Technical Feasibility of Decarbonising Propane in Canada

Collaboration between:

Canadian Propane Association

Christopher Bataille
cbataill@gmail.com
604.863.1259

Seton Stiebert, P.Eng

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Glossary

bioDME – bio-derived Di-methyl-ether

CFR – Clean Fuel Regulations

CI – Carbon Intensity

CO_2e – Carbon Dioxide Equivalent

Conventional Propane – Propane derived from fossil fuels

CPA – Canadian Propane Association

GHG – Greenhouse Gases

HHV – Higher Heating Value

HVO – Hydrotreated Vegetable Oil

LCFS – Low Carbon Fuel Standard

LOHC – Liquid Organic Hydrogen Carrier

LPG – Liquid Petroleum Gas

MJ – Megajoules

MTG – Methanol to Gasoline

NGL – Natural Gas Liquids

RIN – Renewable Identification Number

RFS – Renewable Fuel Standard

SAF – Sustainable Aviation Fuel

TJ - Terajoules

TRL – Technology Readiness Level

Executive Summary

The goal of this report is to demonstrate the propane sector’s path to net-zero propane by 2050. This implies production in Canada of near zero lifecycle emission intensity of propane while maintaining propane’s status as a highly valued energy source in terms of not just environmental impact but also affordability, versatility, and reliability.

For propane to be a valued energy choice in 2050, large scale quantities of renewable propane, or other biofuels that can be blended with propane such as bio dimethylether (bioDME) will need to be produced. **This study examines how renewable propane can be produced in Canada at scale**.

On a full life-cycle basis including production and direct emissions, Canada’s conventional propane has a relatively low-emission intensity compared to other fuels (72 gCO2e/MJ compared to 100 gCO2e/MJ for diesel). Renewable propane pathways have the potential to significantly lower lifecycle emissions or carbon intensity (CI). Existing renewable propane CI is roughly in the range of 7-45 gCO2e/MJ, but there are pathways that could deliver negative CI.

The most promising pathways to produce renewable propane in the near term are related to convincing existing and new biorefineries to capture and market renewable propane, biomass gasification or pyrolysis technologies using low-cost wood waste and catalytic reforming of waste biogases from agriculture or municipal wastes. Production of bio di-methyl ether (bioDME) that can be blended with renewable propane is also a promising technology. However, there are also other recently emerging pathways that could ultimately be more efficient and cost-effective.

Whether a production pathway can be economic depends on factors including process reliability and efficiency, energy requirements, collection and distribution infrastructure and economic margins. A review of production costs of renewable propane suggests they are currently at least twice that of existing (conventional) production costs. This large cost premium is not unique to renewable propane, and most biofuel options including renewable diesel have significant production cost challenges. First-of-kind renewable propane production plants in Canada face large investment risks from securing financing, planning, regulatory permitting, new and unproven technologies and processes, changing carbon policies and uncertain future markets.

Canada has strategic advantages for renewable propane production, including low-cost resources and feedstocks, and leading technology providers that could be capitalized upon. Renewable propane as a fuel also has strategic advantages over both fossil fuels and other biofuel options and electrification. These include storability, portability, reliability, affordability, negligible downstream fugitive methane emissions, versatility in end-use applications (from heating through transport) to use as a chemical feedstock or ultra-low GHG refrigerant, low air quality emissions impacts, and an existing distribution infrastructure with low costs.

Renewable propane represents a unique opportunity to make the best use of smaller scale, remote sources of biogas (agriculture and waste) that provide distributed energy production and supports regional development, particularly in remote communities. The opportunity to pair renewable propane with electric heat pumps to provide back-up heat at very low temperatures, especially in remote regions that are not near natural gas grids, is also a potential pathway to decarbonisation. Similarly, hybrid renewable propane and renewable energy systems, where renewable propane provides backup heat or power could provide a cost-effective solution for off-grid and remote buildings, facilities, and communities.

This study highlights renewable propane production pathways that are likely to be **less expensive than many competing biofuel options such as renewable diesel and hydrogen**. Liquid biofuels have significant regulatory drivers in place in Canada through the Clean Fuel Regulations but are limited for renewable propane.

In the U.S., through announced production tax credits, renewable fuel standards and state level low carbon fuel standards, there are considerable incentives for renewable propane production. A similar level of incentives for renewable propane production could be a catalyst for getting first-of-kind renewable propane production in Canada and driving down future biofuel costs through economies of scale and learning. The CPA should support matching government subsidies and financial instruments for biofuel developers and technology companies that can develop first-of-kind renewable propane projects in Canada. This approach could enable the most cost-effective and efficient pathways to decarbonisation, especially for hard-to-electrify end-uses (such as long-haul trucking, space heating in cold climates and energy demands at remote sites).

To date, little political attention and financial and policy support has been paid to renewable propane, but with equitable policies to encourage first-of-kind renewable propane plants in Canada, renewable propane can play an important role in achieving Canada’s net zero decarbonisation goals.

1 Introduction and Objectives

The Canadian Propane Association (CPA) represents the entire Canadian propane value chain, including producers, wholesale marketers, transporters, retail marketers and manufacturers of propane equipment. As a whole the propane sector is committed to doing its part to reduce emissions. This is a complex goal, over which different individual companies that are part of the propane value chain do not have direct control, meaning that propane as a fuel must progress towards net-zero or expect that in the future, it will not be a marketable green/low carbon, affordable, versatile and reliable option for Canadians.

The CPA seeks to outline a concrete roadmap to achieve net-zero propane and to seek member alignment on the path forward and policy asks. While striving towards production in Canada of a near-zero lifecycle carbon intensity of propane, members also strive to maintain propane's status as a highly valued fuel not just in terms of environmental impact but also affordability, versatility and reliability.

Large scale quantities of renewable propane or biopropane, or other biofuels that can be blended with propane such as bio dimethylether (bioDME) will need to be produced for propane be decarbonized. **The study's objective is to describe how renewable propane can be produced in Canada at scale**. Achieving this objective requires a better understanding of critical technologies, barriers, research and development requirements, and possible pathways to decarbonise propane within Canada. Such analysis has been completed by other jurisdictions, and these regions are now leading the way in producing renewable propane and bioDME, most notable in the U.S. Canada must understand and evaluate this opportunity to decarbonize the propane market quickly and effectively.

Without comprehensive analysis, developing a roadmap at this point would remain an abstract list of potential greenhouse gas (GHG) reduction technologies and strategies with no knowledge of how the first-of-kind low-carbon propane (or multifuel) production facilities can be built in Canada.

This technical feasibility study begins by describing where we are today, detailing Canada's complex supply chain from production to final end-use. It considers what we know about existing lifecycle emissions of conventional propane produced in Canada and investigates lifecycle emissions associated with different pathways to produce renewable propane.

The study then explores different technologies for producing renewable propane that could replace conventional propane in Canada, providing a market and barrier analysis for each of the technology options identified.

Finally, the study builds on the research to determine what it would take to develop first-of-kind renewable propane production facilities and distribution networks in Canada. Specific recommendations for the CPA are provided regarding the next steps and actions to build a strategy and roadmap for decarbonising propane in Canada.

2 Canada’s Propane Supply Chain

Over 90% of propane production in Canada is from the processing of natural gas liquids (NGLs) recovered from gas reprocessing plants (straddle plants) located along natural gas transmission lines and sent to centralized, large-scale fractionation plants for reprocessing into propane and other end products such as ethane, butane, and pentanes. The remainder is produced as a co-product from petroleum refineries. The upstream propane supply chain is dominated by a few large producers who operate most of Canada’s fractionation capacity. There are also smaller producers that include companies that operate petroleum refineries and bitumen upgraders.

Propane is primarily moved by rail or pipeline to export markets or, if for domestic use, to underground storage caverns before eventual distribution by rail and transport truck to propane terminals and downstream retailers. The final distribution of propane to customers is typically by bobtail and tank wagons.

Canadian propane demand is significantly diversified and is used in many applications. In 2021, energy-use represented about 78% of total propane demand with the remainder non-energy use related to the use of propane as a feedstock in chemical and plastic manufacturing.

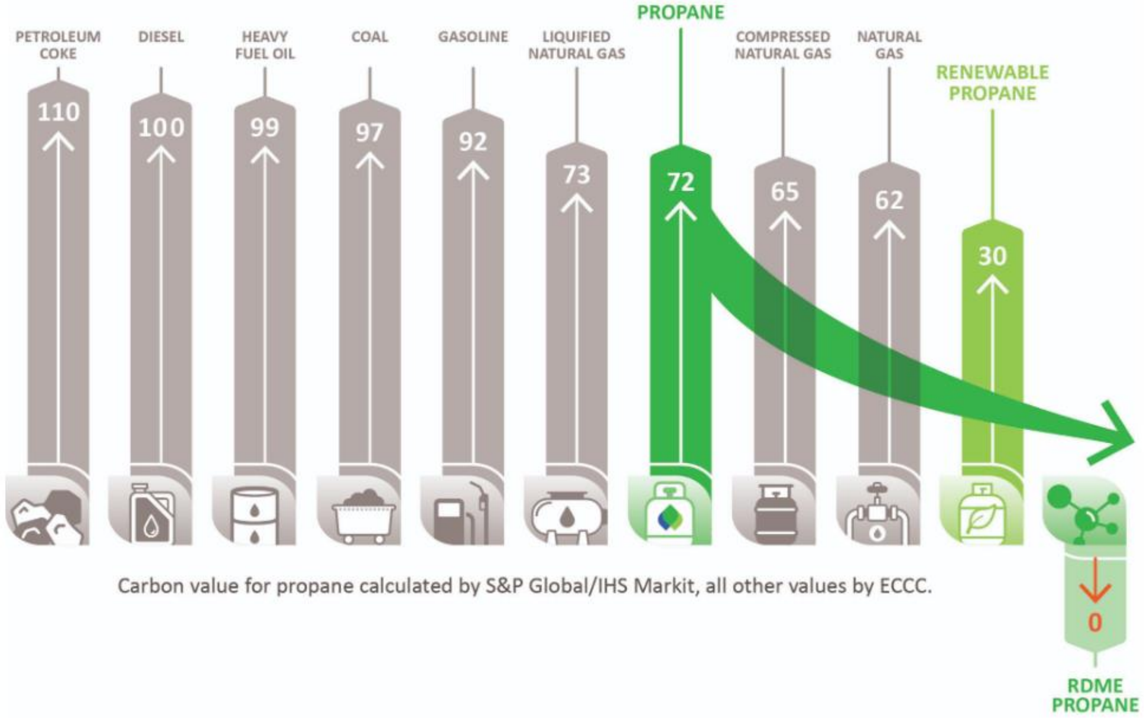
A detailed discussion of Canada’s Propane Supply Chain is provided in Appendix A.

3 Lifecycle Emissions of Conventional Propane and Renewable Alternatives

Direct (or combustion) emissions from conventional propane have a lower emission intensity per unit of energy of around 57 $kgCO_2e/GJ$ HHV, which is lower than most other fuels widely distributed in Canada, with the exception of natural gas. This makes propane currently an environmentally responsible choice for many end-uses not competing directly with electrification.

On a full life-cycle basis, Canada's propane also has a low emission intensity compared to other fuels. The CPA supported a study by S&P Global in 2021 to determine lifecycle emissions for significant propane production pathways in Canada. This study determined that the average lifecycle emissions of propane sold in Canada was 72 gCO_2e/MJ. As shown in Figure 1, this compares favourably to lifecycle emission intensity of other fuel options.

