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PREREQUISITES FOR THE USE OF LOW-CARBON ALTERNATIVE FUELS IN GAS TURBINE POWER GENERATION

Antonio Escamilla*†, Jon Runyon 2, Lorenzo Pilotti***, Stefano Mori******

University of Seville (†a.escamilla@us.es)
*****Uniper Technologies *** Politecnico di Milano **** Cranfield University***
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Abstract

As the world shifts towards mitigating climate change, gas turbine (GT) manufacturers are focusing on enabling low-carbon fuel flexibility in GTs. This comprehensive review examines the current status and prerequisites of alternative fuels (excluding hydrogen) for use in GT power generation with the aim of identifying the most promising low-carbon solutions.

The review considers the thermophysical and chemical properties of non-traditional fuels such as ammonia, biomass or waste-derived fuels, and alcohol-derived fuels compared with standard GT fuels. The viability of these alternative fuels for power generation is evaluated, considering advantages, challenges, and potential barriers such as availability, fuel composition, and lifecycle greenhouse gas emissions. The maturity of each alternative fuel in the market is assessed, considering production methods and generation potential.

Based on the detailed comparison, the study proposes economically, technologically, and environmentally viable alternative fuels, along with knowledge and experience gaps that need to be addressed. This review can serve as a guide for the GT industry in advancing research and development efforts for alternative fuels to support the global energy transition and decarbonization goals.

Introduction

Gas turbines (GTs) are expected to provide a fundamental contribution to the net-zero energy transition, by providing secure, reliable, and dispatchable power generation. In order to play such an important role in the near future, enabling fuel flexibility of GTs has become a key aspect of the turbomachinery sector. GT original equipment manufacturers (OEMs) are already working to enable the low-carbon fuel flexibility of commercially available GT fleets. Though the ability of industrial GTs to operate with a variety of gaseous and liquid fossil fuels has already been demonstrated (General Electric, 2009, General Electric, 2011, General Electric, 2018, Kliemke and Johnke, 2012, Saxena et al., 2021), the need to shift towards renewable and sustainable alternative fuels is becoming more compelling to allow GTs to contribute in the future low-carbon energy system. Indeed, alternative fuel GT demonstrations are again gaining pace such as with methanol (RWG, 2023) and hydrotreated vegetable oil (HVO) (Runyon et al., 2023). Table 1 provides examples of commercial and field testing conducted with alternative fuels and a variety of GT types.

As shown in Table 1, there is a range of options to choose from among existing alternative fuels, however, not all the choices are equal, and several aspects must be taken into account when this selection is made. For instance, many non-conventional fuels are produced by processing biomass or waste, and it is essential to understand if there is enough sustainable feedstock to satisfy the fuel demand. In addition, according to the production process and the supply chain, alternative fuels may vary in terms of lifecycle greenhouse gas (GHG) emissions compared with existing fossil fuels.

Fuel composition and quality may also vary significantly between alternative fuel options and even within the same fuel when produced following different technological pathways. Therefore, it is essential to verify if the fuel composition is in line with the requirements specified by the OEMs for the safe, reliable use of fuels and, if not, which potential issues may arise that can impact fuel storage and handling, compromise the combustion process, or damage hot gas path components.

Table 1: Alternative fuel GT commercial operations and testing

Fuel	Country	Operator (T = Test / C = Commercial)	GT OEM	GT	GT Output (MWe)	Year
Methanol	UK	RWG/Siemens Energy (T)	Siemens Energy	SGT-A20	15	2023
	Israel	Israel Electric Corporation (C)	P&W	FT4C	50	2014
	USA	Southern California Edison (T)	P&W	FT4C	26	1979
	USA	Florida Power Corporation (T)	P&W	FT4C	24	1974
Ethanol	USA	LPP Combustion (T)	Capstone	C30	0.03	2014
	Brazil	Petrobras (C)	GE	LM6000PC	87	2010
	India	Reliance Energy (T)	GE	6B	48	2008
Biogas	Taiwan	Taipei Public Works Department (C)	Capstone	C30	0.03	2016
	Norway	Risavika Gas Centre (T)	Turbec	T100	0.1	2013
Biodiesel (FAME)	Switzerland	Groupe E (T)	GE	6B	36	2007
Biodiesel (HVO)	UK	Uniper (T)	Rolls-Royce	Olympus	17.5	2022
	Germany	Uniper (T)	KWU/Siemens Energy	V93.1	63	2022
	Sweden	Göteborg Energi (T)	Siemens Energy	SGT-800	45	2021
	Sweden	Uniper (T)	KWU/Siemens Energy	V93.0	63	2021
Ammonia	Japan	AIST (T)	Toyota	TPC-50	0.05	2015
	USA	International Harvester Company (T)	Solar	T-350	250 hp	1966

Table 2 reports the density and the mass-specific lower heating value (LHV) of the alternative fuels considered in this work and compares them with the same properties of conventional fossil fuels. In some cases, alternative fuels are able to achieve values close to the fuel they intend to replace (such as HVO and FAME compared to diesel). The same holds for biomethane that in most cases is a product very similar to NG, in terms of composition, density and LHV. Conversely, methanol and ammonia are characterised by a significantly lower LHV if compared to NG and diesel. Thus, a higher volume of fuel is required to provide the same heating rate.

This work analyses different non-conventional fuel alternatives for GT-based power generation such as biomass or waste-derived fuels (e.g., biomethane and biodiesel), alcohol-derived fuels (e.g., methanol and ethanol) and hydrogen-derived (e.g., ammonia) with the aim of identifying the necessary prerequisites for use and establishing a common framework to compare these fuels to identify the most promising alternative fuel for GTs. Thus, the framework in which the work will be developed includes fuels that are established global commodities, excluding hydrogen which has already been covered extensively elsewhere (ETN Global 2020, 2022a, 2022b).

