Natural Gas Networks and Hydraulic Modeling

Basic Needs for Gas Data Sets

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ABSTRACT

U.S. consumption of natural gas for electric generation has increased significantly within the last 10 years and is likely to continue to grow to support renewable integration. Gas and electric modeling has been a challenge throughout the industry, and only a limited number of technically detailed models are available to support the co-simulation effort. Extensive simulations are limited by a lack of realistic data on supply and pipelines as well as the need for a better picture of heating load as the industry transitions from gas to electric. Such information will be especially relevant for transmission planning in already congested urban areas necessitating a detailed pipeline model.

This report describes the data needs for gas modeling for an electric sector audience including pipeline networks and their major components, necessary model inputs to simulate a gas network, typical results obtained from a hydraulic simulation, and the decisions or questions a gas model can inform. The last chapter provides data for a pipeline in the southeastern United States based on publicly available data. With this small but realistic data set, electricity modelers will be able to better simulate gas networks to increase understanding of the reliability, resilience, and economic impacts that gas supply has on the electric system – including the impacts of common cause and extreme events as well as many other gas/electric coordination challenges.

Keywords
Natural gas networks
Natural gas modeling
Gas hydraulic modeling
Energy systems modeling

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1
INTRODUCTION

Natural gas generators and generation have increased significantly in the US within the last 10 years and are likely to continue to grow as certain/firm generation to support renewable integration. Although natural gas has been a primary fuel for the power industry for many years, there have existed many issues in coordination between the gas and electric industries. These challenges have been studied at different levels, from both policy and technical standpoints. At a federal level, the need to better coordinate across electric and natural gas sectors to mitigate risks is reflected in the FERC Orders 787 (2013) and 809 (2015). Conversations between the industries will continue as gas generation continues to expand in the coming years.

One of the technical challenges for gas/electric coordination has been co-simulation and co-optimization modeling for both sectors. There are extensive operational and planning models for both industries, both in academia and published by private software companies. There have also been advances in both co-simulation and co-optimization between the two sectors. The basic challenge of modeling the two sectors together has been overcome by several software vendors and academics. The more difficult challenge for these simulations is data.

There are few data sets that can capture the needs of both sides of the model and no popular data sets that are widely and publicly available. This is especially true of data needed to run dynamic or transient gas models and ac power flow models. This data will also be needed to gain a better picture of heating load as it makes the transition from gas to electric and will be especially relevant for transmission planning in already congested, urban areas, necessitating a detailed pipeline model.

In addition to general coordination needs, as noted in [1], the electric power industry has recognized the importance of natural gas supply curtailment events. In 2011, NERC published a primer on gas-electric interdependency addressing the issue. In 2012, ISO New England was taking steps to prepare for fuel shortages as did other system operators and balancing authorities. However, as of today, fuel security assessment has not been integrated into the realm of resource adequacy evaluation, capacity markets design or integrated resource planning frameworks. Simulations by researchers to support industry needs in this area can often be hampered by lack of test data. The opportunities for R&D work have huge potential once we get past the barrier of having realistic data.

This report provides the data needs and an initial synthetic public data set that can be used for gas/electric modeling in operational and long-term time horizons. The content and level of detail is intended for an electric sector audience, and several analogies to electric terminology are provided. Section 2 describes gas pipeline networks and their major components. Section 3 presents the necessary model inputs to simulate a gas network, the typical results that can be obtained from a hydraulic simulation, and the decisions or questions a gas model can inform. Section 4 presents a realistic natural gas transmission system model based on publicly available data.

With a realistic data set, electricity modelers will be able to better simulate the gas network to better understand the reliability, resilience, and economic impacts that gas supply has on the electric system (and vice versa). The data set will allow for enhanced simulations that examine system resilience and the impact of common-cause and extreme events on the electric system, as well as many other gas/electric coordination challenges.

2
GAS NETWORKS

Introduction

Gas pipeline networks allow for the efficient transportation of natural gas over long distances (i.e., hundreds of miles) from the areas where it is produced to the end use customer. Networks are generally divided into separate types, or pressure systems based on the operating pressure, ranging from high to low pressure. The gas pressure in the pipeline network must be monitored and maintained high enough to comply with contractual pressure requirements for the customer. Maintaining the contractual pressures is critical for large customers like industrial and gas fired power plants that may cease or reduce operations if the pressure requirements are not met.

Natural gas flows from the production sites, including the gathering and processing systems, through the high-pressure transmission network, including storage, and finally to the lower-pressure distribution systems which deliver to smaller end-use customers, residential and commercial. Distribution systems can be further divided into low pressure and medium-to-high-pressure distribution systems. The medium-to-high pressure distribution systems serve some customers but primarily act as a main link between the transmission and low-pressure distribution systems. The low-pressure distribution systems are the largest by mileage and serve the majority of customers.

Table 2-1 shows the general operating pressures of the different gas system types for the United States.

Table 2-1
System types by operating pressure

System Type by Operating Pressure	Pressure (PSIG*)
Transmission	200 - 1,500
Distribution	< 200
- Medium-to-High-Pressure Distribution	60 - 200
- Low-Pressure Distribution	< 60

*PSIG – pounds per square in gauge (gauge in reference to atmospheric pressure)

Networks are composed of pipelines, compressor stations, regulator and metering stations, and storage facilities. They are constrained by maximum pressures and flows, minimum required pressures for compressors and customer deliveries, and installed compressor power. Gas moves through the network from areas of higher pressure to lower pressure and reduces in pressure as it moves. The capacity of the gas network is the quantity, or volume, of gas that can be transported from the supplies, through the network and to the withdrawal points without incurring into system violations. Capacities can also be specified for the components within the network (i.e., pipeline segments, compressors stations, regulator and metering stations) as the quantity of gas that can be moved through that component.

Pipeline networks have a rated maximum pressure for each system, referred to as the Maximum Allowable Operating Pressure (MAOP), and the controls of the network must keep the operating pressure below this maximum. Systems that have different MAOP must have control devices in place to limit the maximum pressure, such as a control valve or regulator. Pipeline systems that operate without controlling devices between them must have the same MAOP or respect the lowest pressure limit of all the pipelines and facilities in the same system.

Gas networks can move a variety of gases and mixtures of those gases. While natural gas is primarily composed of methane, it also contains mixtures of light hydrocarbons and trace amounts of other gases. Gas supplied into the network must be processed after production and must meet the quality specifications of the pipeline operator. These are further described in later sections.

Table 2-2 highlights the main differences between electric and gas networks. The gas pressures and flow rates in a gas network can be interpreted as the companion voltage and current in an electric network. Gas compressor stations and pressure regulating devices in a gas network can be compared to step-up and step-down transformers in an electric network, as they increase/decrease pressure and voltages, respectively.

Table 2-2
Gas and electricity network characteristics

Property	Gas	Electricity
Potential	Pressure	Voltage
Flow	Flow Velocity, Flow Rate	Current, Power
Typical Flow Velocity	10 m/s	3*10^8 m/s
Propagation Speed of Potential Change	Speed of Sound c = sqrt(ZRT)	Speed of Light $c = 3*10^8$ m/s
Continuous Potential Drop in Transport Line	dP = -lambda * L/D ½ * v^2	V = Z * I (Ohm's law)
Instantaneous Potential Raise	Gas Compressor station	Step-Up-Transformer
Instantaneous Potential Reduction	Gas Regulator Station	Step-Down Transformer

Electricity and gas transmission networks are often coupled at gas-fired power plants. The latter act as demands in the gas network and generators in the electricity network. Other coupling elements may exist between electricity and gas networks. These include electric-driven gas compressor stations, electric-driven LNG regasification terminals, electric-driven underground gas storages, and power-to-gas facilities such as electrolyzers. Figure 2-1 depicts example interconnections between gas and electricity transmission networks.

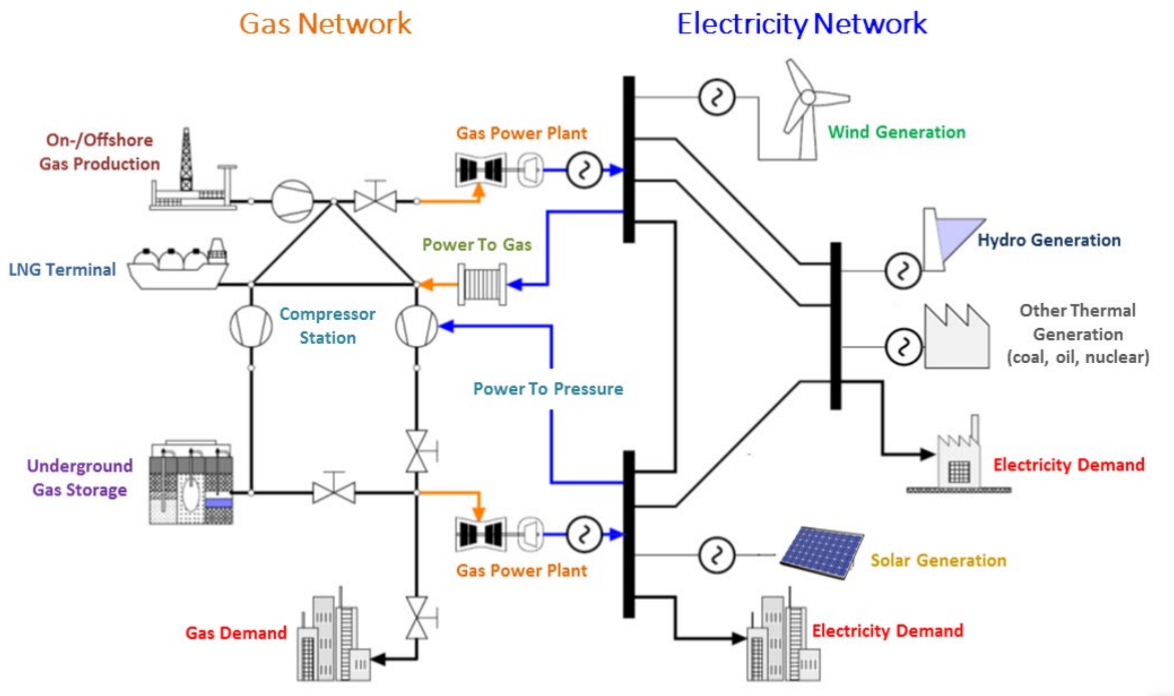

Figure 2-1
Interconnections between electric and gas networks.
Source: Kwabena Addo Pambour

Gas Pipelines

Gas pipelines transport gas between locations, for example, between receipt and delivery points and other gas facilities. The gas flowing in the pipelines is subject to pressure drops due to friction in the direction of the gas flow. The magnitude of the pressure drop depends on

- the flow rate,
- the composition and thermodynamic state of the gas (pressure, temperature), and
- the physical properties of the pipelines (diameter, length, internal roughness, efficiency).

The pipelines in a gas network function as a form of gas storage in addition to transporting gas between locations. The storage within the pipelines is referred to as linepack. Linepack is the total amount of gas stored in the pipeline network and is proportional to the geometric pipe volume, the average pipeline pressure, and the reciprocal of the gas temperature. Linepack is described in volume at reference conditions or thermal (energy) content of that volume.

