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THE IMPACTS OF BLENDING HYDROGEN ON MAINLINE NATURAL GAS COMPRESSION

Author: David Campbell P. Tech (Eng), MBA

Abstract

The aim of this paper is to determine if incorporating hydrogen into a mainline natural gas transmission system Canada will result in positive impacts.. The impacts to centrifugal compressor and pipeline performance as well as gas turbine combustion, emissions and overall power output are impacted with increasing levels of hydrogen. The findings suggest that once a review for acceptability and applicable modifications have been completed, blending of hydrogen into a mainline pipeline should be done in a stepped approach starting with 2.5% then increasing to a 5% blend rate. The stepped approach is based on the impact to existing legacy equipment and the amount of hydrogen that can reasonably be produced in a sustainable way. A suggestion for future research on the impacts of blending hydrogen on the pipeline metallurgy as well as private sector support and research studies in the development of a hydrogen strategy, policy and regulation for Canada.

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Abbreviations

Abbreviation	Definition
AB	Alberta (Province in Canada)
atm	atmospheric conditions
ATR	Auto Thermal Reforming
bara	Bar at atmospheric conditions
BC	British Columbia (Province in Canada)
BCF	Billion cubic feet
btu	British Thermal Unit
btu/scf	British Thermal Unit of energy per standard cubic foot
C	Celsius
C2H2	Acetylene
C6H6	Benzene
CAD	Canadian Dollar
CCUS	Carbon Capture Utilization Storage
CH4	Methane
cm	Centimeter
CO	Carbon Monoxide
CO2	Carbon Dioxide
CSA	Canadian Standards Association
DLE	Dry Low Emissions
EOR	Enhanced Oil Recovery
g/GJ	Grams per Gigawatt
GHG	Green House Gas
GT	Gas Turbine
H2	Hydrogen
H20	Water
HIC	Hydrogen Induced Cracking
hp (HP)	Horsepower
J-T	Joules Thompson
K	Kelvin
kg	Kilogram
kg/hr	Kilogram per hour
LFL	Lower Flammable Limit
LOHC	Liquid Organic Hydrogen Carriers
m2	square meter
MESG	Maximum Experimental Safe Gap
mm	Millimetre

Abbreviation	Definition
MMSCFD	Million standard cubic feet per day
Mt CO2e/year	Million tonnes of carbon dioxide equivalent per year
MW	Megawatt
NEBC	North east British Columbia
NEC	National Electric Code
NG	Natural Gas
NGL	Natural Gas Liquids
NOx	Common abbreviation for three chemical compounds of concern for air pollution. Nitric Oxide (NO), Nitrogen Dioxide (NO2) and Nitrous Oxide (N2O)
O2	Oxygen
OEM	Original Equipment Manufacturer
PJ	Petajoules
PMP	Pulsed Methane Pyrolysis
ppm	Part per million
ppmv	Part per million in terms of volume
PV	Photovoltaic
RNG	Renewable Natural Gas
scf	Standard Cubic Foot
SCR	Selective Catalytic Reduction
sec	Second
SMR	Steam Methane Reforming
TRL	Technology Readiness Level
TWhr	Terawatt Hour
UFL	Upper Flammable Limit
UHC	Unburned Hydrocarbons
USD	United States Dollar
VMR	Verified Market Research (company)
vol	Volume
WHR	Waste heat recovery
Wobbe Number	Fuel Energy Content

1 Introduction

There is a need for a comprehensive evaluation of the impacts and benefits of incorporating hydrogen into a natural gas (NG) transmission system, in Western Canada. Society, government, and industry are putting emphasis on carbon reduction, and hydrogen is one solution that is being presented. Research has been completed on different facets of blending hydrogen, but a comprehensive review of the impacts on a NG transmission system needs to be completed.

As the energy sector strives for carbon intensity reduction by 2030 and to achieve 'net-zero' by 2050 many different technologies and strategies are being explored (Enbridge, 2021). One of the strategies being looked at as a way to decarbonize NG systems is to blend hydrogen into the existing pipeline transmission system (NREL.gov, 2023) (Government of Canada, 2020).

The government of Canada is expecting that 60% of end-use energy needs will be provided by low-carbon fuels by 2050. Hydrogen would play a large role by providing approximately 30% of this energy (Government of Canada, 2020). Hydrogen seems to have a place in the energy landscape, however some question if it is truly a good replacement for NG, if the intent is combustion. (Kuppe, 2020)

2 Literature Review

Hydrogen General

Hydrogen is being looked at by countries, and the private sector, to reduce carbon intensity in hard to abate sectors like long-haul transportation, air and rail transport. Sentiment around hydrogen has been shifting, it has been gaining acceptance globally as a part of the overall energy mix (World Energy Council, 2021). In Canada hydrogen is currently used as a feed stock for several industrial processes like petroleum refining, upgrading bitumen, producing ammonia, methanol production and steel production (Government of Canada, 2020).

According to the Canadian Hydrogen Strategy, Canada is looking to decarbonize the NG system by blending hydrogen in BC, Alberta and Ontario (Government of Canada, 2020). Currently Canada lacks an overarching regulatory and policy framework that covers hydrogen. Policies are not consistent across regions and provinces and have resulted in a 'patchwork' of frameworks and slows adoption of hydrogen (Government of Canada, 2020).

Equipment – Emissions and Performance

Bloomberg puts forward that a large program of upgrades to existing infrastructure would need to be completed prior to introducing hydrogen to the NG system (Bloomberg, 2020). While this may be true for pure hydrogen and high-hydrogen-blends, lower blends of hydrogen may be acceptable within the NG system with modest upgrades (Kurz, et al., 2019).

Impacts on Gas Turbine Emissions

GT engines need to comply with governmental regulations. This means that combustion GT engines with power ratings from 4-70 MW must limit their NOx emissions to 25 ppmv at 15% O2 (ECC Canada, 2017).

The term NOx is a common abbreviation for three chemical compounds of concern for air pollution. Nitric Oxide (NO), Nitrogen Dioxide (NO2) and Nitrous Oxide (N2O), which is a greenhouse gas. NOx emissions are generally related to the combustion of hydrocarbons and are directly related to the temperature of the combustion flame. The amount of NOx emissions increases as the temperature of the combustion flame increases.

GT engines currently use two types of combustion systems within the NG transmission system. Conventional combustion which is also known as diffusion combustion and lean pre-mix or Dry Low Emissions (DLE) combustion. Diffusion combustion has been utilized for several decades and is able to burn various fuel mixtures because the fuel is combined with combustion air in the combustion chamber, not premixed before entering the combustion chamber as shown in Figure 1. This allows for high turndown ratios and fuel flexibility, but results in a high adiabatic flame temperature (Kurz, et al., 2019). Adiabatic flame temperature is the highest temperature that the products of combustion can achieve without heat loss (Zhang, 2009). Pollutants like NOx, CO and UHC increase proportionally with the adiabatic flame temperature. Diffusion combustion pollutant emissions can be reduced by introducing water into the combustion air inlet, reducing the combustion flame temperature (Kurz, et al., 2019) (Kurz, et al., 2020).

DLE combustion is a newer technology than diffusion combustion and produces lower emissions. The main difference between the two combustion systems is how the fuel is introduced into the combustion chamber. DLE combustion premixes the fuel with combustion air prior to entering the combustion chamber, this results in more predictable (lower) emissions of NOx and CO. The fuel-air ratio is lower with DLE and results in a lower adiabatic flame temperature. For hydrogen-blended NG between 0-30% the DLE combustion system there is a small increase in NOx and an increase of less than one part per million (ppm) for CO and UHC (Kurz, et al., 2019) (Welch, 2021).