Table 2: Density and LHV of conventional and alternative fuels.

Fuel	Density at 20°C	LHV [MJ/kg]
Gaseous Fuels		
Natural gas	0.67 kg/m^3	49.5
Biogas	1.2 kg/m^3	13-23
Biomethane	0.67 kg/m^3	45-49.5
Hydrogen	0.085 kg/m^3	120.1
Liquid Fuels		
Diesel	0.83 kg/l	43.1
Ethanol	0.79 kg/l	26.7
Methanol	0.79 kg/l	19.7
FAME	0.88 kg/l	37.1
HVO	0.78 kg/l	44.4
Ammonia*	0.61 kg/l	18.6
* Density at saturation pressure (~8.6 bar)		

The work is organised as follows: 1) the future demand and the potential availability of alternative fuels for power generation is investigated, 2) an overview of the current production capabilities and the future estimates for each of the alternative fuels analysed is given, 3) the GHG reduction achievable through low-carbon fuel use based on the current regulations in Canada as well as Canada's Taxonomy Roadmap Report (CAN Taxonomy, 2022), and 4) the presence of impurities in fuel composition potentially harmful for the GTs components is discussed.

Availability of Alternative Fuels

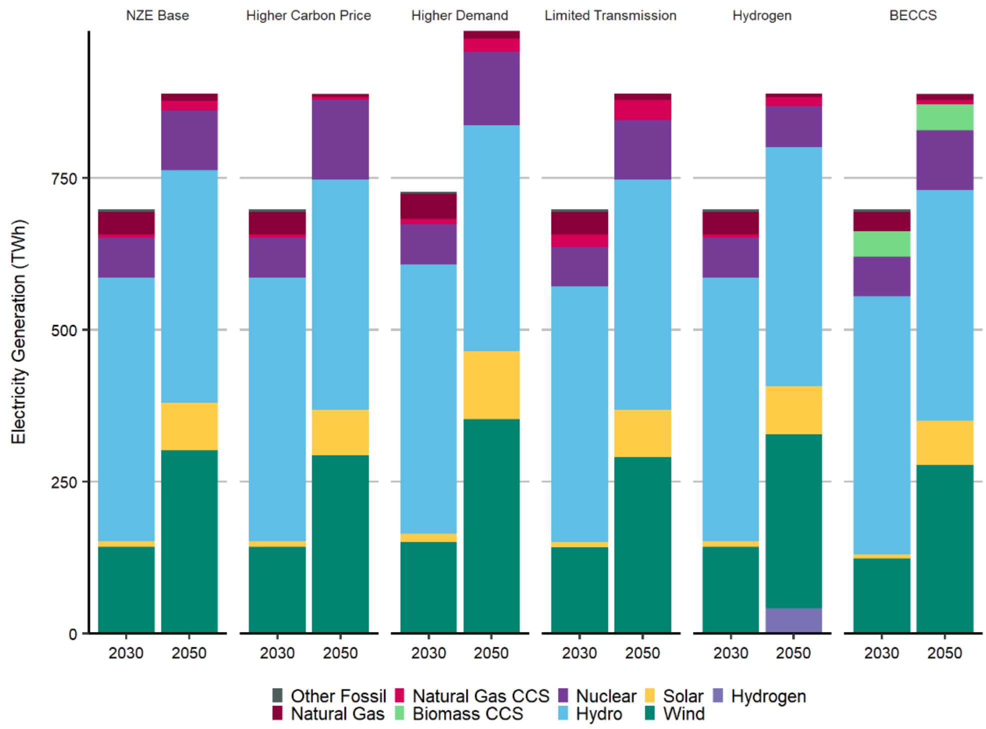
An important initial step in assessing the feasibility of decarbonizing GTs with alternative fuels is to accurately quantify the potential demand for these fuels in the gas-based power generation sector. According to Statistics Canada, the yearly consumption of natural gas (NG) for Canada's NG-based power generation was 74.5 TWh (corresponding approximately to 0.268 EJ) in 2021 (CAN, 2021). It will go down to 37.43 TWh by 2030 and 11.11 TWh by 2050 assuming the Net Zero Emission (NZE) base scenario (CER, 2021). However, NG with carbon capture storage (CCS) is also predicted to grow, adding up to 42.97 TWh and 27.8 TWh by 2030 and 2050 (0.155 EJ and 0.10 EJ), respectively. The deviation of the latter numbers can be visualized for NZE and the other scenarios devised in Figure 1.

Assuming no addition of new NG generation capacity (i.e., only retrofit or replacement of the current capacity) and to decarbonize only a fraction (e.g., 10-20%) of the existing generators through alternative fuel use, the potential demand for alternative fuels would range between 0.0274 and 0.0548 EJ in 2021. If the same estimate is repeated considering global NG consumption (23.47 TWh (IEA, 2022)) this results in a global alternative fuel demand of 2.3 EJ and 4.7 EJ for 10% and 20% capacity retrofit, respectively. It is worth noting that there are also assets running diesel and light fuel oil in Canada, which could potentially be targeted for early adoption of alternative fuels such as HVO or methanol (CAN, 2021). These assets produced 1.24 TWh of electricity in 2021 (CAN, 2021).

Apart from power generation, the significance of gas turbines extends to mechanical drive compressors/pumps, among other applications. This is particularly important in Canada, where an extensive network of pipelines spans 840,000 km, including 117,000 km of large-diameter transmission lines. The CER regulates approximately 68,000 km of operating pipelines, including 48,338 km of gas pipelines and 19,142 km of oil pipelines (CER Gas, 2023). These pipelines facilitate the transportation of natural gas and oil using compression and pumping stations. These stations often rely on aero-derivatives gas turbines. Antonanzas et al. (2023) report that 313 gas turbines and 30 reciprocating engines are used in Canadian transmission compressor stations, accounting for a total rated brake power of 4,792 MW. Thus, considering 50% annual capacity (4,380 hours) of these assets, and repeating the same exercise as before, the potential demand for alternative fuels could be 0.035 EJ (10% retrofitted) up to 0.07 EJ (20% retrofitted).

