Feasibility study of

Canadian biojet fuel supply chain

Executive Summary

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Combined Executive Summary (Phase 1 & 2)

This document is an executive summary of the project “Feasibility, cost, and environmental impact of a biojet fuel supply chain in Canada”.

The project is divided into two phases. Phase 1 examines biojet production options and proposes two potential supply chains for biojet in Canada. The first supply chain anticipates use of commercially available technology and feedstocks within a 2020 timeframe. The second supply chain anticipates use of currently emerging technology within a commercial production timeframe of 2025, with further process refinements occurring until 2030. Phase 1 of the project contains the characterization of regional capacity and outlines for the most viable options for biojet production and supply chain development for 2020 and 2025.

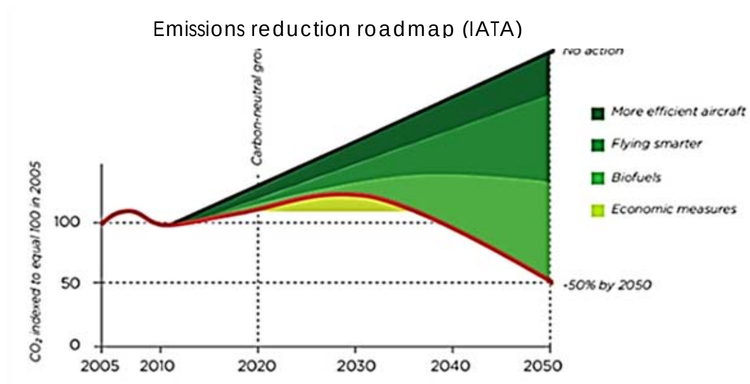
Phase 2 evaluates the potential performance of a domestic biojet industry in terms of its lifecycle emissions analysis, sustainability performance, and economic results. Phase 2 proposes the broad steps required to enable a Canadian biojet industry.

The biojet rationale: reducing emissions from the aviation sector

The international aviation sector remains committed to cap emissions through carbon neutral growth (CNG) from 2020 onwards, and to cut greenhouse gas (GHG) emissions 50% by 2050 compared to 2005 levels. For the industry to achieve the 2020 and eventually the 2050 targets, biojet use is required to complement other GHG emission reduction activities in the sector, including the ‘Market-Based Measures’ (MBM) under development by the International Civil Aviation Organization (ICAO).

Carbon neutral growth beginning in 2020 is a necessary step to enable the deeper emission reductions required in the 2035 – 2050 timeframe.

In Canada, the annual biojet volume required to meet carbon neutral growth is estimated by this project to be 54 ML in 2020, and increase to 923 ML by 2035. This value is based on biojet contributing between 40% – 60% of the needed emission reductions from 2020 – 2050 and includes emissions from all aviation fuel sold in Canada (a portion of which is used on transborder, international, and military flights). Future HEFA biojet production capacity can enable the aviation sector to begin meeting carbon neutral growth commitments beginning in 2020.



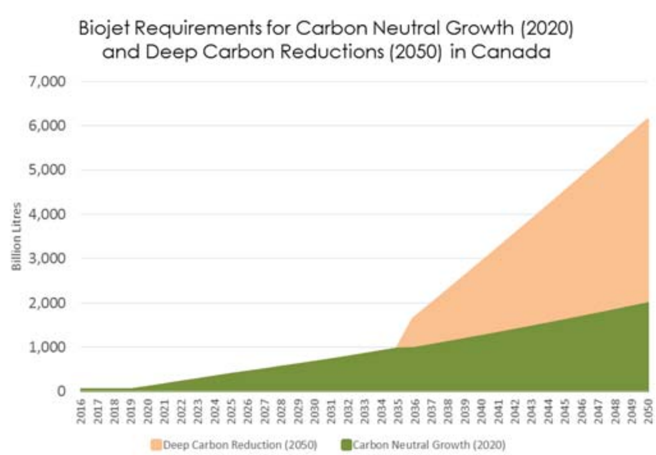


Figure E-0, E-1: Industry voluntary commitments (2020/2050) and biojet requirements for carbon neutral 2020 growth and deep reductions (50% below 2005 levels by 2050).

Introducing key aspects of the biojet supply chain

The biojet fuel supply chain starts with feedstock, which can be any type of biomass that undergoes a refining step to produce a drop-in biojet fuel. This fuel is then mixed with conventional jet fuel and transported to the airport where it is delivered into local storage for distribution into the aircraft.