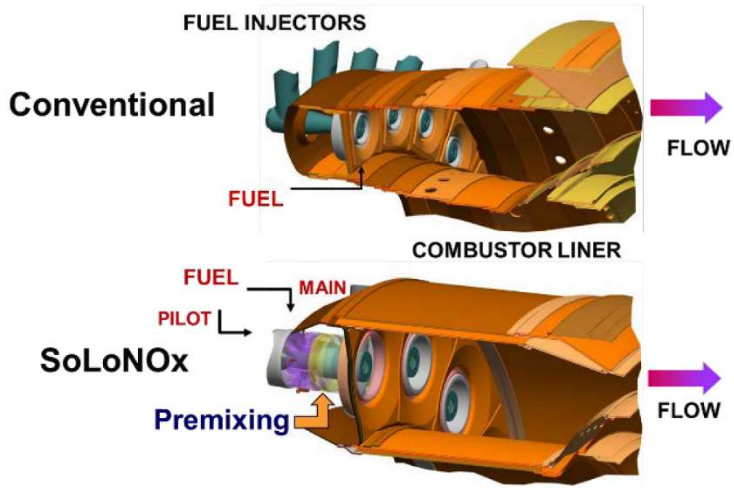

Figure 1: Conventional versus SoLoNOx (DLE) Combustion Chambers

(Kurz, et al., 2019)

Impacts on Gas Turbine Performance

Three main operability issues for GTs as hydrogen-blending increases is autoignition, flashback and combustion instability (Burnes & Camou, 2019).

Autoignition

Autoignition happens when a fuel ignites with no external ignition source, the fuel mixture reaches its autoignition temperature and ignites (Manha, 2009). A GT combustion system needs to provide reliable, safe and efficient operation, if the fuel has a propensity to auto-ignite before the planned ignition, there is risk to personnel safety and equipment damage. Hydrogen has a wider range of flammability, as the percentage of hydrogen-blended into NG increases the upper and lower flammability limit (UFL, LFL) of the mixture widens. This increases the risk of autoignition within the combustion system of the GT and must be managed within the design, for safe operation (Burnes & Camou, 2019).

Flashback

Flashback in a GT combustion system occurs when the flame travels back upstream, because the flame speed is higher than the flowrate of the incoming fuel (Palies, 2020). Due to the combustor design, DLE GT combustion for GT technology today is limited to 20-30% hydrogen-blend (Kurz, et al., 2019). Many manufacturers are working on new multi-flame or micro-mix type combustion burners (Tekin, et al., 2018) (Welch, 2021).

Combustion Instability

Combustion instability can impact engine efficiency, cause mechanical vibration, increase the chance of the combustion flame going out and in extreme cases cause mechanical damage to the combustor

(Cuenot, 2016). Due to the combustion flame speed, wider flammability range and ignition behaviour, GTs must be designed to run on elevated levels of hydrogen (Burnes & Camou, 2019).

Impacts on Centrifugal Compressor Performance

Centrifugal gas compressors used on mainline NG transmission systems are typically designed for high-flow, low-head pressure applications. These compressors are designed for pipeline quality gas with high levels of methane and other minor constituents, including low levels of hydrogen. Hydrogen has high mass calorific value, but low volume calorific value when compared to NG. This means that as hydrogen is blended into the system, more flow through the gas compressor is required to maintain the overall energy content in the pipeline. Also, hydrogen has a low molecular weight in comparison to NG, which makes it significantly more difficult to compress. Taking into consideration the challenges that arise with increasing levels of hydrogen the typical mainline centrifugal compressor is capable of compressing 0-20% hydrogen-blended NG, but must be reviewed on a case-by-case basis (Kurz, et al., 2020).

Equipment – Life Expectancy

Impacts on Pipeline Materials

Metal piping can degrade when exposed to hydrogen over a long period, particularly at high concentrations. Hydrogen embrittlement can cause loss of ductility, martensitic steels are particularly impacted by hydrogen and should not be used with higher blends of hydrogen (Kurz, et al., 2019) (US DOE, 2022). The impact is dependant on many factors, including the type of steel, and needs to be evaluated on a case-by-case basis (Melania, et al., 2013) (The Welding Institute, 2022). There are regions like Hawaii that have been blending hydrogen into their NG system since 2011. The blend ranges from 5-12% hydrogen into the existing system with no significant upgrades to material (General Motors, 2011).

Impacts on Centrifugal Compressors

Centrifugal gas compressor bodies are made of cast steel then carefully machined to ensure efficient flow. Mainline compressor bodies designed for NG service can accept up to 20% hydrogen-blend. It is also important to consider other auxiliary components that would meet hydrogen-blended gas. Typically, 300 series stainless steel is used for instrument tubing lines, and fittings, in hydrogen service (Kurz, et al., 2020).

Impacts on Gas Turbine Engines

A consideration for DLE combustion systems is the speed of the combustion flame, or ‘flame speed’. This is the rate at which the flame will travel through the air-fuel mixture at a certain pressure and temperature. Since the air and fuel in a diffusion combustion system is mixed in the fuel chamber the flame speed does not have an impact. However, for DLE combustion the air-fuel mixture is premixed prior to the combustion chamber, this means that the rate at which the air and fuel is mixed and fed into the combustion chamber must be greater than the flame speed (Kurz, et al., 2019).

Pressure oscillations in the combustion chamber can occur due to heat released from the combustion flame. The result of the oscillations can impact combustion stability and is often termed 'combustion rumble'. If the oscillations are left unchecked, they can lead to mechanical and thermal damage to the GT. Due to the flame speed of hydrogen, additional analysis is required to adjust the fuel-air ratio, fuel supply impedance and the flame temperature, with the goal of reducing the pressure oscillations (Kurz, et al., 2019) (Huber & Polifke, 2008).

For hydrogen-blends of 5% and less, there is no impact to NOx emissions and durability for the latest DLE or diffusion combustion systems. For existing equipment a review of the equipment needs to be done prior to introducing hydrogen-blends for fuel (Kurz, et al., 2019).

Pipeline Capacity

There are four main impacts on pipeline capacity due to blending hydrogen into the transmission system, they are Volume Calorific Value, Compressibility Factor, Dynamic Viscosity and Heat Capacity, the following section will outline the impacts of each.

Volumetric Calorific Value

The mass calorific value of hydrogen is higher than NG, however the volume calorific value of hydrogen is lower than NG. This means that 1 kg of hydrogen contains more energy than 1 kg of NG, but 1 m^3 of hydrogen contains less energy than 1 m^3 NG. This makes hydrogen fuel ideal for applications like rocket fuel, but when blended with NG it reduces the overall energy content of the transmission system (Kurz, et al., 2020). When compared at the same pressure, hydrogen is about one third the energy content of NG (H2 = 274 btu/scf; CH4 = 909 btu/scf) (Lyons & Tarver, 2020). This is represented in table 1, as the Wobbe Index decreases as the percentage of hydrogen is increased. Wobbe Index is a way to determine how much energy is available in the NG mixture, it is calculated using the 'gross heating value of the gas divided by the square root of the gases specific gravity' (Law Insider, 2022). One result of introducing hydrogen to a NG transmission is a reduction of the overall volumetric calorific value.

Compressibility Factor

As the percentage of hydrogen increases in the transmission line the compressibility factor increases. The compressibility of a gas indicates how much work it will take to compress the gas from one pressure to a higher pressure. As the compressibility increases the amount of work required to compress the gas increases (Ariel Corp, 2005). The compressibility of NG as the percentage of hydrogen is increased is shown in Figure 2.

