for nodal pressures $\mathbf{P}^0$ prior to algorithm iteration to compute the compressor station fuel flow rate and the pressure corrections. BlendPATH initializes the nodal pressures based on the pressures of the supply node and the compressor station outlet nodes because these pressures are known. Nodes downstream of the supply node and the compressor station outlet nodes are assigned guess values based on a conservative pressure drop calculation using Equation . Pressures of adjacent pipe-connected nodes cannot be equal to prevent forming a singular Jacobian matrix.

BlendPATH's algorithm iteration proceeds to convergence on nodal pressures when Equation 2.28 computes a maximum nodal error less than BlendPATH's default convergence tolerance, $\varepsilon_{\text{tol}} = 10^{-3}$. BlendPATH uses the numpy.linalg package (Harris et al. 2020) to solve Equation 2.28 to yield a set of δp_i values for each iteration of the network solver. BlendPATH applies a relation factor, C_{relax}, to dampen the rate of change in pressure from one iteration to the next with the following equation:

$$p_i^{k+1} = p_i^k + C_{\text{relax}} \delta p_i^k \qquad \forall i \in N_{\text{Nodes}} \tag{2.34}$$

After the new pressures are assigned on each iteration, the mass flow rate through each node is calculated. This process accounts for the compressor station fuel usage (if fuel extraction is employed), which is calculated based on the compressor inlet and outlet node pressures and then subtracted from the mass flow rate through the compressor

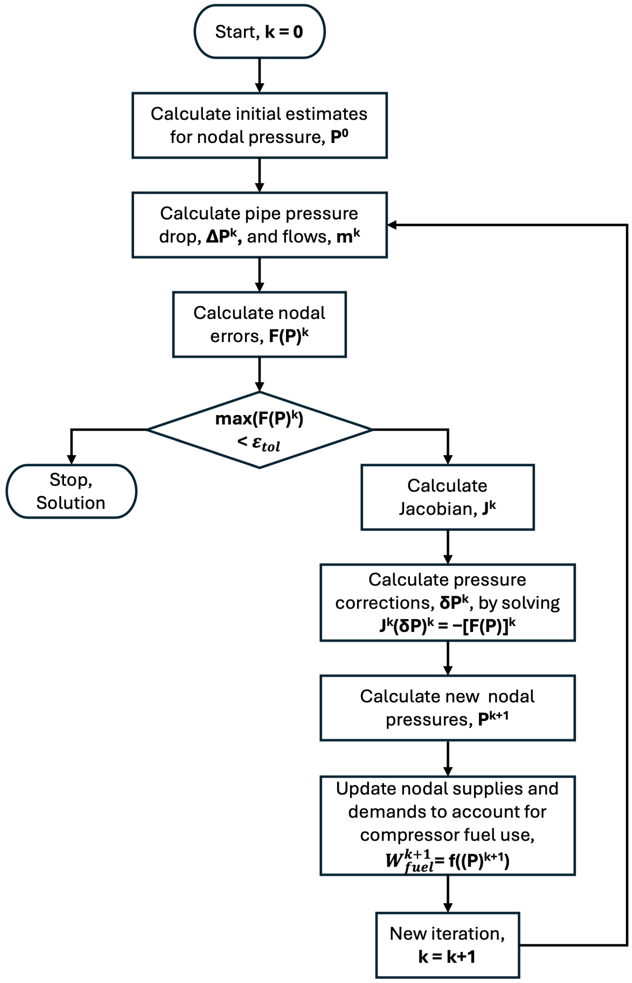

Figure 2. BlendPATH's network algorithm to solve for pipeline pressures given a pipeline network representation as a structure of nodes, pipes, and compressor stations

station. The solver terminates once the difference between the calculated mass flow and the targeted mass flow, which consists of the mass flow rates at demand nodes, reaches a specified error tolerance, $\varepsilon_{\text{tol}} = 10^{-3}$.

2.1.6 Constraints

Network simulations within BlendPATH are subject to pressure and energy demand constraints. Upon reaching a network simulation solution, BlendPATH verifies that the minimum network pressure threshold is not violated. By default, BlendPATH sets the minimum pressure threshold to 290 psig, or approximately 2 MPa-g, which is conservatively higher than the inlet pressure for most U.S. city gate stations (Melaina, Penev, and Zuboy 2015). The energy demand at the demand nodes must be satisfied for BlendPATH's hydraulic model to stop iterating; therefore, every hydraulic simulation requires that the pipeline network energy demand is satisfied.

2.1.7 Verification

BlendPATH's pipeline network hydraulic model was compared to Bainier and Kurz (2019) for model verification. Bainier and Kurz (2019) modeled and simulated a 250-km pipeline case study with an 85-bar inlet, 45-bar outlet, and varying hydrogen blend ratios. Additionally, the pipeline case study was described as having a nominal diameter of 900 mm and a pipe wall roughness of 10 μm. Bainier and Kurz (2019) estimated the energy flow rate for constant-pressure-drop scenarios in which the hydrogen content in the pipeline gas was varied. Figure 3 illustrates a comparison between BlendPATH and Bainier and Kurz (2019) with respect to the latter's case study. Figure 3 shows a maximum error of 2.2% in the energy flow estimates between both methods, thus indicating relative agreement. Note, however, that several differences exist between the two models, namely in the applied EOS and the model scope; these differences could partially account for the observed difference in results. The Bainier and Kurz (2019) model applied the AGA8 EOS, whereas BlendPATH used the Redlich-Kwong EOS for this comparison. Additionally, the Bainier and Kurz (2019) model considers heat transfer effects between the pipeline and the surrounding 15°C environment, whereas BlendPATH assumes isothermal conditions at 15°C. Last, Bainier and Kurz (2019) considers the gas species of argon, helium, hexane, heptane, and i-pentane, which are not available in BlendPATH; however, the mole fractions are all near or less than 0.01% and are considered negligible for BlendPATH in this comparison.

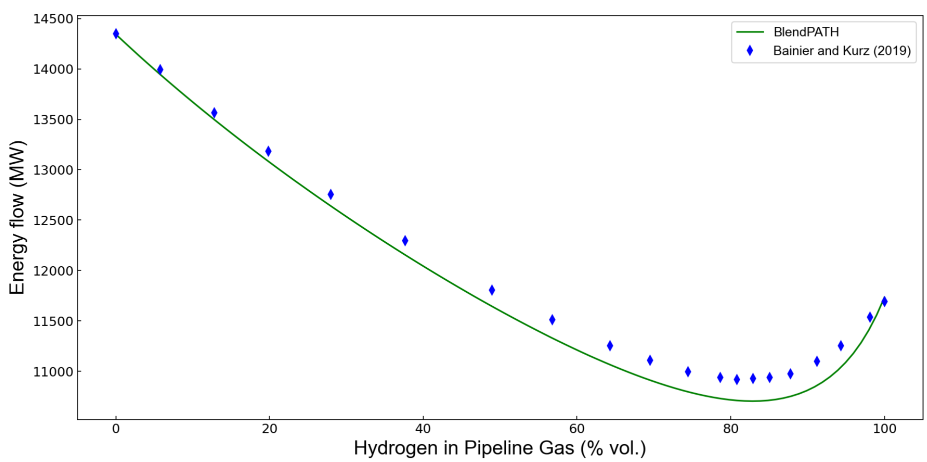

Figure 3. BlendPATH hydraulic network model validation with the results highlighted in Bainier and Kurz (2019)

2.2 Pipeline Assessment

Prior to any modification, BlendPATH assesses the pipeline network in question to divide it into individual line packing segments and to assign maximum allowable operating pressure (MAOP) per line pack segments subject to hydrogen pipeline design standards. This section describes the methods used to segment the pipeline network and to calculate the MAOP.

2.2.1 Transmission Network Segmentation

BlendPATH sections pipeline networks into pipeline segments to perform pipeline design assessments on a per-segment basis. Gas transmission pipeline network segmentation is carried out in accordance with guidance received from industry. This guidance defines a pipe segment as a length of pipeline that is separated by compressor stations, pressure regulation stations, a change in pipeline diameter, or combinations thereof. All pipes within each individual segment should be designed for a uniform MAOP such that the segment is capable of line packing, which is the act of pressurizing an entire pipeline segment to the design pressure to store gas during periods of low demand with the expectation of later periods of high demand. The segment definition described here also ensures that an entire segment could be inspected with the same in-line inspection equipment. Figure 4 provides an example of how BlendPATH segments a section of a simple fictional pipeline network; the highlighted sections indicate unique segments. The compressors serve as the delimiters between the individual segments resulting in three total segments in this example.

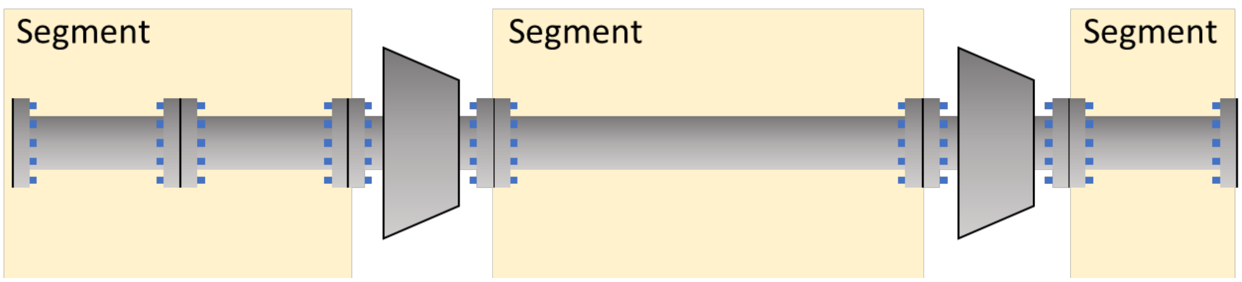

Figure 4. Example demonstration of the approach taken in BlendPATH to segment a simple pipeline network

2.2.2 Design Pressure Assessment

Once the existing gas transmission pipeline network is segmented, BlendPATH calculates the MAOP for the pipe segments as dictated by ASME B31.12 (American Society of Mechanical Engineers 2023) given each pipe segment's diameter, schedule, steel grade, and user-determined design option or design factor. If the pressure in any pipe exceeds the MAOP, then that pipe segment must be modified to meet the end-use energy demand and satisfy the design pressure limits. The equation for MAOP from ASME B31.12 is as follows:

$$p = \frac{2St}{D} FETH_{\mathrm{f}} \tag{2.35}$$

where p is the pipe MAOP (MPa-g); S is the specific minimum yield strength, or SMYS (MPa); t is the nominal wall thickness (mm); D is the pipeline nominal diameter (mm); F is the design factor; E is the longitudinal joint factor; T is the temperature derating factor; and H_{f} is the hydrogen-specific material performance factor. The temperature derating factor is $T = 1$ for fluid temperatures less than 250°F, which encompasses all scenarios of interest for BlendPATH. The material performance factor is a function of design pressure and specific minimum yield strength

(SMYS). For design pressures less than 2,000 psig and line pipe steel with SMYS less than or equal to 52 ksi, the material performance factor is 1. For higher design pressures and/or higher SMYS line pipe steels, the performance factor is less than 1, according to Table 1.

Table 1. Carbon Steel Pipeline Material Performance Factor, H_f (American Society of Mechanical Engineers 2023)

Specified Min. Strength (SMYS) (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	1.000	1.000	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

The design factor, F, depends on the fracture control method applied. Design option A, the prescriptive design method, requires moderate toughness testing, tensile strength of the pipe and welds less than or equal to 100 ksi, SMYS less than or equal to 70 ksi, and Charpy test qualifications for weld procedures. Design option A allows design factors up to $F = 0.5$ for location class 1, division 2 with the use of the appropriated material performance factor given in Table 1. Design option B, the performance-based design method, requires much more detailed testing but allows a design factor of up to $F = 0.72$ for location class 1, division 2 and a material performance factor of $H_f = 1$. Note that both design options are developed with new-build pipes in mind; both methods require testing specimens from the original pipe heats, which are likely not available for much of the vintage material used within the existing natural gas pipe infrastructure.

When it is not possible to employ fracture control methods, ASME B31.12 allows the use of a design factor of $F = 0.4$ with a material performance factor of $H_f = 1$, which is referred to as the "no fracture criterion" design option in BlendPATH. Note that even when employing the lowest design factor of $F = 0.4$, pipeline operators must be capable of performing in-line inspections to monitor defects and crack growth and ensure that these present defects are acceptable at the maximum operating pressures selected. More information on design options and fracture control methods can be found in Table 2. Additionally, BlendPATH allows users to specify a custom design factor (with a material performance factor of 1) to rate existing pipelines. This flexibility is incorporated to maintain BlendPATH usefulness as hydrogen pipeline design standards are updated.