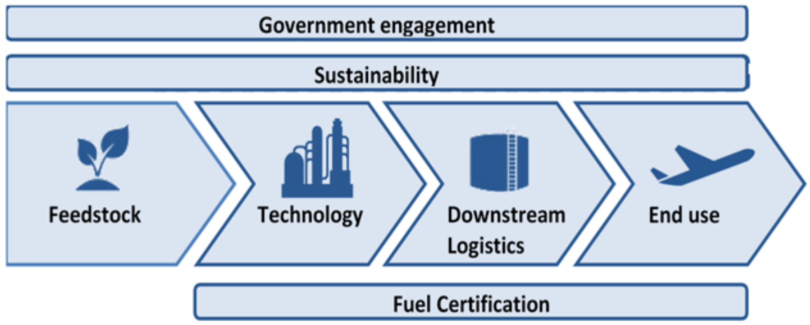


Figure E-1: Overview of the biojet fuel supply chain

The main components of the biojet fuel supply chain are described below:

Feedstock - Generally biomass feedstocks can be divided in four main categories: vegetable oil and animal fat, sugar and starch, lignocellulosic materials, and industrial by-products. In general, the vegetable oil, sugar, and starches are available and are relatively easy to convert to jet fuel. Lignocellulosic biomass and industrial by-products are available and the conversion technologies are still being developed and advanced to commercial scale. Emergent feedstocks, such as algae oils and industrial oilseeds suited to marginal land agriculture, are not currently available in commercial quantities. Feedstocks will vary in their cost, use of available conversion technologies, and performance across sustainability metrics.

Sustainability - The sustainability of the biojet supply chain has ecological, social, and economic aspects. At present, many governmental, non-governmental, and third party initiatives are supporting the development of sustainability criteria and standards for biofuels.

Government engagement - Governments are supporting the development of the nascent biojet sector in various ways. The current methods are generally aimed at de-risking the required investment and supporting research and development of emerging feedstocks and technologies. In the global development of low carbon road transportation fuels, governments have helped create assured market access by implementing renewable fuel standards and establishing competitive investment conditions through capital grants, loan-guarantees, production and blending credits, and excise or fuel tax credits.

Fuel Certification - All aviation fuel used in Canada must meet recognized fuel quality standards and specifications. All commercial jet fuel, whether fossil-based or an alternative fuel, must meet ASTM D1655 Specification for Aviation Turbine Fuels. Certain aviation biofuels are also governed by a separate and newer ASTM standard, ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. D7566 fuels also meet the requirements of ASTM D1655, allowing D7566 fuels to theoretically be seamlessly integrated into the distribution infrastructure and onto aircraft as D1655 certified fuels.

Technology - Technology describes the equipment, processes, and standards – collectively a technology platform – used to convert feedstock to biojet. Technology platforms differ in the type of feedstock they can convert, and the environmental and economic characteristics of the biojet fuel that is produced. Approved aviation fuel blends vary by biojet fuel type. Certain production platforms are available today and are certified to produce fuels for commercial aviation. Other technology platforms are still being developed.

Table 1: Overview of biojet production technologies

Pathway	Certification	Process Description	Feedstock
Fischer-Tropsch(FT)	Approved (up to 50%)	Converts carbon-rich material (e.g., biomass) into syngas, then catalytically converted to jet fuel	All biomass & municipal solid waste
Hydrotreated Esters and Fatty Acids (HEFA)	Approved (up to 50%)	Converts oleochemicals to jet fuel via deoxygenation with hydrogen and cracking	Oils and fats
Direct Sugars to Hydrocarbons (DSHC)	Approved (Farnesene-based up to 10%)	Ferments plant sugars and starches to hydrocarbons which are subsequently thermo-chemically upgraded to jet fuel	Sugars (incl. C6 cellulosic sugars)
Alcohol to Jet (AtJ)	2015	Converts sugar/ starch derived alcohols to jet fuel via dehydration, oligomerization and hydrogenation	Alcohols (potentially derived from biomass, or waste)
Hydrotreated Depolymerized Cellulosic Jet (HDCJ)	2017	Converts any carbon-rich material into a bio-crude oil via thermochemical depolymerization which can then be upgraded to jet	All biomass & municipal solid waste

Downstream logistics - Before the biojet fuel can be placed into the aircraft, it must be certified, blended with fossil jet fuel, recertified, and transported to the airport's tank farm. Ideally, the blended fuel is then co-mingled in common storage at the airport. Biojet can also be supplied using a segregated system where transportation, storage, and distribution to the aircraft are separate from the fossil jet system.