Gas Compressors

Gas compressors are used to facilitate the movement of gas throughout pipeline networks. The compressors move, or push the gas, by increasing the pressure of the incoming inlet gas to a higher outlet pressure. Gas compressors require energy to power the driver of the compressor and are powered using a gas turbine, consuming a portion of the natural gas being transported, or an electric motor to perform the required compression. Compressors are required in the network to ensure continuous transport and delivery of natural gas to its customers at the maximum contracted flow rates, or nominations, and minimum delivery pressures. Nominations are the amount of gas requested by the customer to be transported on the pipeline up to the maximum specified in contracts. Pipeline network operators charge the customers for the fuel required for compression, which is generally paid in additional gas above the customers' requirements.

Gas compressors generally have several control modes and physical or programmed limits. These can include the

- minimum inlet pressure into the compressor,
- the maximum outlet pressure discharged out of the compressor,
- the installed power of the compressor driver that is gas or electric driven, and
- the maximum compression ratio defined as the outlet pressure divided by the inlet pressure.

The factors that most impact operations and the flow of gas through the compressor are the inlet pressure and the power available for the driver. When these limits are reached, the compressor will reduce its operations to stay within them, thereby decreasing the gas flow through the compressor and its outlet pressure.

Gas Regulators and Control Valves

A gas regulator or control valve can reduce the inlet gas pressure to a lower outlet pressure, control the inlet pressure (backpressure control), and regulate or limit the quantity of gas flowing through the facility.

When an increased flow or outlet pressure is required, the control valve will open more, reducing the restriction through the valve and allowing the increase. Conversely when a decrease in flow or outlet pressure is required, the control valve will close more, increasing the restriction and decreasing the flow through the control valve.

Control valves are used at interconnections between different pipeline companies, such as cross-border, receipt, or delivery points, to control the flow between them, and when pressure control is required. Gas networks that operate with different pressure levels or ratings (MAOP's) require a control device. Control valves or regulators are used as the control devices to limit the outlet pressure to a point below the maximum to allow the different pressure systems to be connected to each other.

Gas Valves

A gas valve differs from control valves and regulators in that they impose no active control on the network. A valve is primarily in the open or closed position, on or off. When closed, no gas flows between the pipelines to which the valve is connected. When open, the gas can flow in either direction. Large diameter valves on gas networks, especially on transmission systems, generally have actuators to assist in the movement of these large valves, while smaller diameter valves, on distribution networks, are operated manually.

Valve types are selected based on their intended operations. They can be open, closed, unidirectional, or partially open. A valve with the options of operating open or closed is known as a "isolation" valve. A unidirectional valve, called a "check valve", only allows gas flow in one direction. Check valves are used at pipeline interconnections and gas gathering and processing systems. A partially open or “pinched” valve causes a pressure differential across the valve that restricts the flow of gas through the valve. Pinched valves are generally operated manually during construction and maintenance activities that require changes to the normal operations.

Receipt and Delivery Points

Pipeline operators use the receipt, supply or injection into the network, and delivery, demand or extraction from the network, points along with the network topology to determine the capacity and operations of these systems.

Receipt - Gas Supply

A gas supply, or receipt, injects gas into the pipeline network. Connections from one gas network to another (a pipeline interconnect, or import) are the simplest form of gas supply in the network. Supplies also include direct connects to processing plants and gas storage locations, described further below.

Gas processing plants are where raw gas from production wells is treated and cleaned to remove water and any heavier hydrocarbons, to produce pipeline quality gas which meets the gas quality (further described below) specifications of the pipeline network. The maximum flow and the receipt pressure from the upstream network or plant limit these types of supply.

Delivery - Gas Demand

A gas demand, or delivery, withdraws gas from the network. Gas demand types include deliveries to the end the use customers, and interconnections and exports to other pipeline networks. Demands are generally categorized as small or large based on their usage or volume requirements. Residential and commercial customers have small demand and pressure requirements and will be connected to the low-pressure distribution systems.

The large volume customers will be connected to the transmission or higher-pressure distribution systems. Large volume customers include gas fired power plants, industrial or manufacturing plants, and other pipeline interconnections. The large volumes of gas transported for these customers generally cannot be accommodated by the distribution systems given their smaller pipeline diameters and lower pressures. These large volume customers, like a gas-fired power plant, may also have delivery pressure requirements that can only be accomplished by having a direct connection to the transmission system. This high-pressure delivery must be maintained for the gas-fired power plant to continue operations. If the pressure at the delivery point to the gas-fired power plant drops below the required pressure, the plant will either reduce its gas demand (curtail) to keep the pressure at the minimum or shut down and go offline completely.

Gas Storages

Gas can be stored separately from the pipelines, i.e., not in linepack, with storage connected to the network. Primarily gas is stored in either underground storage or as LNG, liquified natural gas. The main purpose is to store gas during periods of low demand for usage during periods of higher demand.

There are several types of gas storage facilities. Each has advantages and disadvantages and the two most common are further described below.

Underground Gas Storage Facility

An underground gas storage facility uses geologic formations to store gas for later use. Typically, the rate at which gas can be injected into or withdrawn from the gas storage depends on its inventory, the amount of gas stored in the facility or field. This operating region of the gas storage facility is described by its storage envelope, which can vary based on the type of storage facility. The total amount of gas in storage is defined as the sum of the working gas and the cushion gas.

Cushion gas is the amount of gas required to provide the necessary pressure to operate the facility. The cushion gas is dependent on the geology and type of storage field. Cushion gas is also the gas that remains in the storage field and is not used for injection or withdrawal. Working gas is the volume of gas that is used for storage. The working gas level is the gas stored in the facility minus the cushion gas.

Gas storage generally can be categorized as base load, long term, and peak shaving, short term. Base load storage is primarily cycled once per year between injection in the periods of low demand, summer, and withdrawal during high demand, winter. Base load storage can act as both a physical and financial hedge for the gas owner. Peak shaving is used during periods of high demand when pipelines capacity alone cannot meet the required demand. Short-term storage can also include additional storage services such as no-notice transport or enhanced hourly delivery rates. These short-term storage options can cycle between withdrawal during the highest demand in the morning and injection during periods of lower demand in the afternoon on the same day. Common types of underground storage include:

Table 2-3
Underground gas storage types

Underground Gas Storage Type	Storage Category
Depleted Gas and Oil Reservoirs	Longer term
Aquifers	Medium term
Salt Caverns	Shorter term

Liquified Natural Gas Facility

A liquified natural gas, LNG facility can be used for storage and peak shaving or in cases when direct pipeline connections are impractical. These can include when pipeline capacity is constrained, underground storage is not available in the area, or when long distances or challenging geological conditions exist between the gas production regions and the consumption areas. The LNG is stored in insulated tanks for later use and can be produced, liquified, on site or at a location closer to the gas production region and transported, generally by a ship, to an LNG regasification terminal. These terminals offload and store the LNG from the ship in tanks for later use.

An LNG facility or vessel can accommodate large volumes of natural gas thanks to liquefication that occurs by storing at very low temperatures. LNG is approximately 600 times as dense as standard natural gas at these temperatures. Unlike underground storage facilities, the location of an LNG facility is not limited by the geology requirements. This allows LNG facilities to be located closer to the load centers therefore reducing the pipeline and compression requirements to transport the gas to the end users. When needed, the LNG is pumped to high pressures and then heated until it vaporizes and is at temperatures suitable for use in the pipeline networks.

Gas Quality

Natural gas is composed of a mixture of hydrocarbon gases, primarily methane, and trace amounts of non-hydrocarbon gases. The relative amounts of gases in a mixture determine the energy density and physical fluid dynamic characteristics of the mixture. The specifications of these gas mixtures are referred to as the gas quality or gas composition.

Gas transmission and distribution companies require receipts of gas into their systems to meet specific gas quality specifications to ensure the gas mixtures are interchangeable to the customer, ensuring similar characteristics when the gas mixtures are combusted. These specifications can include the methane, hydrocarbon and non-hydrocarbon gas content, the heating value, and water content. While they vary by company, gas quality specifications are generally developed to maintain the interchangeability between systems and pipelines. The heating values set by the pipeline company can vary 10-15% between the minimum and maximum allowed. These values are set by the company's tariff in the gas quality specifications sections.

3

GAS HYDRAULIC MODELS AND STUDIES

Introduction

Hydraulic models of gas pipeline networks determine the network's operational state at given boundary conditions (e.g., input patterns of supply pressures and demand gas flow rates), while considering the system's physical limits and design constraints. The network's operational conditions can be derived for existing or planned scenarios, and include the system-wide distribution of the gas pressure, flow rates, composition, and temperature, as well as the operating and control states of the facilities in the network.

In order to solve for the network pressures and gas flow rates, a suitable mathematical formulation of the fluid-dynamic problem is required. These mathematical models typically combine the one-dimensional continuity equation (conservation of mass), the momentum equation (conservation of momentum), the energy equation (conservation of energy), and the state equation (from the real gas law).

Among their applications, gas hydraulic studies allow determination of:

- Network capacities – the quantity, or volume, of gas that can be transported from the supplies to the withdrawal points without incurring system violations or constraints
- System planning and response - analyzing the system response to contingencies, unexpected events, and abnormal operations during maintenance activities
- Expansions - determining the correct sizing for gas network components in system expansion studies

Hydraulic models determine the volumetric capacity of the pipeline networks. These capacities are generally reported in energy units obtained by converting the volumetric capacity into energy using the energy content of the gas based on its composition. Pipeline capacities in the US are commonly measured in energy, or thermal units of Dekatherms (10 Therms) or MMBtu's. Both units are equal to one million Btu's (British Thermal Unit).

Types of Hydraulic Studies

Gas network simulations can be carried out with different levels of physical details, as well as with different temporal scopes (i.e., steady-state vs. transient). These options come with different modeling and computational challenges, and the choice of the most suitable type of model should rely on the targeted application.

Steady-state simulations are useful when determining the network's conditions at a single point in time, but they are insufficient when accounting for the variations that occur throughout the day. On the other hand, transient simulations incorporate time-varying components of the network equations, adding some degrees of complexity to the numerical solution of the fluid-dynamic problem.

Simulations can also determine the temperature and gas quality, or composition, within the network. Most software applications have options to turn these features on or off as they can impact the time required to solve the model and the results.

Models must account for the maximum and minimum pressures and flows as well as the other limiting factors including compressor capacities. The delivery requirements are based on the transportation contracts, which typically specify the minimum delivery pressures, the total daily flow, and the maximum hourly flow rates.

The maximum hourly flow delivered to a customer can be specified by either contracts or the posted rules and regulations of the pipeline transmission company. Customers of pipeline transmission and distribution companies generally schedule or nominate their required gas consumption the day prior to consumption but may adjust these nominations during specified windows during the day. These nominations specify the quantity of gas as well as the receipt and delivery points per customer. In the US, electricity market and gas nominations cycles are not aligned. The operating day in a day-ahead electricity market starts at midnight. On the other hand, the start of the gas flow for day-ahead gas nominations is at 9 AM Central Time, which marks the start of the gas day. FERC Order 809 from 2015 addressed this issue by shifting forward the first day-ahead gas nomination cycle, so gas-fired generators could nominate gas offtakes while knowing their electricity generation schedule, and by adding an extra intra-day gas nomination cycle to allow for updates based on newer forecasts.

Generally, pipelines require gas usage to be in equal hourly increments throughout the day. Enhanced hourly services can be provided by utilizing storage facilities or specifically designed pipeline and compression systems. A gas hydraulic simulation is needed to understand the behavior of the system in each of these cases.

