Impacts of Hydrogen Blending in Natural Gas Networks

Cooperative Research and Development Final Report

CRADA Number: CRD-20-17030

NREL Technical Contact: Bri-Mathias Hodge

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Technical Report
NREL/TP-6A40-85061
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Cooperative Research and Development Final Report

Report Date: September 16, 2022

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Southern California Gas Company

CRADA Number: CRD-20-17030

CRADA Title: Impacts of Hydrogen Blending in Natural Gas Networks

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$175,000.00
TOTALS	$175,000.00

Executive Summary of CRADA Work:

This work will develop a set of modeling tools that integrate hydrogen production, gas, and electric grid models to aid in the characterization of metrics to better understand the impacts of hydrogen blending into the natural gas grid.

CRADA benefit to DOE, Participant, and US Taxpayer: Adds new capability to the laboratory's core competencies.

Summary of Research Results:

Purpose:

The goal of this project is to create a modeling framework for an integrated model that can consider hydrogen production, blending into the natural system and impacts on the electric grid. Several important metrics will be developed including 1) metrics for system operation including gas composition throughout the gas network, 2) metrics for determining the lifetime impacts of hydrogen blending on the gas network equipment and 3) impacts of fuel composition on gas generators on the electric grid.

The major deliverables for this project include, developing a modeling framework that integrates a hydrogen production model, injection into the gas grid, a gas system model, and an electric grid model to enable the characterization and understanding of the benefits and impacts of hydrogen blending. In addition, a test system will be developed to showcase the capabilities of the integrated model. Finally, the modeling framework will be commercialized through public release.

Tasks performed by NREL and SoCalGas:

Task 1: Develop an electrolyzer model, leveraging existing software on record, that can determine hydrogen production under a variety of conditions and incorporates temporal and spatial variation. Ensure that appropriate operating, logical and any regulatory constraints are integrated into the model.

Task 1 involved leveraging existing modeling and software capabilities to characterize electrolyzer operations, with the subsequent goal of understanding how hydrogen might be injected into the existing natural gas pipeline system under a range of conditions. To that end, we developed a framework to evaluate how hydrogen injections from electrolyzers interact with the natural pipeline system, depicted in Figure 1. This framework provides the basis for assessing the impact of hydrogen injection on operation of gas system through the quantitative evaluation of the effects of different hydrogen injection profiles on facility operations.

The integrated model shown in the figure requires the use of a steady state and a transient flow model for the gas network. The natural gas model consists of a network of interconnected links and nodes, where the nodes function as demand, source/supply, storage, compressor stations (non-pipe inlet and non-pipe outlet node) nodes, and the links function as gas pipelines that transport natural gas between nodes. The simulation starts with the run of the steady state model to create the initial state of the system for transient simulation. The demand profile of natural gas power plants, generated from the power model, are used as an input for the gas model, wherein hourly profiles of system operating conditions and demand profiles are simulated throughout the simulation time, differentiated between non-power gas customers and NGPPs.

As mentioned above, hydrogen blending is modeled in this framework via injection from electrolyzer profiles. The injection point and injection level directly affect the quality of gas distributed through the network, meaning that both the injection points and levels must be carefully determined. At a given pressure, the specific energy per volume of hydrogen is much lower than the natural gas. As a result, a hydrogen enriched gas will need to manage a higher pressure when conveying a similar quantity of burning energy (typically using a calorific value). The framework accounts for this by checking results following the termination of the simulation model to detect if a violation occurred. In case of lack of gas or low pressure to satisfy the gas demand or any violation in technical parameters, operational changes are applied until a feasible solution is obtained.