End use - Blended biojet fuel that is currently approved for use in commercial aircraft offers similar performance as conventional fossil jet fuels.

Technology selection:

Phase 1 of the project selected the most likely technologies for the 2020 and 2025 biojet production supply chains in Canada. As there is currently no commercial scale biojet fuel production in Canada and certain technologies are still being developed, we chose to analyze two scenarios using different time horizons.

Figure E-2: Shortlisting technology options for 2020

1. **2020.** What are the most viable short term feedstocks and technologies to develop a Canadian biojet fuel supply chain?
2. **2025**. What are the most promising supply chain options if we consider feedstocks and technologies with a time to market of roughly 10 years?

Technology selection for the 2020 and 2025 scenarios

Shortlisting technologies for 2020

Error! Reference source not found. shows the criteria used to select the optimal technology for the 2020 timeframe. Based on these criteria, the HEFA platform was selected as the most viable short term option for biojet production in Canada.

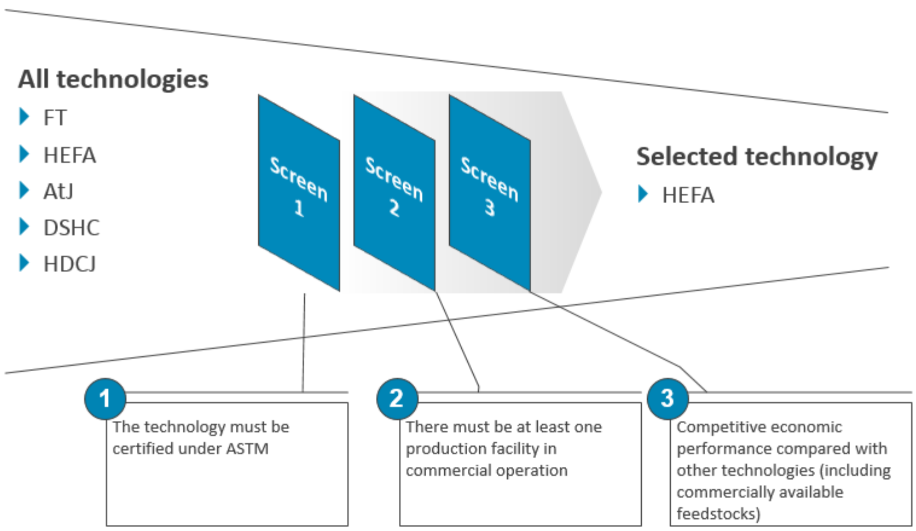


Figure E-3: Shortlisting technology options for 2020

There are only three commercial technologies that are currently certified under ASTM today: FT, HEFA, and DSHC. Each of these technologies is available on a (relatively small) commercial scale today. All FT capacity in place is based on fossil fuel feedstocks (either coal or natural gas), and the technology has not been proven to be commercially feasible using biomass. The economics of all three pathways are challenging but the HEFA pathway scores better than the other pathways. DSHC would depend on expensive imported sugars. FT is capital intensive, which means that it is only viable on a large scale which increases feedstock logistics costs.

Shortlisting technologies for 2025

The selection of a technology solution for the 2025 scenario is more complicated due to uncertainties related to the longer time horizon and more technology options to consider. Therefore, we employed a larger set of selection criteria. Based on our analysis, the Hydrotreated Depolymerized Cellulosic Jet (HDCJ) pathway was selected as the most viable option for the longer term scenario.