Table 2. Design Factor, F (American Society of Mechanical Engineers 2023)

	Design Factor, F		
Location Class	No Fracture Criterion	Option A	Option B
Location class 1, division 2	0.40	0.50	0.72
Location class 2	0.40	0.50	0.60
Location class 3	0.40	0.50	0.50
Location class 4	0.40	0.40	0.40

If the pipeline assessment identifies any pipes in the network that must operate at pressures exceeding the MAOP as dictated by ASME B31.12 to meet end-use energy demand, BlendPATH provides several methods that users can choose from for modifying the network to meet end-use energy demand at the desired hydrogen blend ratio for a given network analysis. The next section describes these methods.

2.3 Pipeline Modification Methods

BlendPATH offers three unique methods to modify the existing gas transmission pipeline network design such that it complies with ASME B31.12 and ensure that it has sufficient compression station capacity to meet end-use energy demand while delivering pure hydrogen or blending the desired fraction of hydrogen. These three modification methods are the direct replacement method, the parallel looping method, and additional compressors method. The following subsections discuss each method in detail. Note that the user is required to specify which pipeline modification methods they wish to run when using BlendPATH.

2.3.1 Direct Replacement Method

In the direct replacement method, BlendPATH substitutes pipeline segments identified for modification because they either surpass the MAOP pressure or experience excessive pressure drop to satisfy end-use energy demand. If any single pipe in a pipe segment requires replacement, then the entire segment must be assessed and replaced to ensure that all of the pipe can reach the same MAOP to satisfy the line packing requirements. Existing pipes can be replaced with new pipes of either the same nominal diameter or larger diameter, but the selection of steel grade and the schedule of the new pipe must enable the necessary operating pressures to be met. Figure 5 shows an example of the direct replacement method. In this example, the first segment is replaced with new pipes of larger diameter and a new steel grade and/or schedule that enables the desired operating pressure to be feasible while complying with ASME B31.12.

Figure 5. Example application of the direct replacement method to enable a pipe network to meet energy demand while accommodating hydrogen and satisfying ASME B31.12 design guidelines

BlendPATH applies a simplifying assumption that all pipe segments requiring modification are upgraded to the same diameter, steel grade, and pipe schedule instead of upgrading to unique diameters, steel grades, and schedules for individual segments. This reduces the computational domain to only intersecting permutations of diameter, steel grade, and schedule instead of exponentially scaling with a large number of options for each individual pipe. Additionally, this simplification assumes that pipeline builders are more likely to purchase larger quantities of the same pipe design rather than multiple unique pipe designs. The direct replacement option evaluates all feasible permutations of replacing a pipe segment or segments within a set of pipe segments identified for replacement. For each segment requiring modification in a permutation, BlendPATH loops through the available steel grades and the next five larger nominal diameters to determine the minimum thickness of pipe required to satisfy the ASME B31.12 MAOP. The schedules of pipe with a thickness greater than or equal to the minimum thickness required are recorded as a viable replacement for that segment. After the viable diameter, steel grade, and schedule combinations are identified for each segment, BlendPATH determines the intersection of viable segment designs across all segments into a set of viable modified pipeline designs where the design of all new pipes in the network have the same diameter, steel grade, and schedule.

All viable modified network designs are simulated in the hydraulic model to verify that the network maintains maximum and minimum pressure limits, compression ratio limits, and end-use energy demand. BlendPATH calculates the material costs and installation costs using the viable diameter, steel grade, and schedule combinations. By default, BlendPATH assumes that the direct replacement method avoids additional right-of-way costs but would require replacing and disposing of pipes that could otherwise be used at lower pressures. Some viable modified pipeline designs might benefit from a driving pressure higher than what was originally provided to the pipeline network at the supply node. To capture this effect, BlendPATH evaluates adding a compressor station at the supply node to increase the supply pressure to a range of pressure between the original supply pressure and the MAOP of the pipe segment at the supply node. BlendPATH iterates through the supply pressures for each direct replacement permutation, nominal diameter, steel grade, and schedule. The CapEx and OpEx associated with the supply compressor are also considered in the levelized cost calculation.

The results of the hydraulic models for all viable modified network designs are sent to BlendPATH's cost model to determine the LCOT for each viable direct replacement. BlendPATH chooses the modified network design that leads to the lowest calculated LCOT for generating the modified pipeline network design.

2.3.2 Parallel Looping Method

In the parallel looping method, BlendPATH builds additional pipes in parallel to the existing pipe to increase the volume of gas that can be passed through a given segment while remaining below the MAOP in each segment as dictated by ASME B31.12. Figure 6 shows an example of how the parallel looping method modifies a section of a fictitious network. In this example, the second segment is assumed to be unable to maintain energy demand, pressure, and/or compression ratio constraints. Placing a length of pipe parallel to the existing pipes allows a greater volume of gas to be transmitted through the segment with a lower driving pressure, even if the parallel pipe does not cover 100% of the segment. Note that the length necessary will depend on the diameter of pipe selected for the parallel line; with too small of a diameter, the loop might not enable the network to meet demand. For this reason, BlendPATH identifies multiple diameters for the parallel looping, iterates through them, and selects the diameter that achieves the lowest LCOT while satisfying the pipeline network constraints.

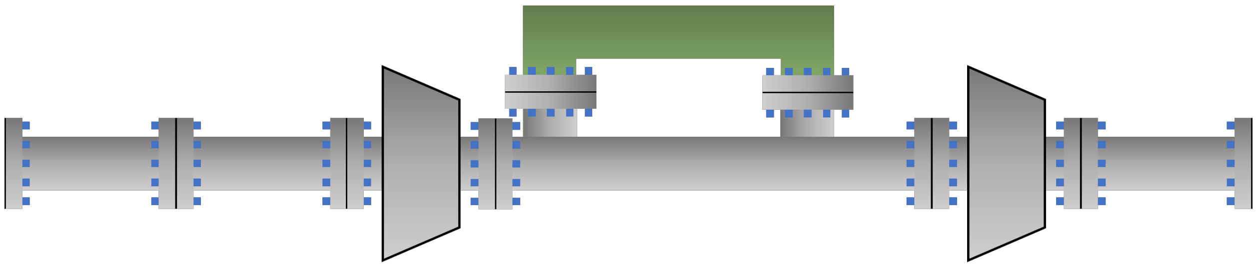

Figure 6. Example application of the parallel looping method to enable a pipe network to meet energy demand while accommodating hydrogen and satisfying ASME B31.12 design guidelines

The parallel looping method allows existing pipes within a given segment to continue service. Leaving existing pipes in place might result in lower material costs than the direct replacement method (due to the amount of new pipe required) but will incur additional right-of-way costs for any new pipe. BlendPATH iterates through a set of user-supplied design compression ratio constraints that are applied for all segments to determine the segment outlet pressures. Internal to the compression ratio and pipe segment iterations, BlendPATH also iterates through the allowable steel grades and the next fifteen larger nominal diameters. The minimum required thicknesses to meet ASME B31.12 design pressures are then compiled for every pipe segment, compression ratio constraint, steel grade, and diameter scenario. Pipe schedules corresponding to thicknesses greater than or equal to the minimum thickness are deemed viable and iterated upon. If the supply pressure is less than the MAOP of segment being repurposed, BlendPATH evaluates adding a compressor station at the supply node that can compress to a pressure between the original supply pressure and the MAOP of the repurposed pipe segment. For each combination of supply pressure, design compression ratio, pipe segment, steel grade, diameter, and viable schedule, BlendPATH estimates the minimum length of parallel loop necessary within each network segment to accommodate the desired flow rate and the segment pressure constraints. BlendPATH requires that parallel loops originate at the start of the segment, but they can terminate anywhere along the pipe segment and reintegrate the gas that they transported into the remaining length of the original pipeline. BlendPATH identifies pipe diameters that are larger than or equal to the existing pipe, and it selects steel grades and schedules such that the MAOP of the loop is greater than or equal to the MAOP of the existing pipe. Each segment is resimulated in the hydraulic model to verify that end-use energy demand, pressure, and compression ratio constraints are satisfied. The design compression ratio is applied across all segments, and the pipe geometry for each segment that corresponds to the minimum LCOT for all segments is selected as the modified network design.

2.3.3 Additional Compressors Method

The final method, additional compressors, adds compressor stations to the existing network so that the existing pipeline can move the desired blended gas volumes below the MAOP as dictated by ASME B31.12 and without having to replace existing pipes or build parallel loops. In this method, no pipeline material nor pipeline right-of-way costs are incurred, but additional compressor stations must be built to accommodate the desired gas flow rates. Figure 7 shows an example of how a fictitious network might be modified using the additional compressors method. In this example, the second segment requires additional compressor capacity due to violating pressure, energy demand, and/or compression ratio constraints. A single compressor station is placed in the middle of the segment such that it is equidistant from either end of the segment. Note that if two compressor stations were added, then the length between stations would be one-third of the total segment length. BlendPATH adds compressor stations until all constraints are met, then it calculates the LCOT given the new segment design.

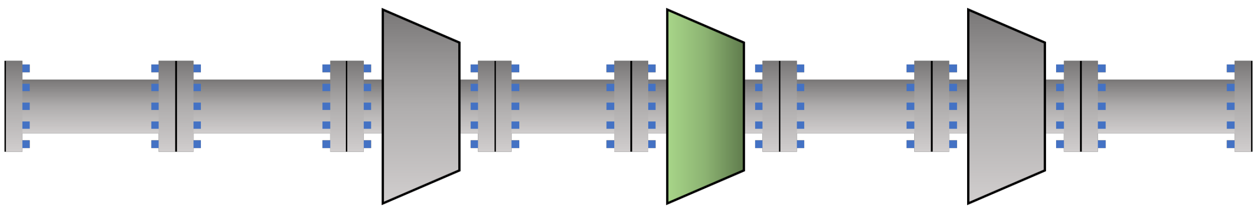

Figure 7. Example application of the additional compressors method to enable a pipe network to meet energy demand while accommodating hydrogen and satisfying ASME B31.12 design guidelines

The additional compressors method estimates the number of equally spaced compressor stations to add to each segment. First, BlendPATH assumes that any existing compressor stations are modified to be capable of achieving the MAOP as dictated by ASME B31.12. Second, BlendPATH iterates through design compression ratios for each segment. The design compression ratio is applied to all compressor stations within the modeled pipeline network, including existing compressor stations that must be revamped. Internal to a pipe segment iteration, BlendPATH solves for the minimum number of equidistantly spaced compressor stations within said segment that ensures the compression ratio of all the compressor stations do not exceed the segment's design compression ratio. If the supply pressure is less than the MAOP of the pipe segment being repurposed, BlendPATH evaluates adding a compressor station at the supply node that can compress to a pressure between the original supply pressure and the MAOP of the repurposed pipe segment. The compressor station at the supply node is not subject to the compression ratio constraint that the new and existing compressor stations abide by. Users should consider compressor station placement as approximate because other details, such as local permitting and right-of-way considerations, might affect the precise placement. If the user dictates that all new compressor stations are powered through fuel extracted from the pipeline, then the mass flow rate will change down the length of the pipe segment. After adding the minimum number of compressors to the pipe segment required to satisfy the design constraints, BlendPATH calculates the LCOT for the segment. This calculation aggregates the CapEx of revamping the existing compressors, the CapEx of new compressors, and the OpEx of all compressors through fuel extraction or electric power. The design compression ratio across all segments that results in the minimum LCOT for all pipe segments is selected as the modified network design.

2.4 Pipeline Cost Model

BlendPATH's pipeline cost model calculates the LCOT using NREL's ProFAST (Kee and Penev 2024) for blended gas or for pure hydrogen by aggregating the residual value of the original pipeline with CapEx associated with new pipeline additions, compressor station upgrades, new compression stations, and valve and meter station modifications, along with OpEx, such as in-line inspection and compressor fuel requirements, over the expected lifetime of the modified pipeline network. Inputs to BlendPATH's cost model include the dimensions and steel grade of the new pipe and the additional power required for existing compressor station modifications and new compressor station deployment. These inputs are used to calculate the CapEx for these assets as well as the compressor fuel requirements.