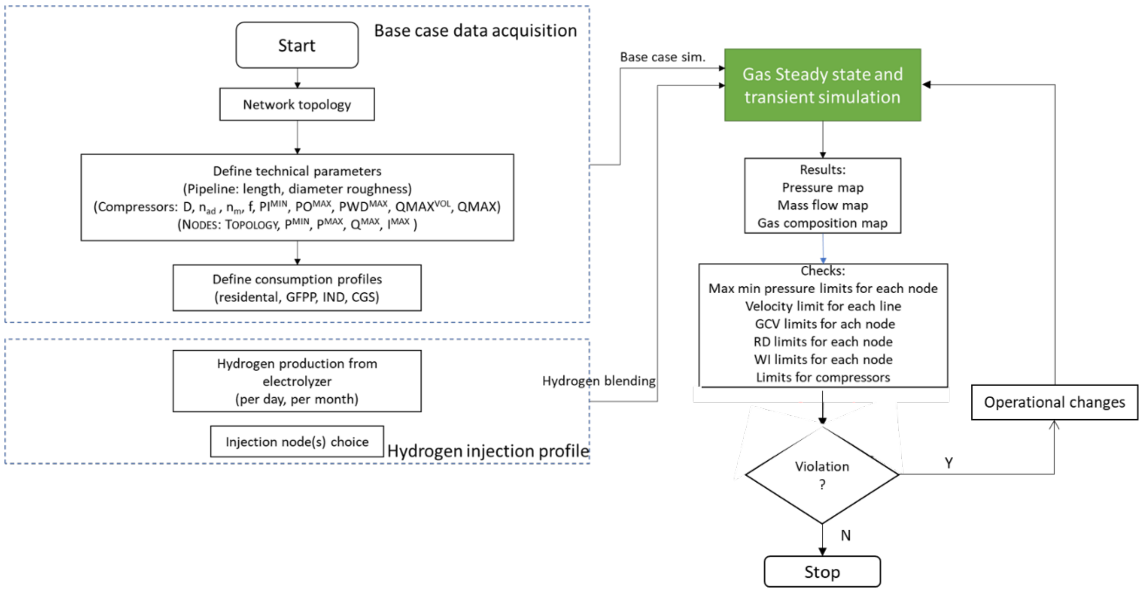

Figure 1. Illustration of the conceptual framework for modeling electrolyzer profiles and injection of hydrogen production as blends into natural gas pipeline networks.

Task 2: Verify that the SAInt model adequately characterizes gas network infrastructure relevant for SoCalGas, and appropriately represents mixtures of natural gas and hydrogen on the gas network.

To implement the framework described in Task 1 above, we utilized the Scenario Analysis Interface for Energy Systems (SAInt) simulation software. SAInt is a software application that allows the combined simulation of gas and electric power systems in a single time frame and simulation environment [1]. Because SAInt includes quality tracking—the accounting of gas composition and properties of the resulting blend—it is well suited to modeling the operational impact of electrolyzer hydrogen injections on the gas network.

Figure 2 illustrates a gas transmission network model in the SAInt software, with steady-state simulation of a test network. NREL worked closely with the partner SoCalGas to verify that the software appropriately captures the representation of key elements of the natural gas network and that the configuration of the test network would provide insight useful to them (see more discussion on the development of the test networks in Task 7 below).

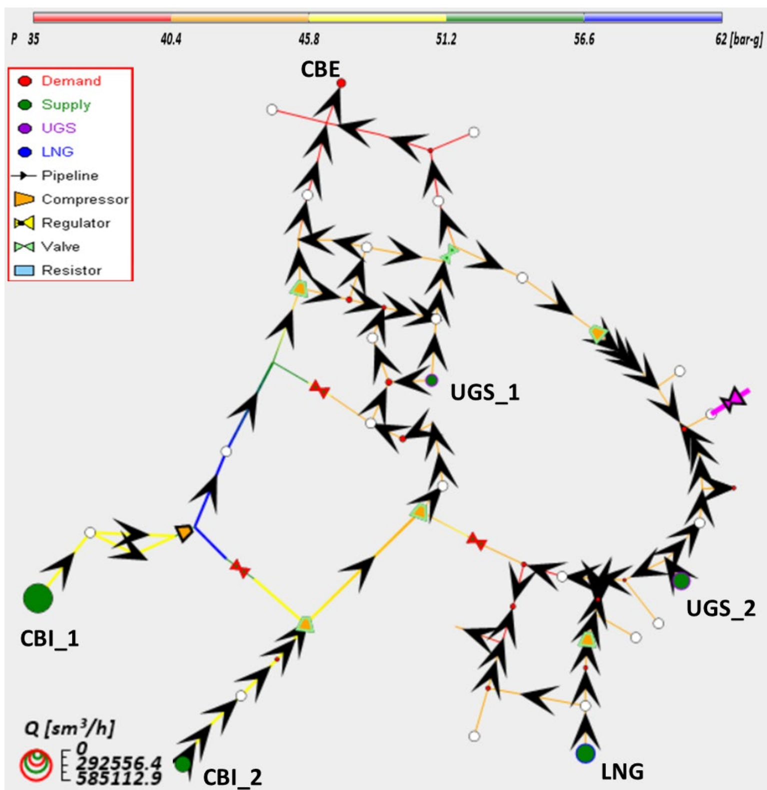

Figure 2. Depiction of SAInt steady-state pressure and load distribution for a test transmission network.