The second step is to consider the availability of the alternative fuels in question. Since most of these fuels are derived from biomass or waste-based feedstocks, it is legitimate to investigate if the potential feedstocks would be enough in the future to sustain the required production of each alternative fuel. Estimates of the feedstock potential availability vary widely at a regional and a global level, and many studies report different values according to the methodology considered (IRENA, 2022, IRENA, 2016).

Figure 1: Electricity generation by technology in different scenarios in Canada (CER TNZ, 2021)



According to IRENA estimates (IRENA, 2022), the global sustainable biomass potential in 2030 ranges from 97 EJ to 147 EJ per year, most of which derives from agricultural residue and waste (37-66 EJ), forest products and residues (24–43 EJ) and energy crops (33–39 EJ). A prudent assumption is to consider the maximum sustainable biomass potential available in 2050 to be constrained to 100 EJ (85 EJ when considering conversion losses), a value close to lower bounds reported by most studies (IRENA, 2016, IRENA 2022). Then, following the IEA projection, half will be directly employed by solid bioenergy for heat and power generation while the remaining half (40-45 EJ) will be equally divided into gaseous and liquid biofuels. This means that assuming an alternative fuels demand corresponding to a global 20% GT fleet decarbonization in 2050, this would lead to a bioenergy supply exploitation limited to 10% of the market (4.7 EJ out of 45 EJ) in 2050. Even considering all the potential competing applications for biomass and waste-derived fuels in 2050 devised by the IEA NZE scenario, the actual demand for alternative fuels required to replace part of the gas-based power generation is indeed met if compared to the overall available potential.

Biofuels

Global biofuel production capacity reached 159.2 billion litres (corresponding to 4.1 EJ) in 2021 (REN21, 2022). The main biofuels in terms of production volume are ethanol, produced mostly from corn, sugar cane and other crops, and biodiesel (fatty acid methyl ester, or FAME), produced from vegetable oils and fats, including wastes such as used cooking oil. In recent years, the production capacity has increased for other diesel substitute fuels, made by treating animal and vegetable oils and fats with hydrogen, such as hydrotreated vegetable oil (HVO) and hydrotreated esters and fatty acids (HEFA). In 2019, ethanol accounted for 59% (in energy terms) of overall biofuel production, FAME biodiesel for 35% and HVO/HEFA for the remaining 6%. To produce such liquid biofuels several production pathways are available that are already mature and have a high Technology Readiness Level (TRL,i.e., 8-9) (IRENA, 2016): ethanol is mainly produced via fermentation of sugars, FAME from transesterification while HVO and HEFA are derived from the hydroprocessing of oils and fats.

Other biofuels included biomethane and a range of advanced biofuels, but their production volumes remained low, representing less than 1% of the total biofuels market (REN21, 2022).

Following the implementation of Canada's Clean Fuel Regulations (CFR) (CAN CFR, 2022), the production of renewable diesel, also referred to as hydrogentation derived renewable diesel (HDRD), in the country has experienced significant growth. Starting from zero production in 2020, it is projected to reach an annual production capacity of 4.07 billion liters by 2027 (CER Diesel, 2022).

In the IEA NZE scenario (IEA, 2021a), the biofuel market is expected to reach 15 EJ by 2030 and then double by 2050, according to IRENA’s long-term forecast for biofuel demand (IRENA, 2022). Such an increase is largely due to the development of advanced biofuels based on waste-derived feedstocks like renewable diesel (HVO/HEFA) while the role of FAME biodiesel and conventional (i.e., crop-based) ethanol will be more limited in the future. Moreover, different biofuels such as FAME biodiesel and renewable diesel compete for the same feedstock, further complicating relative growth between the two biofuels.

Regarding potential applications for liquid biofuel, they are expected to provide a significant contribution to road transport initially, but their market share will be more limited in the future, as electricity will play, progressively, a growing role in this sector (IEA, 2021a). Therefore, biofuel use will shift to shipping and aviation in 2050 and even if not directly accounted for within the NZE scenario, a share of the biofuel market dedicated to power generation could replace the phase-out of other biofuel applications.

Methanol

The interest towards the use of methanol as fuel either by itself, as a blend with gasoline to produce biodiesel, or in other forms has increased in recent years since methanol production has grown significantly for the production of polyethylene and polypropylene, in particular. Hence, methanol is a key intermediate product in the chemical industry, used not only in fuel blending but also to produce formaldehyde, acetic acid, and plastics. Current global methanol production is around 98 million tonnes, nearly all produced from natural gas or coal, with bio-methanol accounting for less than 0.2 million tonnes (IRENA, 2021). Though the current production volumes of bio-methanol are low, the available potential is remarkable: IRENA estimated that up to 1,100 million tonnes of production potential could be made available globally, exploiting all the range of (unused) feedstocks suitable for methanol production (IRENA, 2021). Even if this number already accounted for other biomass uses, it can be considered only a rough estimate for the bio-methanol production potential.

Production processes for bio-methanol starting from the gasification of biomass feedstocks have been demonstrated at scale, however, the production cost is still not competitive from a market perspective, even when low-cost feedstocks are used. Given the lack of current production capacity and the higher costs of bio-based methanol, production volumes are unlikely to increase in the absence of support measures that encourage production and offset the cost differential. Nonetheless, the production cost is likely to reduce in the future, unlocking the methanol production potential: according to IRENA’s Transforming Energy Scenario, methanol demand is projected to achieve 500 million tonnes in 2050, 135 of which will derive from bio-methanol.