Figure 1: Lifecycle Emission Intensities for Different Conventional Energy Sources in Canada and Renewable Propane (gCO_2e/MJ)



Carbon value for propane calculated by S&P Global/IHS Markit, all other values by ECCC.

Source: CPA 2023

Renewable propane lifecycle emissions are typically less than half the level of conventional propane emissions, however, under certain conditions, lifecycle emissions can even be negative, meaning that through sequestration it takes more tonnes of CO_2e out of the environment than it produces.

The carbon intensity (CI) of renewable propane is largely driven by feedstock choice, process efficiency and whether there are intermediate products or additional processes that sequester carbon. For example, for hydrotreatment of vegetable oils and animal fats, the carbon intensity range is 20-60 gCO_2e/MJ depending on the oil (e.g., soybean, corn, used cooking oil).

A more detailed discussion and comparison of lifecycle emissions from conventional propane and renewable propane and other fuels is provided in **Appendix B**. Potential benefits to switching to propane fuel from other higher carbon intensity fuels is discussed in **Appendix D**.

4 Pathways to Produce Renewable Propane

In this pathways analysis for renewable propane, we also include pathways for low carbon fuels that can be blended with renewable propane, such as bio-dimethyl ether (bioDME), and low carbon fuels that have the potential to be carried in propane infrastructure.

Renewable propane is the term commonly used to describe liquid petroleum gas (LPG) derived from production processes that use biomass as the feedstock. For the purposes of this study, renewable propane is the same as biopropane. Potential differences in these terms are discussed in **Appendix A**. LPG is the generic name for mixtures of hydrocarbons that change from a gaseous to liquid state when compressed at moderate pressure or chilled. The chemical composition of LPG can vary but is usually predominantly made up of propane (C3H8) and butane (C4H10). Propane and butane are traditionally produced as a by-product of crude oil refining and natural gas processing, and similarly, renewable propane production from biomass feedstocks can also be a blend of these products. In practice, renewable propane may contain some butane (butane or isobutane, an isomer of butane) and other light hydrocarbons, though most of the emerging production technologies yield primarily propane.

The molecular structure of pure renewable propane is identical to that of conventional pure propane produced from hydrocarbons, so it can be blended or sold in a pure form. As a genuine “drop-in” fuel, it can be used in all current LPG market applications, including spiking of grid-distributed natural gas (bio or conventional methane) to adjust its heating value or heating density.

Dimethyl ether (DME) has the chemical formula C2H6O. DME can be blended with or substituted for LPG up to a limit of about 20% by mass. Today, conventional DME is produced largely from methanol (with natural gas or coal as the feedstock). If biomass is used as the feedstock, the resulting DME is referred in this report as bio-DME.

4.1 Major Production Pathways of Renewable Propane

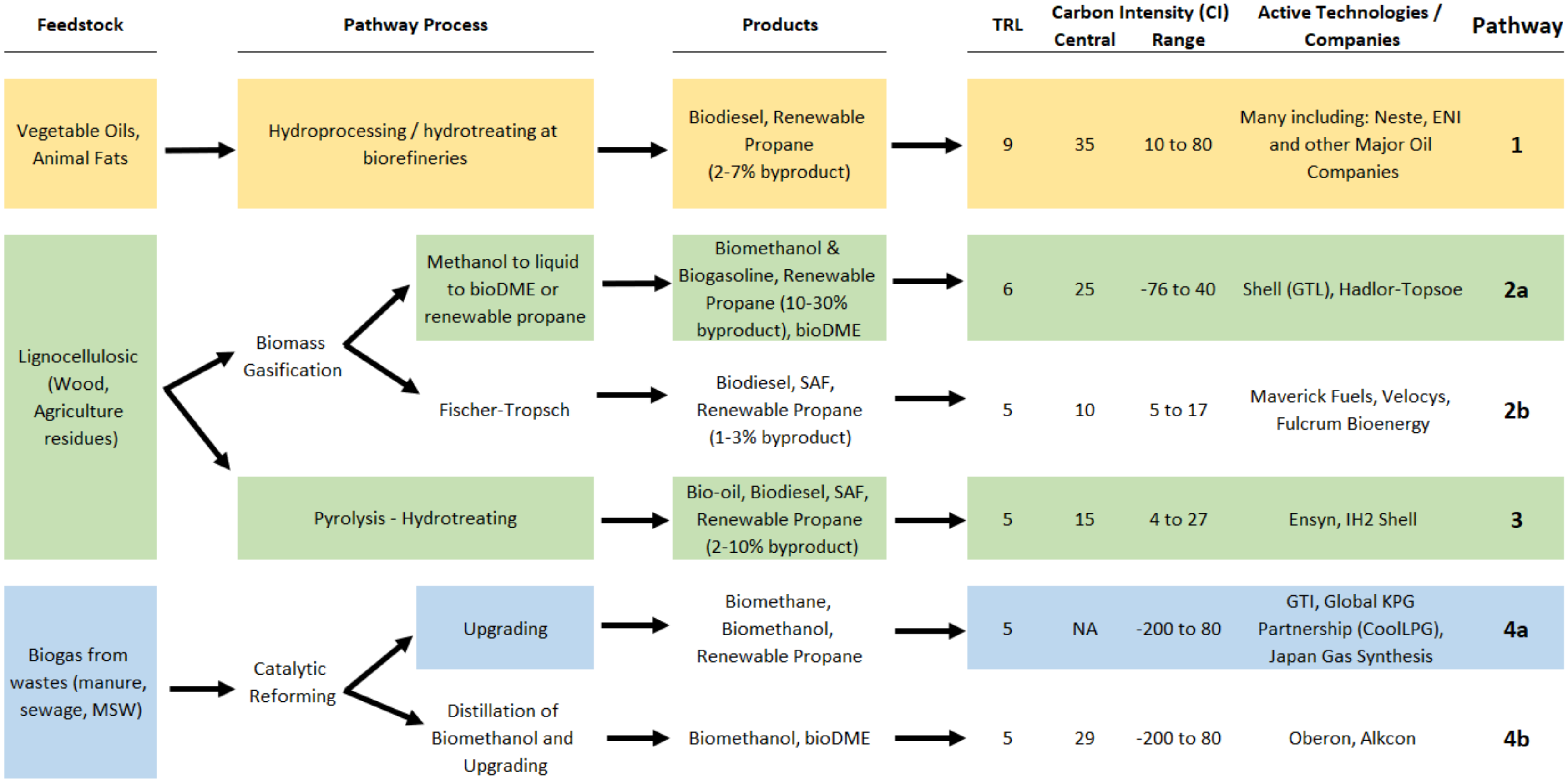
Renewable propane can, in principle, be produced in many ways using different types of thermal and chemical processes, either as a co-product in the production of other fuels or as the principal output. Most investment in the production of renewable propane is currently indirect, in that producers are primarily interested in producing renewable diesel through the hydrotreatment of vegetable oils and animal fats and renewable propane is a by-product. There are currently very few renewable propane production facilities worldwide that market renewable propane (i.e., they produce and separate renewable propane for sale to customers).

Neste, the leading renewable propane producer worldwide, sells renewable propane from its Rotterdam plant, but currently only as part of a mixture of other off-gases and not as a separate fuel. There are only a few other facilities worldwide of relatively small size that sell renewable propane as a product (e.g., Chevron Renewable Energy Group) or bioDME (e.g., Oberon).

Bio-dimethyl ether (bio-DME or rDME) is both another pathway to renewable propane as well as an alternative. It can be blended with renewable propane or used as an intermediate feedstock to produce renewable propane. DME is chemically similar to propane and butane and displays similar characteristics in use. It is increasingly being used as a source of energy but needs approvals for its use as a fuel or blending agent with fuel. DME can be blended into LPG for use in all applications with no equipment modifications, however, the limit of how much DME can be blended into LPG is likely around 20% by mass, as DME is a solvent that can cause corrosion. In addition, because DME has a different gravimetric density to propane, to avoid separation of the blend it may require agitation. This may be naturally achieved for mobile applications but problematic for stationary applications.

Figure 2 details seven different pathways to renewable propane or bioDME, including some with more than one process route to produce renewable propane or bioDME. A final eighth pathway discusses transporting a hydrogen carrier in propane infrastructure. Pathway categorisation is not always distinct due to the variety of processes and feedstocks that can produce the same chemical intermediates and how they can be transformed into renewable propane. Pathways are identified at a high level by common processes or chemical intermediates. Figure 8 details links between biomass feedstocks, processes, and products and includes companies active in developing technologies. The feedstock required for a specific production pathway is critical as supply and preparation costs are typically the largest contributor to overall production cost. Whether a production pathway can be economic depends on a number of other factors including process reliability and efficiency, energy requirements, collection and distribution infrastructure and economic margins. These potential barriers for the most promising pathways are discussed in the section 6.

Figure 2: Pathways to Renewable propane or bioDME



Feedstock	Pathway Process		Products	TRL	Carbon Intensity (CI)		Active Technologies / Companies	Pathway
					Central	Range		
Vegetable Oils, Animal Fats	Hydroprocessing / hydrotreating at biorefineries		Biodiesel, Renewable Propane (2-7% byproduct)	9	35	10 to 80	Many including: Neste, ENI and other Major Oil Companies	1
Lignocellulosic (Wood, Agriculture residues)	Biomass Gasification	Methanol to liquid to bioDME or renewable propane	Biomethanol & Biogasoline, Renewable Propane (10-30% byproduct), bioDME	6	25	-76 to 40	Shell (GTL), Hadlor-Topsoe	2a
		Fischer-Tropsch	Biodiesel, SAF, Renewable Propane (1-3% byproduct)	5	10	5 to 17	Maverick Fuels, Velocys, Fulcrum Bioenergy	2b
	Pyrolysis - Hydrotreating		Bio-oil, Biodiesel, SAF, Renewable Propane (2-10% byproduct)	5	15	4 to 27	Ensyn, IH2 Shell	3
Biogas from wastes (manure, sewage, MSW)	Catalytic Reforming	Upgrading	Biomethane, Biomethanol, Renewable Propane	5	NA	-200 to 80	GTI, Global KPG Partnership (CoolLPG), Japan Gas Synthesis	4a
		Distillation of Biomethanol and Upgrading	Biomethanol, bioDME	5	29	-200 to 80	Oberon, Alkcon	4b

Feedstock	Pathway Process	Products	TRL	Carbon Intensity (CI)		Active Technologies / Companies	Pathway
				Central	Range		
Glycerine / Glycerol	Dehydration / Hydrogenation	Renewable Propane	5	NA	NA	Bio-fuel Solution	**5**
Sugars / Starch	Aquaeous Phase Reforming	Renewable Propane	4	NA	10 to 20	Virent's (Bioforming)	**6a**
	Fermentation	Biobutylene, Renewable Propane	5	15	10 to 20	Global Bioenergies, C3 Bioenergy, Ekobnz, Vertimass	**6b**
Atmospheric or Captured CO2e	E-Fuels. H2 Electrolysis, Carbon Capture, Fischer Tropsch or other formation process	Many possible products including Renewable Propane	3	6	0 - 20	Many start-ups: HIF Global, Advanced Biofuels Solutions, Carbon Recycling International	**7**
Green Electricity for Hydrogen	Hydrogen Carriers in Propane Infrastructure, Fischer Tropsch	Green ammonia transported in propane infrastructure	7	NA	0 - 20	Existing LPG Ships and Tank systems currently transport Ammonia	**8**

Sources: Chen et al. (2021), Johnson E., (2019), Argus (2022), PERC (2023).

Each of the pathways identified in Figure 2 are briefly discussed in **Appendix C** of the report.