Task 3: Review and verify the modeling framework to ensure a directionally accurate characterization of a typical gas network that would emulate key operational features, infrastructure integrity, and safety characteristics.

Task 3 involved verifying that the SAInt modeling framework developed in Tasks 1 and 2 appropriately captures key operational features of the gas pipeline network. Transmission networks include different facilities sensitive to hydrogen injection, such as pipelines, compressors, underground gas storage facilities, meters, etc. In addition, gas-fired power plants and industrial users are also affected by the quality of the gas served. As the consumers connected to the distribution network are also fed from transmission pipelines, the gas quality requirements of the downstream distribution level are also affected by the gas quality at the transmission level.

We evaluated the how the modeling framework performed on a range of metrics, including nodal pressures, volumetric pipeline and nodal flow, compressor station operations (inlet and outlet pressure as well as driver power), and system linepack, among others. Working closely with the partners SoCalGas and encoord GmbH, we assessed whether the network characterizations were accurate. As an illustration, Figure 3 demonstrates the change in pressure of two different gas qualities—pure methane and blend of 70% hydrogen and 30% methane—as the gas moves through the pipeline system. As the gas moves away from the injection point over the pipeline pressure tends to decrease, necessitating the use of compressor stations (C1 and C2) to increase the pressure to sufficient levels of deliver. The figure illustrates that the hydrogen blend experiences faster pressure decrease over distance than pure methane, requiring the compressor stations to increase the pressure to higher levels than the pure methane mixture to compensate for the additional pressure loss. This results in the compressor stations drawing more power to supply the hydrogen gas blend at equivalent delivery pressure, demonstrated by the results in Figure 4 for compressor C1. These results are directionally consistent with the expected effect from blending hydrogen in natural gas mixtures, confirming that the framework proposed captures key operational features of the gas modeling network.

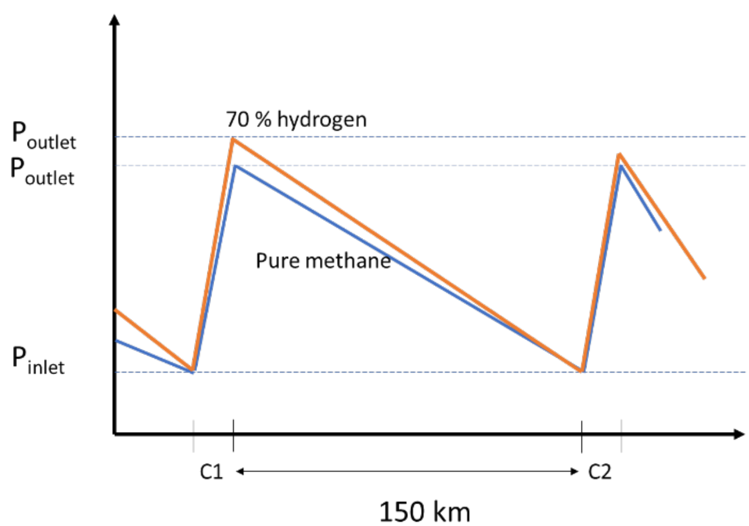

Figure 3. Gas pressure values over distance in the example transmission network. C1 and C2 points indicate locations of the compressor stations, which increase pressure from P_{inlet} to P_{outlet}.

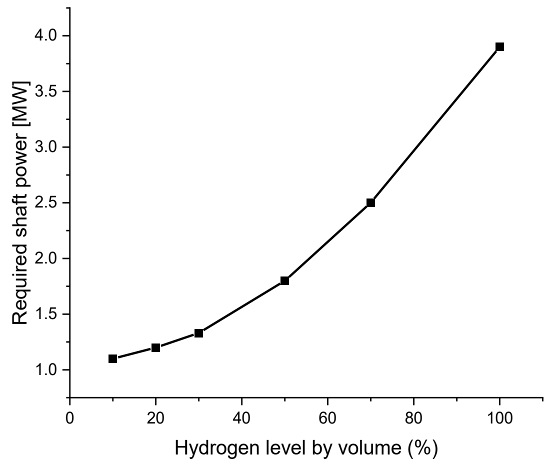

Figure 4. Required power for compressor station C1 at different hydrogen blend levels.