Steady-state Studies

Steady-state analyses neglect the time-varying components of the continuity, energy, and momentum equations, and they assume constant property values and static controls for all the elements in the network.

Since all the equations are independent of time, the linepack of the system (i.e., the quantity of gas inherently stored in the network) is constant as well. As a consequence, a steady-state analysis implies that the gas inflow, supply, and outflow, demand, in the system are equal, and they perfectly balance out. In a steady-state simulation, the “flow balance,” defined as the difference between system-wide gas inflows and outflows, is therefore equal to zero.

Solving a steady-state gas network analysis requires a minimum of one known or “set” pressure in every independent hydraulic subsystem. Each independent hydraulic subsystem can be identified by the connections to facilities that have active control in the network (i.e., supplies, compressors, control valves) and at closed valves. Connected pipelines and open valves would all be in the same hydraulic subsystem.

The set pressures are most often found at the supply points or are enforced by pressure-regulating facilities such as gas compressor stations or gas regulation stations. Additionally, the pressures in the modeled networks are typically limited by the maximum and minimum pressures ratings of the network elements, as well as by the pressure requirements specified in the contractual agreements between the parties. These contracts generally include the maximum and minimum flows and the minimum and maximum delivery pressures. Minimum flows can be zero, however there can be limitations to measurement equipment that requires it to be a non-zero value. Maximum pressures are not always specified in contracts.

Steady-state simulations are used for design purposes and generally on lower pressure transmission and distribution systems. These networks are commonly smaller and operate at low pressures, implying that the effect of their linepack on the system dynamics are not very significant. In these cases, changes throughout the network occur much faster compared to high-pressure gas transmission systems.

The results from steady-state studies used in large transmission systems can be overly conservative or potentially show that existing operating conditions are not possible. Thus, transient studies are appropriate for large transmission systems operated at high pressures, characterized by larger pipeline diameters, and covering longer distances.

Transient Studies

A transient, or dynamic, analysis allow the incorporation of time-varying components, such as changing flow rates at demands or pressure at supplies in the network. Unlike steady-state simulations, a dynamic simulation accounts for the changes in pressure and linepack across the system. This makes transient analyses more suitable for large, high-pressure transmission systems, in order to account for the slower propagation of changes across the network.

When supplies exceed demands, flow balance is positive, system pressures and linepack will increase. This is commonly known as "packing". When demands exceed supplies, flow balance is negative, system pressures and linepack will decrease. This is commonly referred to as "drafting". The linepack of the system can cover some of the variations in demand and supply that occur throughout the day, but this ability depends on the specifics of each system.

Normal operations of the network include changes in supply, demand, and linepack quantities throughout time or the course of the day. The amount of time a network can continue to operate before the abnormal operating conditions are corrected is referred to as survival time. A dynamic analysis can determine survival time during abnormal operations, including supply or compressor limitations or failures. In this case, the pressures and linepack will be reduced as gas is removed from the network. If the contingency continues beyond the survival time, operational restrictions may be violated and/or gas deliveries to the customers may be subject to curtailment.

Dynamic studies on gas networks typically use time-steps in the range of minutes, 10-60 minutes, where 15 minutes is common. Dynamic simulations require a set of initial conditions before the beginning of the simulation, these initial conditions are generally the results of a steady-state simulation.

Input Properties

Hydraulic models require general model properties and settings in addition to those required for each specific network, the topology and facilities. These properties are described below.

Network properties

Network properties are used to describe network-wide parameters such as the ambient temperature and the reference pressure, as well as to customize solver-related options, and the various equations implemented for the solution.

The reference temperatures and pressures are used to relate gas quantities (i.e., mass flow rate) to gas volumes (volumetric flow rate) at reference conditions. The ambient pressure is necessary especially to define gauge pressures: gauge pressures are the absolute pressure minus the ambient pressure. The ambient temperature is useful for temperature-tracking applications, in which the heat exchanges between the gas and the external environment are included in the model, resulting in thermal gains or losses along the pipelines.

As mentioned above, the network properties also contain the equations for calculating the friction and compressibility factors for the network. These properties and equations have default values in most tools, and each has its own ranges of acceptable gas flow conditions (e.g., Reynold's number) and gas composition, in which it can be used. Different equations may be, for instance, used to model distribution vs transmission, low pressure vs high pressure, natural gas vs. hydrogen blends.

Network Nodes

Nodes represent a physical location in the network at the end points of facilities (e.g., pipes, compressor stations, etc.) and the connection between two or more facilities. Nodes are locations at which gas can be added or removed (supply, demand, etc.) from the network. Additionally, the gas nodes in the network also prescribe the minimum acceptable pressure values, as further described below.

Table 3-1
Node properties

Properties	Units	Description
Coordinates (X, Y)	Feet	Location of the nodes in relation to a coordinate system.
Elevation	Feet	Elevation of the node.
Maximum Pressure	PSIG	Maximum pressure at the node.
Minimum Pressure	PSIG	Minimum pressure at the node.

Gas Supplies

A gas supply in a hydraulic model is generally simulated using a pressure control set point. Networks with multiple supplies normally have a mix of control set points with some using pressure and others using flow. This is similar to control schemes in the physical gas network. The supply will have a specified maximum flow rate and associated maximum pressure. Minimum pressures at gas supplies are generally not important for the simulation.

Every gas supply in the network typically requires a gas quality to be defined. A default gas quality (e.g., methane or a reference natural gas composition) is usually deployed if not specified. Input properties of a gas quality object include the molar composition and the thermodynamic properties of the gas mixture, like its gross/net calorific values.

Gas models account for the gas quality and the mixtures of the various chemical components by using the physical properties of each of the components in the mixture. This can include the blending of hydrogen into natural gas streams, which has been discussed as a way to decrease the carbon emissions for the end use customers.

Gas Demands

In a hydraulic model, gas demands typically require a set-point for the gas flow rate. In such cases, the flow rate is known a priori, while the pressure at the demand point is determined by the solver. In other cases, they can also be operated – and modeled – with a pressure control set-point.

Gas demands have a maximum flow rate and associated minimum pressures. The delivery pressures and volumes for the customer are usually specified in the transportation contract with the pipeline company. These minimum pressures must be maintained to comply with the contractual obligations with the customer.

Pipelines

Table 3-2 describes the necessary pipeline properties for the model. The length of gas pipelines, if not specified from a Geographic Information System, GIS, or other data, can be inferred from system maps or other published project documents. The pipeline roughness represents the height of irregularities on the inner wall of the pipeline and is a function of the material type – steel for transmission pressures. Pipeline roughness and efficiency normally use assumed values based on the material and the geometry of the network (i.e., short segments with multiple bend, vs longer segments without).

When available, system operating data can be used to calibrate a hydraulic network model to reflect the real-world performance of the network using the measured flows and pressures throughout the system. This can be accomplished in the gas model by adjusting the pipeline roughness and efficiency parameters to match the observed data.

The inside diameter of the pipeline determines the pipeline’s capacity and is directly linked to the frictional pressure losses. When data for the inside diameter of a pipeline in not available, it can potentially be determined using a hydraulic model. The model would use the network topology and published capacities to determine the pipeline diameter.

Generally, pipeline sizes are described by manufacturers using nominal diameters corresponding to standard sizes with varying wall thickness. The inside diameter can therefore be determined by using the specified outside diameter and the wall thickness. This is important especially with large diameter pipelines as the inside diameter can be much less. For example, a nominal pipeline diameter of 24” may have a wall thickness of 0.750” and an outside diameter of 24”, the resulting inside diameter of that pipeline is 22.5”.

The additional properties listed in Table 3-3 are used when calculating the gas temperature throughout the network. While most software applications allow for temperature tracking or tracing in the models, many network models assume constant temperature (isothermal) gas flow.

Table 3-2
Pipeline properties

Properties	Units	Description
Inner Diameter	Inches	Inner diameter of the pipe.
Length	Feet	Length of the pipe segments between nodes.
Inner Pipeline Wall Roughness	Inches	Inside surface roughness of the pipeline, expressed in units of length. Physical property of the pipeline material type.
Pipeline Efficiency	Fraction or percentage (unitless)	Factor used to account for frictional pressure losses due to the bends, or curvature, of the pipelines or through non-modeled components (pipe fittings). Also used when calibrating models with field data.

Table 3-3
Additional pipeline properties

Properties	Units	Description
Wall Thickness	Inches	Pipeline thickness. Difference between the outer and inner pipe diameters.
Heat Transfer Coefficient	Btu/(h ft^2 °F), British Thermal Unit per hour per Feet Square per Fahrenheit	Thermal conductivity of the pipe material.

Gas Compressors

Table 3-4 describes the necessary compressor properties for the model. The function of a compressor is to increase the pressure of the gas and ensure deliveries to its customers. Compressors have limits such as the power available to do the work of the compressor, the maximum and minimum pressures, the maximum ratio of the pressure rise between the inlet and outlet. These limits determine the rate maximum flow rate, or throughput, of the compressors. The maximum flow rate is generally specified at these limits, while the flow can be larger as operating conditions change but are within these boundaries (i.e., higher inlet pressure).

Table 3-4
Gas compressor properties

Properties	Units	Description
Maximum Compressor Power, Maximum Driver Power	HP (Horsepower)	Power available to the driver motor of the compressor
Maximum Discharge Pressure, Maximum Pressure	PSIG	Maximum pressure at the outlet
Minimum Suction Pressure, Minimum Pressure	PSIG	Minimum pressure requirements at the inlet
Maximum Compression Ratio	Dimensionless Greater than 1	Maximum ratio of the outlet pressure divided by the inlet pressure
Adiabatic Efficiency	Dimensionless	Compressor efficiency. Ratio of ideal work required to the actual work required
Mechanical Efficiency	Dimensionless	Driver efficiency, losses due to friction

Model Outputs

The results of the hydraulic studies will determine if the simulation setup is feasible and reasonable. Results could be feasible but not reasonable if the solution violates constraints that are not correctly accounted for in the model. For instance, if a supply is not limited to its maximum flow in the model.

The simulation will determine the pressures and flows at all points in the network. The pressures must be within the minimum and maximum limits, while the flows must be at or below their maximums. Pressure and flow values are most important at the supplies and demands. If pressures drop below the minimum, the model can help determine the quantity of gas that should be unserved in order to keep the pressure within admitted values. Some modeling tools (like the Scenario Analysis Interface for Energy Systems, SAInt) incorporate functionalities for this kind of analyses.

The simulation also determines the flow rates, the pressure drops, and the linepack of all the pipelines in the network. In the case of multiple gas qualities and non-isothermal (i.e., temperature tracking) models, the simulation also informs on the distribution of the gas composition and of the gas temperature across the network. Finally, the gas network simulation will also inform on the operating state and control status of all the non-pipeline elements like compressor stations and pressure regulation stations. This allows checking that no operational violations occur at these facilities.

Comparison to Electric Network Models

Table 3-5 compares the input, output, and control modes commonly deployed in simulation setups for gas network and electrical AC power flow analyses. The information provided for both gas and electricity simulations may vary with case studies and different modeling needs.