Biogas and biomethane

Annually in Canada, 6 million GJ of energy is produced through biomethane and 0.26 bcm of biogas is used for heat and direct use (CANBIO, 2021). Power generation from biogas includes 196 MW of clean electricity capacity in Canada (CANBIO, 2021). Despite the exponential growth in Canada's biogas production over the last decade, it is evident from various analyses that the country's biogas potential remains largely untapped. Numerous studies conducted in recent years have aimed to assess the available biogas resources across Canada. One notable study, commissioned by Natural Resources Canada and carried out by TorchLight Bioresources in March 2020 (TorchLight, 2020), calculated the regional feedstock availability for biomethane. According to this study, a realistic estimate suggests that there is 155 million GJ of biogas energy from biomethane readily available, which is equivalent to the energy generated by 100 large hydroelectric dams.

According to the statistics, it seems that Canada is only utilizing approximately 13% of its readily-accessible biogas energy potential at present (CANBIO, 2021). This implies that there is a significant opportunity for the sector to bring more than eight times the amount of biogas energy online. The most substantial potential for growth lies within the agricultural sector, constituting two-thirds of Canada's easily-available biogas resources, primarily from crop residues and animal manure (CANBIO, 2021). Additionally, landfill gas represents a significant opportunity, accounting for 21% of Canada's biogas feedstocks. Furthermore, there are important opportunities in wastewater treatment, source-separated organics, and pulp mills.

Biomethane's role is also expected to become more widespread in other parts of the world, particularly in Europe, where the resources of fossil natural gas are limited. Today, 3 billion cubic meters (bcm) of biomethane and 15 bcm of biogas are produced in the EU-27 (Alberici et al., 2022). The European Commission set a target of 35 bcm of annual biomethane production by 2030 in its recent REPowerEU plan (European Commission, 2022). In this report, by applying a unified methodology for each EU Member State (plus Norway, Switzerland and the UK) and considering strict sustainability criteria for feedstock selection (e.g., waste and residues are priorities taking into account sustainable removal rates and existing uses, only sequential crops are included), Alberici et al. (2022) assessed up to 41 bcm of biomethane production potential that could be unlocked by 2030. This number potentially grows to 151 bcm in 2050, representing more than one-third of the 2020 EU NG consumption (400 bcm). Most of the production capacity will be derived from anaerobic digestion (38 bcm in 2030, 91 bcm in 2050), which currently is the most mature production process, while the remaining will come from biomass gasification.

Considering the IEA NZE scenario, biomethane will contribute to global bioenergy supply by 3% and 8% in 2030 and 2050, respectively.

Low-carbon Ammonia

Ammonia has the potential to be used as a low-emission energy carrier in a variety of applications, including power generation. It is produced using hydrogen as raw feedstock, but in contrast to pure hydrogen, it has a higher volumetric energy density and a higher liquefaction temperature, which makes ammonia more suitable for transport and storage. Ammonia has a variety of applications in the chemical sector and, therefore can rely on an already established market: in 2020, 185 million tons (Mt) of ammonia were produced and around 20 Mt were globally traded (IEA, 2021b). In comparison to hydrogen, ammonia has a well-established infrastructure and established practices for safe and reliable storage, distribution, and export, making it a promising alternative fuel for gas turbines. Subsequently, once transported to the desired location, ammonia could be used directly or cracked to yield pure hydrogen for use in GTs or co-fired with NG in existing power plants. For these reasons, ammonia is gaining attention for its potential role in reducing emissions, particularly in the power generation and maritime sectors.

In the IEA Sustainable Development Scenario (IEA, 2021b), the use of ammonia for co-firing in coal power stations climbs to 60 Mt per year and 140 TWh of electricity generation by 2050, up from a handful of pilot and demonstration scale projects today. Despite providing only around 0.2% of global electricity generation in 2050, this application accounts for around a third of the consumption of ammonia for purposes other than its existing uses today such as fertilizer and chemical production.

However, almost all ammonia traded today relies on hydrogen produced from NG, and decarbonised ammonia production and use on a large scale will be limited until the production of low-carbon hydrogen is scaled up.

After reviewing the different alternative fuels availability and production methods, Table 3 introduces their approximate costs, which are currently subject to high uncertainty/speculation and will vary widely depending on the region and feedstock/primary energy availability. Additionally, Table 3 also indicates some of the current challenges for each of these fuels to become widely adopted in this application. The work of Breuer et al. (2022) describes the TRL of alternative fuels from synthetic production from hydrogen to renewable electricity, conventional biofuel production, and advanced biofuel production. It should be noted that lower cost compared with the fossil equivalent is a main challenge for the uptake of all alternative fuels. Therefore, this cost, and that associated with gas turbine retrofit to utilize the alternative fuel, is unlikely to be justified against the fossil equivalent without an increase in the carbon price, government subsidy, or public acceptance (and likely all three are necessary). Economies of scale for many nascent alternative low-carbon fuels are also required to help reduce these costs.

Greenhouse Gas (GHG) Reduction in Canada

The Canadian Net-Zero Emissions Accountability Act (CAN NZEA Act, 2021) sets national targets for the reduction of GHG emissions based on the best scientific information available. The Act aims to promote transparency, accountability and ambitious action to achieve those targets. The final goal is to achieve net-zero emissions in Canada by 2050 and meet Canada's international commitments with respect to mitigating climate change. The national GHG emissions target for 2030 is Canada's nationally determined contribution for that year,

Table 3: Alternative fuel costs (Adam Brown et al., 2020) (IRENA, 2020) (IRENA and AEA, 2022).