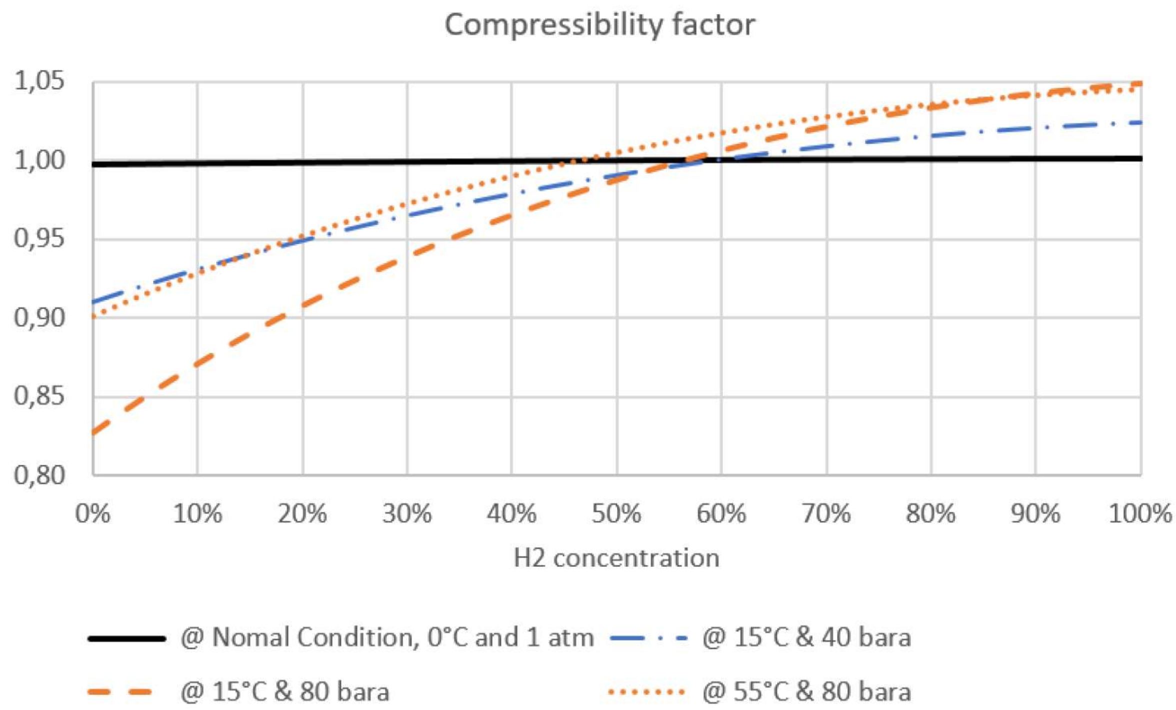

Figure 2: Compressibility of Natural Gas as Hydrogen Content is Increased

(Kurz, et al., 2019)

Dynamic Viscosity

The dynamic viscosity of a gas represents how much the gas resists moving over another layer of fluid (Soares, 2015). The lower the dynamic viscosity the easier it is for the gas to travel through the transmission line. Pure hydrogen flows nearly three times faster than pure methane through a pipeline (Bloomberg, 2020). As hydrogen is blended into the NG transmission line the dynamic viscosity drops until approximately 65% hydrogen content, then the dynamic viscosity begins to climb again. Based strictly on dynamic viscosity the hydrogen-blended gas will flow most easily at 65% hydrogen concentration (Kurz, et al., 2019).

Heat Capacity

Hydrogen demonstrates a negative Joules Thompson (J-T) number, this means that the temperature of the hydrogen will increase as the pressure drops. This is the opposite of NG, as the pressure of NG drops the temperature drops as well. In the analysis done by Li, et al, the J-T number of the gas mixture remains linear as the percentage of hydrogen increases up to approximately 30%. At 30% hydrogen the J-T number decreases by 40-50% when compared to NG. This can have a positive impact that may prevent the formation of hydrates in the NG system, specifically at valves. However, this will have a negative impact on NGL recovery, which relies heavily on the J-T effect to encourage NGL drop out. A larger pressure drop will be required to remove NG liquids from hydrogen-blended NG (Li, et al., 2021) (Kurz, et al., 2019).

Hydrogen-blends can also impact the accuracy of NG meters, although the impact varies with the type of meter. The impact to accuracy may not mean that the meter needs to be replaced, the variance is typically within the acceptable range of recalibration when the NG blend is less than 50% hydrogen (Melania, et al., 2013).

Safety and Additional Social Impacts of Hydrogen-Blending

General safety claims regarding blending of hydrogen into the NG system are difficult because risks change from location to location. Risk factors are assessed for varying hydrogen-blends in different sections of the system, for example mainlines, distribution and service lines. Large scale energy systems all pose different types of risks to the environment and human health, including nuclear, fossil fuel and renewable energy systems. In cases where NG leaks and causes an explosion, an increase of hydrogen of up to 20% results in a minor increase in the severity of the explosion (Melania, et al., 2013).

In hydrogen-blends of greater than 50%, risks in distribution and service lines increase because these lines are typically in confined spaces where gas that leaks could accumulate. The gas that accumulates may cause a risk of explosion or a risk to human health (Melania, et al., 2013). Hydrogen is the smallest element this makes it very permeable in pipeline systems. Special consideration needs to be given to seals, diaphragms and other components made from elastomers. When exposed the hydrogen can permeate the elastomer, if the system is depressurized quickly the elastomer is at risk of explosive decompression issues (Kurz, et al., 2020) (Kurz, et al., 2019).

For GT engines utilizing DLE technology to burn hydrogen-blended fuel, the flame speed is a consideration. The laminar flame speed increases quickly as the percentage of hydrogen increases as shown in Table 1 (Kurz, et al., 2019). Due to the increased flame speed there is risk of flashback into the pre-mix fuel injector, causing damage to the equipment and a safety risk (Kurz, et al., 2020) (Welch, 2021) (US DOE, 2022).

When hydrogen burns the flame is nearly invisible to the human eye, therefore special flame detectors are required (US DOE, 2022). Hydrogen is flammable over a large range (from 4-75% in air). This leads to concerns of the GT flame going out, allowing the potential for an explosive mixture in the exhaust (Kurz, et al., 2019). The GT exhaust may include many components including a silencer, supplementary burner and heat recovery steam generator. An illustration of a typical GT exhaust with waste heat recovery (WHR) is show in figure 3. At mixtures of 20% and less the risk is low, however above 20% hydrogen fuel gas mixture the risk is greater. Also due to the wide LFL and UFL, electrical equipment and enclosures need to be specifically designed for hydrogen. Some original equipment manufacturers (OEMs) recommend electrical device changes, additional fire and gas detection and upgrades to the fuel system when the percentage of hydrogen is above than 4% (Kurz, et al., 2020). Like NG, hydrogen is odorless and colorless, however mercaptans can be added to NG so that it detectable by smell. Mercaptans contaminate hydrogen fuel cells, so they cannot be added to hydrogen (HydrogenAssociation.org, 2020).

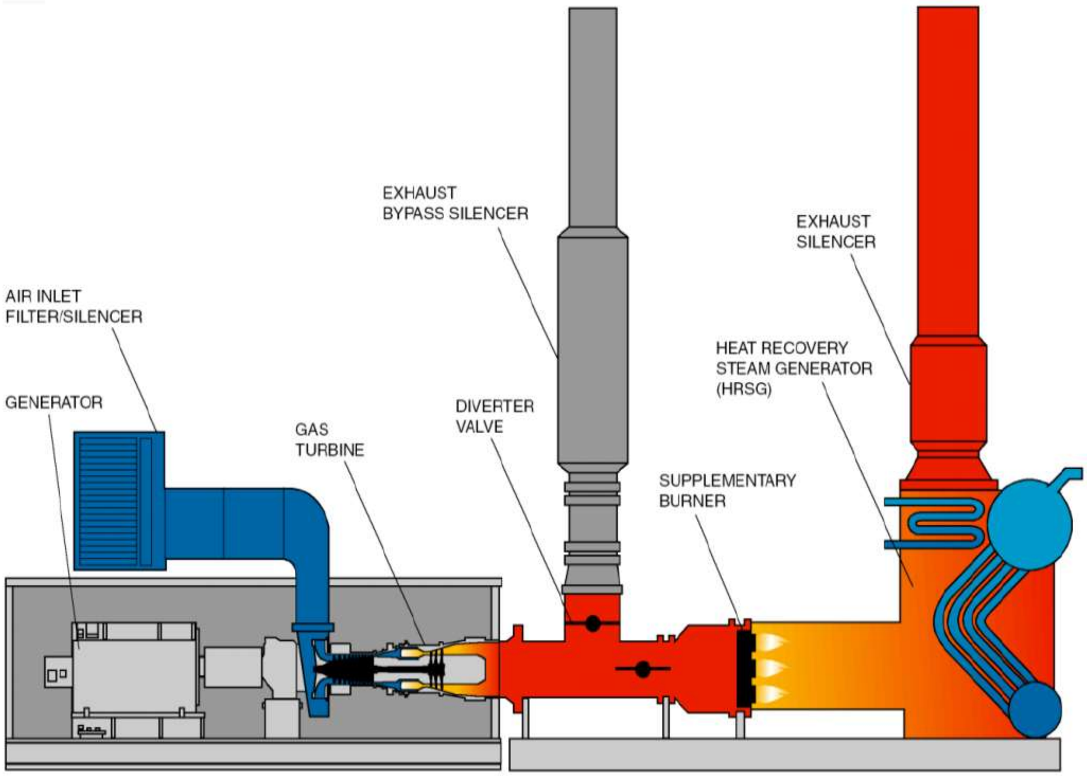

Figure 3: Solar Turbines Gas Turbine with Waste Heat Recovery
(Lyons & Tarver, 2020)

A method used to determine what type of electrical equipment should be used in industrial equipment is the Maximum Experimental Safe Gap (MESG). MESG is the largest gap between two surfaces that "prevents an ignition of flammable gas/air mixture propagating from an inner chamber through a 25-mm long path into a secondary (outer) chamber" (Lim, 2019). This means that as the flammability of the mixture increases, the allowable 'safe gap' becomes smaller. As shown in table 1 the MESG value quickly drops as the amount of hydrogen in the mixture increases. The MESG number drives the decision on the Gas Group required for electrical equipment. For hydrogen-blends the Gas Group does not change until the hydrogen mixture is above 20% (Kurz, et al., 2019).