Table 3-5
Gas and electric simulation comparisons

Network component	Gas (hydraulic simulation)	*Electricity (AC power flow)*
Gas supply / *Electrical generator*	Inputs: pressure set point Outputs: gas flow rate	*Inputs: voltage magnitude set-point, active power set point* *Outputs: voltage angle, reactive power*
Gas demand / *Electrical load*	Inputs: gas flow rate Outputs: pressure	*Inputs: active and reactive power* *Outputs: voltage magnitude and angle*
Gas compressor station / *Step-up transformer*	Control mode: outlet pressure set point Outputs: absorbed power	*Control mode: tap position (transformation ratio)*
Regulators and Control Valves / *Step-down transformer*	Control mode: outlet pressure set point	*Control mode: tap position (transformation ratio)*

4
GAS NETWORK DATA SET

The gas model presented with this report was developed using publicly available data and validated with a hydraulic model using the Scenario Analysis Interface for Energy Systems (SAInt), a commercial modeling software by encoord. This model is of the Sabal Trail Transmission system in the Southeastern US. The pipeline system travels through the states of Alabama, Georgia and Florida providing over 1 billion cubic feet per day (Bcf/d) to customers in Florida. Some of these publicly available parameters include the pipeline diameters, the locations of compressors, supplies and demands, as well as the length of the pipelines. The following subsections detail the properties and constrains for the gas network and the objects included in the data set.

The network contains approximately 515 miles of 24” and 36” nominal diameter pipelines with 18 nodes, 12 pipelines, and 5 compressors. The model includes 5 supplies and 7 demands, of which 3 are located at bi-directional points. The 7 demands include 4 connections to other pipelines, 1 direct connection to a gas-fired power plant, and 2 Local Distribution Companies (LDCs). A bi-directional point can act as either a supply or demand and it is therefore modeled with both a supply and demand at the same location. The model does not contain regulators or control valves, isolation valves, or gas storage facilities (underground or LNG).

Figure 4-1 below shows the network topology of the gas model provided in this data set. The figure is taken from the software SAInt.

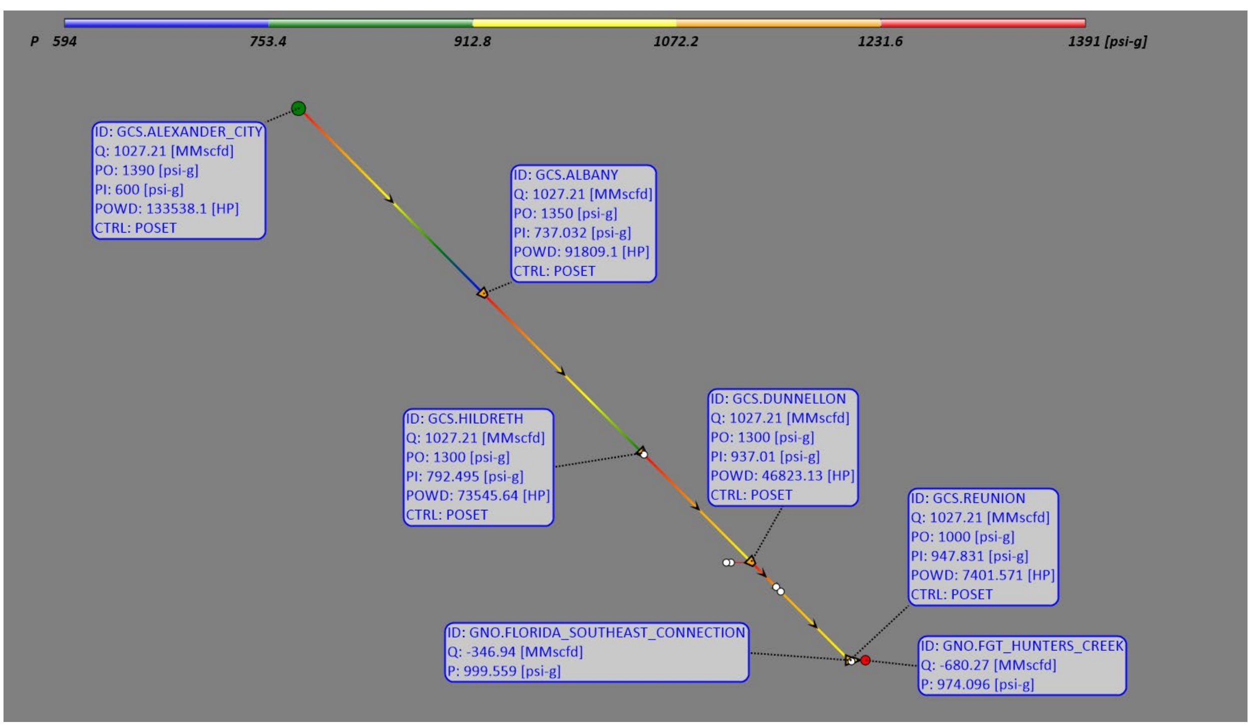

Figure 4-1
Network topology

Object and Properties

The following subsections describe the included nodes, facilities (pipelines and compressors), the supplies and demands, and the gas quality for the network.

Nodes

The gas model contains 18 nodes described in terms of geographical location and admitted pressure ranges, as detailed below. All nodes in the model have an elevation of 0 feet.

Table 4-1
Node data

Node Name	X-Coordinate of the node	Y-Coordinate of the node	Maximum Pressure	Minimum Pressure
	Feet	Feet	PSIG	PSIG
ALEXANDER_CITY	5279.755	0	1440	700
GNO_01	844760.9	-844761	1440	700
GNO_02	1568087	-1568087	1440	700
GNO_03	2064384	-2064384	1440	700
TECO_WILDWOOD	2175259	-2175259	1440	700
LEESBURG	2196378	-2196378	1440	700
FLORIDA_SOUTHEAST_CONNECTION	2518443	-2507884	1440	700
FGT_HUNTERS_CREEK	2581800	-2507884	1440	700
CITRUS	1969349	-2064384	1440	700
ALBANY	839481.1	-839481	1440	700
HILDRETH	1562808	-1562808	1440	700
SUWANNEE	1573367	-1573367	1440	700
DUNNELLON	2059105	-2059105	1440	700
DUKE_CITRUS	1948230	-2064384	1440	600
REUNION	2507884	-2507884	1440	600
GNO_04	2513166	-2507881	1440	700
GULFSTREAM	2518443	-2513164	1440	700
TRANSCO	0	0	1440	550

Pipelines

The gas model contains 12 pipelines, which are detailed in the table below. All pipelines have a Roughness of 0.0016 inches, an efficiency of 0.99 and wall thickness of 1.5 inches. The Length property is used by the hydraulic model. The Length differs from the distance between the coordinates of the nodes, as these are used only for visualization purposes in the software.

Table 4-2
Pipeline data

Pipeline Name	From Node	To Node	Diameter	Length
			Inches	Feet
GPI_00	ALEXANDER_CITY	ALBANY	34.5	841065
GPI_01	GNO_01	HILDRETH	34.5	723326.5
GPI_04	GNO_03	TECO_WILDWOOD	34.5	112986.8
GPI_05	TECO_WILDWOOD	LEESBURG	34.5	21119.02
GPI_06	LEESBURG	REUNION	34.5	347407.9
GPI_09	FLORIDA_SOUTHEAST_CONNECTION	FGT_HUNTERS_CREEK	34.5	68108.84
GPI_10	GNO_03	CITRUS	22.5	92395.72
GPI_02	GNO_02	SUWANNEE	34.5	5279.755
GPI_11	CITRUS	DUKE_CITRUS	22.5	18479.14
GPI_07	FLORIDA_SOUTHEAST_CONNECTION	GNO_04	34.5	527.9755
GPI_08	FLORIDA_SOUTHEAST_CONNECTION	GULFSTREAM	34.5	527.9755
GPI_03	SUWANNEE	DUNNELLON	34.5	488377.4

Gas Compressors

The gas model contains 5 gas compressors, as detailed below. All compressors have an adiabatic efficiency of 0.87 and mechanical efficiency of 0.34.

Table 4-3
Gas compressor data

Compressor Name	From Node	To Node	Maximum Pressure	Minimum Pressure	Driver Power	Shaft Power	Maximum Pressure Ratio
			PSIG	PSIG	HP *1,000	HP *1,000	N/A
ALBANY	ALBANY	GNO_01	1440	700	107	37	2.2
HILDRETH	HILDRETH	GNO_02	1440	700	107	37	2.2
DUNNELLON	DUNNELLON	GNO_03	1440	700	65	25	2.2
REUNION	REUNION	GNO_04	1440	600	75	30	2.2
ALEXANDER_ CITY	TRANSCO	ALEXA NDER_ CITY	1440	550	140	47	2.5

Gas Quality

The gas quality and components for the natural gas used in this model are described in the table below. This composition uses gas quality data from the transmission company.

Table 4-4
Model gas components

Gas Component	Abbreviation	Component Percentage (Mol %)
Methane	C1	94.735
Ethane	C2	3.363
Propane	C3	0.211
Carbon Dioxide	CO2	1.103
Nitrogen	N2	0.501
iso Butane	IC4	0.031
n Butane	NC4	0.028
iso Pentane	IC5	0.009
n Pentane	NC5	0.007
n Hexane	NC6	0.012

Table 4-5
Gas properties

Gas Property	Value	Description
Energy Content: Gross Calorific Value	1,029	Unit: Btu/scf
Specific Gravity	0.587	Density ratio compared to air
Wobbe Number	1,343	Interchangeability index of fuel mixtures

Hydraulic Model Simulation Results

The following sections describe the outputs and the results from the hydraulic model. These results include the pressures and flows throughout the network and the operating states of the compressors. These results are used to determine if the simulation is feasible and within the requirements of all the constraints.

System Linepack and Flow Balance

The network provided is designed to provide high levels of hourly deliveries to the demands, greater than equal hourly increments during the day, 1/24th of the daily demand. This flexibility beyond the equal hourly flows is accomplished using compression and linepack within the network. However, the customer must keep their total daily usage equal to their daily nomination. This requires the customer to reduce the hourly usage during other portions of the day. In this case, the demand is highest in the afternoon, lower in the morning and equal to the daily average during the middle and overnight periods of the day. This usage profile is further detailed below.

Figure 4-2 below shows the variations in the total network outflow (QOUT) and inflow (QIN). QOUT represents the total of the 2 active demands in the model and QIN represents the total of the one active supply. The demands are interconnections to other pipelines; the other supplies and demands are not active in the scenario modeled.