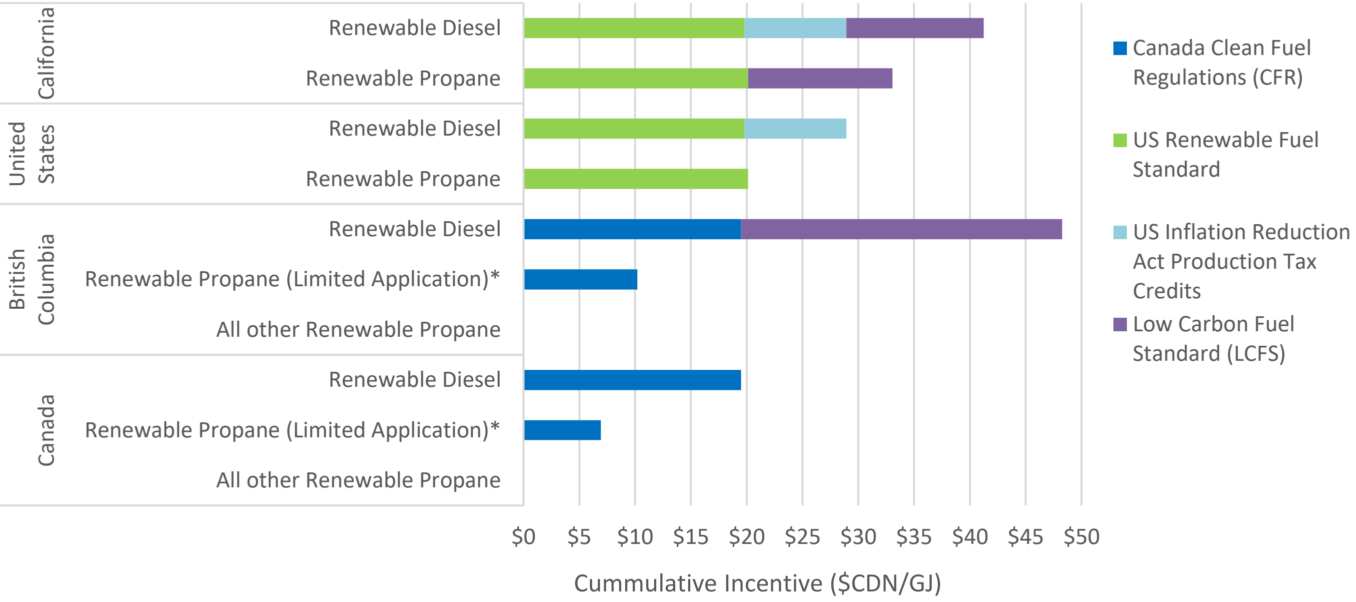
5 Market and Barrier Analysis

The total cost of production of renewable propane is the critical factor in determining whether plants get built in Canada, and it is expected that all pathways in the near term will be significantly more expensive than current conventional production. Evidence suggests that production costs of renewable propane will be initially at least twice that of existing production costs. This large cost premium is not unique to renewable propane, and most biofuel options, including renewable diesel, have significant production cost challenges.

In this case, renewable propane market prices will need to be significantly above current conventional propane market prices ($15-$30/GJ delivered to various end-uses) to drive production, either as a significant market premium over conventional propane, a significant credit for associated emission reductions or both.

While renewable propane cannot be a drop-in replacement for renewable diesel in all cases, it is useful to compare renewable propane incentives to renewable diesel production incentives in Canada and the U.S. that have triggered significant investment and production. Figure 3 outlines the current incentives for renewable propane and renewable diesel in British Columbia, California, and other U.S. State jurisdictions.

Figure 3: Estimated level of incentive for renewable propane and renewable diesel in Canada and the US



Note: (1) Renewable propane limited to replacement of liquid transportation fuels only (analysis based on diesel)

Source: Estimates are based on publicly available information on credit prices under the Renewable Fuel Standard and regional LCFS. Prices for Canada's CFR are based on limit credit values set out in the CFS. These prices are all subject to considerable fluctuation due to trading and estimates use average prices between January 2020 and August and average reported CIs in 2023 to estimate incentive levels.

In the U.S., we observe in Figure 3 that stacked incentives are on the order of $28 and $41 per GJ ($1.10 and $1.58 per litre) for renewable diesel produced with an average carbon intensity on the order of 35 gCO_2e/MJ, has contributed to a considerable increase in renewable production from 968 million gallons in 2020 to almost 1,900 billion gallons in 2022; a doubling in two years.

Currently the limited renewable propane production in Canada from biorefineries is used internally and is not marketed. This renewable propane reduces the carbon intensity of the produced renewable diesel and therefore contributes to a lower carbon intensity under the regulation. However, in California the cumulative incentive for renewable propane is currently estimated at $33/GJ based on contributions from both the U.S. Renewable Fuel Standard and California LCFS and a CI assumption of 30 gCO_2e/MJ. This level of incentive has opened up markets for renewable propane as a fuel choice in California for some transport applications.

There is evidence in the U.S. that the Renewable Fuel Standard alone ($20) is not enough for biorefineries to make additional investments in separation units for renewable propane to bring it to market. An additional incentive of around $10/GJ as evidence from the California LCFS appears to be required and this is also supported in the literature (Argus 2022). Without a total incentive price support around $30/GJ, biorefineries would likely choose to utilize byproduct renewable propane onsite to reduce the CI of liquid biofuel products.

Credits under the CFR and BC LCFS can be earned by fuel switching from liquid conventional fuels (e.g., diesel and gasoline) to propane in transportation. In this way there is a limited opportunity for renewable propane to earn an incentive around $10/GJ. Other project level funding for renewable propane in Canada is possible through programs like the Strategic Innovation Fund (SIF), but similar to other project types, this funding is not guaranteed, and this program has limited funding.

Initial research on production supply costs of renewable propane suggests there are potential pathways to produce renewable propane that may be lower than other biofuel pathways, especially when compared to renewable diesel where renewable propane shares many of the same useful attributes that benefit rural and remote communities (i.e., storability, portability, affordability and versatility for many end-use applications from heating to transport). While a comprehensive analysis must also include downstream costs such as distribution, marketing and retail for different end-use applications, on an energy basis renewable propane is expected to be competitive. If an incentive of $26-$39/GJ ($0.70-$1.05/L for propane), similar to what is available in the

U.S. for renewable diesel, were available to propane producers and retailers, we expect that many first-of-kind renewable propane production facilities could be built in Canada. These first-of-kind facilities would help to demonstrate technology, reduce perceived investment risk, and drive production costs down with learning and scale. Subsequent second-generation plants would require smaller premiums and eventually, renewable propane production could be less expensive than other competing biofuel options.

In addition to renewable propane production incentives, it may also be possible to generate a premium market for renewable propane. This will require the ability to certify the renewable propane according to the carbon footprint and renewable content.

The RFS in the U.S. is adaptable and recognizes renewable propane as eligible for renewable identification credits (RINs) which can then be traded and receive credit values. Several renewable propane-producing projects already have been ruled to qualify by the Environmental Protection Agency and further updates can be requested by producers. The system allows for renewable propane produced and used as a biorefinery process fuel to qualify for RINs. Canada’s system of accreditation is still being developed and it is not clear how quickly new renewable propane production pathways can be added.

The adaptability of U.S. policy is demonstrated through Oberon’s development of comparable fuel for rDME. Incentives from the California government and recognition at a national level were crucial to the commissioning of their first commercial plant.

6 Conclusions

This study highlights that although specific pathways and technologies to produce large scale quantities of renewable propane, renewable propane or BioDME are emerging, they are not close to being available as simple drop-in solutions to Canada's supply-chain with known costs and risks. Any first-of-kind renewable propane production plant in Canada faces large investment risks from securing financing, planning and regulatory permitting, to new and unreliable technologies and processes, changing carbon policies and uncertain future markets. These risks are not unique to renewable propane, many other industrial decarbonisation strategies face similar barriers, so there is an opportunity to align with other industry organizations on common issues. There are, however, distinct issues that the CPA will need to address on its own.

Recommendations for the CPA are provided in the sub-sections below.

6.1 Key Lessons Learned from this Study

1. While there are emerging options that exist for significantly reducing the carbon intensity of propane sold in Canada and decarbonising Canada's propane supply chain, they involve significant financial, policy and regulatory risks for the investment community.
2. Most of the current global production of renewable propane is from biorefineries that are attached to traditional petroleum refineries using hydrotreatment of vegetable oils or animal fats to produce liquid biofuels. In this case, the technology is mature, but renewable propane is a by-product in the same way that propane is a by-product in petroleum refinery production. Currently, most renewable propane produced in this way is not separated or marketed and is utilized on site for energy. This condition is unlikely to change without significant financial incentive to overcome the costs of processing renewable propane.
3. Other first-of-kind renewable propane production pathways that hold the most promise of being commercialized in the near-term include gasification technologies that can use inexpensive lignocellulosic materials like wood waste (Pathway 2) and catalytic reforming of biogas wastes to renewable propane or bioDME (Pathway 4). Most gasification pathway routes also would produce renewable propane as a by-product and so have the same challenges as Pathway 1 - HVO production. Catalytic reforming of biogas wastes has an advantage in that renewable propane or rDME can be selectively produced, providing a dedicated and stable marketable supply while also improving the management and reducing the emissions of biowastes.

4. Pathways that use other feedstocks including glycerine, sugars, and starch. Pathways based on green hydrogen and CO_2 (e-fuels) are technologically viable but currently expensive. While these are unlikely to be economically viable in the near-term, it is worth following these efforts.
5. Canada has strategic advantages for renewable propane production, including low-cost resources and feedstocks, and leading technology providers that could be capitalized upon.
6. The pathway of using propane and propane infrastructure as a carrier for renewable hydrogen has technology barriers and more assessment is required. The main issue is that hydrogen under low pressure has a very low volumetric energy density and so ultimately, the amount of hydrogen energy that can be stored in a propane tank at typical pressure is very low (more than 10 times lower energy per unit volume).

   An additional problem is that hydrogen can corrode and cause mechanical damage to tanks and metals it comes into contact with (hydrogen embrittlement). Direct hydrogen blending with propane does appear to be impractical given the issues with separation. Most promising is the use of a hydrogen carrier such as ammonia that has a much higher volumetric energy density then hydrogen at typical pressures of propane infrastructure. While feasible, safety issues due to the high toxicity of ammonia need to be resolved, as well as the development of distributed end-uses similar to propane fuel. Methanol or formic acid could also serve as hydrogen carriers but require a low GHG carbon source.
7. The biofuel production space has an extraordinary number of technology developers globally pursuing different pathways. Many of these developers have failed to advance from laboratory scale or failed at the pilot scale due to technical issues and unreasonable costs.
8. Renewable propane production will likely need to compete at a price point significantly lower than liquid biofuels. For example, sustainable aviation fuel currently trades on a premium market for as much as $90/GJ. It would also need to command a market price significantly above the market price of natural gas that is currently as low as $10-15/GJ delivered to end-users.
9. Initial research suggests that renewable propane production pathways are likely to be less expensive than many other biofuel pathways. Considering that liquid biofuel incentives in the U.S. have been successful in building the first-of-kind plants and ramping up production, similar incentives per unit of energy delivered, could also produce renewable propane. An initial incentive structure that provides between $38-$58/GJ ($0.70-$1.06/L) could be a catalyst for getting first-of-kind renewable propane production in Canada and driving down future biofuel costs through economies of scale and learning. This approach could

enable the most cost effective and efficient pathways to decarbonisation, especially for hard-to-electrify end-uses.