2.4.1 New Pipe Costs

The new pipe installed cost includes four components: material, labor, right-of-way, and miscellaneous. The pipe material costs are based on cost data from Savoy Piping Inc. (2022) on a per-kilogram weight basis; Table 3 shows these costs for the various line pipe steel grades considered. Both direct replacement and parallel looping modification methods inform the BlendPATH cost model of the new pipes' geometry; the additional compressors method does not add any new pipes. The total volume of new pipe is calculated and multiplied by the density of steel (assumed to be 7,840 kg m^{-3}) to determine the total mass of new pipe. BlendPATH calculates the pipe material costs as the product of steel price provided in Table 3 and the mass of new pipe.

Table 3. Steel Pipe Material Costs Based on Weight (Savoy Piping Inc. 2022)

Steel Grade	Price ($/kg)
B	1.8
X42	2.2
X46	2.4
X52	2.8
X56	2.9
X60	3.2
X65	4.3
X70	6.5

Labor, right-of-way, and miscellaneous costs are also included in the total cost of the new pipes. These costs are selectively applied based on the modification method that was performed on the pipeline network. Table 4 provides a summary of new pipeline CapEx components that are applied per the selected modification method. Note that the direct replacement method assumes that the right-of-way for the existing pipeline could be reused, whereas the parallel looping and the additional compressors method require all and none of the new pipe cost components, respectively.

Table 4. New Pipeline CapEx Applied for Each Modification Method

Pipe Cost Component	Direct Replacement	Parallel Looping	Additional Compressors
Material	✓	✓	
Labor	✓	✓	
Right-of-way		✓	
Miscellaneous	✓	✓	

Each new pipe cost component except for materials is determined using pipeline per-unit CapEx correlations. Brown, Reddi, and Elgowainy (2022) presents unitized pipeline CapEx correlations that are derived from natural gas pipeline cost component data reported by the Oil & Gas Journal Research (2020), which, in turn, references the Federal Energy Regulatory Commission Certificates of Public Convenience and Necessity. Brown, Reddi, and Elgowainy (2022) provides these cost correlations for different U.S. regions with the unitized CapEx regression equation as follows:

$$C_{\text{pipe},r,t} \quad (2018\$/\text{inch-mile}) = aD^{b}L^{c} \tag{2.36}$$

where $C_{\text{pipe},r,t}$ is the pipeline cost per inch-mile for region r and cost type t; D is the nominal diameter of the new pipe in inches; L is the length of new pipe in miles; and a, b, and c are the regression parameters determined from the cost correlation curve fitting in Brown, Reddi, and Elgowainy (2022). Table 5 provides the values for a, b, and c as they relate to cost type and different regions in the United States. The methodology for demarcating U.S. regions in terms of new pipeline costs can be reviewed in Brown, Reddi, and Elgowainy (2022).

2.4.2 Compressor Station Costs

Compressor station-related CapEx can be incurred in each pipeline modification method, albeit to different scopes. Table 6 provides a summary of new compressor CapEx that are applied to existing and new compressor stations per the selected modification method. If the original pipeline network has any preexisting compressor stations, these will require modifications to operate at new conditions (i.e., addition of hydrogen). Existing compressor stations might also require capacity expansion. Any new compression capacity will have an associated CapEx. The parallel loop method does not consider the addition of any new compressor stations, but it might require modification or expansion of existing compressor stations. The additional compressors method installs new compressor stations and allows for existing stations to be modified and/or expanded. The direct replacement method allows for the modification and expansion of existing compressor stations. All modification methods might require a new compressor station at the modeled supply node to increase the supply pressure to the new MAOP.

Table 5. Regional Pipeline CapEx Component Correlation Parameters (Adapted from Brown, Reddi, and Elgowainy (2022))

Region	Cost Component	a	b	c
Great Plains, Rocky Mountain	Labor	10406	0.20953	-0.08419
	Miscellaneous	4944	0.17351	-0.07621
	Right-of-way	2751	-0.28294	0.00731
New England	Labor	249131	-0.33162	-0.17892
	Miscellaneous	65990	-0.29673	-0.06856
	Right-of-way	83124	-0.66357	-0.07544
Mid-Atlantic	Labor	43692	0.05683	-0.10108
	Miscellaneous	14616	0.16354	-0.16186
	Right-of-way	1942	0.17394	-0.01555
Great Lakes	Labor	58154	-0.14821	-0.10596
	Miscellaneous	41238	-0.34751	-0.11104
	Right-of-way	14259	-0.65318	0.06865
Southeast, Pacific Northwest	Labor	32094	0.06110	-0.14828
	Miscellaneous	11270	0.19077	-0.13669
	Right-of-way	9531	-0.37284	0.02616
Southwest, California	Labor	95295	-0.53848	0.03070
	Miscellaneous	19211	-0.14178	-0.04697
	Right-of-way	72634	-1.07566	0.05284

Table 6. Compressor Station CapEx Considered for Each Modification Method

Compressor Cost Component	Direct Replacement	Parallel Looping	Additional Compressors
New compressor station deployment at supply node	✓	✓	✓
Existing compressor station modification	✓	✓	✓
Existing compressor station expansion	✓	✓	✓
New mid-segment compressor station deployment			✓

New Compression Station Cost

The cost of a new compressor station is based on the compressor station capacity. BlendPATH assumes that the minimum compressor station capacity is 3,000 hp (Rui 2011). The compressor station capacity can be used with the following equation to determine the compressor station CapEx:

$$C_{\mathrm{CS\_gas},t} \;\; (2008\$) = a + bS + cS^2 \tag{2.37}$$

where $C_{\mathrm{CS\_gas},t}$ is the gas-driven compressor station cost for cost type t; S is the compressor station capacity rating in horsepower; and a, b, and c are the regression parameters determined from the cost correlation fitting from Rui (2011). Table 7 provides the values for a, b, and c as they relate to cost type.

The Rui (2011) cost correlation asymptotes are near 30,000 hp; therefore, BlendPATH assumes a fixed \$/hp cost exceeding 30,000 hp evaluated at 30,000 hp for each compressor cost type.

Table 7. Compressor Station Cost Coefficients (Adapted from Rui (2011))

Cost Type t	a	b	c
Material	3175286.00	532.7853	0.0010416
Labor	1581740.00	299.2887	0.0011420
Miscellaneous	1696686.00	184.1443	0.0018417
Land	66216.72	0	0.0001799

If the user specifies that the compressor will have no fuel extraction, then it is treated as an electric-driven compressor. In these cases, the electric-driven compressor is assumed to be 30% more expensive than a gas-driven compressor (Interstate Natural Gas Association of America 2010). BlendPATH will apply a 1.3 markup factor to any electric-driven compressor as:

$$C_{\text{CS\_electric},t} = 1.3 C_{\text{CS\_gas},t} \tag{2.38}$$

Compressor Station Refurbishment and Expansion

Scenarios might arise within BlendPATH where an existing compressor station needs to be refurbished or modified to allow operation with a hydrogen blend and/or a different operating pressure. The necessary refurbishments and/or modifications might depend on the hydrogen blend ratio and the design aspects specific to the compressor station in question. When hydrogen is blended with natural gas, centrifugal compressors must operate at higher speeds to maintain the same pressure rise while transmitting the same amount of energy due to the low molecular weight (and therefore density) of hydrogen (Bainier and Kurz 2019). Whether a given centrifugal compressor can accommodate that increase in speed depends on how close its typical operating speed is to its maximum speed. Bainier and Kurz (2019) describe that for at least one particular compressor, a hydrogen blend ratio of slightly less than 20% is feasible while remaining below the compressor's maximum velocity. Alban (2022), however, showed that for a compressor with a maximum operating speed 5% greater than the design speed, the compressor would exceed safe operating limits with hydrogen-natural gas mixtures exceeding 10 vol % hydrogen. Studies have also documented that adding hydrogen to natural gas increases the required compression work to transmit the same amount of energy (Bainier and Kurz 2019; Zabrzeski et al. 2017), which could lead to scenarios where a compression station is power-limited by the compressor motor or turbine. Prime movers that use natural gas to drive compressors (including turbines and internal combustion engines) will additionally see a reduction in the volumetric energy density of their fuel, which could further limit the compression station capacity (Domptail et al. 2020).

BlendPATH assumes that existing compression stations will require significant modifications to continue operation with all modification methods and hydrogen fraction in pipeline gas. For the direct replacement method, existing compression stations might receive blended gas outside of the compressor inlet operating limits (e.g., higher volumetric flow rate and/or lower pressure) such that modifications might be required to compress higher volumetric flow rates over larger pressure ratios. Because both the parallel looping and additional compressors methods require a reduction in inlet and outlet compressor operating pressures (and therefore an increase in volumetric flow rate), it is also not clear without further analysis whether the existing compression stations would still be capable of providing the necessary pressure rise. Presently, BlendPATH conservatively assumes that all existing compression stations require refurbishments that cost 66% of the material, labor, and miscellaneous costs of a new-build compressor station, which is based on a cost estimate by Southern California Gas on a natural gas compression station (Southern California Gas Company 2014). Land cost is ignored for these retrofits because the physical site has already been occupied by the existing compressor station. Any additional compression capacity required for an existing compression station is costed based on the additional required compression capacity instead of the total required compression capacity.

Compressor Fuel Costs

If the BlendPATH user specifies that compressors are gas-driven, then BlendPATH will model compressor stations in the pipeline network to consume a portion of the transported fluid to power the compressor via a gas-fueled driver, such as a gas turbine. The hydraulic network model calculates the revised compressor station fuel extraction flow rate for the modified network based on the operating pressure and flow rate. The cost of the compressor fuel is determined using the cost of the natural gas, the cost of the hydrogen, and the energy fraction of hydrogen in the pipeline gas as follows:

$$C_{\mathrm{CS\_fuel}} = \frac{X_{\mathrm{H_2}} HHV_{\mathrm{H_2}} C_{\mathrm{H_2}} + X_{\mathrm{NG}} HHV_{\mathrm{NG}} C_{\mathrm{NG}}}{X_{\mathrm{H_2}} HHV_{\mathrm{H_2}} + X_{\mathrm{NG}} HHV_{\mathrm{NG}}} \tag{2.39}$$

where $C_{\mathrm{CS\_fuel}}$ is the cost of the compressor station fuel, $X_{\mathrm{H_2}}$ and X_{NG} are the mole fraction of hydrogen and natural gas in the pipeline gas, $HHV_{\mathrm{H_2}}$ and HHV_{NG} are the molar-basis higher heating values of hydrogen and natural gas, $C_{\mathrm{H_2}}$ is the cost of hydrogen as injected, and C_{NG} is the cost of natural gas. The formula weights the cost of hydrogen and natural gas on an energy basis.

The compressor fuel usage, $\dot{m}_{\mathrm{CS\_fuel}}$, is calculated from the compressor shaft work as follows:

$$\dot{m}_{\mathrm{CS\_fuel}} = \frac{\dot{W}_{\mathrm{shaft}}}{\eta_{\mathrm{driver}} HHV_{\mathrm{blend}}} \tag{2.40}$$

where $\dot{W}_{\mathrm{shaft}}$ is the compressor shaft work, η_{driver} is the driver efficiency, and HHV_{blend} is the higher heating value of the blended pipeline gas. For a gas-driven compressor, the default driver efficiency is 0.357. If the compressor is electrically driven, the electricity consumption can be calculated as follows:

$$\dot{W}_{\mathrm{CS\_fuel\_elec}} = \frac{\dot{W}_{\mathrm{shaft}}}{\eta_{\mathrm{driver}}} \tag{2.41}$$

The default driver efficiency is calculated with Equation 2.19 for an electric-driven compressor.

2.4.3 Sectionalizing Valve and Meter Station Modification Costs

Repurposing pipelines for hydrogen blending or for pure hydrogen might also necessitate sectionalizing valve and meter station modifications to maintain pipeline subsegment isolation and gas measurement accuracy, respectively. BlendPATH provides a means to estimate the CapEx associated with both sectionalizing valve and meter stations given a simplifying assumption regarding equipment compatibility with blends. We conservatively assume that any amount of hydrogen in pipeline gas will require replacing sectionalizing valves, pressure regulators, and meters because additional research and/or engineering analysis will be necessary to determine if a given piece of equipment is compatible with hydrogen (Topolski et al. 2022). If users have this information at the time that they apply BlendPATH to perform their analysis, they can override the default cost assumptions and use their own sectionalizing valve and gas meter costs. Cost overrides are discussed in Section 5.1.4.