Fuel	Cost [€/MWh]	CurrentChallenges
HVO	51 – 91	- Waste feedstock availability - Competition from transport applications
Biomethane – anaerobic digestion	40 – 120	- Low production volumes
Cellulosic ethanol	103 – 158	- Low feedstock availability - Poor retrofitability - Competition from transport fuel blending
Methanol and methane – biomass	62 – 112	- Low production volumes - Poor retrofitability
Methanol and methane – wastes	48 – 89	- Low production volumes - Poor retrofitability
FT liquids – biomass	75 – 144	- Lack of commercial production
FT liquids – wastes	53 – 104	- Lack of commercial production
FAME	79 – 139	- Long-term storage stability - Competition from transport fuel blending
Green hydrogen	90 – 195	- Efficient storage/transmission infrastructures - Low NO_x combustion system development.
Green ammonia	140 – 270	- Green hydrogen availability - Efficient ammonia synthesis - Geographic separation of production and use - Low NO_x combustion system development

communicated under the Paris Agreement. Table 4 reflects the targets imposed, sector by sector, by the 2030 Emissions Reduction Plan with the ultimate goal of net-zero emissions by 2050.

Table 4 2030 Emissions Reduction Plan – sector-by-sector (CAN 2030 ERP, 2022)

Sector	2005 Emissions (Mt)	2019 Emissions (Mt)	Estimated Change (2005-2030)
Electricity	118	61	-88%
Oil&Gas	160	191	-31%
Heavy Industry	87	77	-39%
Buildings	84	91	-37%
Transportation	160	186	-11%
Agriculture	72	73	-1%
Waste	31	28	-49%

The Minister must set the subsequent national GHG emissions reduction targets:

1. For the 2035 milestone year, no later than December 1, 2024;
2. For the 2040 milestone year, no later than December 1, 2029; and
3. For the 2045 milestone year, no later than December 1, 2034.

In order to achieve the targets, several regulations and incentive programs have been launched to ensure that the different sectors are able to achieve the goals by the set dates. Thus, there is a huge potential for low-carbon alternative fuels to be used mainly in three sectors reflected above: electricity, oil & gas, and heavy industries. In the past, gas turbines have been crucial to the growth of these industries and have also contributed to reducing carbon emissions by transitioning from coal to natural gas. It is anticipated that gas turbines will continue to play a vital role in decarbonizing these industries through the use of alternative fuels with low carbon emissions.

The Clean Fuel Regulations (CFR) (Canada CFR, 2022) is a performance-based approach to reducing greenhouse gas emissions in Canada. The CFR replaces the current federal Renewable Fuels Regulations (CAN RFR, 2009).

The purpose of the CFR is to encourage innovation and the adoption of clean technologies, as well as to promote the widespread use of low-carbon intensity fuels across the economy. By offering fuel suppliers flexibility, they can meet the requirements in a cost-effective manner that suits their individual circumstances. Moreover, these Regulations provide an incentive for industries to embrace cleaner technologies, thereby reducing their compliance expenses.

The CFR defines the carbon intensity (CI) of fuel as grams of CO_2-equivalent (CO_2e) per megajoule of fuel energy. The CO_2e includes all GHGs that are released over the fuel's lifecycle including its production, transport, and end use. In this regard, the CFR require liquid fossil fuel (gasoline and diesel) suppliers to gradually reduce the carbon intensity from the fuels they produce and sell for use in Canada over time. The goal by 2030 is to reduce the carbon intensity of gasoline and diesel used in Canada by approximately 15% (below 2016 levels). (See Table 5).

Table 5: CFR CI limit for liquid fossil fuels (2023-2030 and after) – gCO_2e/MJ.

Liquid Fossil Fuel	2023	2024	2025	2026	2027	2028	2029	2030 and after
Gasoline	91.5	90.0	88.5	87.0	85.5	84.0	82.5	81.0
Diesel	89.5	88.0	86.5	85.0	83.5	82.0	80.5	79.0

To facilitate emission reduction efforts, the CFR introduce a credit market wherein each credit signifies a lifecycle emission reduction of one tonne of CO_2e. These compliance credits can be generated through three distinct methods.

1. Compliance Category 1: projects that reduce the CI of liquid fossil fuels (e.g., CCS, on-site renewable electricity, co-processing);
2. Compliance Category 2: supplying low carbon fuels (e.g., bio-derived fuels or renewable fuels of non-biological origin such as e-fuels).
3. Compliance Category 3: supplying fuel or energy to advance vehicle technology.

In line with the application of the CFR, a Fuel LCA Model has been developed to ease the quantification of the project emission reductions and allow projects to quantify their credits.. The calculation changes depending on the project. The following baseline quantification methods have been developed:

- Quantification method for Low-Carbon-Intensity Electricity Generation
- Quantification method for CO_2 Capture and Permanent Storage
- Quantification method for Enhanced Oil Recovery with CO_2 Capture and Permanent Storage
- Quantification method for Co-processing in Refineries

A generic quantification method has also been introduced to allow the adoption of cutting-edge technologies and projects. However, any new quantification methodology would need to be revised and approved.

In support of the Quantification Methods and the Fuel LCA Model, default CI is provided. Tables 11 to 16 in the document "Clean Fuel Regulations: Specifications for Fuel LCA Model CI Calculations" (CAN CFR Specifications, 2022) provide the default carbon intensity values of fossil fuels and hydrogen, default carbon intensity values of electricity by province and territory, electricity generation carbon intensity values by technology, and other emissions factors and carbon intensity values included in the Fuel LCA Model.