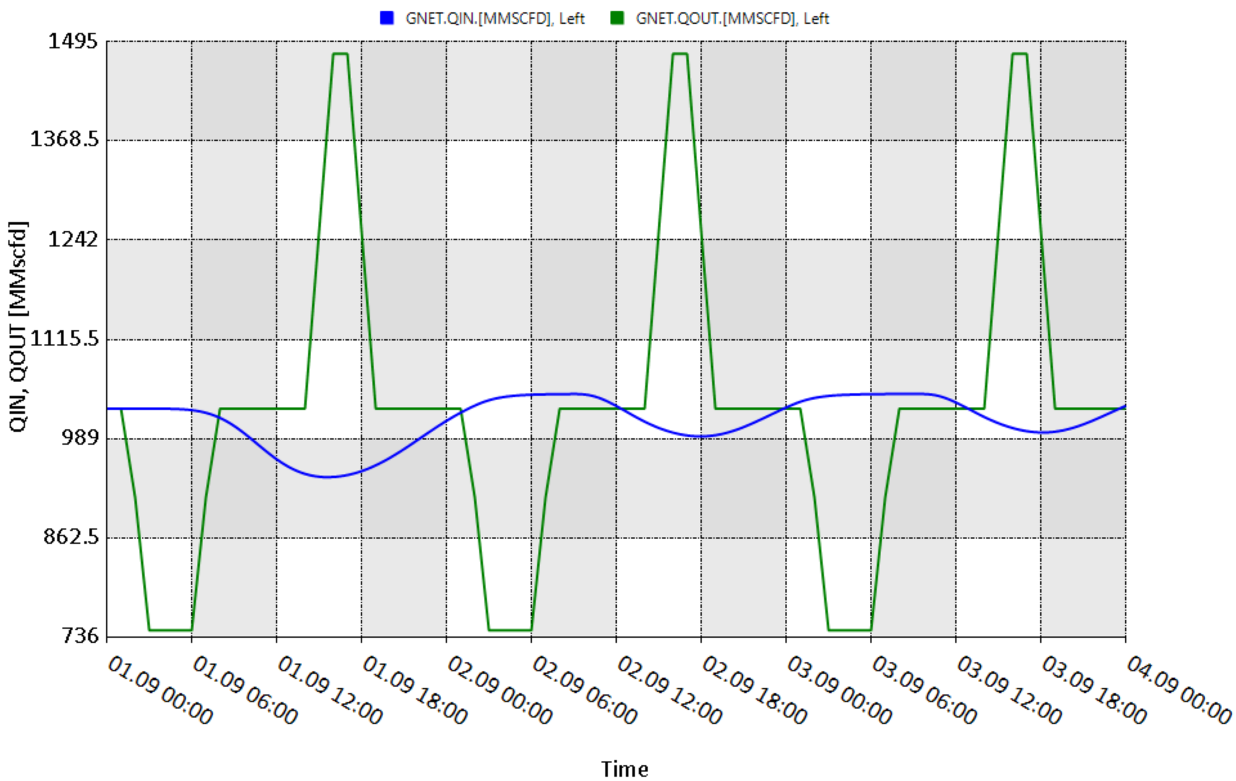

Figure 4-2
Total gas inflow (GNET.QIN) and outflow (GNET.QOUT) for the network

In this model, the hourly values of total gas supply and demand show large differences along the day. This results from the large size of the system and from its linepack, which contributes to a time shift between the gas withdrawal at the demand, and the gas injection at the supply point. While the differences are large for this system, it is common for gas transmission systems to have differences in supply and demand throughout the day. This behavior can only be accounted for with a transient model which takes the time variations into account. The figure below shows the flow balance (FB) and the effects on the system linepack (LP).

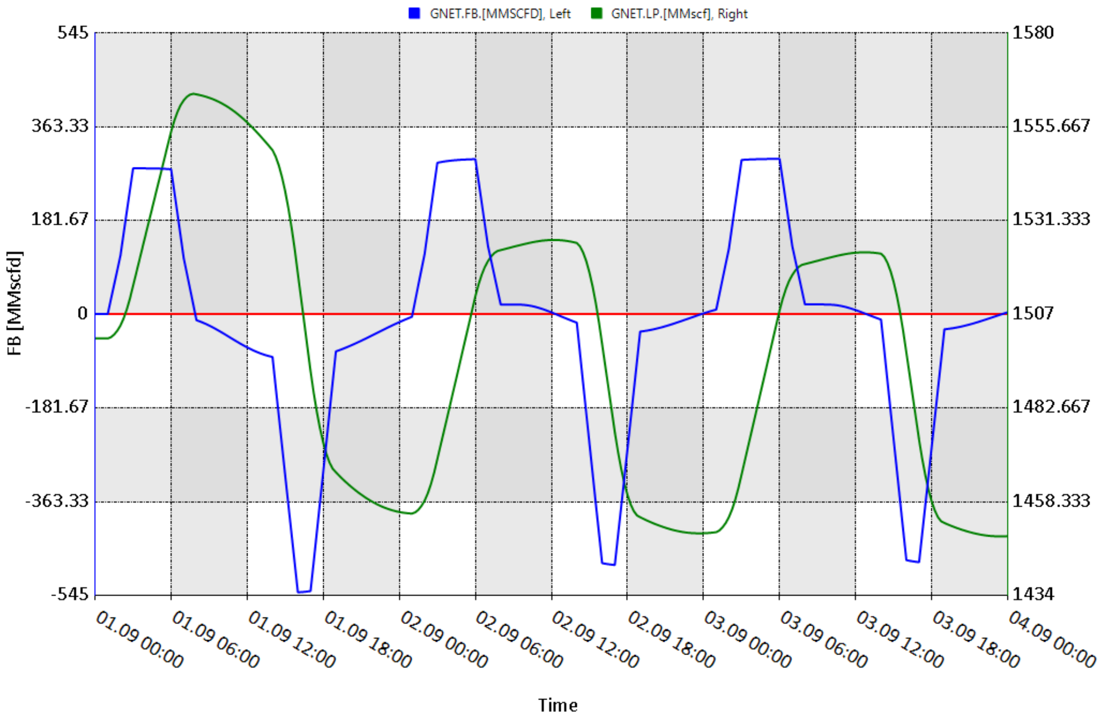

Figure 4-3
System linepack (LP) and flow balance (FB)

This model contains 5 segments (listed GGRP_0 to GGRP_4) or hydraulic areas between the compressors from the north to the south. The figures below show the linepack (LP) for each segment and the changes over time.

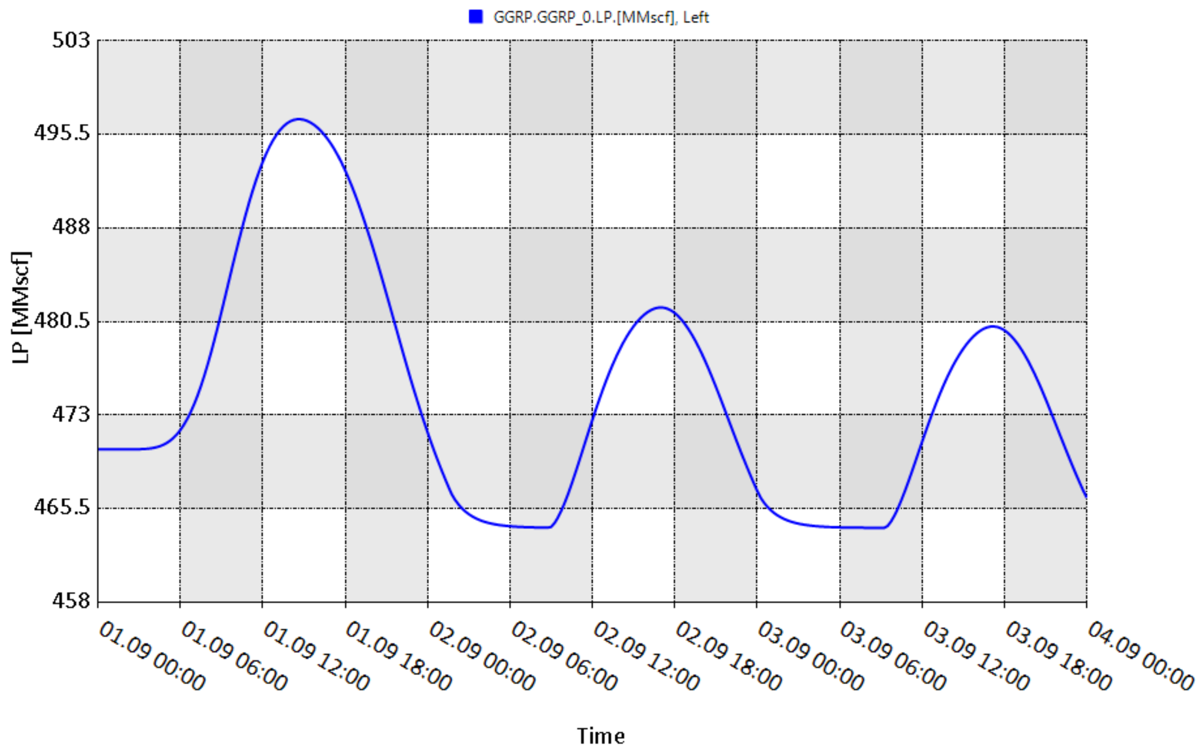

Figure 4-4
Linepack (LP) in Segment 0 (GGRP_0)

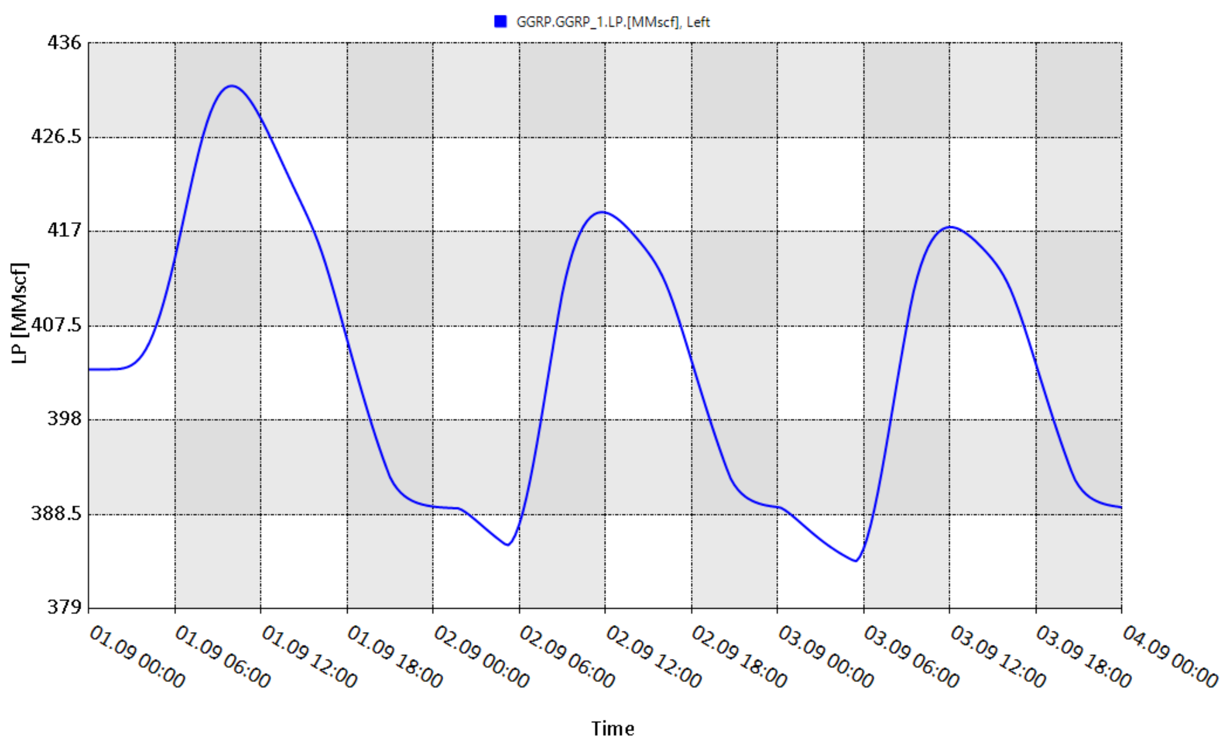

Figure 4-5
Linepack (LP) in Segment 1 (GGRP_1)