10. Under the Clean Fuel Regulations (CFR) in Canada, liquid biofuels such as renewable diesel are expected to generate compliance credits that translate to about \$300/tCO_2e reduced or about \$19/GJ. Developers of first-of-kind renewable propane production in Canada are limited by the CFR to earning credits only for projects that fuel switch from liquid conventional fuels used in transportation to propane or renewable propane, which is reasonable given that propane is a non-obligated fuel. However, there could be an opportunity for renewable propane to generate offsets under the system.

6.2 Why Renewable Propane Needs to be Part of the Future Energy Mix of Canada

Key messages:

1. Recent evidence of progress towards national net-zero emissions indicates that we are not on track for 2030 targets. There is considerable debate about what contribution to reduction different low-carbon energy sources, technologies and options will have to make to reach net-zero however, numerous strategies will need to be pursued to affordably decarbonize the Canadian energy system. We need as many viable pathways to a net-zero energy system as possible, and relying on electrification, renewable electricity, green hydrogen, or carbon capture and storage is not a viable or robust strategy. Even increasing the electricity grid an extraordinary threefold by 2050 simply will not meet our energy requirements and we will still need gaseous and liquid fuels in key market segments.
2. Renewable propane has a number of strategic advantages over both conventional propane and other biofuel options and electrification. These include: storability, portability, affordability, no downstream fugitive methane emissions, versatility for many end-use applications from heat to transport, the possibility of being a low GHG non-HFC refrigerant for refrigerators and heat pumps, and an existing distribution infrastructure with low costs.
3. Renewable propane is an ideal fuel to be paired with electric heat pumps to provide back-up heat at low temperatures, especially in remote regions that are not near natural gas grids. It can also be used as a non-HFC refrigerant for heat pumps.
4. Renewable propane represents a unique opportunity to make the best use of smaller scale, remote sources of biogas (agriculture and waste), that provide distributed energy production, supports regional development, and provides an effective solution for capture and utilization.

5. Hybrid renewable propane and renewable energy systems could also provide a cost effect energy solution for off-grid and remote buildings, facilities, and communities. In these systems renewable solar or wind could provide baseload energy and renewable propane could be used for peak load and to provide support when renewables are not available.
6. Research suggests that renewable propane production costs per unit of energy are relatively low, particularly compared to liquid biofuels. While renewable propane cannot be a drop-in replacement for all liquid biofuel applications, energy cost parity or better would allow renewable propane to compete for a number of end-use applications. In this way, renewable propane production is a large opportunity to enable pathways to decarbonisation in Canada that are cost effective, meet the needs of rural and remote communities, and reach hard to abate end-uses.

7 Recommendations to Accelerate Propane Decarbonisation

The CPA strongly advocates that competing energy sources across Canada have similar needs for incentive structures that recognize emission reductions, portability, versatility, and scalability. In particular, because promising renewable propane production pathways are at a low Technology Readiness Level (TRL) and have received significantly less attention, it is paramount that first-of-kind facilities have production incentives so that they can compete and learn on a level playing field. We are confident with the right policies to encourage first-of-kind renewable propane plants in Canada, that they will have an important role in achieving Canada’s net zero decarbonisation goals.

7.1 Recommendation to Support First-of-Kind Renewable Propane Production in Canada

Canada does not currently have favourable conditions for building the first-of-kind renewable propane production facilities that are necessary for decarbonisation. The U.S. Inflation Reduction Act (IRA) and the European Green Deal Investment Plan (EGDIP) are recent large scale government responses to accelerate investment in near-zero industrial production by providing significant process subsidies. These significant subsidies currently put Canada at a competitive disadvantage. The CPA should support matching government subsidies and financial instruments that can enable first-of-kind facilities with a good chance of success.

Biofuel production in most jurisdictions requires the stacking of different financial incentives. For example, biofuel production in California is supported by the state LCFS, the federal RFS and blenders tax credits (soon to be replaced by production tax credits) under the IRA. Ensuring that these incentives stack up to a level that provides a minimum level of support for at least 10 years, a typical period for core capital amortization, is critical for investment in first-of-kind plants.

The propane sector should seek to actively work with biofuel developers and technology companies to develop first-of-kind renewable propane projects in Canada.

First, the CPA should highlight Canada's strategic advantages for renewable propane production globally:

1. Low cost and abundant bio feedstocks for renewable propane production (e.g., wood waste, agriculture biogas).
2. Biogas utilization for propane production that can also help to reduce and manage current emissions from biowastes such as municipal solid waste, wastewater, and agricultural manure.
3. Technology leaders.
4. Low cost and extensive regional transportation networks.
5. Demand for versatile, low-carbon fuels that can meet the challenges of remoteness, flexibility, and storage.
6. Benefits of renewable propane from an energy-security perspective that reduces reliance on imported energy and increases the potential for energy exports.
7. Benefits of renewable propane that favour dispersed local and regional production and contribute to regional economic stimulus and growth. This includes jobs in rural and economically disadvantaged communities.

The CPA should also identify that currently, the federal carbon fuel levy on propane will likely raise more than $350 million dollars in 2023 alone across Canada based on coverage and carbon prices from the Canadian Institute for Climate Choices. Despite this sizeable contribution, there currently has been no subsidy or investment support for any type of renewable propane production in Canada to date. Opportunities for support through the Strategic Innovation Fund (SIF) Net-Zero Accelerator Program and under the CFR and British Columbia LCFS for limited applications of renewable propane to replace liquid transportation fuels exist. However, the SIF Net-Zero Accelerator is a competitive, not guaranteed, and limited fund that has no requirement to support all pathways, while the CRF and LCFS are narrowly restricted in scope for both obligation and compliance crediting.

The CPA could also provide general support to increase the profile of renewable propane decarbonisation pathways and technology options. This type of support includes meetings, initiating discussion forums, and communicating regulatory and investment barriers. The CPA could also stimulate discussion with financial institutions to build decision-maker interest in developing renewable propane projects and reducing risk premiums and financing costs.

7.2 Recommendations to Develop Green Premium Markets for Renewable Propane

The CPA should explore how low-carbon premium markets for renewable propane could be established, helping to identify propane customers who are able and willing to support higher energy prices for the environmental (and other) benefits that renewable propane has to offer. Since propane is already a preferred fuel for remote communities where there is already an extra transport supply cost, it is possible that some of these markets could offer some potential, e.g., remote energy and mining work sites, fishing, and hunting camps.

Low-carbon premium markets already exist for a number of other biofuels. Sustainable aviation fuel (SAFs) producers have direct contracts with airlines to buy SAF to power their planned flights. This mostly occurs using a credit system, although SAF credits are purchased by an airline, the actual SAF fuel is consumed at a local airport for other flights, similar to a carbon offset system.

Offtake agreements are emerging in the global shipping chain for low-emission intensity fuels such as green methanol. For example, OCI Global, the world's largest green methanol producer, has negotiated green methanol offtake agreements.

Long-term purchase contracts and offtake agreements can be crucial to make first-of-kind production "investable" since other carbon pricing incentives, such as carbon pricing, may or may not be politically durable over the lifetime of the project. Large consumers of propane that have clear goals for decarbonisation may be good candidates for purchase contracts or offtake agreements. For example, the mining and oil and gas industries already use significant amounts of propane at remote sites that will be expensive and difficult to decarbonize. Provincial and federal governments are also large consumers of propane that could develop low-carbon public procurement policies that include renewable propane.

For first-of-kind renewable propane production it may be essential for contracts and off-take agreements to flow all the way from production to final end-use to ensure that long-term market support is guaranteed for all participants (i.e., producers, distributors and retailers and final end-users).

7.3 Recommendations to Streamline Regulatory Framework to Support Renewable Propane

The CPA should support streamlining regulatory policies and reducing red tape on approval processes as well as developing the regulatory framework that could encourage investment in Canada, including:

1. Reducing the permitting timeline for required project approvals. Timeframes in Canada for final project approval can be typically three to seven years for large projects such as large biorefineries which is incongruent with 2030 and 2050 decarbonisation targets. Streamlined applications, procedures and regulatory processes will help to de-risk and preserve projects, particularly first-of-kind facilities.
2. Accelerating analysis on lifecycle carbon intensity of biopropane pathways including those used for the federal Clean Fuels Regulations.
3. Enabling regulatory programs to recognize biopropane.
4. Providing provincial and federal regulation and standards for propane blending that will enable development of biopropane production pathways to reach markets.
5. Developing a biogas offset protocol under the Federal GHG Offset System that recognizes the environmental benefits of renewable propane pathways and potentially avoided methane emissions.

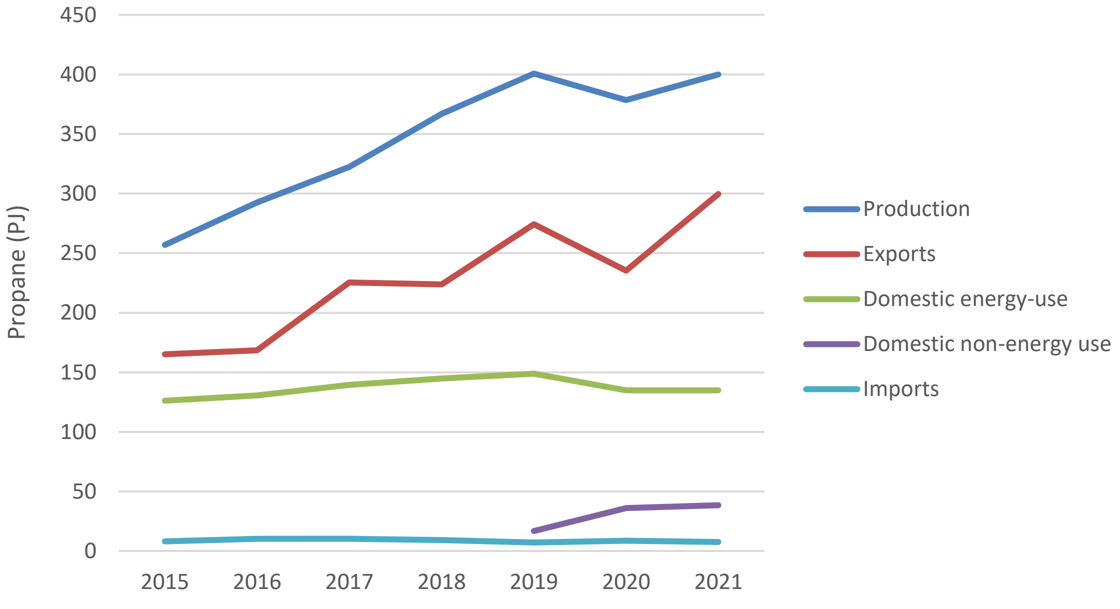
APPENDIX A: Canada's Propane Supply Chain

A.1 Propane Production and Use

Historically, over 90% of propane production in Canada is from the processing of NGLs at natural gas plants, with the remainder produced as a co-product from petroleum refineries. The supply of propane from refineries has been relatively stable and limited by total refining capacity. The ratio of propane produced relative to other finished petroleum products is only about 1% by volume.

Canada has significantly increased total propane production from field gas and straddle plants over the last ten years. Most of this production has gone to export markets in the U.S. as propane demand in Canada has been relatively flat over the same period. In 2021, exports rose to their highest level ever, and accounted for 75% of production. Figure A.1 Identifies Canada's historic trend in propane supply and domestic use.