To incentivise adoption of low-carbon alternative fuels, the Government of Canada has also launched the carbon pollution pricing system across Canada (CAN CO2, 2018). The minimum national price for carbon pollution in explicit price-based systems, which directly establish a price on emissions, is set at $65 per tonne of CO_2e for the year 2023. The price will then rise by $15 annually, reaching $170 per tonne CO_2e by the year 2030, following the schedule below:

Table 6: Minimum National Carbon Pollution Price Schedule (2023-2030).

Year	2023	2024	2025	2026	2027	2028	2029	2030
Minimum Carbon Pollution Price ($CAD/tonne CO_2e)	$65	$80	$95	$110	$125	$140	$155	$170

In addition to the carbon pricing system, other regulations are in place such as the methane regulations which require the oil and gas sector to reduce methane emissions by 40-45% below 2012 levels by 2025. Canada committed to developing regulations to reduce methane emissions from the oil and gas sector by at least 75% below 2012 levels by 2030.

Regarding the electricity sector, the Canadian government is presently in the process of drafting the Clean Electricity Regulations (CER) with the aim of advancing towards a net-zero electricity grid by 2035. The development of clean electricity will play a crucial role in attaining Canada's climate targets for 2030 and 2050.

By adhering to three core principles, Canada's CER hold the potential to facilitate a smooth transition to a net-zero electricity grid by 2035 while ensuring that Canadians can continue to benefit from a dependable and affordable electricity system.

- Maximize greenhouse gas reductions to achieve net-zero emissions from the electricity grid by 2035;
- Ensure grid reliability to support a strong economy and ensure Canadians are safe by having the energy to support their cooling needs in the summer and warmth in the winter; and,
- Maintain electricity affordability for homeowners and businesses.

The CER is expected to be published before the end of 2023.

Canadian Taxonomy

Taxonomies offer a uniform method for comparing economic activities that align with both domestic and global climate objectives. It helps investors, businesses, and policymakers identify and support activities that are environmentally friendly and aligned with climate objectives.

Canada has not yet implemented a comprehensive national taxonomy for classifying sustainable economic activities but has made progress in recent months. In May 2021, the Sustainable Finance Action Council (SFAC) received a directive to offer counsel and proposals to Canada's Deputy Prime Minister and Minister of Finance, as well as the Minister of Environment and Climate Change, regarding the establishment of a green investment framework or "taxonomy”. The Taxonomy Roadmap Report (CAN Taxonomy, 2022) was endorsed by the SFAC in September 2022.

The initial proposal of the Canadian Taxonomy sets it apart from the EU Taxonomy by not only recognizing green projects but also actively involving transition projects. The Taxonomy Roadmap Report establishes a system to score green and transition projects, according to their relative transition opportunities and risks, reflecting the proposed criteria introduced in the report. However, the scoring system has been developed to test the feasibility of the concept and may serve as a starting point for the Taxonomy Custodian. Tables 7 and 8 show the criteria and measures for green and transition projects, and Figure 2 showcases hypothetical green and transition projects. Hence, newly built GTs with an alternative or low-carbon fuel capability would likely need to meet the transition or green project criteria as set out by the Canadian Taxonomy.

Table 7: Criteria and Measures for Green Projects (CAN Taxonomy, 2022)

Criteria	Measure
Emissions intensity relative to sector/product average	0 = N/A (negative emissions) 1 = Below sector/product average 2 = Meets sector/product average 3 = Above sector/product average
Size of value chain by 2050 in a 1.5ºC pathway	1 = Large value chain by 2050 2 = Moderate value chain by 2050 3 = Small or non-existent value chain by 2050
Sequestration Projects Only	
Extent to which sequestered emissions may be re-emitted into the air	0 = N/A 1 = High certainty of permanence 2 = Moderate certainty 3 = Low certainty

Table 8: Criteria and Measures for Transition Projects (CAN Taxonomy, 2022)

Criteria	Measure
Emissions intensity relative to sector/product average (today)	1 = below sector/product average 2 = meets sector/product average 3 = above sector/product average
Emissions intensity relative to sector/product average in 2030 (based on net-zero pathways)	1 = well below 2030 sector/product average 2 = below 2030 sector/product average 3 = meets 2030 sector/product average
Size of value chain by 2050 in a 1.5ºC pathway	1 = Large value chain by 2050 2 = Moderate value chain by 2050 3 = Small or non-existent value chain by 2050
Sequestration Projects Only	
Extent to which emissions may not be captured or sequestered emissions re-emitted into atmosphere	0 = N/A 1 = Low risk 2 = Moderate risk 3 = High risk
Demand-side risk projects only	
Project lifetimes relative to global demand for product in a 1.5 °C pathway	0 = N/A 1 = Short lifetime 2 = Medium lifetime 3 = Long lifetime

Alternative Fuel Composition

Many of the proposed alternatives to NG and diesel are not primarily produced for use as fuel in GTs. Hence, the level of impurities present from the production process is not necessarily analyzed following a standard for GT fuels (e.g., ASTM D2880). ASTM D2880 sets the maximum acceptable level of impurities that could potentially be harmful to the GT components, shown in Table 9 in terms of chemical elements that could increase the degradation of hot gas path materials, such as V, Na, K, Ca, Pb and so on. Some of the fuels are produced and analyzed considering different standards, such as ASTM D4806-21a for ethanol or D6751-20a for biodiesel. These standards do provide instructions for the use of such compounds as fuel for spark engines (ASTM D4806) and as blended fuel (ASTM D6751).

Figure 2: Hypothetical green and transition projects (CAN Taxonomy, 2022).