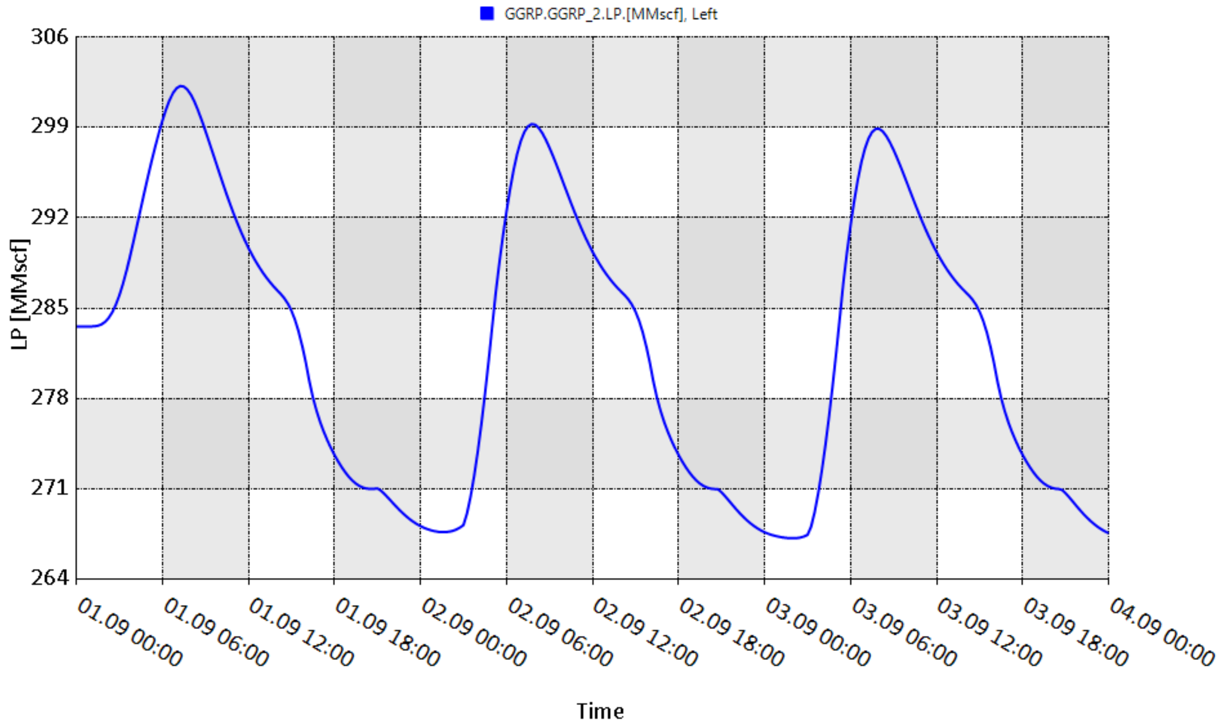

Figure 4-6
Linepack (LP) in Segment 2 (GGRP_2)

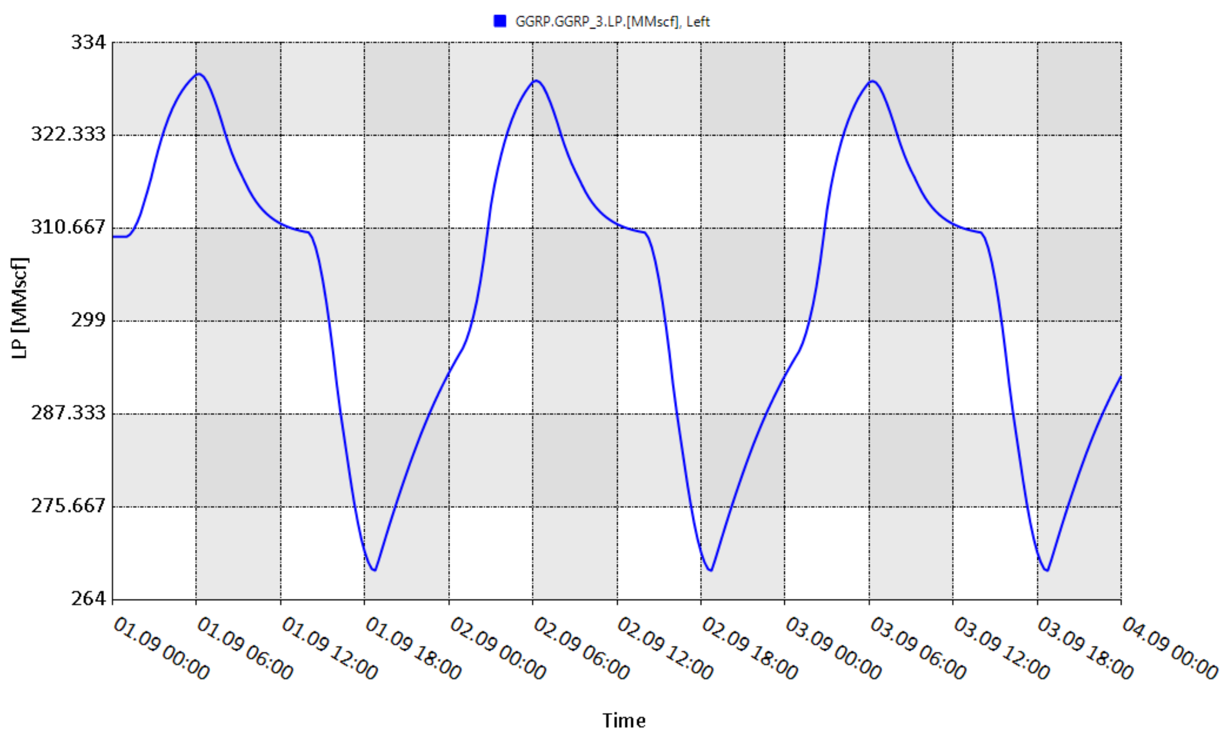

Figure 4-7
Linepack (LP) in Segment 3 (GGRP_3)

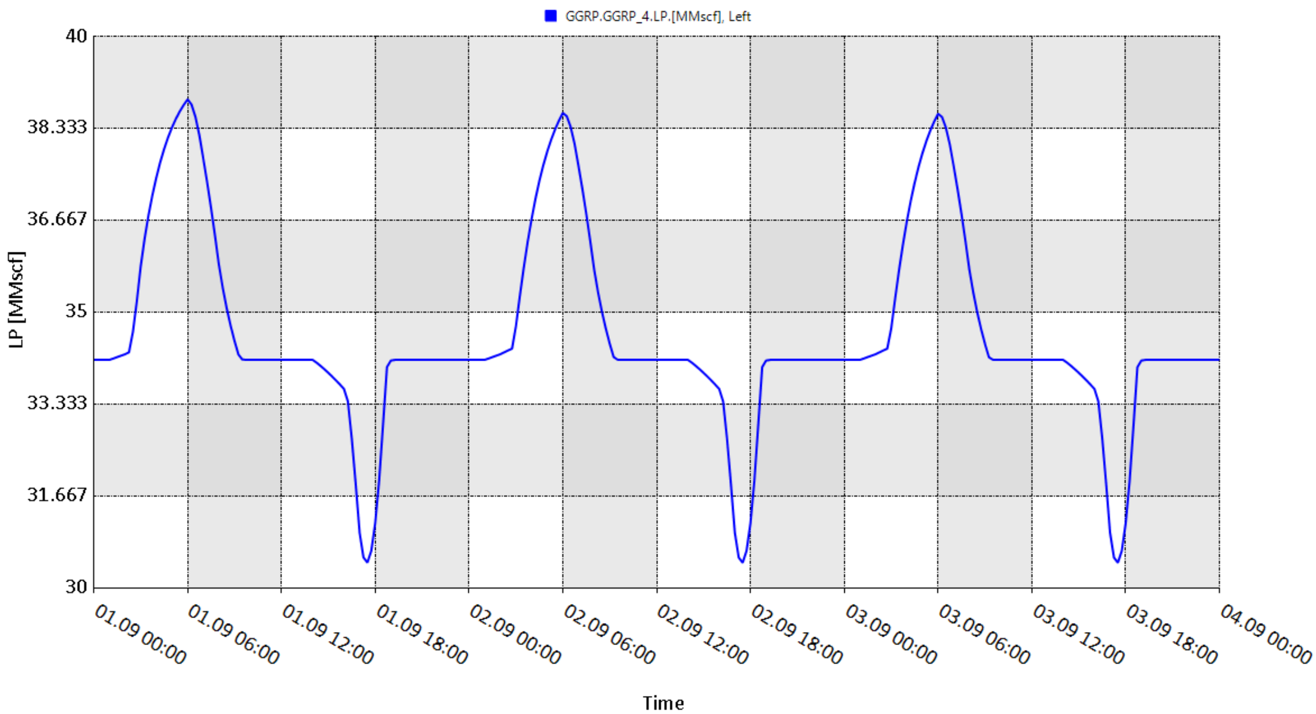

Figure 4-8
Linepack (LP) in Segment 4 (GGRP_4)

Network Gas Compressors

The 5 compressors in the model operate between their outlet, discharge, setpoints and their other operating constraints. The figures below show the pressures at the inlet (PI) and outlet (PO), the flowrate (Q) and the control mode (CTRL).

Table 4-6
Compressor control types

Control Type	Control Description
POSET	Outlet pressure set point
PMIN	Minimum inlet pressure
POWDMAX	Maximum driver power
NRPB	Non-return bypass. Flow through compressor without pressure increase

The compressors are initially operating at POSET, controlling the outlet pressure while the flow and inlet pressure vary. As the simulation continues, the compressors change their operations and control modes based on their constraints.

The demand decreases during the morning hours of the simulation. This causes the pressures to rise within the system and at the inlets to the compressors, reducing the flow and the power input to the compressors. If the inlet pressure increases to or above the outlet pressure set point, the compressor will turn off while still permitting flow through, this control mode of the compressor has changed to non-return bypass. If the inlet pressure drops below the outlet set point, the compressor will revert to the POSET control.

As the demand and flow through the compressor increase, the pressure at the inlet will decrease requiring more power input to the compressor. This continues until another constraint is reached. The compressors in the model will reach either the maximum driver power (POWDMAX) or the minimum inlet pressure (PMIN) constraints and control model. In both, the flow through the compressor will decrease due to the power limit of the compressor (POWDMAX) or to keep the inlet pressure to the compressor at its minimum (PMIN). Later, as the demand and compressor flows reduce, the compressors will revert back to their POSET control.