BlendPATH approaches sectionalizing valve station modification using ASME B31.12 sectionalizing valve spacing requirements to determine the number of mid-segment sectionalizing valves required on a given pipeline segment. Table 8 provides the sectionalizing valve spacing requirements given in ASME B31.12. The sectionalizing valve replacement cost over a pipeline segment is determined as the product of the number of mid-segment sectionalizing valves and the valve installed cost. BlendPATH provides default values for sectionalizing valve installed costs, which are described in Section A.1.

Table 8. ASME B31.12 Sectionalizing Valve Spacing Interval Requirements (American Society of Mechanical Engineers 2023)

Location Class	Valve Spacing Interval (mi)
1	20
2	15
3	10
4	5

For meter station modification costs, BlendPATH assumes there is a meter station for each offtake and that each meter station is furnished with both metering and pressure regulators capable of handling up to the given offtake capacity. BlendPATH scales meter replacement costs with offtake capacity as a linear function. The default linear regression is described in greater detail in Section A.2.

BlendPATH applies pressure regulator replacement costs as a fixed installed capital charge per offtake capacity. Equation 2.42 provides a default method for estimating the regulator installed cost using data from Southern California Gas Company (2014):

$$C_{\text{Regulator}}[2020\$] = 248,722 \cdot \left\lceil \frac{\dot{m}_{\text{offtake}} HHV}{311,400 \text{ MMBTU/d}} \right\rceil \tag{2.42}$$

where $C_{\text{Regulator}}$ is the installed cost of the regulator. Note in Equation 2.42 that the ratio of offtake capacity, $\dot{m}_{\text{offtake}}HHV$, in units of MMBTU/d to the reference value of 311,400 MMBTU/day is rounded up to the nearest integer to determine the required number of regulators. The number of regulators is multiplied by the reference regulator unit cost of $248,722.

Additionally, the presence of hydrogen in the gas delivered through the meter stations might require the addition or expansion of gas chromatography at each offtake. BlendPATH by default applies a fixed installed capital charge of 856,757 in 2020 dollars (Donaldson et al. 2014) per offtake to account for additions or expansion of gas chromatography at each meter station.

2.4.4 In-Line Inspection Costs

BlendPATH provides the capability to estimate in-line inspection costs given the modified pipeline network design and a user-specified inspection interval. BlendPATH estimates in-line inspection costs by multiplying a unitized per-mile in-line inspection cost with the length of inspected pipeline for a given diameter. Default unitized costs for in-line inspection are described in Section A.3. For the direct replacement and additional compressor modification methods, the length of the inspected pipeline is set as the length of the existing pipeline being repurposed for hydrogen blends or pure hydrogen. For the parallel looping method, the length of the inspected pipeline also includes the length of any parallel loops added. The total in-line inspection costs are then annualized according to the user-specified inspection interval.

2.4.5 Overrides

BlendPATH allows users to override many default cost correlations to best represent their own unique case study, including those for gas chromatography, in-line inspection, meter replacement, regulator, steel cost, and valve costs. Additionally, users can override the pipe cost correlations in units of $/inch-mile for labor, right-of-way, and miscellaneous. Compressor cost can be overridden for material, labor, miscellaneous, and land in units of $/hp. Examples of how to override these costs are provided in the examples folder and in Section 5.1.4.

2.5 ProFAST

BlendPATH uses ProFAST (Kee and Penev 2024) to perform financial analysis on the modifications to the pipeline. ProFAST is a Python version of the Hydrogen Financial Analysis Scenario Tool (H2FAST) (Penev et al. 2017) developed by NREL. The model uses generally accepted accounting principles to provide fast in-depth financial analysis. Both H2FAST and ProFAST conform to generally accepted accounting principles and are compatible with analysis for International Financial Reporting Standards. Table 9 provides the default financial parameters in BlendPATH. Note that the default nominal discount rate, debt interest rate, and debt-to-equity ratio values in Table 9 reflect higher-relative-risk profiles of emerging hydrogen technologies (Penev et al. 2024); users can provide custom financial parameters to overwrite these and other default values featured in Table 9.

Table 9. Default Economic Parameters in ProFAST in the Absence of User-Supplied Parameters (Reznicek et al. 2024; Penev et al. 2024)

Parameter	Value
Analysis start year	2020
Operating life	50 years
Installation months	36 months
Long-term utilization	100%
Property tax and insurance	0.9%
Administrative expense	0.5%
Total income tax rate	25.74%
Capital gains tax rate	15%
General inflation rate	2.5%
Nominal discount rate	13%
Debt-to-equity ratio	0.62
Debt type	Revolving debt
Debt interest rate	7%
Cash on hand	3 months

The dominant ProFAST inputs relevant to this study are CapEx and OpEx. The major CapEx include the residual value of the existing network, any new pipes, any new compressor stations, and compressor station refurbishments. CapEx specifications for a given piece of equipment require a dollar value, depreciation type, depreciation schedule, and refurbishment schedule. For the scenarios considered in BlendPATH, this study employs a 30-year straight line depreciation schedule. The user must specify compressor fuel feedstock costs on a per-unit commodity basis at an initial price. This feedstock price escalates at a user-specified inflation rate. The inputs considered in ProFAST for each modification method are highlighted in Table 10.

Table 10. ProFAST Parameters

Type	Name	Direct Replacement	Parallel Looping	Additional Compressors
CapEx	New pipeline CapEx	✓	✓	
	Existing pipeline/equipment CapEx	✓	✓	✓
	New compressor stations			✓
	New supply compressor station	✓	✓	✓
	Compressor station refurbishment	✓	✓	✓
	Meter & regulator station modification	✓	✓	✓
	Valve station modification	✓	✓	✓
	Original network residual value	✓	✓	✓
OpEx	Compressor station fuel	✓	✓	✓
	New supply compressor station fuel	✓	✓	✓
	In-line inspection	✓	✓	✓

ProFAST iterates on the total transport price of the natural gas-hydrogen blend or hydrogen stream until the after-tax nominal net present value is equal to zero at the completion of the project while achieving a user-specified rate of return. The commodity price that achieves this net present value of zero is the break-even price or the levelized cost if accounting for the price throughout the lifetime of the plant. Although BlendPATH does not estimate the costs of supplying natural gas or hydrogen, BlendPATH accepts these costs as analysis inputs to determine the total compressor station fuel costs if gas-driven (and, by extension, LCOT) as well as the delivered cost of energy that end users might see for blended gas or pure hydrogen service. The ProFAST analysis balances the revenue streams from the sold commodity, CapEx, inflow and outflow of equity, and debt types. The model also produces yearly cash flow tables and performance metrics, such as internal rate of return, as outputs.

3 Disclaimer

BlendPATH was developed to provide the user with economic analytical capabilities to evaluate potential natural gas transmission pipeline modifications for accommodating hydrogen blending or pure hydrogen streams and to assess the potential associated economic impacts. This model is intended for use during the early stages of pipeline repurposing concept evaluation, which is defined here as the initial project phase when the developer has already gathered the relevant pipeline material design and operation data but has not yet conducted the detailed pipeline materials testing, as specified in ASME B31.12, or performed the in-line inspections that qualify a given pipeline section for hydrogen or hydrogen blending service. Despite BlendPATH using ASME B31.12 to assess existing natural gas transmission pipelines and establish potential pipeline modifications for a natural gas transmission pipeline network to meet ASME B31.12 design requirements, BlendPATH does not qualify the examined pipeline network or modifications thereof for pure hydrogen or hydrogen blending. Pipeline owners and operators must conduct additional evaluations as specified in ASME B31.12 and other relevant code and regulations, independent of BlendPATH application, to qualify actual natural gas transmission pipelines for operation with hydrogen. Failure to do so may result in pipeline fatigue and/or rupture. It is the sole responsibility of the pipeline owner and operator to ensure that their pipeline qualifies for the ASME B31.12 design option that they choose, and any other relevant code and regulations, and that any defects present in the pipeline are acceptable at the operating pressure chosen.

4 Getting Started

Current BlendPATH access and use requires knowledge of and familiarity with Git and Python. The instructions in this user manual use conda environments, which also require Anaconda, a Python distribution. Both Git and Anaconda are open source and free to download.

The source code for BlendPATH is found on GitHub at https://github.com/NREL/BlendPATH. To download the source code, the user should enter the following command in a Git Bash terminal:

```
git clone https://github.com/NREL/BlendPATH.git BlendPATH
```

Once the user has locally cloned BlendPATH, they will be able to install it as a Python package by using pip, Python's package manager. After opening an Anaconda Powershell Prompt and navigating to the directory containing BlendPATH files, users should create a virtual environment for BlendPATH with the command:

```
conda create -n MY_ENV_NAME python=3.10
```

where `MY_ENV_NAME` is the user's environment name of choice. We recommend using Python Version 3.10 for installing and running BlendPATH. Activate the environment using the following command:

```
conda activate MY_ENV_NAME
```

Once the environment is activated, navigate to the directory to which BlendPATH was cloned. In many cases, this folder will be located at ~/Documents/GitHub/BlendPATH if the user cloned BlendPATH files from GitHub using the default GitHub settings. Navigate to the directory using the following commands in Bash (note that the user might need to edit this command if the files were cloned to a different location):

```
cd ~/Documents/GitHub/BlendPATH
```

Run the following command to install the BlendPATH package:

```
pip install .
```

This command will install BlendPATH and all of its required dependencies.

When using BlendPATH with an integrated development environment, such as Visual Studio Code, ensure that the integrated development environment is set to use the previously created conda environment.

5 Model Usage

BlendPATH requires a specific file directory structure and metadata to run effectively. In the following scenario, `RUN_SCRIPT.py`, `CASE_STUDIES`, and `SAVE_DIRECTORY` can be renamed as needed. The only required file for a case study is `network_design.xlsx`. All other files are optional and only modify the analysis or reduce repetitive entries. In particular, the `overrides` directory is only shown for completeness and is not required if the default cost functions are being used.

```
RUN_SCRIPT.py
CASE_STUDIES
    SAVE_DIRECTORY
    network_design.xlsx
    default_inputs.csv
    financial_params.json
overrides
    compressor_cost.csv
    GC_cost.csv
    inline_inspection_costs.csv
    meter_replacement_cost_regression_parameters.csv
    pipe_cost.csv
    regulator_costs.csv
    steel_costs_per_kg.csv
    valve_costs.csv
```

5.1 Case Study Setup Files

5.1.1 Network Design File

BlendPATH requires a network file to define the pipeline network design, and it must use the name `network_design.xlsx`. The network design file contains the pipeline network layout, which includes pipe lengths, diameters, wall thicknesses, connection node locations, compressor station locations, and discharge pressure constraints. The network design file also specifies supply pressures and demand node energy delivery requirements as boundary conditions. These boundary conditions should represent the pipeline operation seen when serving peak gas demand or whatever demand level operators wish to serve within hypothetical blending scenarios. The network design file also defines the composition of the preblended pipeline gas based on a molar or volumetric fraction basis. Table 11 provides a full list of the entries required in the network design file. The following discussion provides additional details for each sheet.

The NODES sheet in the network design file defines all the required nodes in the network. All pipes and compressor stations require nodes for representing both inlet and outlet. Additionally, all supply and demand require nodes. Table 12 provides descriptions and examples for the columns in the NODES sheet within the network design file. There are only two entries for the NODES sheet: the node name and the node maximum pressure. Each node name must be unique and should match a from_node or to_node in the PIPES and/or COMPRESSOR sheet. The node

Table 11. BlendPATH Network Design File Inputs

`network_design.xlsx` sheet name					
PIPES	NODES	COMPRESSORS	SUPPLY	DEMAND	COMPOSITION
pipe_name	node_name	compressor_name	supply_name	demand_name	SPECIES
from_node	p_max_mpa_g	from_node	node_name	node_name	X
to_node		to_node	pressure_mpa_g	flowrate_MW	
diameter_mm		pressure_out_mpa_g			
length_km		rating_MW			
roughness_mm		extract_fuel			
thickness_mm		eta_s			
steel_grade		eta_driver			

maximum pressure is in units of MPa-g. The maximum pressure is only used in the direct replacement method, where one design consideration is to replace the existing pipe with a new pipe that would enable the same operating pressure.

Table 12. Network Design File—NODES

Column	Description	Entry Type	Units	Example
node_name	Unique identifier for the node—which is referred to in pipes, compressors, supply, and demand—to make connections	string		N00
p_max_mpa_g	Maximum allowable pressure at the node given the existing network design and pipeline gas composition. Primarily used in direct replacement where new pipes can be designed to allow operation at the same maximum pressure	float	MPa-g	12.0

The PIPES sheet in the network design file defines all pipes that connect nodes. These pipes are expected to have the same properties throughout the length. If any properties change throughout the pipe, the specified pipe should instead be dissected into small enough portions such that the properties are representative. Table 13 provides the description and examples for the PIPES sheet.