Figure A.1: Canadian Propane Supply and Domestic Use 2015-2021 (TJ)

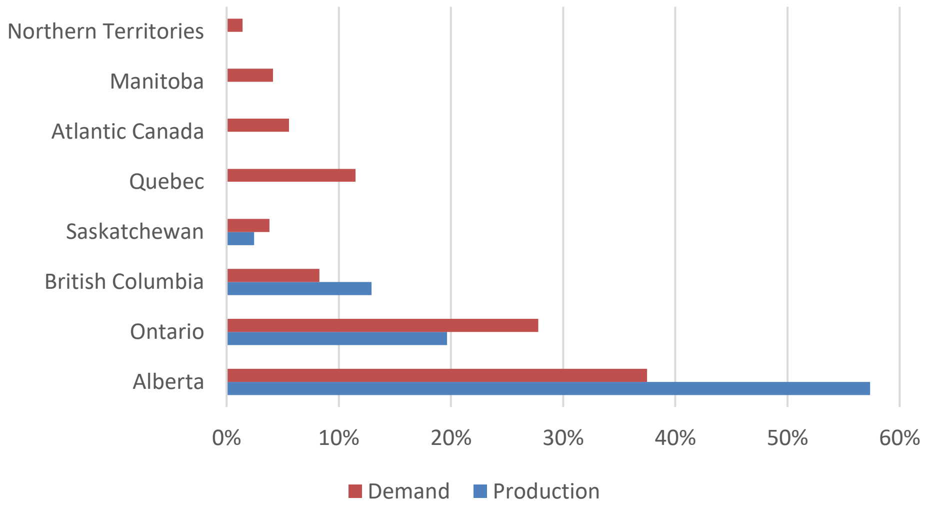


Source: Statistics Canada. Table 25-10-0026-01 Supply and demand of natural gas liquids, annual

Most of propane production and demand is in Alberta, accounting for 57% of production and 37% of domestic demand in 2020. Ontario is the second largest producer and consumer of propane with 20% of production and 28% of domestic demand. In the last five years, British Columbia has seen a rapid increase in NGLs and condensate production with average annual production jumping 111% from 2017 to

2022 as Montney operators targeted more liquids-rich areas. New project announcements by large British Columbia operators suggest liquids production will continue to climb for the remainder of the decade. Figure A.2 indicates the regional production and demand profile of Propane in 2020.

Figure A.2: Regional Production and Demand in Canada in 2020 (%)



Source: CPA. Regional Profiles Dashboard. Final Version May 2022.

The upstream propane supply chain is dominated by a few large producers who operate most of Canada's fractionation capacity. There are also smaller producers that include firms that operate petroleum refineries and bitumen upgraders. As an example, just five producers account for more than 50% of the natural gas produced from processing plants in Alberta and British Columbia.

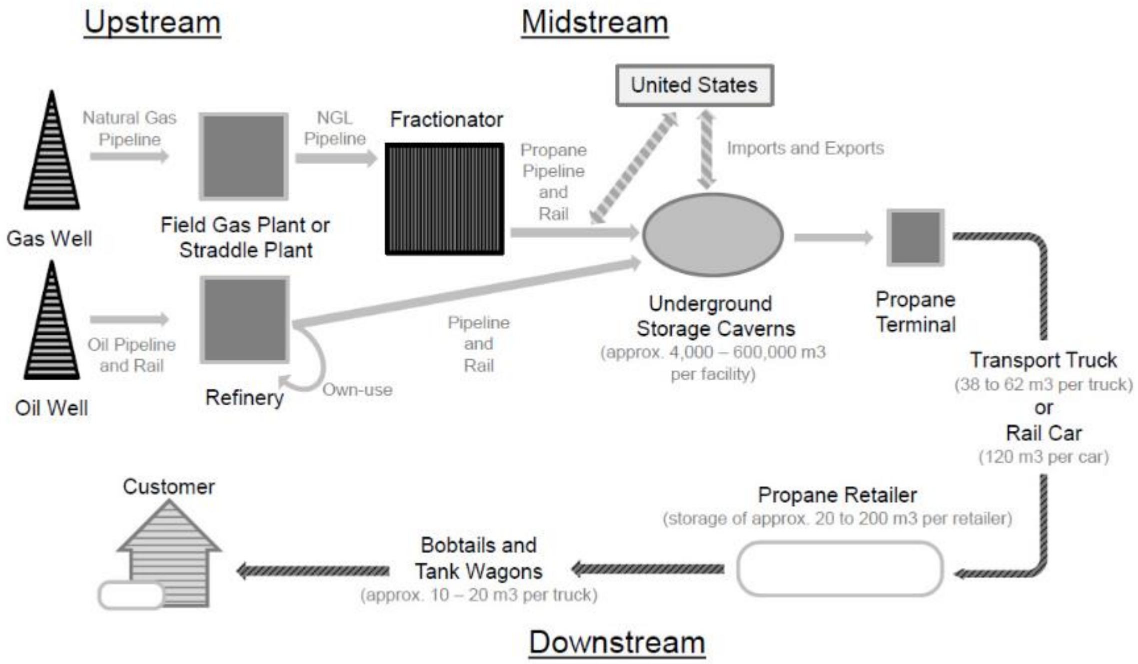
Table A.1: Distribution of Production for Natural Gas Plant Processing Propane Producers in Alberta and British Columbia

Quartile	Number of Producers in each Quartile	Estimate of Average Size Sales Volume (units) for Members in each Quartile
1st Quartile	2	2,500,000
2nd Quartile	3	1,750,000
3rd Quartile	5	850,000
4th Quartile	80	45,000

A.2 Propane Supply Chain and Demand

Most propane is moved by rail or pipeline to export markets or if used for domestic use to underground storage caverns before eventual distribution by rail and transport truck to propane terminals and downstream propane retailers. The final distribution of propane to customers is typically by bobtail and tank wagons.

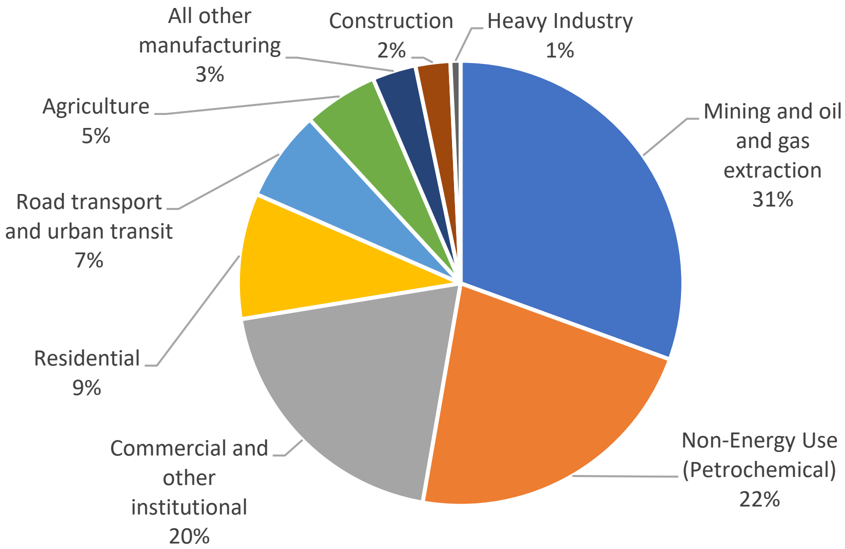
Figure A.3: Illustration of Canadian Propane Industry Supply Chain



Source: National Energy Board (2014). Propane Market Review. Accessed at https://natural-resources.canada.ca/energy/energy-sources-distribution/refining-sector-canada/propane-market-review-final-report/15927#supchain

Canadian propane demand is significantly diversified and is used in many applications. In 2021, energy-use represented about 78% of total propane demand. Non-energy use represented 22% of total demand and is primarily related to the use of propane as a feedstock in chemical and plastic manufacturing. The largest energy user of propane is the mining and oil and gas extraction sector accounting for 31% of total propane demand. Most of this energy demand is consumed by upstream oil and gas producers and never reaches downstream propane retailers. Another large downstream energy end-use for propane, 20% of the total, is for the commercial and institutional sector. Most of this propane is used for space heating and water heating. Residential home heating, water heating and cooking makes up approximately 9% of total domestic propane demand. Transportation, agriculture, manufacturing, construction, and heavy industries make up the remaining energy demand as illustrated in Figure A.4.

Figure A.4: Canadian Propane Demand by Sector (2021)



Source: Statistics Canada. Table 25-10-0026-01 Supply and demand of natural gas liquids, annual

Like upstream producers, downstream retailers are dominated by a few players; however, there are many smaller active players indicating that the market is not consolidated. The CPA membership, for example, includes 140 retailer members; however, three of these members account for nearly 50% of sales volumes.

Table A.2: Distribution of Sales Volumes for CPA Retailer Membership 2023

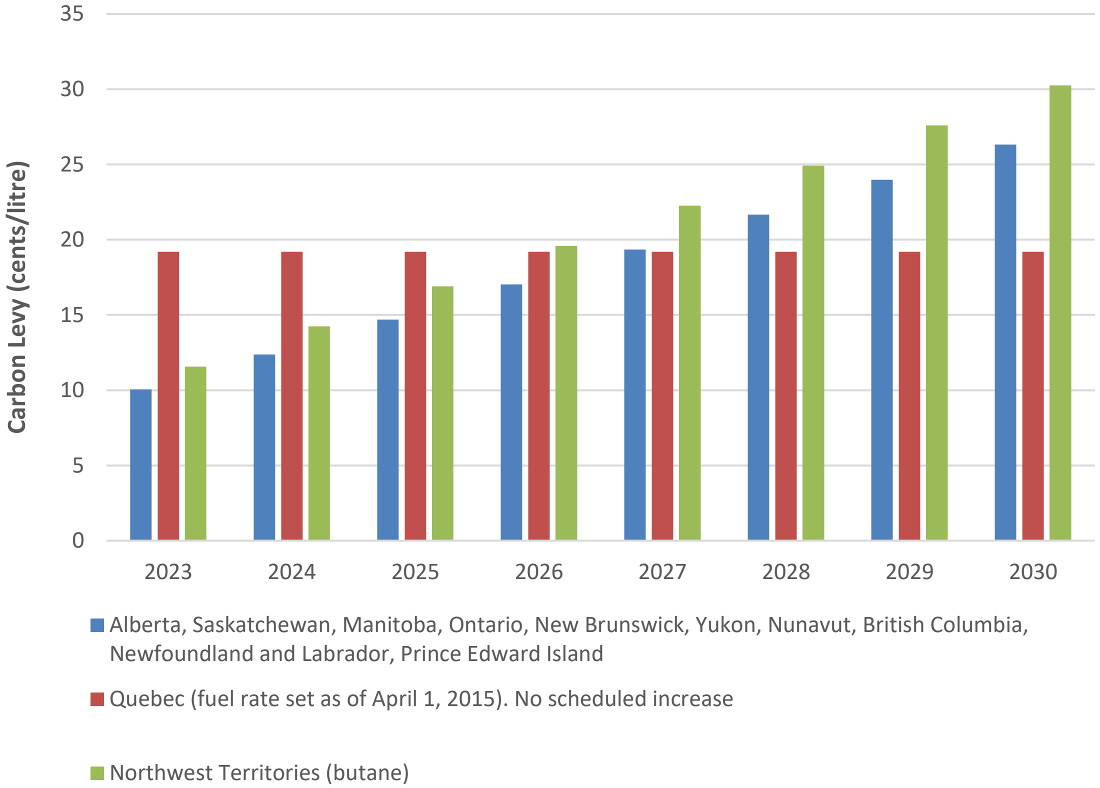
Distribution	Number of Members	Estimate of Average Sales Volume (m3) per Member
50% of Sales Volumes (1st and 2nd Quartile)	3	1,000,000
3rd Quartile	12	90,000
4th Quartile	125	8,300

Source: CPA (2023). Membership and Volume Levels.