Task 4: Expand the model interface framework to exchange data and constraints with the electrolyzer model, gas grid model, and electricity grid model.

Having successfully validated the performance of the gas and hydrogen injection framework in Task 3, we then expand the modeling approach to account for interactions with the electric grid. A primary point of coupling between the gas and electricity networks is the natural gas power plant, which consumer natural gas—traditionally delivered via the pipeline network as a fuel to generate electricity. An important aspect of this interaction is that gas fired power plants typically have a minimum pressure requirement for gas delivered. In instances where the pressure falls below this requirement, the gas power plant is forced to curtail generation, producing less electricity than scheduled or in many cases shutting off entirely.

Task 4 set out to capture this dynamic in the modeling framework. To do this, we started by configuring the requested gas demand of the natural gas generators in the network based on results from production cost modeling run of the electricity network, which captures operational dynamics of the power plants, electric transmission network, and electric loads. The gas demand is determined based on the gas facilities' heat rate—the fuel required to produce a unit of electrical output—and the dispatch set point based on the production cost model. Figure 5 provides an example of the load profiles of nine natural gas plants based on the production cost modeling runs for a winter demand week in January. Although the production cost modeling was conducted using Energy Exemplar's PLEXOS modeling tool in this study, SAInt has more recently incorporated unit commitment and economic dispatch into its simulation software, enabling a more direct linkage between gas, electric, and hydrogen production modules for future analyses.

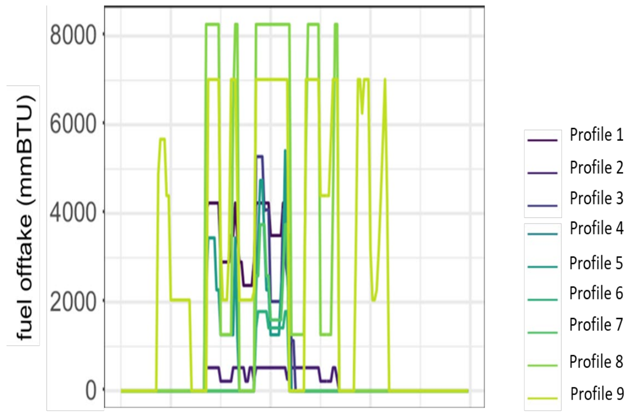

Figure 5. Natural gas fuel offtake for modeled natural gas fired power plants, which serve as the coupling point between the electric and natural gas networks.

As mentioned above, if the pressures at natural gas power plant delivery nodes falls below the minimum delivery pressure, the unit is forced to curtail some of its expected power output. Such curtailments can be measured on the gas network side through the metric of gas not served (GNS), which reflects the difference between the requested gas delivery and the actual amount of gas successfully delivered. Figure 6 depicts the total GNS for a system evaluated with a gas blend of 20% hydrogen injected at two nodes in the network, reflecting that fact that in this scenario, the injection results in delivery pressure are below the requirement, yielding curtailment and GNS. The results indicate that the framework proposed successfully captures interactions between the power and gas networks, including when the gas network accounts for natural gas and hydrogen blends based on injections from electrolyzers.