Table 13. Network Design File—PIPES

Column	Description	Entry Type	Units	Example
pipe_name	Unique identifier for the pipe	string		P00
from_node	One connection node of the pipe. Must match a node name in the NODES sheet	string		N00
to_node	One connection node of the pipe. Must match a node name in the NODES sheet.	string		N01
diameter_mm	Inner diameter of the pipe	float	mm	592
length_km	Length of the pipe	float	km	10
roughness_mm	The absolute roughness of the pipe	float	mm	0.012
thickness_mm	Thickness of the pipe. Inner diameter plus 2 $\times$ thickness should add to outer diameter	float	mm	8.7
steel_grade	API 5L pipe steel grade. BlendPATH Version 2.0 allows X42, X52, X56, X60, X65, or X70.	string		X70

The COMPRESSORS sheet in the network design file defines the compressors that can connect nodes. Compressors are defined with an outlet pressure that is set at the to_node. The variable "extract_fuel" flags whether a compressor is gas driven and therefore must extract fuel from the pipeline to operate. The sum of the mass flow rates at the to_-node and the fuel extraction is equal to the mass flow rate at the from_node. The fuel extraction flow rate will change as the inlet pressure is calculated. If "extract_fuel" is set as "FALSE," the compressor is specified as electricity driven and does not extract fuel from the pipeline to operate. Table 14 provides the description and examples for the COMPRESSORS sheet.

Table 14. Network Design File—COMPRESSORS

Column	Description	Entry Type	Units	Example
compressor_name	Unique identifier for the compressor	string		C00
from_node	Low-pressure or inlet node of the compressor. Must match a node name in the NODES sheet.	string		N01
to_node	High-pressure or outlet node of the compressor. Must match a node name in the NODES sheet.	string		N02
pressure_out_mpa_g	Outlet pressure of the compressor at to_node. This fixes the pressure at to_node.	float	MPa-g	12.0
rating_MW	Original rating of the compressor station. Used to determine if capacity upgrades are required after network modifications	float	MW	12.0
extract_fuel	Boolean for flagging if the compressor uses pipeline gas to power the compressor or if electrically driven. If TRUE, then pipeline gas is extracted at the from_node prior to compression.	bool		TRUE
eta_s	Isentropic efficiency of the compressor. If extract_fuel is TRUE, then the efficiency describes a gas-driven compressor, and if extract_fuel is FALSE, then the efficiency describes an electric-driven compressor.	float		0.78
eta_driver	Driver efficiency of the compressor. If extract_fuel is TRUE, then the efficiency describes a gas-driven compressor, and if extract_fuel is FALSE, then the efficiency describes an electric-driven compressor.	float		0.357

The SUPPLY sheet in the network design file defines the supply node with a reference supply pressure at a given node. Supply nodes are where pipeline gas enters the network at a specified pressure. The flow rate is calculated such that the demand node energy flow rates are satisfied. Setting a supply node fixes the pressure at the specified node as a pipeline network boundary condition. At least one supply node is required per network. Table 15 provides the description and examples for the SUPPLY sheet.

Table 15. Network Design File—SUPPLY

Column	Description	Entry Type	Units	Example
supply_name	Unique identifier for the supply node	string		SN00
node_name	The node at which the supply is located. This fixes the pressure at node_name. Must match a node name in the NODES sheet	string		N00
pressure_mpa_g	Pressure at which the pipeline gas is supplied at the node	float	MPa-g	12.0

The DEMAND sheet in the network design file defines the demand nodes that establish the energy demand boundary conditions at the offtake nodes. Demand nodes are where mass flows of pipeline gas exit the network to satisfy an external energy demand. The energy demands are defined in units of energy and are converted to mass flow rate based on the higher heating value of the gas-phase mixture. At least one demand is required per network. Table 16 provides the description and examples for the DEMAND sheet.

Table 16. Network Design File—DEMAND

Column	Description	Entry Type	Units	Example
demand_name	Unique identifier for the demand node	string		DN00
node_name	The node at which the demand is located. Multiple demands can be defined at a single node. Must match a node name in the NODES sheet	string		N02
flowrate_MW	Energy demand at the node	float	MW	5000

The COMPOSITION sheet in the network design file defines the composition of the gas in the network before hydrogen blending. Composition is set as molar or volumetric fraction, and the summation of all species' mole or volume fractions should be unity. BlendPATH Version 2.0 allows for the following species (expressed in the input file without subscripts, as depicted here) in a composition: CH_4, C_2H_6, C_3H_8, CO_2, N_2, C_4H_{10}, iC_4H_{10}, and C_5H_{12}. The species should be entered into Excel without subscripts. The defined composition is applied at all nodes in the network because the steady-state solution is used in the BlendPATH, and the composition is assumed to be uniform throughout the network. Table 17 provides the descriptions and examples for column names in the COMPOSITION sheet.

Table 17. Network Design File—COMPOSITION

Column	Description	Entry Type	Units	Example
SPECIES	Name of the gas species	string		CH4
X	Molar or volumetric fraction of species. Summation of all values of X should add to 1.	float		0.5

The file folder `examples/Wangetal2018` provides files for an example case study originally published by Wang et al. (2018). Users are encouraged to use the example case study as a starting point for describing their own pipeline case study network design file.

5.1.2 Default Inputs File

Users are given the option to provide a `default_inputs.csv` file to specify the inputs to the BlendPATH_-scenario in the format of a CSV file rather than directly inputting these values in a Python script. This file is particularly useful for setting inputs that are not expected to change within a sensitivity analysis. Table 18 shows the full list of parameters available to be set in the BlendPATH_scenario. The only parameter than cannot be set in the `default_inputs.csv` is casestudy_name because this points to the directory where `default_inputs.csv` is located. For example, the path to `default_inputs.csv` should be casestudy_name/default_inputs.csv.

The `default_inputs.csv` is formatted to have header columns of Parameter and Value. Users can define custom values for the specific parameters listed under Table 18 by listing the parameters and values under the Parameter and Value columns in `default_inputs.csv`, respectively. If a given parameter default value is acceptable for analysis, the user can omit the specifying said parameter in `default_inputs.csv`.

5.1.3 Financial Parameters File

BlendPATH users can customize the financial parameters to best represent their case study. ProFAST is used as the financial model to determine the LCOT. ProFAST accepts json files to describe the financial structure. If the casestudy_name/financial_params.json file exists, then BlendPATH will incorporate the described financial parameters into the analysis rather than using the defaults listed in Table 19. The `financial_params.json` must follow the json input file format as dictated by ProFAST and shown in the table. For more detailed information on the ProFAST parameters, refer to Kee and Penev (2024).

5.1.4 Cost Overrides Directory

The cost correlations used in BlendPATH can be overwritten with user-specified values in the overrides directory. Table 20 demonstrates the format for each cost override. Users must create individual override files for any of the following they wish to override: compressor costs, gas chromatography costs, meter replacement costs, pipe costs, pressure regulator costs, steel material costs, and sectionalizing valve costs. These override files must be placed in the overrides directory under the casestudy_name directory.

The format of all the files excluding pipe_costs.csv can be found in the BlendPATH/costing/ in the source files as well as in the examples directory. The pipe_costs.csv can allow either empty quotations (“”) as an entry or a numerical value. Any parameter assigned empty quotations as a value in pipe_costs.csv will use the Brown, Reddi,

Table 18. Parameters for BlendPATH_scenario

Name	Description	Type	Default Value
casestudy_name	Name of the case study folder in the working directory. The directory contains ‘network_-design.xlsx’, the overrides directory, and all other input files must be in this directory.	str	
results_dir	Directory in which the simulation results are stored. Note that this will be inside the casestudy_name directory.	str	‘out’
design_option	ASME B31.12 design option for initial assessment of the original pipeline network. Options are ‘a’, ‘b’, ‘nfc’ or a fraction denoting the hoop stress limit as a fraction of pipeline SMYS.	str, float	‘b’
location_class	Location class for use in ASME B31.12. Options are 1, 2, 3, or 4.	int	1
joint_factor	Longitudinal joint factor for use in ASME B31.12. Refer to Table IX-3B in Mandatory Appendix IX of ASME B31.12.	float	1
T_rating	Temperature derating factor for use in ASME B31.12. Refer to Table PL-3.7.1-3 of ASME B31.12.	float	1
blend	Fraction of hydrogen (volume basis) to be blended in the pipeline gas.	-	0.10
ng_price	Price of natural gas ($/MMBTU)	float	7.39
h2_price	Price of delivered hydrogen to injection site ($/kg)	float	4.41
region	Region in Brown, Reddi, and Elgowainy (2022) for assessing right-of-way, labor, and miscellaneous costs. Options are: CA, GL, GP, MA, NE, PN, RM, SE, SW.	str	‘GP’
design_CR	Design compression ratios. This is the compression ratio for any added compressors and is used to establish the outlet pressure of pipe segments.	list[float]	[1.2,1.4,1.6,1.8,2.0]
final_outlet_pressure_mpa_g	Minimum pressure required at the pipeline terminus in units of MPa-g.	float	2
verbose	Flag for verbose output	bool	True
eos	EOS for evaluating gas-phase thermodynamics. Options are ‘rk’ for Redlich-Kwong or ‘papay’ for Papay.	str	‘rk’
ili_interval	Frequency in years when pipeline operators are to reassess the pipeline network with in-line inspection to detect and monitor pipeline defects	float	3
original_pipeline_cost	Depreciated CapEx of original pipeline network	float	0
new_compressors_electric	Flag if new compressors added should be electric-driven.	bool	True
existing_compressors_to_electric	Flag if existing compressors should be converted to electric-driven	bool	True
new_comp_eta_s	Isentropic efficiency for any new gas-driven compressors added	float	0.78
new_comp_eta_s_elec	Isentropic efficiency for any new electric-driven compressors added	float	0.88
new_comp_eta_driver	Driver efficiency for any new gas-driven compressors added	float	0.357
new_comp_eta_driver_elec	Driver efficiency for any new electric-driven compressors added	float	np.nan

and Elgowainy (2022) values by default. The compressor_costs.csv can allow either empty quotations as an entry

Table 19. ProFAST Financial Parameters Options

Parameter	Value
long term utilization	1
demand rampup	0
analysis start year	2020
operating life	50
installation months	36
TOPC[1]	{“unit price":0.0,“decay":0.0,“support utilization":0.0,“sunset years":0}
commodity	{“initial price":2.0,“name":“-","unit":“-",“escalation":0.0}
annual operating incentive	{“value":0.0,“decay":0.0,“sunset years":0,“taxable":true}
incidental revenue	{"value":0.0,"escalation":0.0}
credit card fees	0.0
sales tax	0.0
road tax	{“value":0.0,“escalation":0.0}
labor	{“value":0.0,“rate":0.0,“escalation":0.0}
maintenance	{“value":0.0,“escalation":0.0}
rent	{“value":0.0,“escalation":0.0}
license and permit	{“value":0.0,“escalation":0.0}
non depr assets	0.0
end of proj sale non depr assets	0.0
installation cost	{“value":0.0,“depr type":“Straight line",“depr period:3,“depreciable":true}
one time cap inct	{“value":0.0,“depr type":“MACRS",“depr period":3,“depreciable":true}
property tax and insurance	0.009
admin expense	0.005
tax loss carry forward years	0
capital gains tax rate	0.15
tax losses monetized	true
sell undepreciated cap	true
loan period if used	0
debt equity ratio of initial financing	0.62
debt interest rate	0.07
debt type	“Revolving debt"
total income tax rate	0.2574
cash onhand	3
general inflation rate	0.025
leverage after tax nominal discount rate	0.13

[1] Take or pay contract

or a numerical value. Any parameter assigned empty quotations as a value in compressor_costs.csv will use the Rui (2011) values by default.