A.3 Status of Regulatory Compliance of Propane

Propane, like all conventional fuels covered under the fuel charge of the Greenhouse Gas Pollution Pricing Act, has a “carbon levy” that is imposed on fuel distributors that reflects a federal carbon price rising from $65 per tonne of carbon dioxide equivalent (CO2e) in 2023 to $170 per tonne by 2030. Federal and provincial carbon levies can vary based on different carbon pricing policies and there are exemptions of fuel taxes in some cases, but generally, propane sold in Canada is impacted by the rates in Figure A.3.

Figure A.3: Federal and Provincial Carbon Levies (cents/litre)



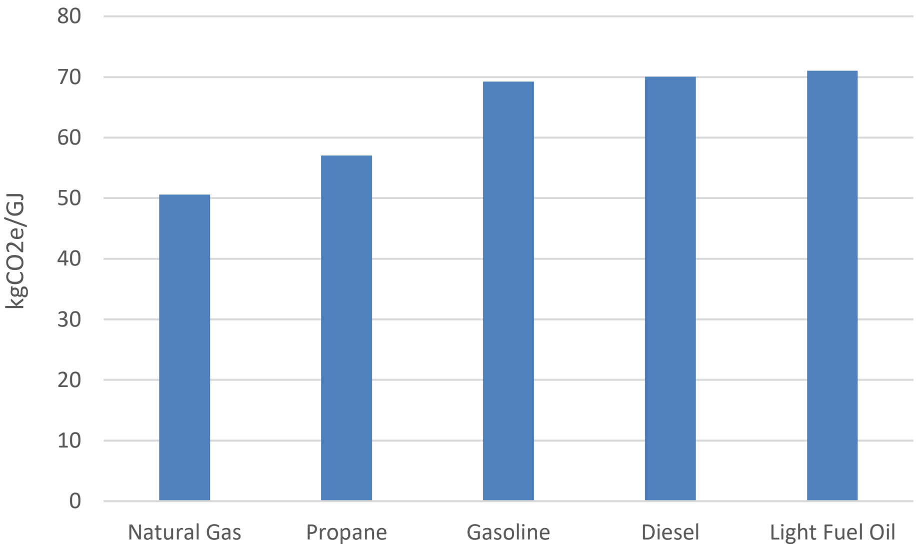
Source: [Canada Revenue Agency. Accessed September 8, 2023](#).

Currently, propane is not a regulated fuel under the federal Clean Fuel Regulations or British Columbia’s Low Carbon Fuel Standard.

Appendix B: Lifecycle Emissions of Propane and Renewable Alternatives

Direct (or combustion) emissions from conventional propane production have a lower emission intensity per unit of energy than almost any other fuel widely distributed in Canada (see Figure 5). This makes propane currently an environmentally responsible choice for many end-uses not competing directly with electrification.

Figure 5: Relative Comparison of Direct Emission Intensity of Common Fuels in Canada 2021 (kgCO2e/GJ HHV)

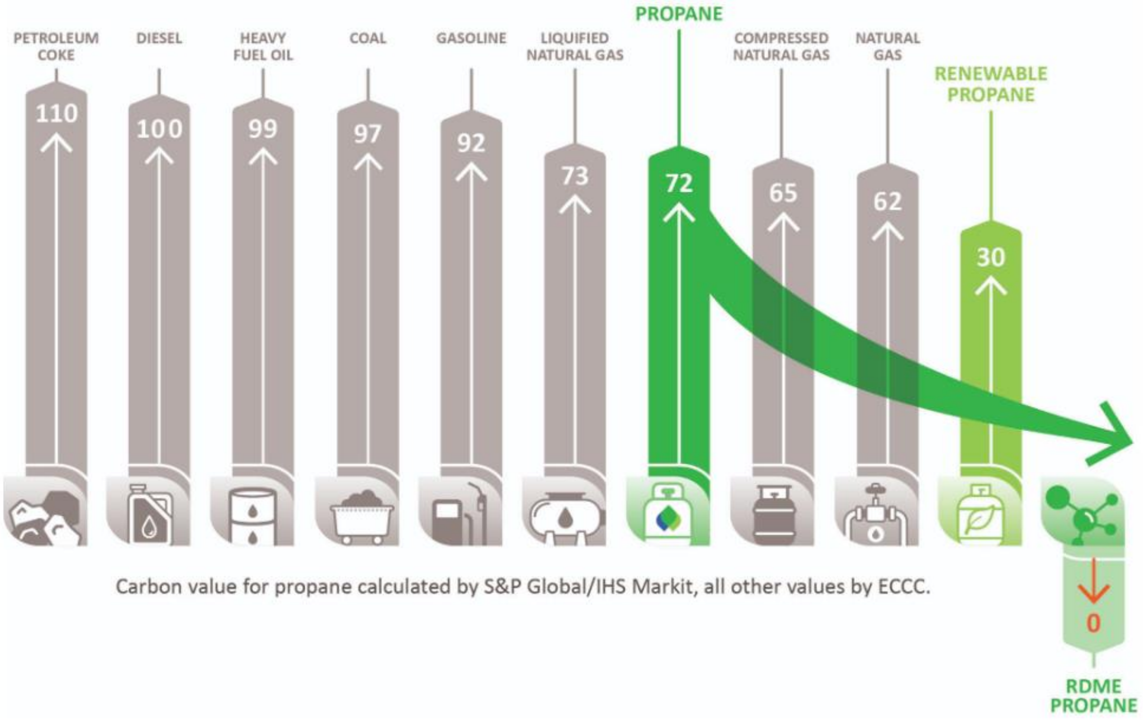


Source: ECCC (2023). National Inventory Report 1990-2021 Greenhouse Gas Sources and Sinks in Canada.

On a full life-cycle basis, Canada's propane also has a low emission intensity compared to other fuels. The CPA supported a study by S&P Global in 2021 to determine lifecycle emissions for significant propane production pathways in Canada. This study determined that the average lifecycle emissions of propane sold in Canada was 72 gCO2e/MJ. As shown in Figure 6, this compares favourably to lifecycle emission intensity of other fuel options.

Other sources of data for lifecycle emission intensity will vary depending on the methodology and pathway. An important consideration is that Canada's lifecycle emission intensity is lower than estimates from other countries as it is primarily produced from natural gas liquids recovered from the processing of raw natural gas. This has a lower lifecycle emission intensity than propane that is a by-product of crude oil refining. Lower than average upstream emissions from co-processing and separating from natural gas also contribute to a low average Canadian emission intensity.

Figure 6: Lifecycle Emission Intensities for Different Conventional Energy Sources in Canada and Renewable Propane (gCO_2e/MJ)



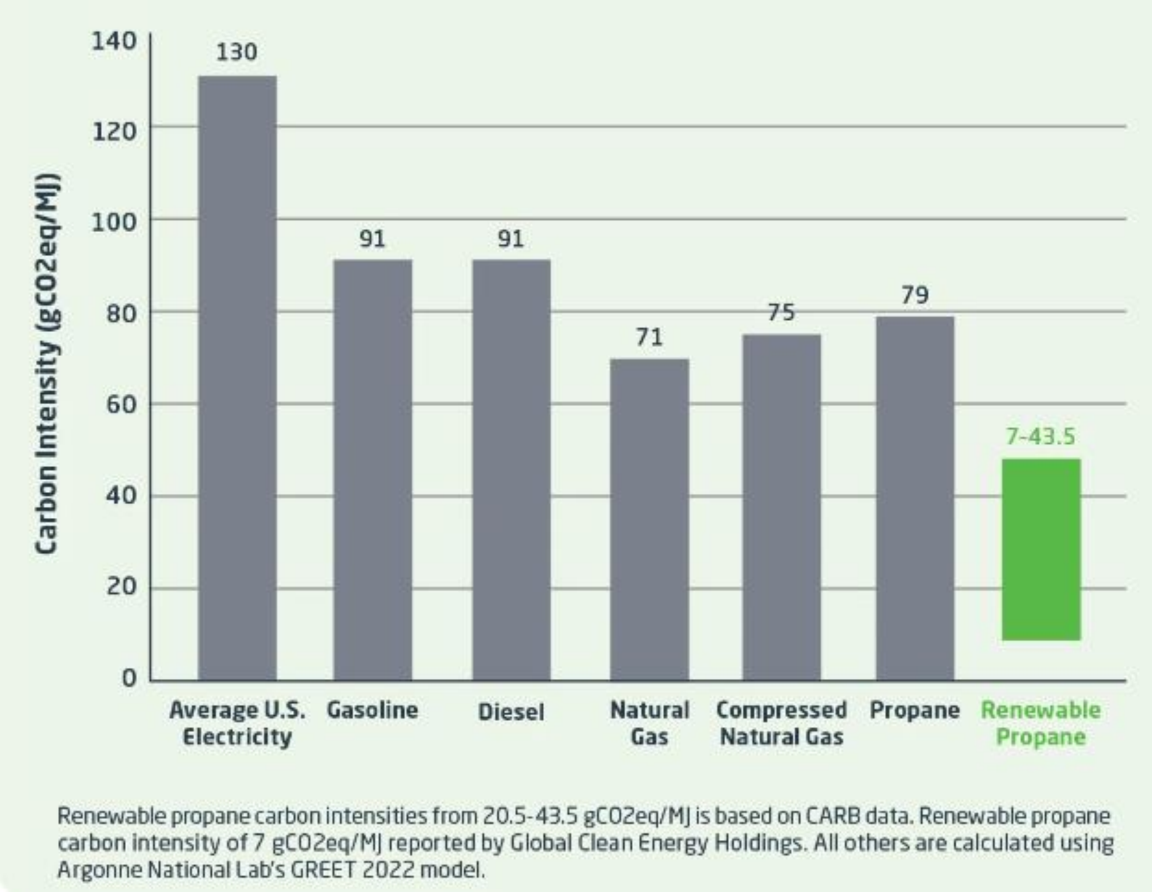
Source: CPA 2023

While there is reasonable confidence in the lifecycle emission intensity of 72 gCO2e/MJ for propane in Canada, it should be noted that the Federal Clean Fuel Regulations use a default value of 76 gCO2e/MJ. This value was based on the higher end of emission intensity associated with the production of propane as a by-product of refining that accounts for less than 10% of Canadian propane supply.

There is also an additional lifecycle advantage of propane compared to natural gas. Unlike natural gas, propane does not contribute to downstream fugitive methane emissions or leaks from transportation, distribution, storage, fueling and use. Downstream fugitive emissions from natural gas are releases of methane, which is a greenhouse gas with a 100-year global warming potential (GWP) that is approximately 28 times that of carbon dioxide, while propane's GWP if leaked is negligible. These downstream fugitive methane emissions from natural gas use contribute approximately 3 gCO2e/MJ on a lifecycle basis for natural gas end-uses.

Renewable propane or renewable propane lifecycle emissions are typically less than half the level of conventional propane emissions, however, under certain conditions, lifecycle emissions can even be negative, meaning that it takes more carbon or GHG emissions out of the environment than it produces through sequestration. Figure 7 indicates a range between 7-43.5 gCO_2e/MJ of carbon intensities for different renewable propane pathways that have been certified by the California Air Resources Board (CARB) program.