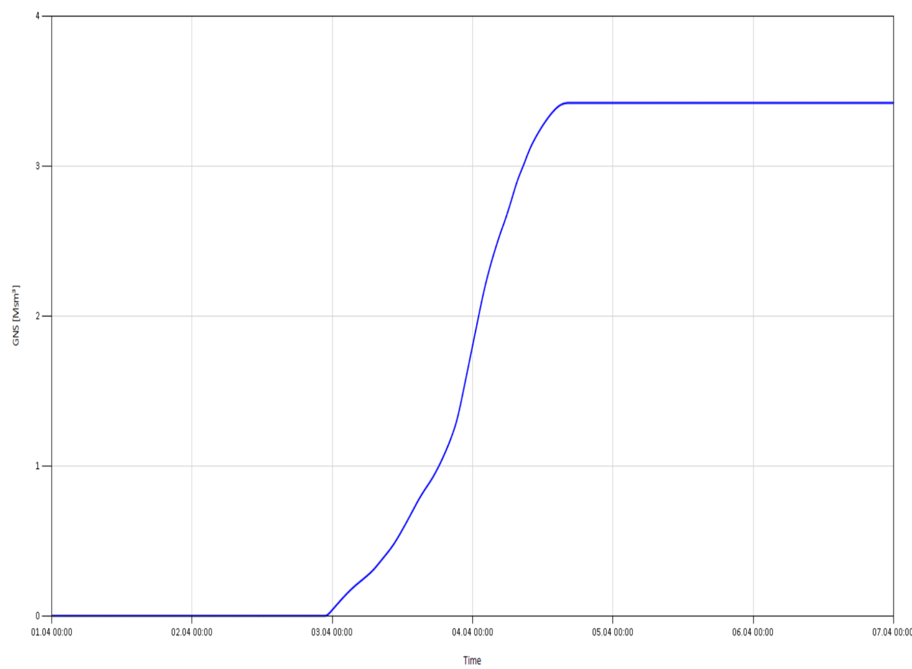

Figure 6. Total GNS for the natural gas transmission network test case scenario.

Task 5: Develop a tool to characterize the extent of blending (i.e., gas composition) across the gas network for different hydrogen injection levels and at different locations.

As alluded to in Task 4, a key component for understanding the impacts of hydrogen blending into the natural gas network is the capability to track gas quality, or the composition of a gas, over different parts of the network based on the various injection points of different gases and the topology of the system. Tracking the gas composition over the network is critical as different levels of hydrogen and natural gas blends have different characteristics, such as calorific value, relative density, and Wobbe Index, reflected in Table 1 below. These characteristics determine important elements of the system operation; for example, the volume of gas required for delivery to a natural gas plant is dependent on the calorific value of the gas.

Table 1. Summarize of characteristics of different levels of hydrogen blends.

Gas Properties	Default Gas	Hydrogen 10	Hydrogen 20	Hydrogen 30	Hydrogen 50
Gross calorific value [MJ/sm^3]	41.895	39.197	36.498	33.8	28.403
Molar weight of gas mixture[g/mol]	17.619	16.216	14.814	13.411	10.606
Relative density	0.608	0.56	0.511	0.463	0.366
Wobbe Index [MJ/sm^3]	53.714	52.383	51.034	49.671	46.937

The SAInt modeling software and framework deployed in this project provides this functionality as part of its transient gas network simulation, thus enabling characterization of gas composition at any part of the network, as well as direct integration of the characteristics of that particular gas composition into the simulation. Figure 7 provides a demonstration of the supply trace of gas injection from one of the import stations, with gas composition due to mixing evaluated at each node in the system.

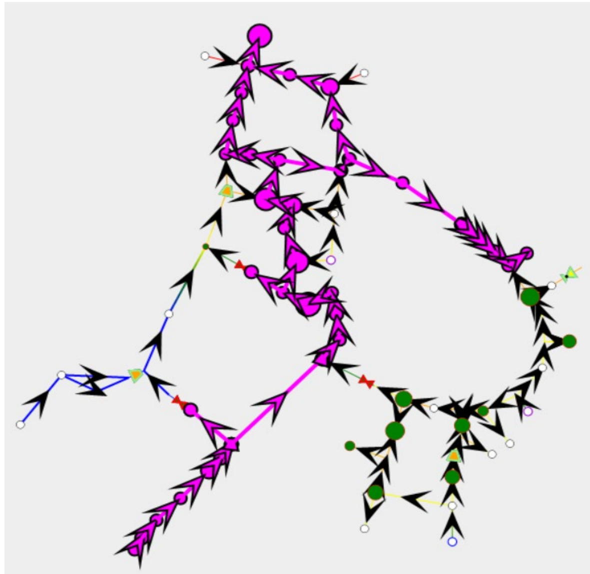

Figure 7. Depiction of tracking of gas flow from injection point to offtake node.

Task 6: Develop a tool to capture the metrics necessary to determine lifetime impacts of hydrogen blending on the gas network equipment

The appropriate limit on hydrogen blending levels is likely to vary significantly in response to factors such as hydrogen injection location, gas network characteristics, natural gas composition, flow rate, and downstream end-use applications. Table 2 provides a summary of some of the key challenges explored in the project, including some of the lifetime impacts on gas network equipment.