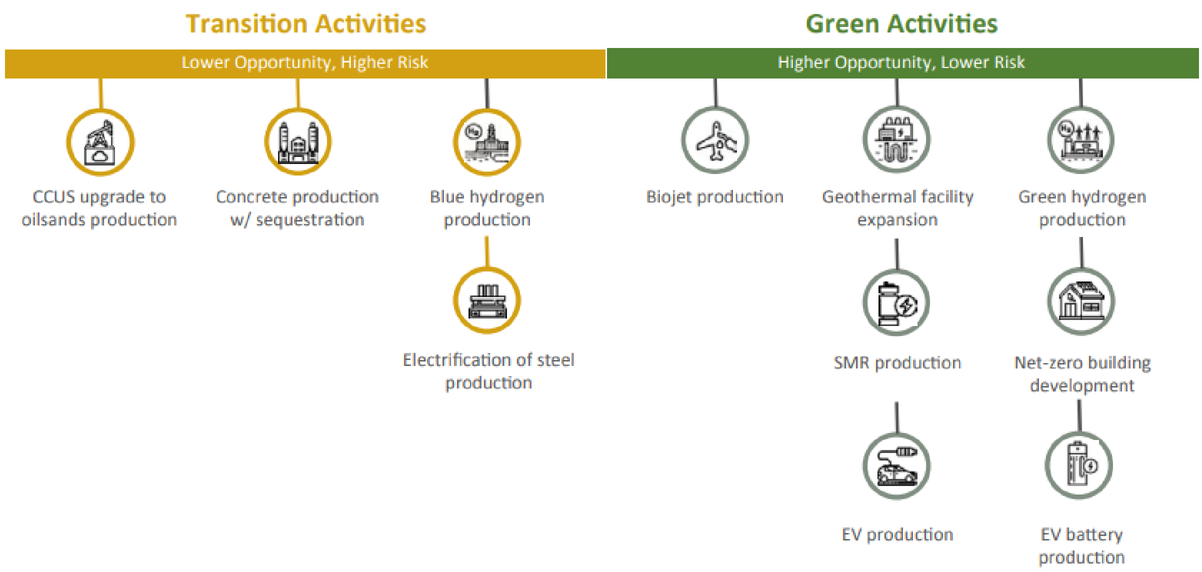


Table 9: Limits of trace metals entering the GT combustors (adapted from ASTM D2880).

Designation (1)	Trace Metal Limits mg/kg			
	V	Na+K	Ca	Pb
0-GT	0.5	0.5	0.5	0.5
1-GT	0.5	0.5	0.5	0.5
2-GT	0.5	0.5	0.5	0.5
3-GT	0.5	0.5	0.5	0.5
4-GT	Consult Turbine Manufacturer			

1. No. 0-GT includes naphtha, Jet B fuel and other volatile hydrocarbon liquids. No. 1-GT corresponds in general to specification D396 Grade No. 1 fuel and D975 Grade 1-D diesel fuel in physical properties. No. 2-GT corresponds in general to Specification D396 No. 2 fuel and D975 Grade 2-D diesel fuel in physical properties. No. 3-GT and No. 4-GT viscosity range brackets specification D396 Grades No. 4, Grade No. 4-D diesel fuel in physical properties.

Most of the standards though, do not provide guidelines on the level of the contaminants (impurities) of interest for GT fuels. Therefore, in order to gather relevant information for GT applications, it is necessary to consult various sources, including research papers, manufacturer guidelines, and studies including Amri et al. (2021), in order to obtain comprehensive and up-to-date insights. Amri et al. (2021) compared the values of different impurities found in FAME biodiesel, with the requirements set by ASTM D2880 and the GE-HD OEM guidelines. Selected results of the study are summarized in Figure 3 and Table 10.

Figure 3 shows a comparison between the measured value in biodiesel and the accepted values of ASTM D2880 and GE-HD (manufacturer). As it can be seen, the ASTM standard does set strict standards, and the biodiesel could meet the standard for Pb and V. These two metals are quite detrimental when present in the exhaust stream. In fact, V can form vanadate, which is responsible for corrosion damage (Ozgurluket al., 2018). In terms of other impurities, the analysis reveals that biodiesel contains approximately three times the amount of Ca+Mg compared to the standard and twice the amount of Na+K as per the standard. However, these levels are lower or similar to the specifications set by GE-HD. Ca+Mg is responsible for the CMAS type of attack in GTs; while Na+K can react with S contained in the exhaust stream (S could come from the fuel or air as impurities) and form (Na,K) SO_4 which can attack the alloys of the blades. The alloys with low Cr content as alloying elements are quite prone to the attack of S-containing molecules, especially at lower temperatures, around 700°C (Mori et al., 2022).

Looking at ammonia the situation appears to be less definitive or conclusive. There are no established standards for the utilization of ammonia as a fuel. Presently, ammonia is commercially available in various grades in the market (Atchison, 2020):

Figure 3: Measured impurities in biodiesel (blue columns) and standards ASTM D2880 (red line) and GE-HD (black lines) – (Amri et al., 2021).

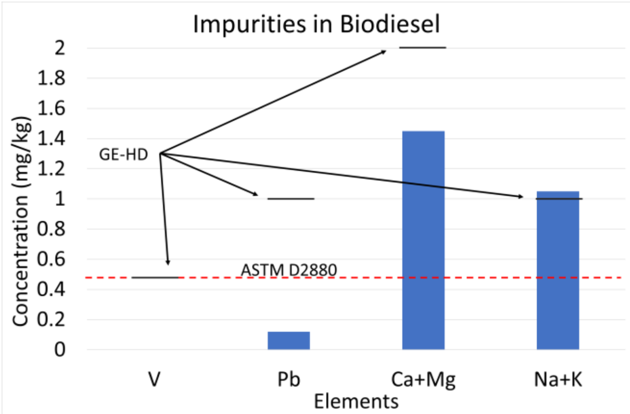


Table 10: Impurity levels of FAME biodiesel, adapted from Amri et al.(2021).