Table 1: Variation of Key Gas Turbine Characteristics with Hydrogen Additions to Pipeline Gas Focusing on the Range of 5-30% (Excerpt)

H2 Blend	0%	5%	10%	20%	30%	100%
Laminar Flame Speed (cm/sec)	124	127	130	139	150	749
Wobbe Index	1215	1199	1183	1150	1116	1039
Maximum Experimental Safe Gap (MESG)	1.1	1.06	1.02	0.94	0.86	0.28
NEC/CSA & IEC Gas Groups	D & IIA	D & IIA	D & IIA	D & IIA	D & IIB	B & IIC

(Kurz, et al., 2019)

3 Discussion of Results and Findings

The OEM companies that have been focused on are GE Power (Baker Hughes), Solar Turbines and Siemens Energy. Data has been anonymized to protect confidentiality and the competitive nature of the data provided. Where public information has been used the OEM name has been referenced, when confidential or competitive information is used the OEM names have been changed to OEM A, B or C.

Equipment – Emissions and Performance

Impacts on Gas Turbine CO2 Emissions

The intent of blending hydrogen into a NG pipeline system is to reduce overall CO2 emissions. As hydrogen is blended it provides a progressive reduction of CO2 emissions, however the reduction of CO2 is non-linear. Figure 4 below, provided by Siemens Energy, shows the relation between CO2 emissions and the percentage of hydrogen by volume.

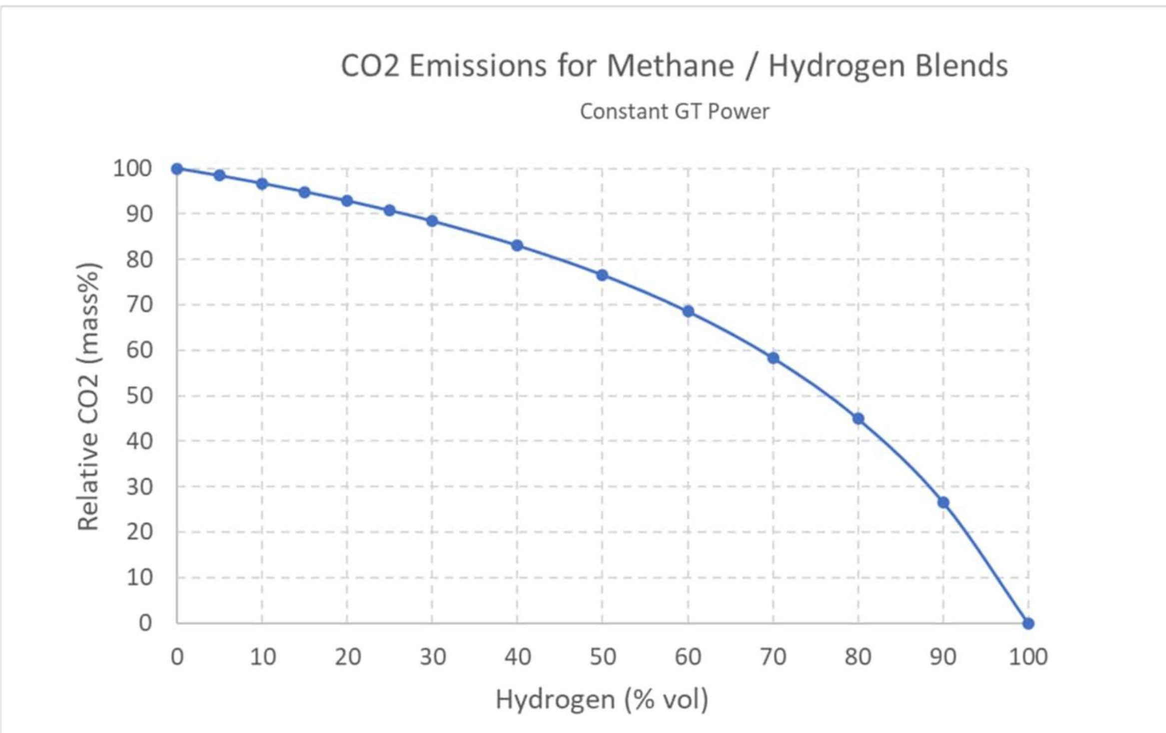

Figure 4: CO2 Emissions for Methane H2 Blends
(Siemens Energy, 2022)

As hydrogen is blended into the NG stream, it is reasonable to assume that the CO2 emissions would drop a corresponding amount. As demonstrated in figure 4 the relation relationship between hydrogen-blending and relative CO2 (mass %) emissions is non-linear, meaning that the relative CO2 emissions are reduced slightly until higher volumes of hydrogen are blended. For example, 5% hydrogen-blending will result in relative CO2 reduction of about 1.6%, 20% hydrogen-blending will reduce relative CO2 emissions by less than 10%. At approximately 50% hydrogen-blend the relative CO2 emissions begin to show a greater reduction of about 23%, and an 80% hydrogen-blend will reduce relative CO2 emissions by slightly over 50%. While the relative CO2 emission reduction may be minimal as hydrogen is introduced to the NG pipeline, smaller amounts of hydrogen can still make a significant impact on relative CO2 emissions over time. Relative CO2 emissions are often how CO2 emissions are represented in terms of combustion emissions.

Figure 5 below, provided by OEM A, shows three different GT engines (GT1, GT2, GT3) running on 0-20% hydrogen-blended fuel as shown in appendix 2. Hydrogen is shown by the volume percentage blend, the flowrate increases to ensure the GT has enough energy content in the fuel to maintain the increasing required output power. The flowrate of hydrogen-blended fuel must increase as the percent volume of hydrogen-blending increases.

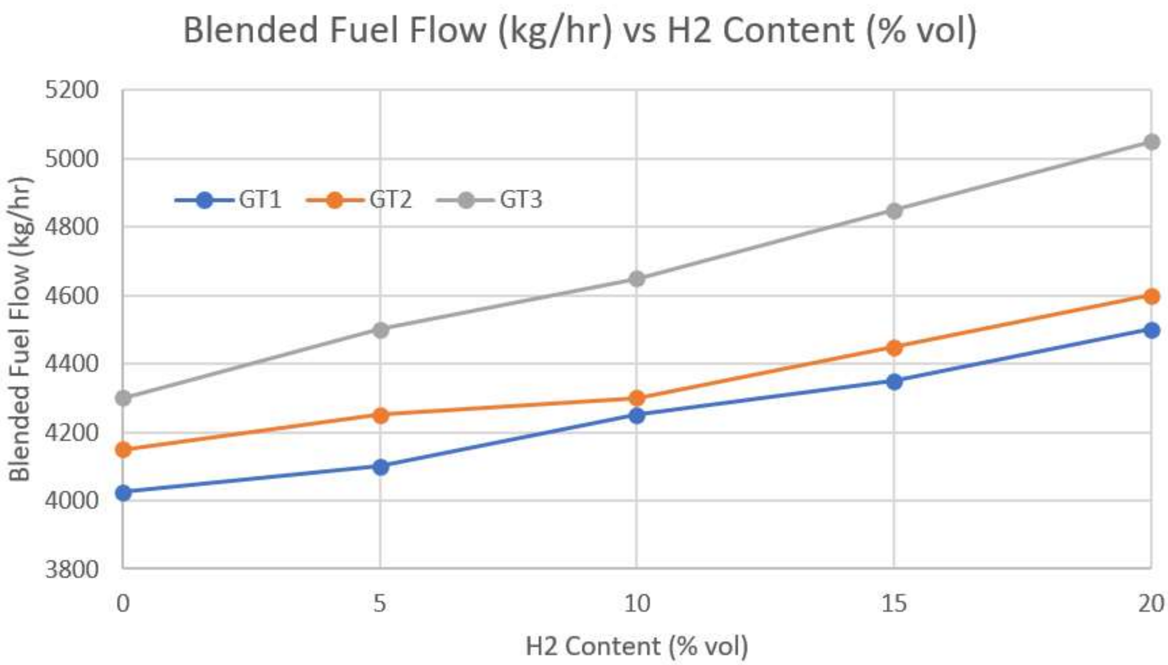

Figure 5: Blended Fuel Flow (kg/hr) vs H2 Content (% vol)
(Adapted from information provided by OEM A)

When the CO2 emissions of GT engines running on hydrogen-blended fuel are considered in terms of hydrogen mass flowrate (kg/hr) and hydrogen-blending in percent volume there is a net increase in CO2 emissions. This is demonstrated in figure 6 below, adapted from information provided by OEM A.