Figure 7: Comparison of Lifecycle Emission Intensities under CARB Program to Conventional Fuels (gCO_2e/MJ)



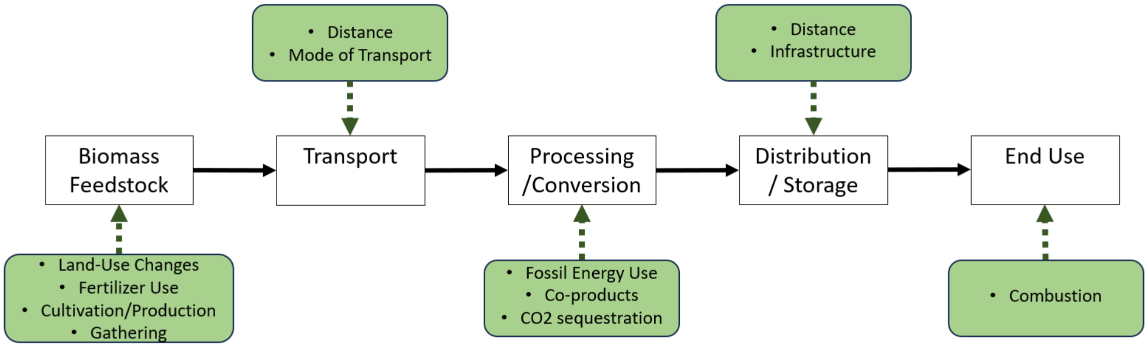
Renewable propane carbon intensities from 20.5-43.5 gCO2eq/MJ is based on CARB data. Renewable propane carbon intensity of 7 gCO2eq/MJ reported by Global Clean Energy Holdings. All others are calculated using Argonne National Lab's GREET 2022 model.

Source: Propane Education and Research Council 2023

The carbon intensity (CI) of renewable propane or renewable propane is largely driven by feedstock choice, process efficiency and whether there are intermediate products or additional processes that sequester carbon. For example, for hydrotreatment of vegetable oils and animal fats, the carbon intensity range is 20-60 gCO2e/MJ depending on the oil (e.g., soybean, corn, used cooking oil). Near zero CIs or negative CIs can only be achieved where carbon is stored or sequestered in other products. CIs as low as -200 gCO_2e/MJ have been reported for biofuels derived from methane biogases that are unmanaged (e.g., agricultural manure) as the project assumes that the baseline would be the release of methane to atmosphere, rather than the capture of methane and conversion into a fuel. While these high negative CIs exist under programs such as that run by CARB, there is a question of whether the baseline (unmitigated release of methane to atmosphere) is likely to remain the common practice over time.

The carbon intensity (CI) of renewable propane depends on emissions that are emitted at different lifecycle stages as indicated in Figure 8. The predominant contributions for renewable propane pathways are typically biomass feedstock emissions and processing, and conversion emissions. However, if biomass does not need to be cultivated and grown as is the case for waste biogases, contributions from biomass feedstock can be low. Some pathways also can sequester CO_2 and remove carbon which can also significantly lower CI and sometimes result in negative CI values.

Figure 8: Lifecycle stages for Biofuels and Major Contributors to Carbon Intensity (CI)



Appendix C: Pathways to Produce Renewable Propane

The difference between renewable propane and renewable propane is subtle as they both can be produced from the same biomass feedstocks and have identical physical characteristics. The distinction emerges out of the production of biodiesel and renewable diesel that are produced through different processes and have different properties (energy content, oxygen content). These same processes can also produce renewable propane and renewable propane; however, in this case, the renewable propane or renewable propane molecules are the same and the only reason to distinguish them are for tracking purposes.

Renewable propane is produced in a biorefinery using hydroprocessing or hydrotreating. If the biorefinery co-processes conventional crude oil (which is common) the propane produced contains a mix of conventional carbon and biogenic carbon (from biomass sources). The fraction of propane that contains biogenic carbon and the fraction of propane that contains conventional carbon, have the same physical properties, but in calculating carbon intensity of the mixed product it is important to be able to distinguish the input ratio; hence the renewable propane label is used.

The pathway descriptions provided below relate to Figure 2 in the report and are based on research and studies published by Chen et al. (2021), Johnson E., (2019), Argus (2022), and PERC (2023). Additional insights and information were provided by experts from the Propane Education and Research Council and the World LPG Association that reviewed the report.

Pathway 1: Hydrotreated Vegetable Oil / Animal Fats

In this technology, renewable propane is a by-product of biodiesel production. Vegetable oil (a triglyceride) is directly catalytically hydrogenated into paraffins. The glycerine chain of the vegetable oil triglyceride is hydrogenated to produce propane. The process removes oxygen from the oil so that the diesel is not an oxygenate, as is traditional fatty acid methyl ester (FAME) biodiesel. The technology allows flexible use of any vegetable or waste oil.

Since the process involves the application of hydrogen, near-zero biofuel production requires green hydrogen production as well. The process is well suited to integration at existing refineries, as processes, equipment and infrastructure are similar. At present, hydrogenated vegetable oil (HVO) renewable propane produced at biorefineries in Canada is not typically separated from other off-gases and the renewable propane and off-gases are used for heat production on-site or near-site or used as a feedstock for hydrogen production. Capturing marketable renewable propane requires additional purification units to separate out the renewable propane and commercialize.

Pathway 1: Description of Hydrotreated Vegetable Oil or Animal Fats (HVO)

Description of Pathway and Technology	Direct catalytic hydrogenation of vegetable oil to produce propane. The process is well suited to integration at existing refineries, as processes, equipment and infrastructure are similar.
Technology Readiness Level (TRL)	**9** (Many full-scale plants in operation and many different technology providers.)
Products	Primary product is generally biodiesel or Sustainable Aviation Fuel. Renewable propane is a byproduct with a 2-7% yield. In most applications, renewable propane is not separated from other off-gases and is used for heat production or as a feedstock for hydrogen production. Capturing marketable renewable propane requires additional purification units to separate out the renewable propane and commercialize.
Required Feedstocks	Vegetable oils or animal fats Significant additional volumes of vegetable oil or animal fats may be difficult to acquire given competition with agricultural products and high utilization of existing animal fats. It is also possible to use wood-based oil feedstock using HVO technology. UPM, a Finnish forestry-to-biofuels company, completed the first biorefinery in the world producing wood-based renewable diesel using HVO technology. Small quantities of renewable propane are among the by-products, but it is not marketed separately from other off-gases used for process energy.
Scalability	Largest production units are roughly 100,000 tonnes per year.
Active Technology Developers and Deployment	Neste was the first operator of a full-scale plant since 2015. ENI and other major energy companies operate more than 10 full scale plants globally, although only a few plants capture marketable renewable propane.
Emission Intensity	CARB identifies the emission intensity of this route for production in the U.S. between 20-43 gCO2e/MJ depending on the oil used, energy used for processing and transportation emissions.

Pathway 2: Biomass Gasification

Biomass gasification is a mature technology pathway that uses a controlled process involving heat, steam, and oxygen to convert biomass through partial combustion with a controlled amount of oxygen, high pressure, and temperature to a synthetic gas before being further processed into different products.

Renewable propane can be produced as a by-product of various gasification technologies to produce products including methanol, DME, gasoline and diesel. The product yields depend on the makeup of the syngas, the type of process, the process temperature and the catalyst used. There are several different sub-gasification technologies that are being developed for renewable propane production.

Pathway 2a: Gasification Methanol to Liquid Fuels to BioDME or Renewable propane

BioDME is produced by converting biomass to a syngas (gasification) and then converting it to DME in a two-step process via methanol. There are also one-step processes, such as those being developed by Haldor Topsoe and the Japan Synthesis Gas (JGS) Company that conduct methanol synthesis and dehydration in the same process unit, eliminating the intermediate methanol synthesis stage and promising gains in efficiency and cost. JGS have demonstrated two catalysts that can produce yields of 50-85% bioLPG.

Methanol-to-gasoline (MTG) technology, an indirect liquefaction process, involves the gasification of any type of conventional fuel or biomass to produce syngas, which is then converted to crude methanol and low-sulphur, low-benzene biogasoline or biodiesel in separate stages. MTG technology was first introduced by ExxonMobil to convert methanol to gasoline. Depending on the configuration of the plant and the composition of the syngas, renewable propane output can be as high as 30%.

Pathway 2b: Fischer-Tropsch Gasification: Biomass-based syngas can also be reformed to liquids using the well-established Fischer-Tropsch technology, which involves synthesising syngas into liquid hydrocarbons by passing the syngas through a reactor containing catalysts. However, the output of LPG from this process is small, at a few per cent of the total hydrocarbons output. A wide range of feedstocks can be used including lignostic and waste biomass. While the Fischer-Tropsch process is mature in processing biomass, the requirements for a high syngas purity to protect the catalyst are challenging and there are considerable issues with fouling that have prevented successful commercial demonstration.

Fulcrum Bioenergy has a pilot plant in Reno Nevada that has begun producing synthetic crude oil from landfill waste; however, there is no evidence that it plans to produce renewable propane as its focus is on sustainable aviation fuel (SAF).

Pathway 3: Pyrolysis Hydrotreating

Pyrolysis involves the thermal decomposition of organic compounds, such as wood and agricultural waste products, to create pyrolysis oil (or biocrude), which can then be hydro-processed into gasoline, diesel and/or kerosene. LPG (propane and butane) is produced as a by-product in both steps, amounting to about 10-15 % by weight. Shell's IH2 biomass to liquid process uses fast hydroconversion and hydropyrolysis to produce gasoline and LPG at a yield of 10%. The technology was being scaled up in a demonstration plant but has not reached commercialization and development may have been suspended.

The Canadian company, Ensyn, has developed a technology – Rapid Thermal Processing – that uses a fast pyrolysis process that involves the thermal cracking of woody biomass feedstock to gases and vapours. The yields from processing dry biomass (with 8% moisture) are approximately 65-80% liquid by weight, with 12-16% each of char and combustible gas, including small amounts of renewable propane.

Pathway 4: Biogas – Catalytic Synthesis of Renewable propane or BioDME

Catalytic Synthesis of biopropane or BioDME from available biogases. Biogas production from anaerobic digestion and landfill capture is a mature technology. Biomethane can be separated out from this biogas and then reformed to produce a syngas through nonthermal routes that use catalysts.

Pathway 4a: Catalytic Reforming and Upgrading with High Selectivity for Renewable propane

The CoolLPG technology developed by the Global LPG Partnership proposes to use biogases generated from the anaerobic decomposition of biowastes (e.g., manure, sewage) to produce renewable propane through catalytic reforming and selective upgrading to achieve a high concentration of renewable propane and renewable butane. The process is based on a methanol intermediate and because the process is selective, the direct aim is renewable propane production.

Pathway 4b: Catalytic Distillation and Upgrading to rDME

Oberon operates a pilot plant that has produced rDME from biogas wastes through catalytic distillation.

Pathway 5: Glycerine and Glycerol Feedstocks

Research and development continue on converting glycerine (sometimes called glycerol) – a residue of biodiesel production using conventional first-generation biodiesel production processes that produce Fatty Acid Methyl Ester (FAME) – into more valuable forms of energy such as renewable propane.

Glycerine can also be processed into renewable propane or bioDME via hydrogenation. It is also possible then to convert DME to LPG using hydrogen and catalysts, though the technology has not yet been commercialised.

Pathway 6: Sugar / Starch

Sugars and starches can also be a feedstock for renewable propane production.

Pathway 6a: Fermentation

Fermentation of sugars is a pathway that can lead to the production of renewable propane. Fermentation is widely practiced to produce bioethanol from crops such as corn and sugarcane. However, even though conversion technologies of ethanol into LPG are available via different ethanol coupling and synthesis routes, the market value of the bioethanol or bio-olefin intermediates is higher than the bioLPG produced and therefore not a promising route. A Polish company Ekobnz currently upgrades small quantities of bioethanol produced via fermentation into bioLPG through catalytic conversion.