Parameters	Units	Methods	SNI 7182	EN14214	GE-HD
Phosporus	wt%	ASTM D4951	4	4	-
Ca+Mg	mg/kg	ASTM D7111	-	5	2
V	mg/kg	ASTM D7111	-		0.5
Pb	mg/kg	ASTM D7111	-		1
Na+K	mg/kg	ASTM D7111	-	5	1

Looking at ammonia the situation appears to be less definitive or conclusive. There are no established standards for the utilization of ammonia as a fuel. Presently, ammonia is commercially available in various grades in the market (Atchison, 2020):

- Premium or Metallurgical (Met-grade) ammonia at 99.995% purity.
- Refrigeration (R-grade) ammonia at 99.98% purity.
- Commercial or Agricultural (C-grade) ammonia at 99.5% purity.

It is believed that ammonia to be used as fuel would sit at a C-grade or below C-grade (Atchison, 2020), thus lower than 99.5% purity. This could pose several problems, as the exact composition of the C-grade ammonia is not well specified, and a correct quantification of impurities such as V, Pb, Na, K, Ca, S is needed for application as fuel for a GT. This presents an opportunity for further experimental investigations involving the interaction of exhaust gases from the combustion or use of ammonia with alloys that are expected to be used as blade materials.

Works assessing the corrosiveness of ammonia in different types of applications already exist. Valera-Medina et al. (2018) concluded that high-temperature cycling could induce nitridation of the alloy, but further studies are needed to assess the impact of the flow rate. In the same study (Valera-Medina et al., 2018), it was reported that ammonia is particularly corrosive when mixed with water. In fact, ammonia causes a rapid increase in pH (up to 11.6), causing problems for several materials, especially alloys such as copper, brass and zinc. The compatibility of different materials with ammonia is reported in Table 11.

As shown in Table 11, different types of materials could suffer severe degradation when in contact with ammonia, not just metals, but also polymers. This effect could pose problems even in the storage and distribution of ammonia, especially when stored at high pressure. This is because the increase in pressure could increase the diffusivity of the NH_3 molecules inside the materials, with the possibility of causing damage and leakage.

Table 11: Compatibility of different materials with ammonia, where A = Excellent, B = Good (but some effort), C = moderate effect (continuous use not recommended), D = severe. Adapted from (Valera-Medina et al., 2018).

ABS plastic	D	CPVC	A	Polycarbonate	D
Acetal (Delrin ®)	D	EPDM	A	PEEK	A
Aluminium	A	Epoxy	A	Polypropylene	A
Brass	D	Fluorocarbon (FKM)	D	Polyurethane	D
Bronze	D	Hastelloy-C ®	B	PPS (Ryton ®)	A
Buna N (Nitrile)	B	Hypalon ®	D	PTFE	A
Carbon graphite	A	Hytrel ®	D	PVC	A
Carbon Steel	B	Kalrez	A	PVDF (Kynar ®)	A
Carpenter 20	A	Kel-F ®	A	Silicone	C
Cast iron	A	LDPE	B	Stainless Steel 304	A
Ceramic Al2O3	N/A	Natural Rubber	D	Stainless Steel 316	A
Ceramic magnet	N/A	Neoprene	A	Titanium	C
ChemRaz (FFKM)	B	NORYL ®	B	Tygon ®	A
Copper	D	Nylon	A	Viton ®	D

The information collected during this review does show a variegated picture. The different alternative fuels could potentially contain different contaminants/impurities, that when combusted could form compounds potentially harmful to the turbines' hot gas path components (in particular blades). It would be crucial to correctly choose the operating parameters (such as pressure and temperatures). Other thermal power plants faced a similar challenge in the past. For example, some solid-fuels fired power plants switched from coal to biomass, but to achieve the same lifetime for heat exchangers, they were forced to run at lower temperatures (Montgomery et al., 2011). This was due to the difference in composition between coal and biomass (especially the difference in Cl and S content) that resulted in a different post combustion environment (Mori et al., 2021, 2022 and 2023). A similar scenario may be anticipated for GTs, but caution is necessary when extrapolating lessons from other industrial sectors. Further studies should be conducted to comprehensively understand the potential composition of the exhaust stream, and based on these findings, formulate a focused experimental plan for GTs.

Conclusions

The current study reviews the alternative fuels that have established global markets, although perhaps not currently as fuel, and that could substitute natural gas or fossil diesel in industrial GTs. Hydrogen has been widely covered in other studies and reports, and therefore, the efforts have been focused on: HVO, FAME, ethanol, methanol, biogas/biomethane, and low-carbon ammonia. The aim of this study is to provide a comprehensive review of the existing alternative fuels and derive the best prerequisite parameters to assess the potential of each to be used in industrial gas turbine applications such as power generation or mechanical drive.

Many industries are looking towards low-carbon alternative fuels to achieve decarbonization. Sectors like transportation and oil & gas are particularly difficult to electrify, which is why alternative fuels will play a crucial role in the coming years. In contrast, the electricity sector will rely on renewable energy, but GTs will still be needed to provide power during times when renewable energy is unavailable. Therefore, low-carbon alternative fuels and carbon capture technologies are two potential pathways for making GTs net-zero while ensuring a stable grid.

Lastly, the absence of established standards for alternative fuels which cover the GT application is a significant obstacle to the progress and widespread adoption of the technology in GTs. Current standards do not address the limitations of certain impurities, and there is no standard for the use of ammonia as fuel. Consequently, further fuel standard development is required.

To determine the optimal low-carbon alternative fuel for each GT application, a methodology is needed that can transition from qualitative to quantitative methods. This methodology, currently under development by the ETN Global Alternative Fuels Taskforce and Young Engineers Committee, will consider current technological advancements, economic factors, and environmental limitations.

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