5.2 Importing and Using BlendPATH

Once BlendPATH has been successfully installed (see Section 4), it can be imported with the following Python command:

```
import BlendPATH
```

Table 20. Overrides Files Formatting

compressor_cost.csv		
Parameter	Price [$/hp]	
Material	“”	
Misc	“”	
Labor	“”	
Land	“”	
GC_cost.csv		
Item	Installed cost [2020$]	
Gas chromatograph	856757	
inline_inspection_costs.csv		
DN	ILI cost [2020$/mi]	
100	5576	
⋮	⋮	
1800	24580	
meter_replacement_cost_regression_parameters.csv		
m [2020$/MMBTU-day]	b [2020$]	
0.762	256092	
pipe_cost.csv		
Parameter	Price [$/in/mi]	
ROW	“”	
Misc	“”	
Labor	“”	
regulator_costs.csv		
Capacity [MMBTU/day]	Installed regulator cost [2020$]	
311400	2248722	
steel_costs_per_kg.csv		
Steel grade	Price [$/kg]	
B	1.8	
⋮	⋮	
X80	10	
valve_costs.csv		
DN	Install type	Installed valve cost [2020$]
100	Buried	523413
⋮	⋮	⋮
1800	Buried	2747918

5.2.1 Creating a BlendPATH_scenario

Once BlendPATH is imported, a new BlendPATH_scenario can be created. A BlendPATH_scenario is an analysis scenario instance in which users can assess the hydrogen transport cost (as a blend or pure stream) and design impacts on a supplied pipeline network given user-specified inputs. The subsequent example follows the example script available in the examples directory using the Wang et al. (2018) case study. A BlendPATH_scenario can be created using the following command:

```
wangetal = BlendPATH.BlendPATH_scenario(
    casestudy_name="examples/wangetal2018"
)
```

This command creates a new instance of the BlendPATH_scenario class using the casestudy_name that points to the input files for the case study. The examples/wangetal2018 directory contains the BlendPATH input files `default_inputs.csv`, `financial_params.json`, and `network_design.xlsx`. The `default_inputs.csv` includes parameters from Table 18 to set up the BlendPATH_scenario. The `financial_params.json` file holds the financial structure parameters used to compute the LCOT. The `network_design.xlsx` file defines the pipeline network geometry and operating conditions.

Once the BlendPATH_scenario instance is created and any cost overrides are imported, BlendPATH will create and segment a BlendPATH_network. Users can then assign an ASME B31.12 design option or a fraction denoting the hoop stress limit as a fraction of pipeline SMYS with which to assess the original, unmodified network using the following command:

```
wangetal.update_design_option(design_option = 'b')
```

The hydrogen blend ratio can be set with the following command:

```
wangetal.blendH2(blend = 0.2)
```

Note that both the design option and the blend can also be set using the `default_inputs.csv` input file instead of using these commands in a Python script.

5.2.2 Pipeline Modifications

After the BlendPATH_scenario is created, users can employ the available modification methods to investigate options to enable their network to transport the desired amount of hydrogen, meet ASME B31.12 pressure constraints, and meet end-use energy demand. Users can employ the `run_mod` function to modify the existing pipeline network with the modification method they choose such that the network meets ASME B31.12 design pressure specifications and fulfills energy demand while blending hydrogen. This function can only be applied after the BlendPATH_scenario is instantiated. The `run_mod` function can be applied using the following code :

```
blendpath.run_mod(mod_type,design_option)
```

The `run_mod(...)` function takes two arguments; `mod_type` and `design_option`. The input `mod_type` allows the user to select one of the three pipeline network modification options described in Section 2. The input `design_option` provides the user an ASME B31.12 design option to rate the design pressures of a new pipe. If design_option is not specified, then design option 'b' is picked by default. Table 21 describes these input arguments in more detail.

Table 21. Parameters for run_mod

Name	Description	Type	Example
mod_type	The modification method to analyze. The choices are 'direct_replacement', 'parallel_-loop', or 'additional_compressors'. Shorthand is also allowed as 'DR', 'PL', and 'AC'.	str	'direct_replacement'
design_option	The design option for the modified pipeline. Options are 'a', 'b', 'no fracture criterion', or a fraction denoting the hoop stress limit as a fraction of pipeline SMYS. The default option is 'b'.	str, float	'b'

5.2.3 Result Files

The `run_mod(...)` function generates output files that describe the updated pipeline network design and result analysis. These files are stored in the casestudy_name directory under the `casestudy_name/results_-dir/NetworkFiles` file folder, where `results_dir` is the user-inputted results directory location, or in "out/" if the user does not specify a location when defining the scenario class. The key output file that describes the updated pipeline network design and boundary conditions is `network_design.xlsx`, which is formatted as input files to BlendPATH_network. The `network_design.xlsx` file will have the modification method, blend ratio, and design option as a prefix to the filename. For example, `AC_0.01_a_network_design.xlsx`, was created using the additional compressors method, 1% hydrogen, and design option A. BlendPATH then uses these files as inputs for simulating the modified network to validate the network hydraulics and update values for the compressor station fuel consumption, which serves as an input to the financial analysis.

BlendPATH generates a results summary Excel output file after performing each analysis in the `casestudy_-name/results_dir/ResultsFiles` file folder where the user specifies `results_dir`. The modification method, blend ratio, and design option applied to assess the existing pipeline network construct the output filename (e.g., `AC_0.01_a.xlsx`). The results file includes seven sheets: disclaimer, inputs, results, modified network design, compressor design, pressure profile, and demand error.

Each results file sheet describes the techno-economic analysis performed and the resulting network design. The first sheet, disclaimer, reminds the user of the intent, limitations, and scope of BlendPATH. The inputs sheet reports all the inputs (including any defaults) specified that are available in Table 18, which allows the user to reproduce any analysis under the same conditions. Any values that have been specified in the `default_inputs.csv` will also be shown in the inputs sheet. The inputs sheet is presented in a two-column name-and-value format.

The remaining sheets describe the results of the techno-economic analysis. First, the results sheet provides users with a high-level summary of the techno-economic analysis. Values such as the LCOT can be viewed on this sheet. The results sheet is further broken down into four sections: top-level summary values, breakdown of original pipe, breakdown of new pipe, and breakdown of compression stations. Table 22 describes the parameters listed in the first section of the results sheet.

Table 22. Top-Level Summary Parameters in Results Sheet in the Results File

Parameter	Description
LCOT: Levelized cost of transport	LCOT to make the necessary changes to the pipeline such that the blended gas can be delivered while meeting end-use energy demand and ASME B31.12 pressure constraints
LCOT: New pipe CapEx	LCOT cost contribution from purchasing new pipe
LCOT: New compression capacity CapEx	LCOT cost contribution from expanding the capacity of existing compression stations
LCOT: Refurbished compressor capacity CapEx	LCOT cost contribution from refurbishing existing compression stations
LCOT: Supply compressor CapEx	LCOT cost contribution from a compression station added at the supply
LCOT: Meter & regulator station modification CapEx	LCOT cost contribution from updating meter and regulator stations
LCOT: Valve replacement CapEx	LCOT cost contribution from replacing sectionalizing valves
LCOT: Original network residual value	LCOT cost contribution from the undepreciated cost of the original network
LCOT: In-line inspection	LCOT cost contribution from annual in-line inspections
LCOT: Compressor fuel	LCOT cost contribution from gas-driven compressor fuel
LCOT: Compressor fuel (electric)	LCOT cost contribution from electricity-driven compressor fuel
LCOT: Supply compressor fuel	LCOT cost contribution of fuel from a gas-driven supply compression station
LCOT: Supply compressor fuel (electric)	LCOT cost contribution of fuel from an electricity-driven supply compression station
LCOT: Fixed O&M	LCOT cost contribution from fixed operations and maintenance (O&M) costs, including administrative expenses and property insurance
LCOT: Taxes	LCOT cost contribution from taxes, including income taxes, capital gains taxes, and monetized tax losses
LCOT: Financial	LCOT cost contribution from financing, including non-depreciable assets and cash on hand
Hydrogen injection price	Hydrogen price at the injection site in units of $ per kilogram
Natural gas price	Natural gas price in units of $ per MMBTU
Blended gas price	Calculated price of the blended gas on an energy-weighted basis for compressor fuel usage
Pipeline capacity (daily)	End-use energy demand of the pipeline on a daily basis, which will be the summation of all demands in the network
Pipeline capacity (hour)	End-use energy demand of the pipeline on an hourly basis, which will be the summation of all demands in the network
Added pipeline (km)	Total length of pipeline added after pipeline modifications in units of kilometers
Added pipeline (mi)	Total length of pipeline added after pipeline modifications in units of miles
Added compressor stations	Number of compressor stations added after pipeline modifications
Added compressor capacity	Compressor station capacity in units of horsepower added after pipeline modifications
Compressor fuel usage (daily)	Compressor station fuel usage in gas-driven compressors on a daily basis
Compressor fuel usage (hourly)	Compressor station fuel usage in gas-driven compressors on an hourly basis
Compressor fuel usage (electric)	Compressor station fuel usage in electricity-driven compressors in units of kilowatts
New pipe	Summation of all CapEx regarding new pipe added after pipeline modifications
New compressor stations	Summation of all CapEx regarding new compressor stations added after pipeline modifications
Compressor station refurbishment	Summation of all CapEx regarding compressor station refurbishment after pipeline modifications
Meter station modification	Summation of all CapEx regarding meter station modifications after pipeline modifications
Valve modifications	Summation of all CapEx regarding valve replacement after pipeline modifications

The remaining three sections of the results sheet provide the breakdown on the original pipe, new pipe, and compressors. The original pipe breakdown aggregates the pipe existing in the original network diameter, steel grade, and schedule. The length is reported as the summation of all pipes with the same diameter, steel grade, and schedule. This section can be useful to verify that the network design supplied in `network_design.xlsx` matches what BlendPATH has interpreted. The new pipe breakdown is similarly aggregated by diameter, steel grade, and schedule. The pipes are purposely grouped as same-design pipes because the pipe cost is calculated in BlendPATH using the aggregated pipe lengths. The breakdown of new pipe also reports the material, labor, miscellaneous, and right-of-way cost for the new pipe. The breakdown of compressors by station reports all existing and new compressors in the modified network. The breakdown includes shaft power, original capacity, required additional capacity, number of compressor stations, average compressor station capacity, costs, and fuel requirements.

The modified network design sheet details all the pipes in the network post-modification. Pipes can be added in the direct replacement and parallel loop methods. Pipes are not added if the additional compressors method is applied; however, existing pipes can be separated by a compressor and will appear as a new name. Pipes can also be separated as a result of the parallel loop method. Pipes separated by either a loop or a compressor are denoted with the 'pre-' or 'post-' identifier in the pipe name. The columns in the modified network design sheet are shown in Table 23.

Table 23. Modified Network Design Sheet in the Results File

Column name	Description
Pipe segment	Pipeline segment that the pipe has been grouped with
Pipe name	Name identifier for the pipe. Unchanged pipes will use the same name as originally specified.
FromName	Name of the from node at one end of the pipe
ToName	Name of the to node at one end of the pipe
Type	Either 'Existing' or 'New' depending on whether BlendPATH added this pipe as part of a modification
Flow rate (kg/s)	Mass flow rate through the pipe in units of kilograms per second
DN	Nominal diameter of the pipe in units of millimeters
Schedule	Schedule of the pipe
Thickness (mm)	Thickness of the pipe in units of millimeters
Steel grade	Steel grade of the pipe
MAOP (MPa-g)	MAOP of the segment in units of megapascal-gauge. Individual pipes might be able to operate at higher pressures, but the reported MAOP is limited by the minimum MAOP in the segment
Length (km)	Length of the pipe in units of kilometers
Length (mi)	Length of the pipe in units of miles
Inlet pressure (Pa-g)	Pressure at the from node in units of pascal-gauge
Outlet pressure (Pa-g)	Pressure at the to node in units of pascal-gauge
Max velocity (m/s)	Maximum velocity observed in the pipe in units of meters per second
Max Mach number	Maximum Mach number observed in the pipe
Erosional velocity (m/s)	ASME B31.12 erosional velocity in the pipe

The compressor design sheet describes all compressor stations within the modified network design. Compressor stations include any compressors that existed in the network prior to modification and/or new compressors added after network modification. The operating conditions, sizing, and fuel requirements are reported in the compressor design sheet. Both electricity- and gas-driven compressors are reported; however, the electricity-driven compressors will have an entry in the 'Electric power (kW)' column, whereas the gas-driven compressors will have an entry in the 'Fuel consumption (MMBTU/hr)' column. The columns describing relevant compressor station design parameters in the compressor design sheet are shown in Table 24.

The pressure profile sheet describes all the nodes in the network and the pressure at each node. All nodes are connected by pipes and compressors. Supply nodes and compressor outlet nodes remain at a fixed pressure. Table 25 describes the columns in the pressure profile sheet.