Global Bioenergies has demonstrated a process that converts sucrose into isobutene using genetically engineered microorganisms, but the technology does not appear to have reached commercialization.

A chemical process for making propane from corn or sugarcane was also developed by C3 BioEnergy based in Cambridge. The process uses supercritical water – water at a high temperature and pressure – to facilitate chemical reactions that turn products from the fermentation of the sugars found in corn or sugarcane into renewable propane.

Pathway 6b: Aqueous Phase Reforming

Aqueous Phase Reforming involves catalytically transforming soluble plant sugars into gasoline and diesel, with renewable propane produced as a by-product (the yield is not known). It is expected that much if not all the LPG produced would be used for process heat, though it could, in principle, be separated out of the gaseous streams and marketed separately. While a few pilot projects (Tesoro) have demonstrated the pathway there do not appear to be any current efforts to commercialize the technology.

Virent's sugars-to-aromatics (S2A) technology has produced synthesized aromatic kerosene that can be used as a drop-in replacement of SAF. This technology might also be able to produce significant quantities of renewable propane.

Pathway 6: Description of Fermentation

Description of Pathway and Technology	Primarily sugars or starch to bioethanol via fermentation and then coupling to biobutadiene or bioolefins before hydrogenation to renewable propane.
Technology Readiness Level (TRL)	**5** (Processes to convert bioethanol to renewable propane are well known, but high cost is a barrier to implementation.)
Products	Intermediate biobutadiene, bio-olefins and bio-alcohols may have a market value such that additional conversion processes to renewable propane are not economic.
Required Feedstocks	Primarily sugars and starch, which may require dedicated agricultural land for growing fuel crops. However, fermentation of syngas from cellulosic biomass has also been realized.
Scalability	Currently laboratory or pilot scale.
Active Technology Developers and Deployment	The only evidence of commercial operation is small quantities produced by Ekobenz where the primary product is bioethanol.
Emission Intensity	Emission intensities for this pathway are unknown, however, the emission intensity is likely more than it is for bioethanol, which CARB identifies between 21-50 gCO2e/MJ, depending on the process energy source and upstream emissions of corn production.

Pathway 7: E-Fuels

The E-fuels pathway involves reacting carbon dioxide with renewable hydrogen to create E-propane. Ambient carbon dioxide can be captured from the air directly or captured from combustion exhausts (e.g., a power plant). Renewable hydrogen can be made by hydrolysis of water using low-carbon electricity powered by hydro, solar or wind energy. Often the process uses Fischer-Tropsch synthesis to combine hydrogen with the extracted CO_2 to produce liquid E-fuels.

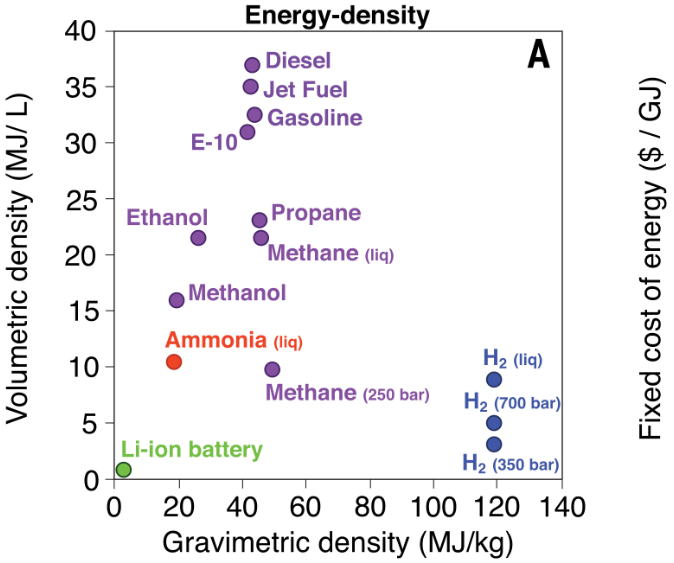
Numerous companies are pursuing this pathway to make E-fuels. Production so far is at the laboratory scale (e.g., Carbon Engineering and Nordic Blue Crude) and future cost and commercialization is unclear. HIF Global in Chile makes e-gasoline and the local retailer Empresas GASCO has an off-take agreement to receive and market E-propane.

One interesting breakthrough at the laboratory stage is a CO_2 to propane conversion developed by the Illinois Institute of Technology. A flow electrolyzer directly converts CO_2 gas and water to renewable propane. The institute has partnered with SHV Energy to scale up the system and commercialize. The process if it can be scaled would allow for the continuous production of renewable propane from modular sized electrolyzers.

Pathway 8: Using Propane Infrastructure as a Carrier for Renewable Hydrogen

Large-scale transportation, distribution and storage of hydrogen is critical if renewable hydrogen is to act as a low-emission energy carrier. The pathway of using propane and propane infrastructure as a carrier for renewable hydrogen offers a possible solution to this issue. Densified storage, via compressed gas and liquid hydrogen, is a major issue because enormous system pressures are required to achieve a useful volumetric energy density. For example, under typical pressures for propane tanks, the volumetric energy density of hydrogen would be more than 10 times lower than propane. This low volumetric energy density suggests that it would be uneconomic to use propane or other energy infrastructure to transport and distribute gaseous hydrogen. In addition, pure hydrogen can corrode and cause mechanical damage to tanks and metals it comes into contact with (hydrogen embrittlement), while direct hydrogen blending with propane is also not practical, given issues with separation in propane tanks.

The solution to transporting hydrogen may be to use propane infrastructure to transport "circular" hydrogen carriers. These are chemicals that have been produced using green hydrogen, such as ammonia, methanol, formic acid, or propane itself, which has the highest gravimetric and volumetric density of several proposed net-zero liquid energy carriers, see figure below. These "circular" hydrogen carriers capture gas molecules (CO_2 and N_2) from the atmosphere in synthesis and then are released back when used.



Source: Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., … Caldeira, K. (2018). Net-zero emissions energy systems. Science, 9793(June). https://doi.org/10.1126/science.aas9793. Hydrocarbons (purple), ammonia (orange), hydrogen (blue) and current lithium-ion batteries (green)

An ideal “circular” hydrogen carrier should not only have a high hydrogen content but also satisfy other requirements such as stability, reaction rate, cost, safety, and compatibility with propane infrastructure. Ammonia is the leading candidate of circular hydrogen carriers as it has a high energy density, does not exhibit the same embrittlement properties as hydrogen, and has promising stationary generation applications to supply power in regions where renewable energy is difficult to produce and grid extensions cannot reach. Its role as an H_2 carrier is less certain due to the large energy requirement for cracking and compressing at end-use. Combustion as ammonia directly leads to significant amounts of NOx and could contribute to PM2.5 via formation of ammonium sulphate.

The main issue of ammonia in comparison to propane is that while it has a much lower flammability risk, it has a much higher health and environmental risk if an accidental leak were to occur. It is rated as a toxic substance that is poisonous to human by inhalation and oral. Exposure to high concentration can damage skin, eyes, and lungs. Ammonia spills to water and land also pose severe toxic effects to aquatic and terrestrial life.

Ammonia is already shipped today on liquefied petroleum gas tankers vessels and in larger tanker trucks above 3,000 gallons. It liquifies at similar pressures and temperatures as propane (6 – 10 bar). Tank systems for ammonia storage are similar to the principles used for LPG, but there are likely to be additional safety systems included in the design. Tank cars used for LPG can be used for anhydrous ammonia, but some small conversions are necessary to replace fittings with copper alloys, including brass that can be corroded by ammonia, and careful purging and cleaning is required. Smaller propane storage tanks and cylinders are currently not used to hold ammonia, as their existing brass valves are incompatible and subject to severe corrosion and deterioration, and conversions may not be practical or cost effective.

Additional barriers to using propane tanks for ammonia service is that there is a requirement from ASME and Transport Canada that ammonia tanks be stress relieved and Transport Canada requires ammonia vessels be built to 265 psi as opposed to 250 psi for propane. Propane tanks are not typically stress relieved at the time of manufacture.

There are also additional liquid organic hydrogen carriers (LOHC) and novel hydrogen carriers that could potentially be explored for delivering hydrogen with propane infrastructure; however, the low TRL of these carriers likely means they will not emerge in the near term.

Appendix D: Potential Benefits of Fuel Switching to Propane

Heating Oil Furnaces

The number of households with heating oil furnaces has been declining significantly over the last 20 years. However, there are still an estimated 440,000 households using heating oil as a primary source of heat in Canada. Switching these oil furnaces to propane can offer considerable emission and cost reductions. As an example, if 25% of existing households with heating oil furnaces were switched to propane, GHG emissions could be reduced by 212,000 tCO2e per year of operation. These calculations are based on lifecycle analysis and could be achieved for the lifetime of the furnaces (at least 10 years).

The estimate is based on the following assumptions:

1. The new propane furnace is replacing a new oil furnace, reflecting that replacement is likely to occur near end-of-life of existing furnaces (emission reductions would be significantly greater if replacing older oil furnaces).
2. The average rated furnace efficiencies are 87% for a new oil furnace and 93% for propane furnaces.
3. Heat demand is based on average Canadian household heat demand of 62 GJ/household.
4. A propane direct emission intensity of 57 gCO2e/MJ and lifecycle emission intensity of 72 gCO2e/MJ.
5. Furnace fuel oil blended with 10% biodiesel (B10) with a direct emission intensity of 64.8 gCO2e/MJ and lifecycle emission intensity of 94.2 gCO2e/MJ.

Commercial non-passenger medium-duty trucks and vans

Switching on-road vehicles from gasoline or diesel to propane can have cost saving and emission reduction benefits. Targeting school buses, smaller commercial truck and van fleets where electric options are not yet widely available and where propane vehicles and conversions are readily available may be the most attractive option. Commercial non-passenger medium-duty trucks and vans are defined here as trucks and vans with a gross rated carrying capacity weight between 4.5-12 tonnes. They exclude pickup trucks that can be in this size category, as well as all tractor trailers that are in a higher weight category. Below we provide an estimate of the emission reductions that could be achieved by switching these types of vehicles to propane.

In Canada we estimate that there are at least 113,000 vans and 151,000 trucks in this size category. Commercial fleets of these type of vehicles are typically used for short-haul deliveries and consume either gasoline or diesel fuels. As an example, if 10% of this vehicle fleet (~26,000 vehicles) was converted to propane GHG emissions could be reduced by 417,000 tCO2e per year of operation. These calculations are based on lifecycle analysis and could be achieved for the lifetime of the vehicles (at least 10 years).

The estimate is based on the following assumptions:

1. An average gasoline vehicle efficiency of 6.7 MJ/tonne*km and demand of 78,000 Tonne*km for vans and diesel vehicle efficiency of 5.73 MJ/tonne*km and demand of 188,000 Tonne*km for medium-duty trucks based on national averages.
2. A 2% fuel efficiency penalty (GJ/tonne*km) for propane engines versus diesel or gasoline engines.
3. A propane direct emission intensity of 57 gCO2e/MJ and lifecycle emission intensity of 72 gCO2e/MJ
4. Diesel blended with 10% biodiesel (B10) with a direct emission intensity of 64.8 gCO2e/MJ and lifecycle emission intensity of 94.2 gCO2e/MJ
5. Gasoline blended with 10% ethanol (E10) with a direct emission intensity of 62.3 gCO2e/MJ and lifecycle emission intensity of 86.8gCO2e/MJ