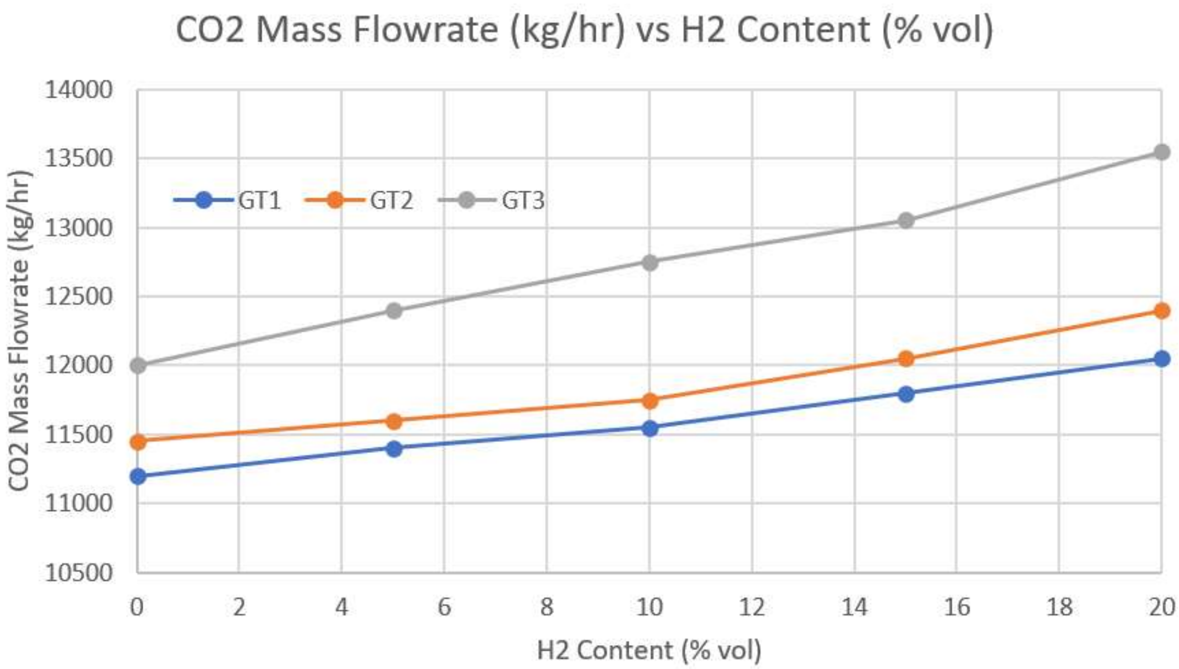

Figure 6: CO2 Mass Flowrate (kg/hr) vs H2 Content (% vol)
(Adapted from information provided by OEM A)

As the hydrogen is blended into the fuel gas, additional flowrate is required to ensure the GT has adequate energy content in the fuel to produce the increasing required power, as shown in figure 5. Because the fuel flowrate is increased, more mass flow of fuel and ambient air is consumed by the GT, the resultant is additional CO2 emissions, as shown in figure 6.

Impacts on Gas Turbine NOx Emissions

As discussed the in literature review (Link: Impacts on Gas Turbine Emissions) the amount of hydrogen-blending and the combustion design used by the GT can impact the NOx emissions (ECC Canada, 2017), (Klein, 2022), (Kurz, et al., 2019), (Kurz, et al., 2020), (Welch, 2021).

Hydrogen has a higher flame temperature than NG, leading to higher NOx emissions unless mitigated by combustor design changes, air intake water injection or by reducing power. Depending on the OEM, the increase in flame temperature for blends of 20-30% volume of hydrogen is small and will not generally result in significant increases in NOx. Hydrogen-blends of 20-30% can be handled by new DLE combustion systems, existing GTs with DLE combustors will need to be reviewed.

Diffusion combustion technology uses pre-or-post-combustion treatment and can handle 100% hydrogen with no increase in NOx emissions and keep CO emissions within current limits. GT OEM companies will use either water/steam injection (wet NOx) or post combustion SCR to abate NOx, as hydrogen-blending percentage increases. This has the added benefit of increasing power.

Impacts on Centrifugal Compressor Performance

Centrifugal gas compressors that are designed for NG service can handle small variations in the constituents of the gas flowing through. Legacy installed compressors should be reviewed to ensure elevated levels of blended hydrogen are acceptable. As discussed in the literature review (Link: Impacts on Centrifugal Compressor Performance) due to the lower energy content of hydrogen (volume), as hydrogen-blending is increased the flow must increase to maintain a constant energy flowrate in the pipeline (Kurz, et al., 2020). Figure 7 below shows the impact to the gas energy content in terms of volume as the level of hydrogen increases, this graph uses the gas composition in appendix 2 to calculate energy content.

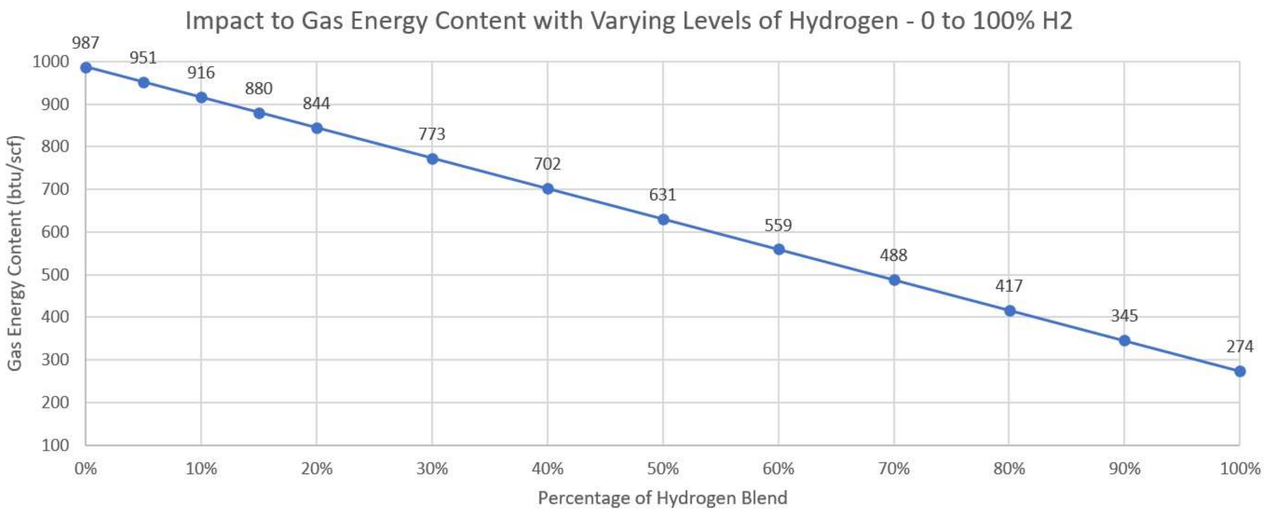

Figure 7: Impact to Gas Energy Content with Varying Levels of H2 – 0-100% H2
(Adapted from Appendix 2 Gas Composition, 0-100% H2 Blend)

Figure 7 shows that, as the percentage of hydrogen-blending increases the energy content of the gas decreases. At 5% hydrogen-blending the energy the energy content of the gas only drops by approximately 3.6%, at 50% hydrogen-blend the energy content drops by 36% and at 100% hydrogen the energy content drops by more than 72%. Figure 8 combines data from the North and South site conditions in appendix 1 and gas composition in appendix 2 to show flowrate changes to maintain energy content.