Table 24. Compressor Design Sheet in the Results File

Column name	Description
Segment	Pipeline segment that the compressor has been grouped with. Existing compressors will not be part of any preexisting segment and are denoted by a blank entry. New compressors will have a numeric segment value.
Name	Name identifier for the compressor
FromName	Name of the from node at the inlet of the compressor
ToName	Name of the to node at the outlet of the compressor
Type	Either 'Existing' or 'New' depending on if BlendPATH added this compressor as part of a modification
Cumulative length (km)	Distance of compressor from supply node in units of kilometers
Cumulative length (mi)	Distance of compressor from supply node in units of miles
Pressure ratio	Ratio of outlet pressure to inlet pressure
Fuel consumption (MMBTU/hr)	Pipeline gas fuel consumption for a gas-driven compressor station in units of MMBTU per hour
Shaft power (MW)	Shaft power required by the compressor station in units of megawatts
Shaft power (hp)	Shaft power required by the compressor station in units of horsepower
Electric power (kW)	Electric power required by the drive motor of an electricity-driven compressor station in units of kilowatts
Rating (MW)	Capacity rating of the compressor station in units of megawatts. Any new compressor stations or compressor stations with capacity expansion will be rated at the shaft power
Isentropic efficiency	Compressor isentropic efficiency relating adiabatic head to shaft power, expressed as a fraction
Driver efficiency	Compressor station driver efficiency relating shaft power to driver power, expressed as a fraction
Cost ($)	CapEx of the compressor station for any capacity expansion or for a new compressor station
Revamp cost ($)	CapEx if the compressor station requires revamp
Total cost ($)	Total CapEx of the compressor station including revamp and capacity expansion

Table 25. Pressure Profile Sheet in the Results File

Column name	Description
Node	Name identifier for the node
Pressure (Pa-g)	Pressure at the node in units of pascal-gauge

The demand error sheet provides a comparison of the energy demand requirement to the calculated energy throughput at each demand node to verify that the energy demand is satisfied. Each demand node in the network is required to meet the specified energy demand. The energy demand does not change with blend ratio; however, the flow rate at the demand node will change as the higher heating value changes with the blend ratio. Table 26 describes the columns in the demand error sheet.

5.3 BlendPATH Limitations

BlendPATH is subject to several limitations that restrict the complexity of the pipeline networks that it can examine. Pipeline network complexity is limited to a class of pipeline networks where the pipeline network is linear (no branching or looping), has one diameter between compressor stations, and has one gas supply point that coincides with the location of the hydrogen injection. The model treats changes in diameter as a change in pipeline "segment" because different in-line inspection equipment would be required to inspect the diameter downstream of the change. As a result, it assesses ASME B31.12 design pressure independently for both segments. If the downstream segment

Table 26. Demand Error Sheet in the Results File

Column Name	Description
Demand node name	Name identifier for the demand node
Flow rate set point (kg/s)	Expected flow rate based on the energy set point and higher heating value. Flow rate is reported in units of kilograms per second.
Flow rate calculated (kg/s)	Calculated flow rate based on the hydraulic model simulation results. Flow rate is reported in units of kilograms per second.
Higher heating value (MJ/kg)	Higher heating value of the blended gas composition in units of megajoules per kilogram
Energy set point (MW)	Required energy and the demand node in units of megawatts
Energy calculated (MW)	Calculated energy at the demand node based on the hydraulic simulation results in units of megawatts
Error in energy (%)	Percentage error between energy set point and calculated energy

has a smaller diameter and a lower ASME B31.12 design pressure, a pressure reduction station would be necessary to enable line packing upstream of the diameter change while remaining below the MAOP in the segment downstream; however, the model does not yet include network modification logic to consider pressure reduction stations. Last, BlendPATH applies logic within each modification method to identify the lowest cost of transport by indexing and evaluating the impact of the pipe segment design parameters (e.g. thickness, steel grade, and diameter) on the hydraulic and cost models. This indexing, however, does not include other network design parameters that might have a considerable impact on the modified network cost of transport, such as gas supply pressure and gas cost. BlendPATH users can assess the impact of these parameters on the modified network's cost of transport by applying sensitivity analysis with said parameters.

5.4 Example Python Script

This section provides an example script that can serve as a template for users to initiate their analyses with BlendPATH. The default values shown in Tables 18, 19, and 21 serve as placeholders that the user can update with their case study-specific values. Users can also find this script in the `BlendPATH/examples/` folder.

```
# Import BlendPATH functions into Python script for use in analysis
import BlendPATH


# Define a case study scenario that models a network of interest with data from
# network_design.xlsx, default_inputs.csv, and override/ files
wangetal = BlendPATH.BlendPATH_scenario(
    casestudy_name="examples/wangetal2018",
)
# Define the relevant ASME B31.12 design option to set the maximum allowable
# operating pressure for existing pipeline segments that will transport hydrogen
```

```
# as a blend or in pure form
wangetal.update_design_option(design_option = 'nfc')

# Set the desired hydrogen content (in vol. %) in pipeline gas for analysis
wangetal.blendH2(blend = 0.2)

# Run pipeline modification analysis with run_mod using the defined mod_type
# modification strategy. New pipeline infrastructure that is added to the
# existing pipeline network is rated to the defined design option with run_mod
wangetal.run_mod(mod_type = 'direct_replacement', design_option = 'b')

# Result xlsx files are outputted within a user-designated result_dir (defined in
# default_inputs.csv) under the casestudy_name folder.
```

6 Case Study

This section applies BlendPATH to an example pipeline case study derived from Wang et al. (2018). It consists of a 250-mile natural gas pipeline comprising a single diameter, steel grade, and schedule, with three 12.5-MW compressor stations and a class 1 location. The input files `network_design.xlsx`,`default_inputs.csv`, and `financial_params.json` are provided in the `examples/wangetal2018` directory for users to test BlendPATH. The example case study `overrides` directory is also populated with a suite of example override files. These overrides are currently set to the same values that are provided by default within the model, but they provide examples of how to properly format override files. The pipeline network model featured in `network_design.xlsx` consists of 10 nodes connected by 9 pipes. The network file specifies the gas supply pressure and outlet pressures for the three compressors and the energy demand at the three offtake points. The compressor outlet pressures are set to the existing pipeline network's design pressure. Tables 27 and 28 provide an overview of the pipeline network segment design and boundary conditions.

Table 27. Wang et al. (2018) Modified Case Study Segmented Pipeline Network Design

Pipeline Segment ID	0	1	2	3
Diameter (DN)	650	650	650	650
Schedule	S Std	S Std	S Std	S Std
Steel grade	X60	X60	X60	X60
Length (mi)	43.5	80.8	62.2	62.2
Design pressure (MPa-g)	8.7	8.7	8.7	8.7

Table 28. Wang et al. (2018) Modified Case Study Boundary Conditions

Boundary Condition	Value	Unit
Gas supply pressure	8.7	MPa-g
CS1 outlet pressure	8.7	MPa-g
CS2 outlet pressure	8.7	MPa-g
CS3 outlet pressure	8.7	MPa-g
Offtake 1 demand	1150	MW
Offtake 2 demand	2991	MW
Offtake 3 demand	2301	MW

The user can run the template file provided in Section 5, `examples/template.py`, to apply BlendPATH to this case study and obtain the results shown here. These results detail the BlendPATH application to the modified Wang et al. (2018) case study where hydrogen is blended up to 100% vol. for each modification method. The design pressure of the existing pipeline network is assessed using the ASME B31.12 no fracture criterion option. Table 29 shows the LCOT for each modification method applied. Tables 30, 31, and 32 display the pipeline network modification results from BlendPATH for transporting hydrogen blends up to 50% vol. for the modified Wang et al. (2018) case study. Additional results for 20% and 100% vol. hydrogen in pipeline gas scenarios can be found in the `wangetal2018/out/ResultFiles` folder.

Table 29. Modified Wang et al. (2018) Case Study LCOT for a Hydrogen Blend Ratio of 50% vol. in Pipeline Gas and the ASME B31.12 No Fracture Criterion Option

Modification Method	LCOT ($/MMBTU)
Direct replacement	0.44
Parallel loop	0.41
Additional compressors	0.75

Table 30. Modified Pipeline Design Results When Applying the Direct Replacement Method for a Hydrogen Blend Ratio of 50% vol. in Pipeline Gas and ASME B31.12 No Fracture Criterion Option

Pipeline Segment ID	0	1	2	3
Diameter (DN)	750	750	750	750
Schedule	S Std	S Std	S Std	S Std
Steel grade	X56	X56	X56	X56
Length (mi)	43.5	80.8	62.1	62.1
Design pressure (MPa-g)	7.14	7.14	7.14	7.14

Table 31. Modified Pipeline Design Results When Applying the Parallel Looping Method for a Hydrogen Blend Ratio of 50% vol. in Pipeline Gas and ASME B31.12 No Fracture Criterion Option

Pipeline segment ID	0	1	2	3
Loop diameter (DN)	750	800	650	650
Loop schedule	S 5S	S 5 10	S 10	S 10
Loop steel grade	X60	X52	X42	X42
Loop length (mi)	41.5	80.7	59.0	40.6
Design pressure (MPa-g)	5.1	5.1	5.1	5.1

Table 32. Modified Pipeline Design Results When Applying the Additional Compressors Method for a Hydrogen Blend Ratio of 50% vol. in Pipeline Gas and ASME B31.12 No Fracture Criterion Option

Compressor ID	Type	Mile Post	Operating Shaft Power (MW)	Rated Power (MW)
C_0_0	New	7.3	3.7	3.7
C_0_1	New	14.5	3.7	3.7
C_0_2	New	21.7	3.7	3.7
C_0_3	New	29.0	3.7	3.7
C_0_4	New	36.2	3.6	3.6
CS_1	Original	43.5	3.6	12.5
C_1_0	New	51.6	4.1	4.1
C_1_1	New	59.7	4.0	4.0
C_1_2	New	67.7	2.7	2.7
C_1_3	New	75.8	2.2	2.2
C_1_4	New	83.9	2.2	2.2
C_1_5	New	92.0	2.2	2.2
C_1_6	New	100.0	2.1	2.1
C_1_7	New	108.1	2.1	2.1
C_1_8	New	116.2	2.1	2.1
CS2	Original	124.3	2.1	12.5
C_2_0	New	139.8	4.4	4.4
C_2_1	New	155.3	4.4	4.4
C_2_2	New	170.9	4.4	4.4
CS3	Original	186.4	4.3	12.5
C_3_0	New	201.9	4.3	4.3
C_3_1	New	217.5	4.3	4.3
C_3_2	New	233.0	4.2	4.2

7 Technical Support

This user manual is part of the Version 2.0 release of BlendPATH, which is subject to future development to address the limitations discussed in Section 5, add more features, and improve accuracy. Please email jamie.kee@nrel.gov and kevin.topolski@nrel.gov with any questions or comments regarding BlendPATH.

7.0.1 Known Issues

At certain pressures with high hydrogen content, Cantera can throw a `MixtureFugacityTP::solveCubic` warning. This warning is thrown when Cantera has issues solving the implicit EOS. BlendPATH has a fix for this where the pressure is slightly perturbed to allow the EOS to be solved; however the warnings are kept in the output for informative purposes.

References

Alban, T. 2022. "Blending Hydrogen into Existing Gas Grid: Opportunities and Challenges for Pipeline e-Motor Compressor System Design." In *17th Pipeline Technology Conference.* Berlin, Germany: EITEP Institute.

American Gas Association, American Petroleum Institute, American Public Gas Association, and Interstate Natural Gas Association of America. 2019. *Response to Notice of Review of Guidance.*

American Society of Mechanical Engineers. 2023. *Hydrogen Piping and Pipelines: ASME Code for Pressure Piping, B31,* 12.

Bainier, F., and R. Kurz. 2019. "Impacts of H_2 Blending on Capacity and Efficiency on a Gas Transport Network." In *Volume 9: Oil and Gas Applications; Supercritical CO_2 Power Cycles; Wind Energy,* V009T27A014. Phoenix, Arizona, USA: American Society of Mechanical Engineers, June. ISBN: 978-0-7918-5872-1, accessed August 24, 2021. https://doi.org/10.1115/GT2019-90348.

Brown, D., K. Reddi, and A. Elgowainy. 2022. "The Development of Natural Gas and Hydrogen Pipeline Capital Cost Estimating Equations." *International Journal of Hydrogen Energy* (August): S0360319922034048. ISSN: 03603199, accessed August 29, 2022. https://doi.org/10.1016/j.ijhydene.2022.07.270.

Domptail, K., F. Frey, S. Hildebrandt, G. Hill, D. Maunder, F. Taylor, and V. Win. 2020. *Emerging Fuels - Hydrogen SOTA, Gap Analysis Future Project Roadmap.* Technical report. Pipeline Research Council International, Inc.