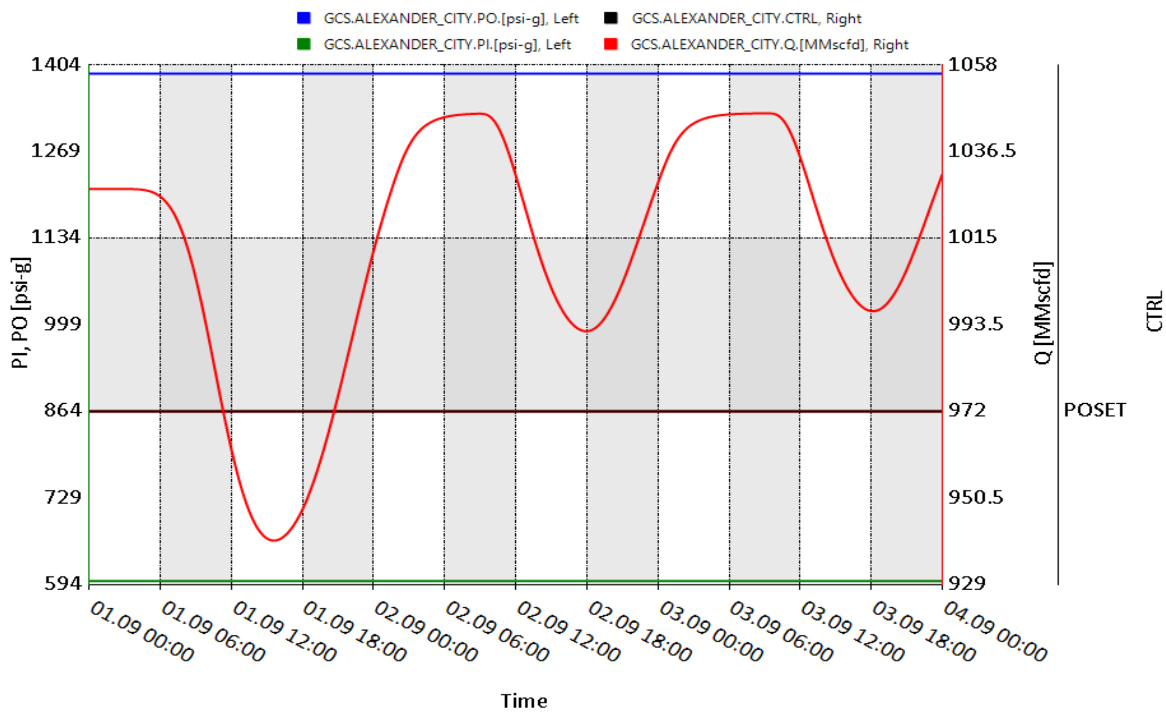

Figure 4-9
Compressor (GCS) Plot – ALEXANDER_CITY (PO – Outlet Pressure, PI – Inlet Pressure, CTRL – Control Mode, Q – Flow Rate)

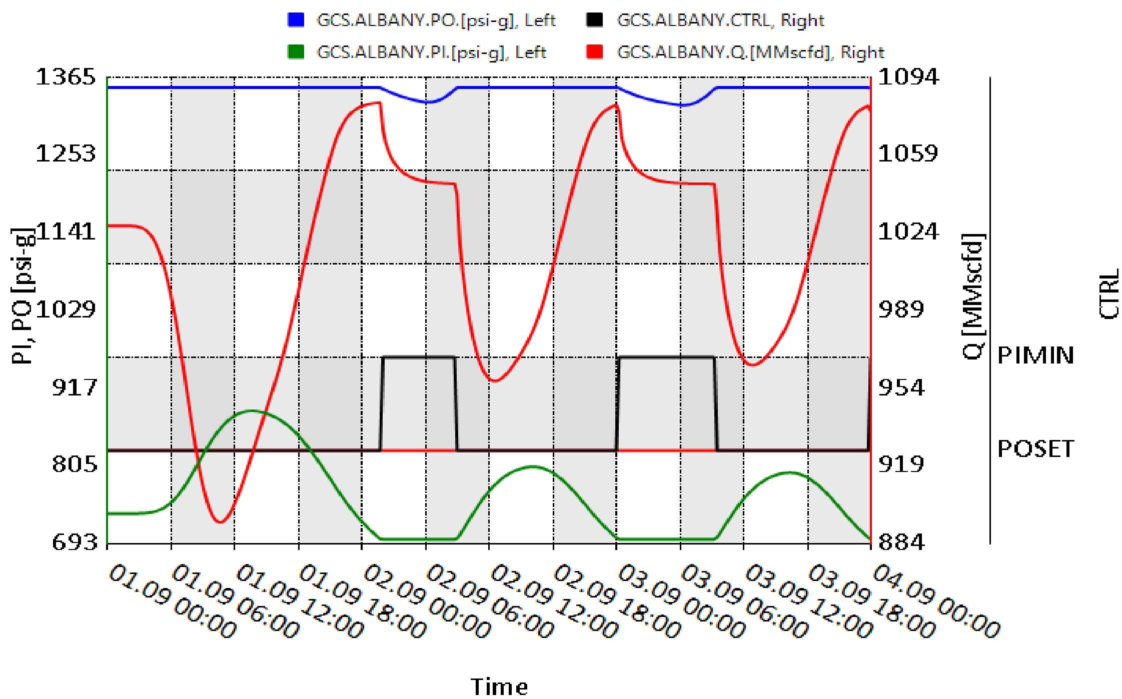

Figure 4-10
Compressor (GCS) Plot – ALBANY (PO – Outlet Pressure, PI – Inlet Pressure, CTRL – Control Mode, Q – Flow Rate)

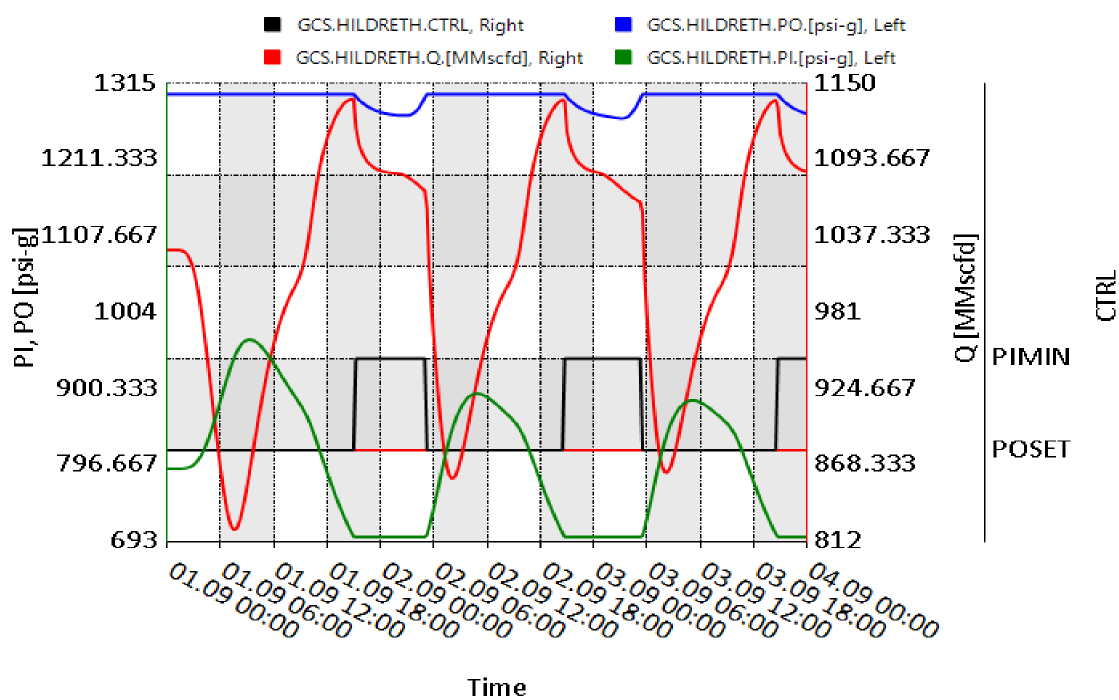

Figure 4-11
Compressor (GCS) Plot – HILDRETH (PO – Outlet Pressure, PI – Inlet Pressure, CTRL – Control Mode, Q – Flow Rate)

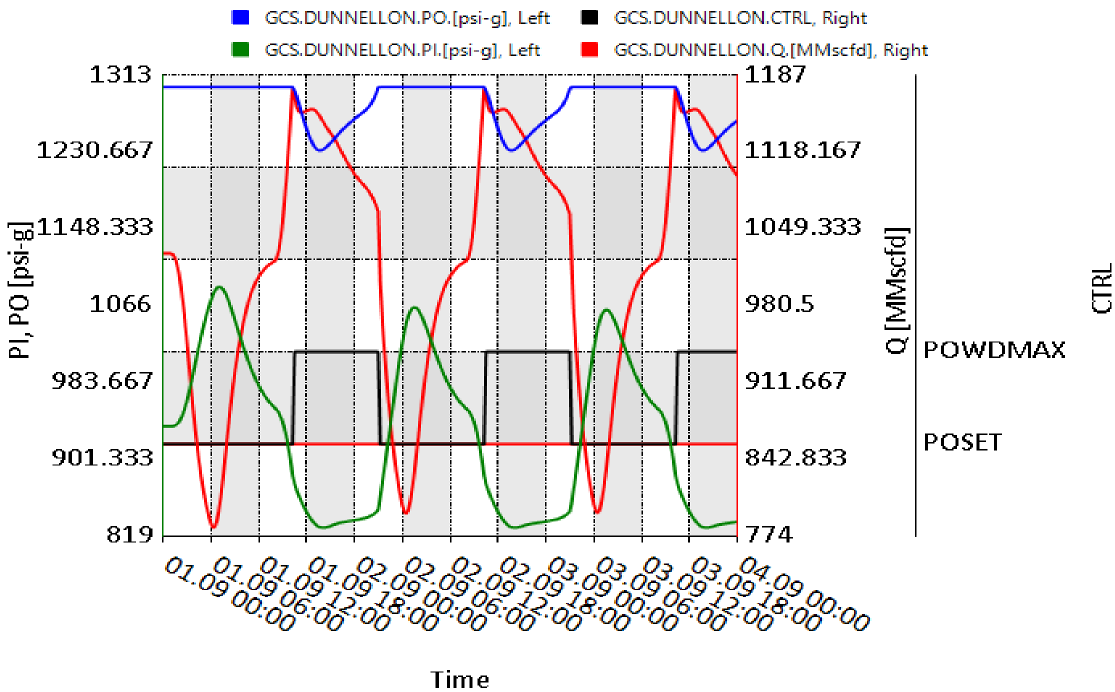

Figure 4-12
Compressor (GCS) Plot – DUNNELLON (PO – Outlet Pressure, PI – Inlet Pressure, CTRL – Control Mode, Q – Flow Rate)