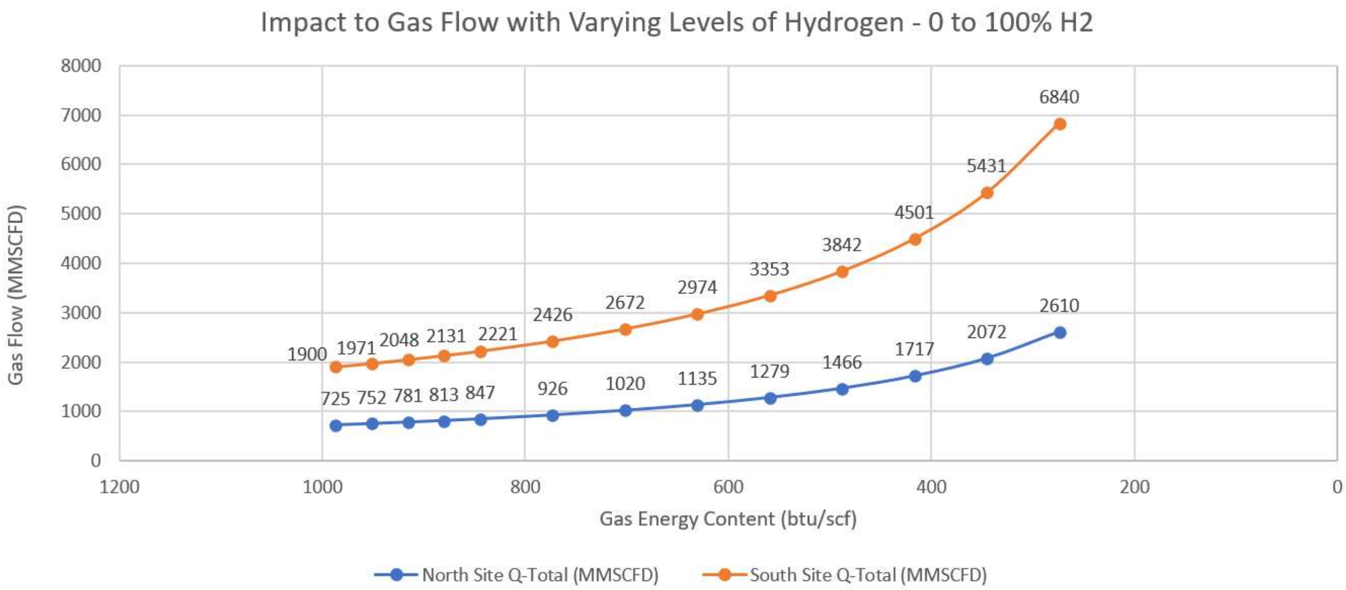

Figure 8: Impact to Gas Flow with Varying Levels of H2 – 0-100% H2
(Adapted from Appendix 1 and appendix 2)

Figure 8 shows the required increase in gas flow to maintain a constant energy content for both the North and South Sites as described in appendix 1. The flowrates are shown in MMSCFD, and correspond to the increasing hydrogen-blending rates. The low flowrates on the left side of the graph are at 100% NG. The flowrates increase as the graph moves to the right, ultimately showing a 360% increase in flow required at 100% hydrogen. This increase in flow will result in an impact to compressor sizing, potentially changing the size or quantity of compressors required.

Impacts on Gas Turbine Performance

There are two ways hydrogen-blending may impact the performance of a GT, first as a fuel to power the GT and secondly the increased power requirements due to compressor flow requirements. The effects of blending hydrogen into NG fuel includes changes to the combustion system as discussed in the literature review (Link: Impacts on Gas Turbine Performance). Legacy installed equipment needs to be evaluated to ensure capacity to handle elevated levels of hydrogen-blending (Burnes & Camou, 2019), (Palies, 2020), (Kurz, et al., 2019), (Cuenot, 2016).

As shown in figure 5 and figure 8 the required flowrate to maintain a constant energy content increases as the percent of hydrogen by volume increases. The increased flowrate required through the compressor will drive a higher power requirement from the GT. The additional GT power required is shown in figure 9, and has been adapted from information provided by OEM A and B. The hydrogen-blending to be used as a fuel for the GTs shown in figure 9 has been limited to a maximum of 20% hydrogen by volume.

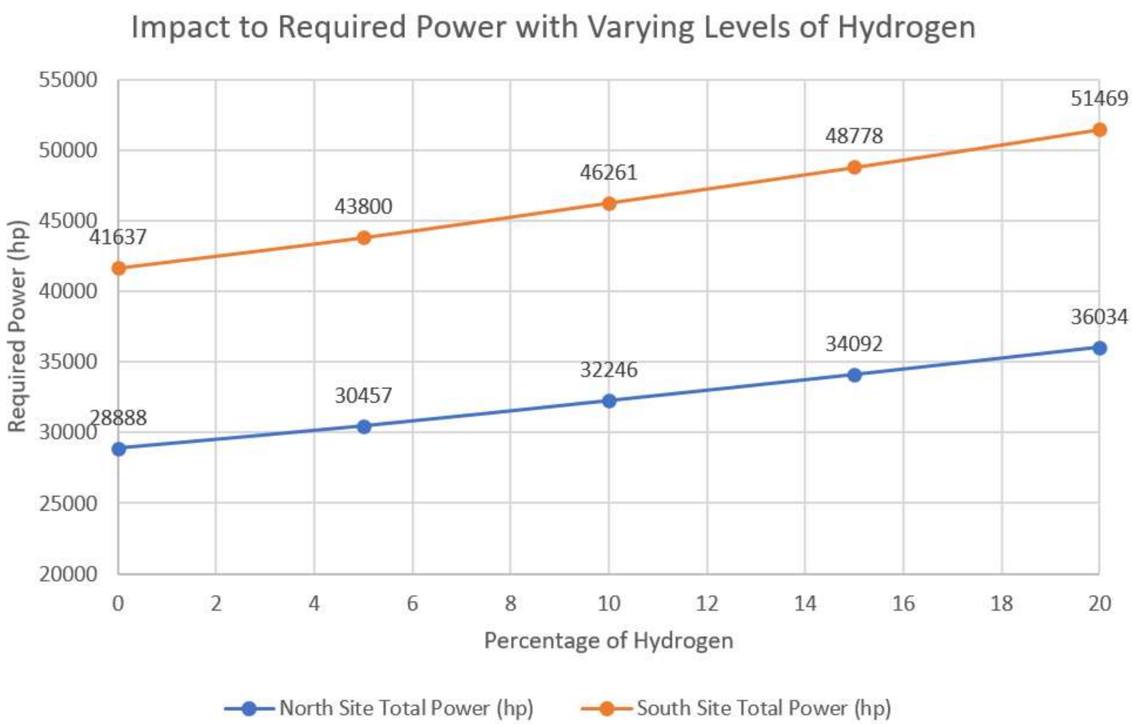

Figure 9: Impact to Required Power with Varying Levels of Hydrogen
(Adapted from information provided by OEM A and B).

As shown in figure 9 substantial increases in GT output power is required as the pipeline gas is blended with increasing levels of hydrogen. At 5% hydrogen-blend an increase of approximately 5% additional power is required, at 20% blend, almost 25% additional power is required from the GT.

Equipment – Life Expectancy

Pipeline Life Expectancy

As shown in figure 8, the flow increases dramatically as increased levels of hydrogen are blended into the pipeline system. Figure 10 below has been adapted from the data in appendix 1 and appendix 2 and shows the impact to pipeline gas flow as the hydrogen-blending is increased from 0-20%. Figure 10 also shows the change in energy content as the hydrogen-blending increases. Blending of hydrogen increases from left to right.