Table 2. Summary of some of the operational and lifetime impacts of hydrogen blending

Key challenges		
Operational	Planning	Economic
-Operation and system impacts -Pressure fluctuations through pipelines -Gas quality considerations -Technical limits of facilities -Infrastructural flexibility	-Leakage rates and detection -Metal embrittlement -Steel and plastic compatibility -Electrical equipment compatibility -End user gas quality requirements -Measurement accuracy -Advanced appliance testing -Reliability of facilities -Environmental factors -Risk of explosion	-Infrastructural upgrades -End user switching costs -Variable hydrogen production cost -Hydrogen separation

One of the key areas affected by hydrogen blending is expected to be transmission pipelines. Transmission pipelines generally use low-carbon and high-strength steel; simultaneous hydrogen exposure and mechanical loads on pipe steel can impose problems related to hydrogen embrittlement. Hydrogen embrittlement is a complicated failure process that is difficult to detect and influenced by many parameters, of which complete understanding is still lacking. Although the framework developed in this project helps to provide the context for understanding the operational implications of hydrogen blending, more work is needed to be done to understand the lifetime materials impacts on parts of the system. To that end, the work in this project has built the foundation for other research efforts, including the HyBlend initiative which intends to provide a deeper analysis of this issue.

Task 7: Complete development of a test system to showcase the capabilities of the integrated model.

In order to demonstrate the modeling framework capabilities, two test systems were developed: a transmission network test case and a distribution network test case. Table 3 provides an overview of the two test networks, while Table 4 illustrates the results of various hydrogen injection and blending scenarios for the distribution network. The quantity of unserved gas demand varies depending on the hydrogen blending and injection profile scenario, illustrating the capability of the integrated model.

Table 3. Summary of key features of the test system developed.

	Transmission	Distribution
Nodes: total / supply / demand	91 / 2 / 46	373 / 2 / 66
LNG / underground storage	1 / 2	-
Pipelines: segments / total length	89 / 3,725 km	376 / 37.8 km
Compressor stations	2	-

Table 4. Summary of key metrics and results for different hydrogen injection scenarios for the distribution network test system, including gas not served (GNS) and energy not served (ENS).

Scenario	H2 blend at transmission injection node [%]	H2 blend at the electrolyzer node [% of transmission injection]	GNS [ksm3]	ENS [GJ]	# of Nodes with GNS	Volumetric flow at the transmission network injection node [ksm^3]	Volumetric flow at the electrolyzer node [ksm^3]
1	0	0	0	0	0	150.55	0
2	0	10	0	0	0	146.07	13.95
3	0	20	0	0	0	143.69	26.7
4	0	30	0	0	0	138.61	39.48
5	10	0	0.013	0.48	2	167.06	0
6	10	10	0	0	0	161.61	15.44
7	10	20	0	0	0	157.81	29.58
8	10	30	0	0	0	152.55	43.14
9	20	0	0.337	11.56	5	179.86	0
10	20	10	0.008	0.27	2	173.89	16.6
11	20	20	0	0	0	169.10	31.83
12	20	30	0	0	0	163.28	46.48
13	30	0	1.162	36.78	10	194.41	0
14	30	10	0.306	9.69	3	187.91	17.96
15	30	20	0.015	0.48	2	182.20	34.44
16	30	30	0	0	0	175.71	50.02

Task 8: Hold project meetings approximately every three months to track progress and receive feedback from the project team.

The project team held regular meetings to track progress and receive feedback.

Task 9: Commercialize modeling framework through public release.

The modeling framework is planned to be made publicly available through pending publications of the analysis in the hope of disseminating information on the approach for wider use among the natural gas and electric grid modeling communities.

For greater detail on the process and analysis, the researchers are publishing a forthcoming journal article titled *A review of technical and regulatory limits for hydrogen blending in natural gas pipelines*. In the event the article is not accepted by any currently seeking publication in academic or industry journal, it may be published by NREL.

References:

[1] Pambour KA, Cakir Erdener B, Bolado-Lavin R, Dijkema GPJ. "SAInt – A novel quasi-dynamic model for assessing security of supply in coupled gas and electricity transmission networks". *Appl Energy* 2017;203:829–57. https://doi.org/10.1016/j.apenergy.2017.05.142.

Subject Invention Listings:

None

ROI #:

None