Donaldson, B., M. Collins, J. Seegers, A. Isensee, S. Walia, and S. Clevenger. 2014. *Uniontown to Gas City Project Texas Eastern Transmission, LP.*

Goodwin, D., H. Moffat, I. Schoegl, R. Speth, and B. Weber. 2023. *Cantera: An Object-oriented Software Toolkit for Chemical Kinetics, Thermodynamics, and Transport Processes.*

Harris, C. R., K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, et al. 2020. "Array Programming with NumPy." *Nature* 585, no. 7825 (September): 357–362. https://doi.org/10.1038/s41586-020-2649-2.

Hofer, P. 1973. "Beurteilung von Fehlern in Rohrnetzberechnungen."

ICF International. 2016. *Cost and Benefit Impact Analysis of the PHMSA Natural Gas Gathering and Transmission Safety Regulation Proposal.* Technical report.

Interstate Natural Gas Association of America. 2010. *Interstate Natural Gas Pipeline Efficiency.* Technical report. Washington, D.C.: Interstate Natural Gas Association of America.

Kee, J., and M. Penev. 2024. *ProFAST.* U.S. Department of Energy Office of Scientific and Technical Information.

Kotter, G., and S. Snarr. 2001. *California Emergency Action Application for Temporary and Permanent Certificates of Public Convenience and Necessity With Pre-Granted Partial Abandonment.*

Kotter, G., and R. Stapler. 2001. *2003 Kern River Expansion Project Application for Certificate of Public Convenience and Necessity.*

Lohmeier, D., D. Cronbach, S. R. Drauz, M. Braun, and T. M. Kneiske. 2020. "Pandapipes: An Open-Source Piping Grid Calculation Package for Multi-Energy Grid Simulations." *Sustainability* 12, no. 23 (November): 9899. ISSN: 2071-1050, accessed February 21, 2022. https://doi.org/10.3390/su12239899.

Lu, Y., T. Pesch, and A. Benigni. 2022. "GasNetSim: An Open-Source Package for Gas Network Simulation with Complex Gas Mixture Compositions." In *2022 Open Source Modelling and Simulation of Energy Systems (OSMSES),* 1–6. Aachen, Germany: IEEE, April. ISBN: 978-1-66541-008-3, accessed March 24, 2023. https://doi.org/10.1109/OSMSES54027.2022.9769148.

Melaina, M. W., M. Penev, and J. Zuboy. 2015. *Hydrogen Blending in Natural Gas Pipelines.* Technical report. Chichester, UK: John Wiley & Sons, Ltd, July. Accessed February 4, 2021. https://doi.org/10.1002/9781118991978.hces205.

Nexant, Inc, Air Liquide, Argonne National Laboratory, Chevron Technology Ventures, Gas Technology Institute, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and TIAX LLC. 2008. *H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Res.* Technical report DE-FG36-05GO15032.

Oil & Gas Journal Research. 2020. *2020 US Pipeline Economics Study.*

Osiadacz, A. 1987. *Simulation and Analysis of Gas Networks.* Houston, TX: Gulf Publishing Company.

Papay, I. 1968. *OGIL Musz. Tud. Kozl.* Budapest.

Penev, M., M. Melaina, B. Bush, and J. Zuboy. 2017. "Hydrogen Financial Analysis Scenario Tool (H2FAST): Spreadsheet Tool User's Manual," 46.

Penev, M., A. Gilbert, N. Rustagi, J. Kee, M. Koleva, and M. Chung. 2024. *Capital Structure for Techno-Economic Analysis of Hydrogen Projects.* Technical report NREL/TP-5400-90103. National Renewable Energy Laboratory (NREL), Golden, CO (United States), July. Accessed July 18, 2024. https://doi.org/10.2172/2397248.

Potts, S. 2024. *Williams, Personal Communication,* February.

Redlich, O., and J. N. S. Kwong. 1949. "On the Thermodynamics of Solutions. V. An Equation of State. Fugacities of Gaseous Solutions." *Chemical Reviews* 44, no. 1 (February): 233–244. ISSN: 0009-2665, accessed July 17, 2024. https://doi.org/10.1021/cr60137a013.

Reznicek, E., M. Koleva, J. King, M. Kotarbinski, E. Grant, S. Vijayshankar, K. Brunik, et al. 2024. "Techno-Economic Analysis of Low-Carbon Hydrogen Production Pathways for Decarbonizing Steel and Ammonia Production." *Joule, in press.*

Rui, Z. 2011. "Comprehensive Investigation into Historical Pipeline Construction Costs and Engineering Economic Analysis of Alaska In-State Gas Pipeline." PhD diss., University of Alaska Fairbanks.

Savoy Piping Inc. 2022. *Live Stock List & Current Price.* https://www.savoypipinginc.com/blog/live-stock-and-current-price.html. Accessed September 22, 2022.

Southern California Gas Company. 2014. *Updated Report: Adelanto Compressor Station Adelanto to Moreno Pipeline.*

Srinivasan, S., K. Sundar, V. Gyrya, and A. Zlotnik. 2023. "Numerical Solution of the Steady-State Network Flow Equations for a Nonideal Gas." *IEEE Transactions on Control of Network Systems* 10, no. 3 (September): 1449–1461. ISSN: 2325-5870, 2372-2533, accessed July 12, 2024. https://doi.org/10.1109/TCNS.2022.3232524.

Topolski, K., E. Reznicek, B. Erdener, C. San Marchi, L. Fring, K. Simmons, O. J. G. Fernandez, B.-M. Hodge, and M. Chung. 2022. *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology.* Technical report NREL/TP-5400-81704, 1893355, MainId:82477. October. Accessed November 7, 2022. https://doi.org/10.2172/1893355.

Wang, B., Y. Liang, J. Zheng, R. Qiu, M. Yuan, and H. Zhang. 2018. "An MILP Model for the Reformation of Natural Gas Pipeline Networks with Hydrogen Injection." *International Journal of Hydrogen Energy* 43, no. 33 (August): 16141–16153. ISSN: 0360-3199, accessed November 4, 2021. https://doi.org/10.1016/j.ijhydene.2018.06.161.

Zabrzeski, Ł., P. Janusz, K. Liszka, M. Łaciak, and A. Szurlej. 2017. "The Effect of Hydrogen Transported through a Gas Pipeline on the Functioning of Gas Compression Station Work." *AGH Drilling, Oil, Gas* 33 (4): 959. ISSN: 1507-0042, accessed October 26, 2021. https://doi.org/10.7494/drill.2017.34.4.959.

Appendix A.

A.1 Default Sectionalizing Valve Installed Costs

Default values for sectionalizing the valve installed costs are given in Table A.1. These defaults costs are linearly extrapolated from the data presented in a *Response to Notice of Review of Guidance* addressed to the Pipeline and Hazardous Material Safety Administration (American Gas Association et al. 2019) and are adjusted to 2020 dollars. We also conservatively assume that the sectionalizing valves considered for addition and replacement are buried, in which we apply an assumed two-fold cost multiplier to the linearly extrapolated cost data to obtain the values featured in Table A.1. The two-fold cost multiplier for installed buried sectionalizing valve costs is based on feedback received from industry (Potts 2024).

Table A.1. Default BlendPATH values for Sectionalizing Valve Installed Costs (American Gas Association et al. 2019; Potts 2024)

Valve Size (DN)	Installation Cost per Valve (2020$)
100	523,413
150	588,840
200	654,266
250	719,693
300	785,119
350	850,546
400	915,973
450	981,399
500	1,046,826
550	1,112,252
600	1,177,679
650	1,243,106
700	1,308,532
750	1,373,959
800	1,439,385
850	1,504,812
900	1,570,239
1000	1,701,092
1050	1,766,519
1100	1,831,945
1150	1,897,372
1200	1,962,798
1300	2,093,652
1400	2,224,505
1500	2,355,358
1600	2,486,211
1700	2,617,064
1800	2,747,918

A.2 Default Meter Installed Costs

BlendPATH applies a linear cost correlation between meter station capacity and installed modification costs. Given a lack of publicly available meter station cost correlations, we developed a linear cost regression using limited installed meter station cost and capacity data taken from Kern River Gas Transmission Pipeline applications for Certificates of

Public Convenience and Necessity (Kotter and Snarr 2001; Kotter and Stapler 2001). The meter station capacity and cost data as well as the linear regression are presented in Figure A.1.

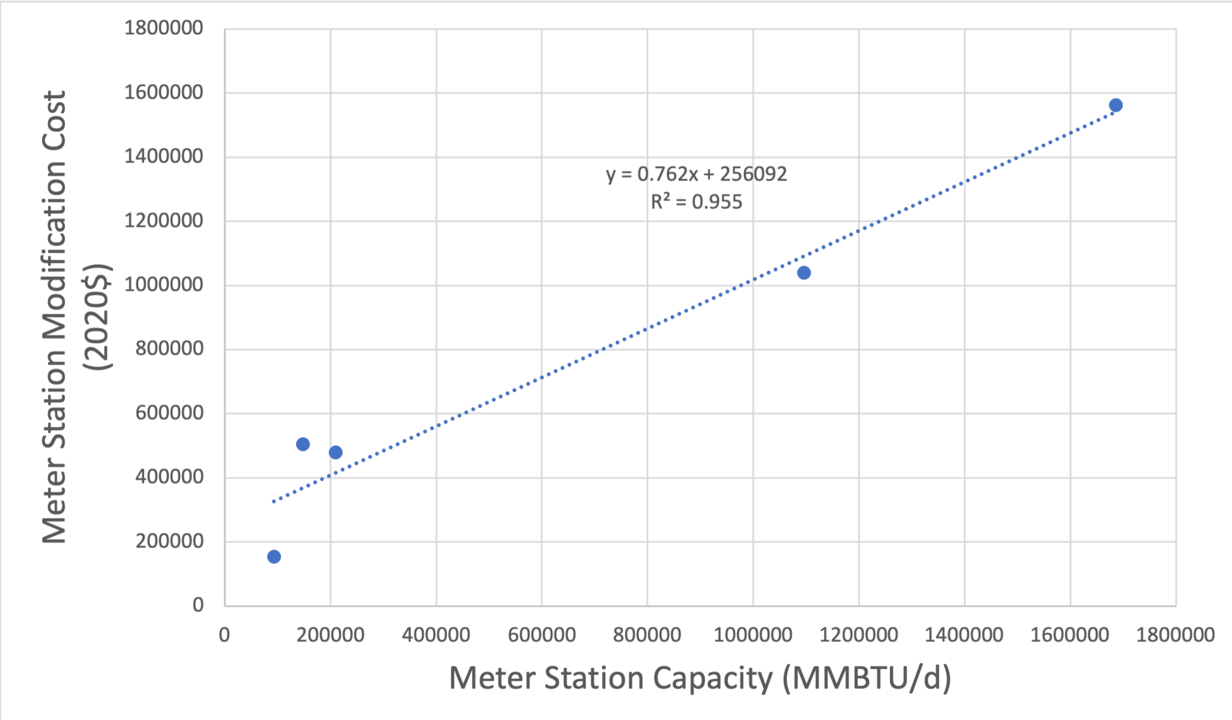

Figure A.1. Default meter station modification cost data and linear regression (Kotter and Snarr 2001; Kotter and Stapler 2001)

A.3 Default In-Line Inspection Costs

BlendPATH default in-line inspection cost data are derived from both industry input and ICF International (2016). ICF International (2016) presents sample in-line inspection costs for examining 60-mile-long pipe segments with diameters ranging from DN 100 to DN 1200, from which we extrapolate DN 1200 costs for pipe diameters up to DN 1800. We also include an assumed $1MM cost adder for pipe segments with diameters greater than or equal to DN 250 to account for electromagnetic acoustic transducer technology in the in-line inspections, given feedback received from industry (Potts 2024). These in-line inspection costs are normalized on a per-mile basis and are presented in Table A.2

Table A.2. Default BlendPATH Values for In-Line Inspection Costs (ICF International 2016; Potts 2024)

Pipeline Diameter (DN)	In-Line Inspection Cost per Mile (2020$/mi)
100	5,576
150	5,576
200	5,576
250	23,920
300	23,920
350	24,250
400	24,250
450	24,250
500	24,250
550	24,250
600	24,250
650	24,250
700	24,580
750	24,580
800	24,580
850	24,580
900	24,580
1000	24,580
1050	24,580
1100	24,580
1150	24,580
1200	24,580
1300	24,580
1400	24,580
1500	24,580
1600	24,580
1700	24,580
1800	24,580