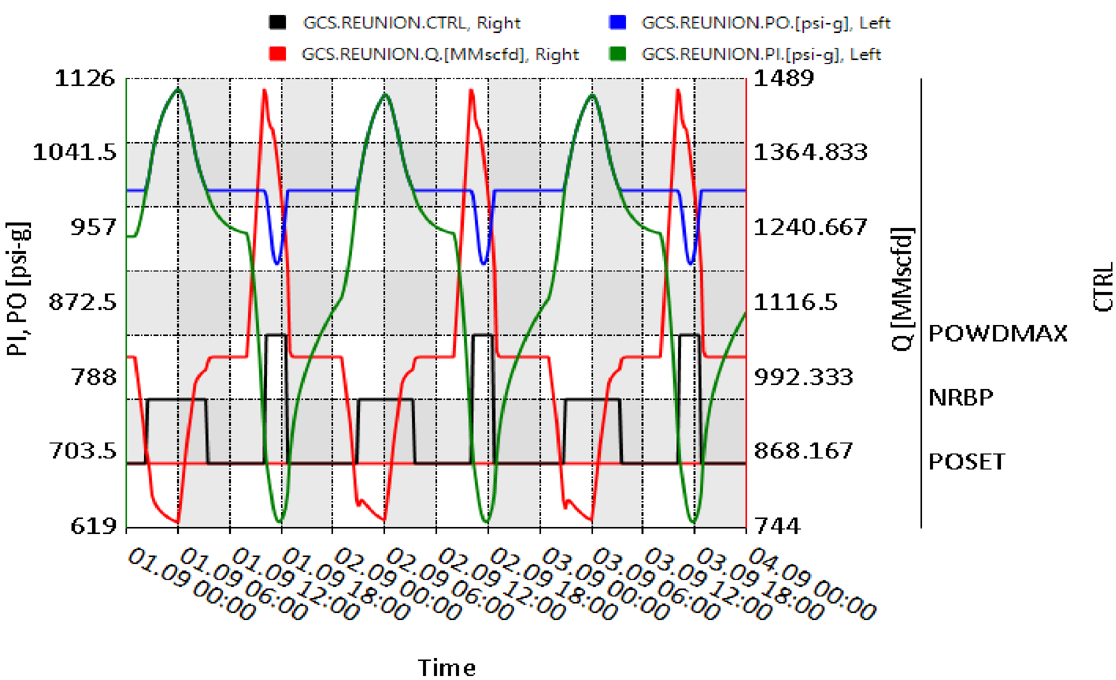

Figure 4-13
Compressor (GCS) Plot – REUNION (PO – Outlet Pressure, PI – Inlet Pressure, CTRL – Control Mode, Q – Flow Rate)

Demands

The pipeline network must maintain the minimum pressures at the required flow rates. The 2 active demands in the network are modeled with a minimum pressure requirement of 700 PSIG. The changes in flow rates at the demands during the day create large pressure variations between at those points. Table 4-7 and Figure 4-14 show the normalized gas demand profile used in the model that repeats daily. Figure 4-15 and Figure 4-16 show the pressure (P) and the flowrate (Q) at each demand (GDEM).

Table 4-7
Normalized usage profile

Hour	Value
0	1.000
1	1.000
2	0.890
3	0.725
4	0.725
5	0.725
6	0.725
7	0.890
8	1.000
9	1.000
10	1.000
11	1.000
12	1.000
13	1.000
14	1.000
15	1.220
16	1.440
17	1.440
18	1.220
19	1.000
20	1.000
21	1.000
22	1.000
23	1.000

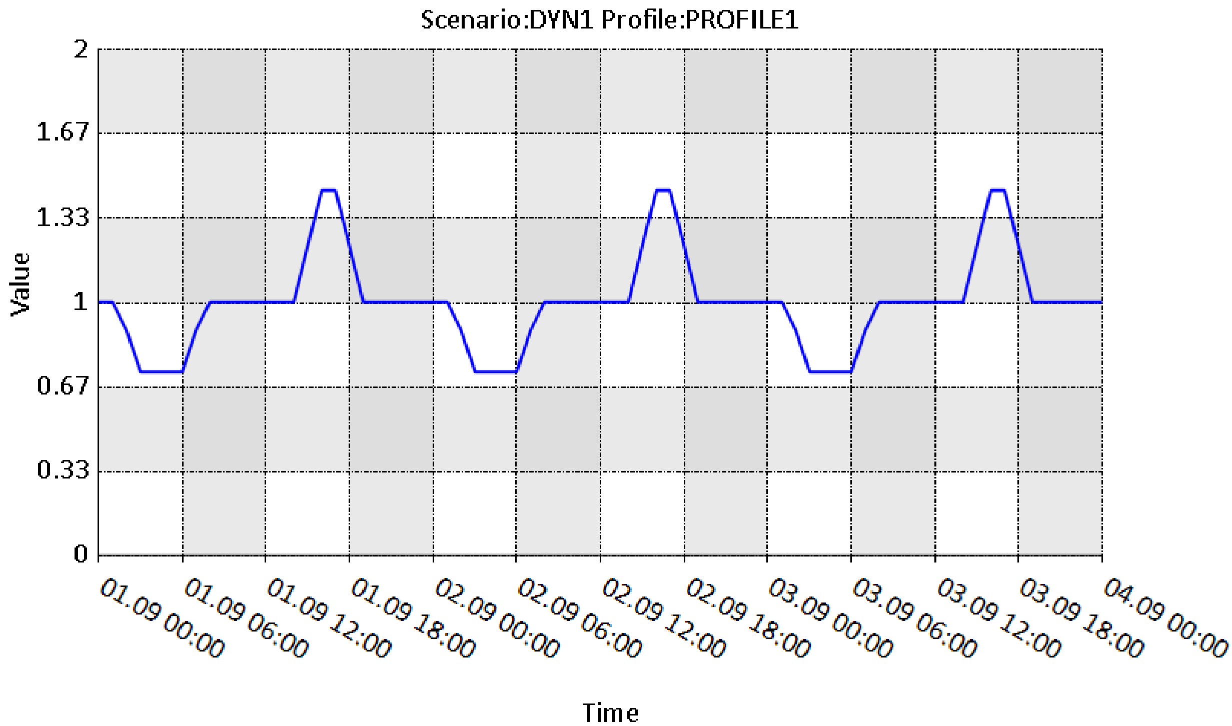

Figure 4-14
Normalized usage profile

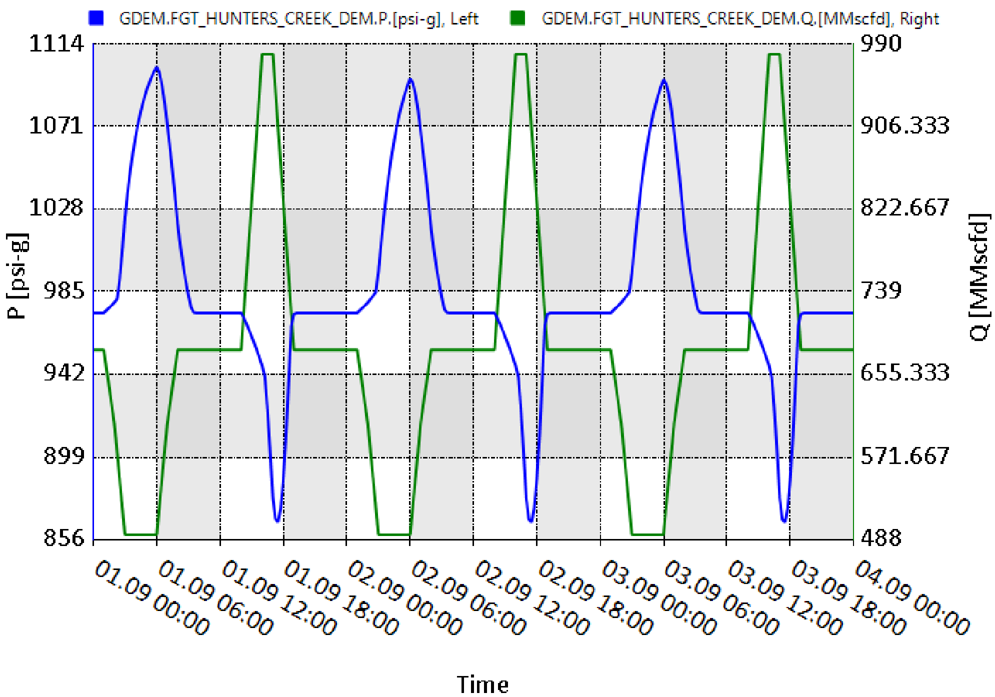

Figure 4-15
Demand (GDEM) Plot - FGT_HUNTERS_CREEK_DEM – Pressure (P) and Flow (Q)

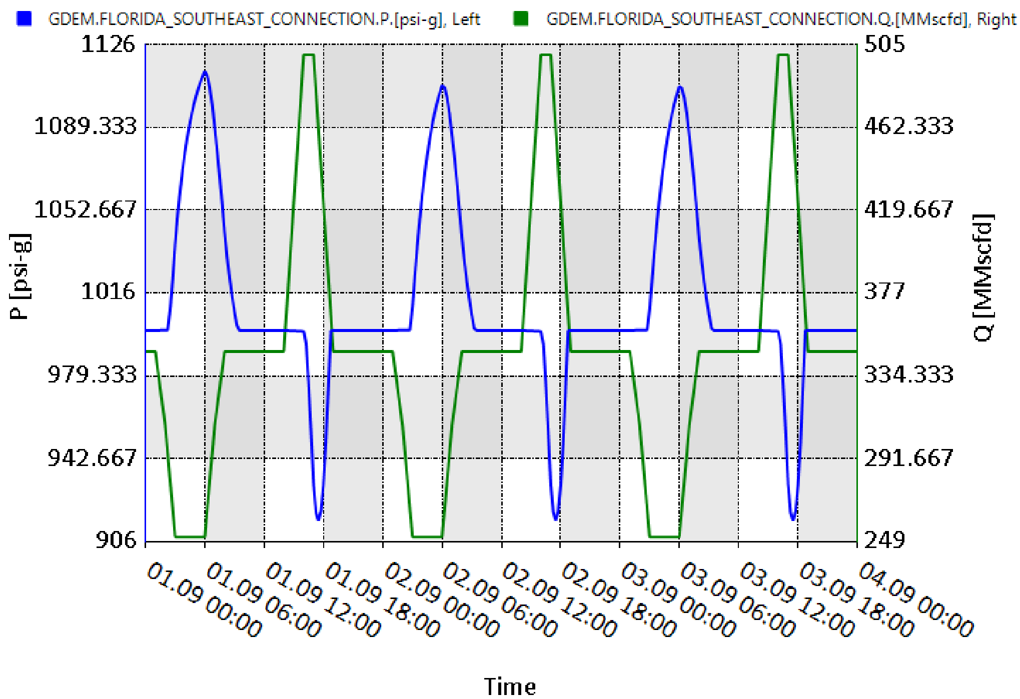

Figure 4-16
Demand (GDEM) Plot - FLORIDA_SOUTHEAST_CONNECTION – Pressure (P) and Flow (Q)

How to Use This Data

The data contained within this chapter in Tables 4-1 to 4-7 are the necessary components of data needed to simulate this gas network. The previous sections provide longer descriptions about the inputs and further reading can be found in Section 6. To those who might prefer a standalone file format, please contact the EPRI Principal Investigators or EPRI customer service.

5 CONCLUSION

The information and data contained within these sections provide the background and descriptions needed to model a basic natural gas network. In addition to providing realistic data for gas network modeling, this report aims to introduce gas simulation to an electric industry audience. Section 2 summarizes the necessary components of a high-fidelity gas network model, with details needed to run a hydraulic simulation. Section 3 provides background on the type of studies done for natural gas networks and the input and output of each. There are many similarities between gas and electric networks, many of which are discussed in Table 2-2 and Table 3-5. The basics of supply and demand are similar, but the fundamental instantaneous nature of electricity, travel at the speed to light, is not present in gas networks. The slower character of gas provides some benefits compared to electricity, including the ability to store energy in the pipelines. The differences between the two systems make modeling their interdependencies difficult, but their interconnectedness also makes it essential. While this data set represents a small piece of the larger US gas network, it provides an example data set for a gas network model to co-simulate gas and electricity. Increased co-simulation and coordination can help operators and planners prepare for future challenges, including extreme events and common-cause outages.

6
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