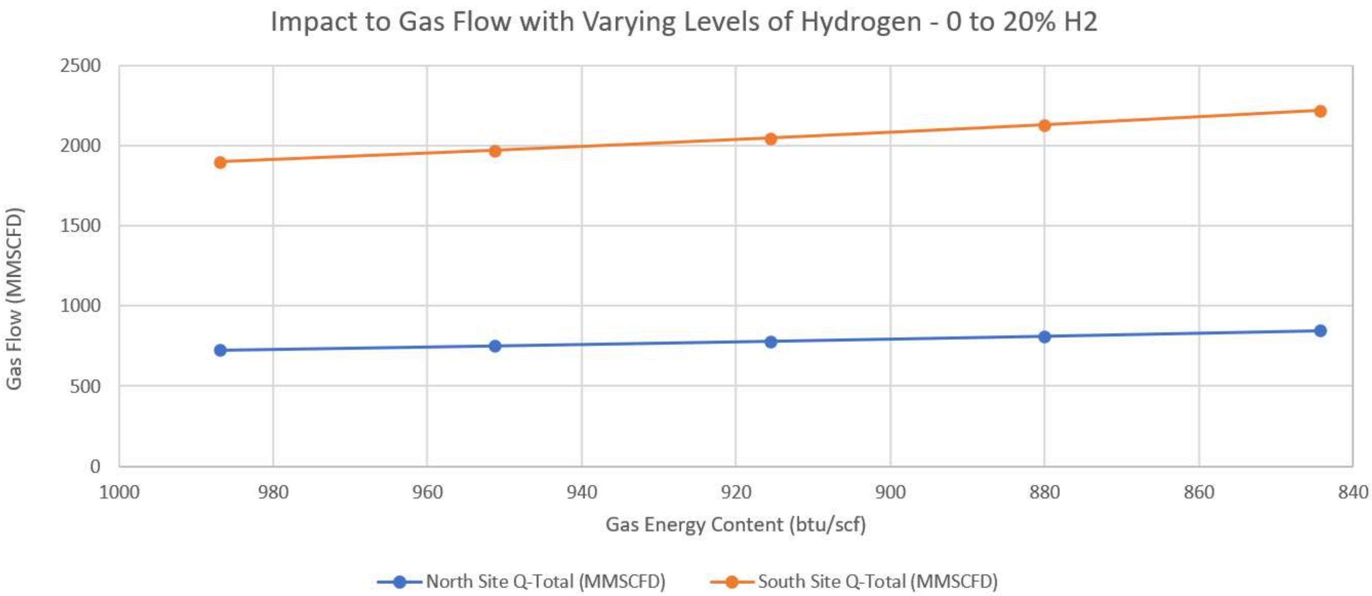

Figure 10: Impact to Gas Flow with Varying Levels of Hydrogen – 0-20% H2
(Adapted from Appendix 1 and Appendix 2)

Table 2: Change in Energy Content with low levels of H2 Blending

H2 Blend	Change in Energy Content
0%	0%
5%	-3.50%
10%	-7%
15%	-11%
20%	-14.50%

(Adapted from Appendix 2 Gas Composition, 0-100% H2 Blend)

Gas Turbine and Centrifugal Compressor Life Expectancy

The life expectancy of new GTs and centrifugal compressors (at low blends of hydrogen) is not impacted by the increased blending of hydrogen. Legacy installed equipment must be reviewed for compatibility and in some cases retrofitting will be required to upgrade internal materials.

For GTs operating at or below 15% hydrogen-blend there is no changes in life expectancy. For hydrogen-blends above 15% and especially above 25% an OEM maintenance management plan and an inspection regime is required.

Pipeline Capacity

Pipeline capacity is sold by energy content/volume, the gas received by the end user must meet explicit specifications. If the energy content were to decrease below the specified energy content, changes will be required to the end user's equipment. In terms of a pipeline transmission system this may include equipment like GTs, gas driven generators and process heaters. Ultimately the gas will be used by small businesses and homes. It is important to maintain a level of gas interchangeability, ensuring that as the hydrogen is blended into the pipeline the energy content stays above the minimum level required to run end user equipment. Figure 11 is adapted from appendix 2 and outlines the impact to gas energy content (btu/scf) as the percentage of hydrogen increases.

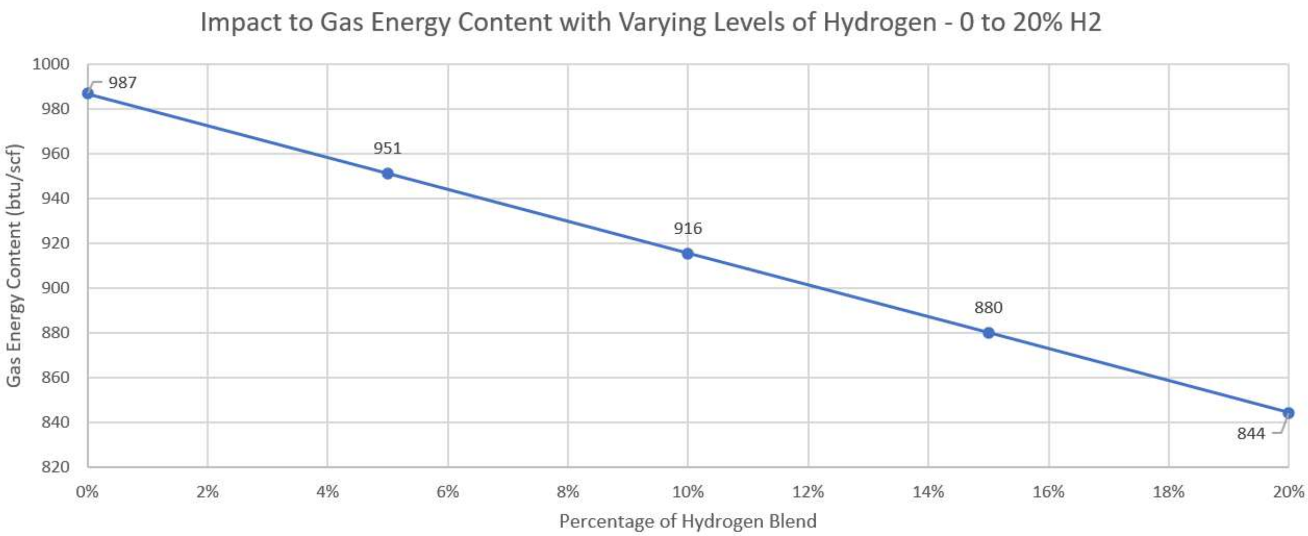

Figure 11: Impact to Gas Energy Content with Varying Levels of H2 – 0-20% H2
(Adapted from Appendix 2 Gas Composition, 0-100% H2 Blend)

As shown previously in figure 10, if the percentage of hydrogen-blending is kept below 20% by volume, the increase in flow is reasonable. However, as the hydrogen-blending percentage increases above 20% by volume the required flowrate increases exponentially, as shown in figure 8.

Gas Turbine Compressor Package Safety Considerations

Gas compressor packages typically consist of a GT driver, a compressor, heat exchangers, process instrumentation, gas piping, utility piping, electrical devices and wiring, turbine combustion air intake, exhaust and a WHR system. For package design the properties of hydrogen present some challenges:

- Hydrogen has a lower density than NG resulting in higher skid edge pressures (Lyons & Tarver, 2020)
- Hydrogen is a very small molecule, resulting in higher leakage rates than NG (Melania, et al., 2013)

- Hydrogen has a wider flammability range and lower ignition energy than NG, resulting in greater potential for ignition of leaks (Kurz, et al., 2019) (Melania, et al., 2013).
- Hydrogen has low flame radiation and luminosity, making it harder to see a hydrogen flame than a NG flame (US DOE, 2022)

These challenges drive package design changes based on the amount of hydrogen-blended into the NG stream. The following section outlines the OEM recommended changes made to GT compressor packages at three different levels of hydrogen-blending.

Compressor Package Considerations: H2 Blending: 0-15% H2 by Volume

In general, no changes are required to the package, depending on local rules and regulations, NG fuel composition, equipment standard, certification standard and condition of the unit (Kurz, et al., 2019). Depending on fluctuation of hydrogen-blending changes to the combustion system programming may be required to accommodate fluctuations in Wobbe number (Law Insider, 2022) (Kurz, et al., 2019).

Compressor Package Considerations: 15-25% H2 by volume

The following package modification are recommended based on OEM engineering evaluation:

1. Engine exhaust and WHR system review to ensure hydrogen build up in the exhaust plenum is accounted for during potential start-up issues or flame-out (Kurz, et al., 2020).
2. Fire suppression system review (US DOE, 2022).
3. Fire and gas detection calibration for elevated levels of hydrogen (US DOE, 2022).
4. Fuel system update, including larger fuel valve and material upgrades.
5. Control settings update to match blended fuel characteristics (Kurz, et al., 2020)
6. Package ventilation review, if enclosed
7. Nitrogen purge for dual fuel engines

Compressor Package Considerations: 25-100% H2 by Volume

Package modifications required for 25-100% hydrogen are the same as 15-25% hydrogen-blend with the addition of the items below as recommended based on OEM engineering evaluation:

1. Fire and gas detection calibration for elevated levels of hydrogen, and the addition of hydrogen gas and flame detectors (US DOE, 2022).
2. Electrical device updates to account for the different gas group classification (Lim, 2019) (Kurz, et al., 2019) (Welch, 2021).
3. GT combustion system change to diffusion (conventional) (Kurz, et al., 2019) (Kurz, et al., 2020).

4 Conclusions, Recommendations

How Much H2 Could Reasonably be Blended Into a pipeline system?

A hydrogen-blend amount below 20% may seem to be a good starting point. This would allow for typical NG compressors to function without significant adjustments, and a 20% blend would be in the range of DLE GT combustion systems. However, 20% hydrogen-blend would drop the energy content of the gas by 14.5%, requiring a derate to the pipeline or increasing the pipeline flowrate by almost 17%. This would in turn increase the required GT power requirement by approximately 25%. A 20% hydrogen-blend would also increase the fuel gas rate of the GT by 17%, driving up the CO2 emissions by 13%. A 20% hydrogen-blend would demand a large consistent flowrate of hydrogen, which may be many years away from being readily available.

A lower hydrogen-blend rate may be more reasonable. The overall impacts to energy content, flowrates, GT CO2 emissions and power requirements are greatly reduced at a hydrogen-blend rate of 2.5-5%. A hydrogen flowrate of 92 MMSCFD (at 2.5%) and 187 MMSCFD (at 5%) would still be required to maintain the blend ratio.

Legacy installed GTs and centrifugal compressors will be able to accept a 2.5-5% increase in hydrogen-blending, after a review by the OEM. Some modifications may be required to ventilation, purging, fire suppression, fire and gas detection and electrical devices. After OEM review conventional and DLE GTs will be able to handle these low amounts of hydrogen-blending without major impacts to NOx, CO and UHC emissions.

Meter stations were touched on in the literature review (link: Heat Capacity), and are able to handle up to 50% hydrogen-blending with adjustments to accuracy (Melania, et al., 2013).

Practical Recommendations

Hydrogen Blend Rate

A review of each compressor station for modifications required to accommodate hydrogen-blending is required prior to introducing hydrogen into the system. Blending should be done in a stepped approach based on percentage of hydrogen-blend percentage by volume. Once a review for acceptability and any modifications are completed a blend of up to 2.5% hydrogen by volume can be introduced. A maximum of 2.5% hydrogen-blend would allow for the system to normalize, and unknown issues to be fixed. 2.5% hydrogen-blend would also produce only minor impacts to energy content, flowrate and GT required power. A 2.5% hydrogen-blend rate would also create a demand for up to 92 MMSCFD of hydrogen at the conditions shown in appendix 1.

Once the blend rate of 2.5% hydrogen has settled out and if the hydrogen production is available the blend rate can be increased to a maximum of 5% hydrogen by volume. Many of the modifications that were completed for 2.5% hydrogen would apply for a 5% hydrogen-blend. An increase of 5% in GT power output may need to be reviewed based on the turbine capacity. A hydrogen flowrate of 187 MMSCFD would be required at 5% hydrogen-blend.

Recommended Scope for Future Research

Pipeline Metallurgy Study

Additional research is required on the impact to pipeline life expectancy. However, jurisdictions like Hawaii have been transporting and utilizing hydrogen-blends with no significant upgrades to material (General Motors, 2011). Syngas with high levels of hydrogen was a staple source of energy for many years in North America starting in the late 1800s (Clarke, 2015). There is precedence transporting hydrogen-blended gas. An engineering study should be commissioned to analyze the metallurgy of the existing pipeline material within the pipeline system to verify acceptance of hydrogen-blending.

Hydrogen Policy and Regulatory Framework

Canada currently lacks a comprehensive long-term policy and regulatory framework that includes hydrogen (Government of Canada, 2020). Private sector support and research studies in the development of a hydrogen strategy, policy and regulation may help government to create a realistic hydrogen framework for Canada.

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APPENDIX 1 – North and South Site Conditions

North Site	Imperial Units		Metric Units	
Inlet Pressure	700	psig	4826	kPag
Inlet Temperature	59	°F	15	°C
Outlet Pressure	1450	psig	9997	kPag
Outlet Temperature	178	°F	81	°C
Ambient Temperature	59	°F	15	°C
Discharge Cooling	YES	N/A	YES	N/A
Temperature to Pipeline	120	°F	49	°C
Outlet Flow	725	MMscfd	20483	E3m3/d
Fuel		MMscfd		E3m3/d
Horsepower – Available at Site		HP		HP
Site Elevation	2487	fasl	758	masl
Atmospheric Pressure	13.45	psia	92.73	kPaa

South Site	Imperial Units		Metric Units	
Inlet Pressure	620	psig	4274.75	kPag
Inlet Temperature	67	°F	19.4	°C
Outlet Pressure	936	psig	6453.49	kPag
Outlet Temperature	123	°F	50.5	°C
Ambient Temperature	59	°F	15	°C
Discharge Cooling	YES	N/A	YES	N/A
Temperature to Pipeline	120	°F	49	°C
Outlet Flow	1900	MMscfd	53679	E3m3/d
Fuel		MMscfd		E3m3/d
Horsepower – Available at Site		HP		HP
Site Elevation	3395	fasl	1035	masl
Atmospheric Pressure	12.98	psia	89.49	kPaa

Run Points	Gas Turbine Fuel % H2 Content	Centrifugal Compressor % H2 Content
1	0	0
2	5	5
3	10	10
4	15	15
5	20	20
6	30	0
7	40	0
8	50	0
9	60	0
10	70	0
11	80	0
12	90	0
13	100	0

HYDROGEN PERFORMANCE NOTES

1. Run Lean Premix combustion, increase hydrogen content until power or emissions cannot be maintained, then switch to Diffusion combustion. Emissions for Diffusion combustion will be unabated.
2. Emissions targets
   a. CO_2 - as low as practicable
   b. NO_x - 25 ppm
   c. CO - 50 ppm
3. Please adjust flow to maintain energy content of the gas, as hydrogen blending increases.
4. Modifications within the compressor body (i.e. re-wheeling) can be utilized as hydrogen blending increases. Please maintain the same compressor body.
5. Please ensure that engine performance runs include emissions information at the 13 Run Points (listed above).

APPENDIX 2 – Gas Composition, 0 – 100% H2 Blend

% of H2 Blend	0%	5%	10%	15%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Component	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)	(mol %)
H2S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.21	0.20	0.19	0.18	0.17	0.15	0.13	0.11	0.08	0.06	0.04	0.02	0.00
N2	0.23	0.22	0.21	0.20	0.18	0.16	0.14	0.12	0.09	0.07	0.05	0.02	0.00
H2	0.00	5.00	10.00	15.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
C1	90.27	85.76	81.24	76.73	72.22	63.19	54.16	45.14	36.11	27.08	18.05	9.03	0.00
C2	7.55	7.17	6.80	6.42	6.04	5.29	4.53	3.78	3.02	2.27	1.51	0.76	0.00
C3	1.31	1.24	1.18	1.11	1.05	0.92	0.79	0.66	0.52	0.39	0.26	0.13	0.00
iC4	0.15	0.14	0.14	0.13	0.12	0.11	0.09	0.08	0.06	0.05	0.03	0.02	0.00
nC4	0.19	0.18	0.17	0.16	0.15	0.13	0.11	0.10	0.08	0.06	0.04	0.02	0.00
iC5	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.00	0.00
nC5	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.00	0.00
C6	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
C7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Max. Water content lbs/MMSCF	4	4	4	4	4	4	4	4	4	4	4	4	4