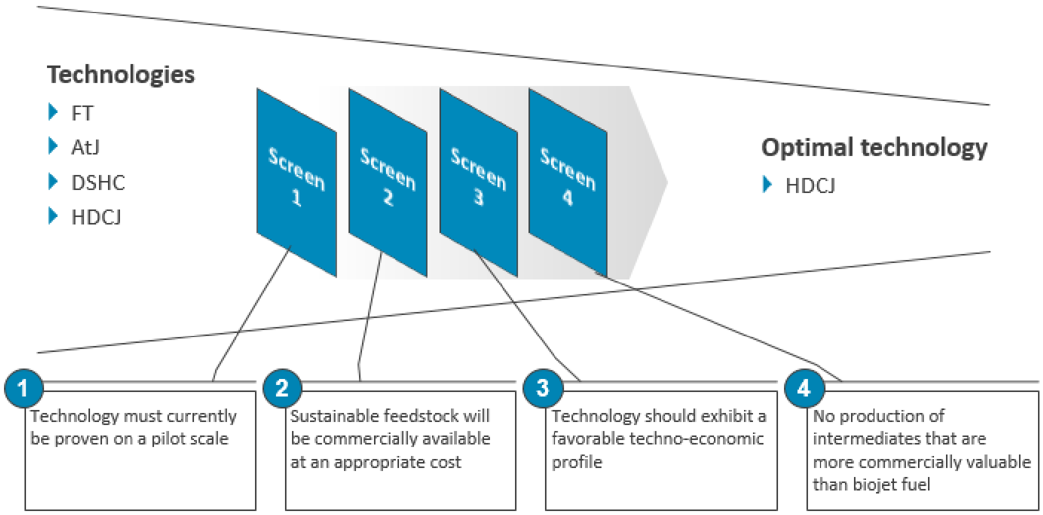


Figure E-4: Shortlisting technology options for 2025

Overall, the analysis suggests that a HDCJ platform is the most promising for Canadian biojet supply chain. Similar to the previously selected HEFA platform, the HDCJ pathway has challenges. The technology is not yet proven and the resultant biojet fuel remains to be certified.

Regional location and feedstocks

During the two phases of this project, specific regions, technologies, and feedstock mixes were selected for detailed analysis for bio jet production and supply chain development:

Table 2: Regions with highest potential identified in Phase 1

Production Timeframe	Technology Scenario	Feedstocks	West Location(s)	East Location(s)
2020	Hydrotreated Esters and Fatty Acids (HEFA) 2020	Oleochemicals: commercially available and emerging oilseeds, animal fats, used cooking oil	Edmonton Region	Southwestern Ontario / Sarnia
2025	Hydrotreated Depolymerized Cellulosic jet (HDCJ) via pyrolysis 2025	Lignocellulosic materials: forestry and agriculture residues	Edmonton Region / Northern Alberta Prince George	Southwestern Ontario / Sarnia Montreal/Quebec City

In the second phase of this project, the above options were evaluated using lifecycle analysis (LCA), sustainability analysis (SA), and techno-economic performance analysis (TEA). The results are briefly summarized below.

Analysis results: biojet is technical feasible in Canada

The analysis indicates that biojet production in Canada is technically feasible. Existing technologies, using commercially available and emerging feedstocks produced in multiple regions of Canada, are available to build production capacity. For biojet production in a 2020 timeframe, hydrotreated esters and fatty acids (HEFA) technologies for production of biojet fuels are currently mature. Established HEFA facilities currently produce the volumes of biojet fuels (outside Canada) that are being used on a limited basis. There is no existing fuel quality certification hurdle for HEFA biojet fuels; they have achieved ASTM certification for up to 50:50 blends with fossil jet fuel, and have been extensively tested in single and dedicated route commercial flights.

There exists sufficient oleochemical feedstock production in Canada to sustainably supply biojet production from the HEFA technology platform to initiate 2020 market supply; feedstock demand for biojet fuels could reach 5% of available oleochemical feedstock supply by 2025.

Developments underway to blend HEFA derived renewable diesel (called HDRD, green diesel, or HEFA-diesel) into the fossil aviation fuel supply will enhance the technical feasibility of Canadian biojet production and lower biojet production costs.[1]

In the 2025 timeframe and beyond, the hydrotreated depolymerized cellulosic jet (HDCJ) technology platform using lignocellulosic feedstock (forestry and agriculture residues), was evaluated to be the most viable option to expand biojet production capacity in Canada.

Analysis results: biojet in Canada would have positive sustainability performance

Sustainability is central to efforts to assure GHG reductions and manage impacts from widespread production and use of renewable fuels. Within the aviation sector, there are multiple approaches to sustainability evaluation and certification. The global nature of the aviation sector necessitates that emerging standards and approaches are aligned to manage impacts across domestic and trans-border aviation.

Biojet made in Canada using HEFA and HDJC technologies and feedstocks would deliver significant GHG emission reductions compared to fossil jet fuel. The carbon intensity of Canadian biojet fuels is, on a full life-cycle assessment (LCA) basis, modeled to be 46 – 88 % below petroleum jet fuels, depending on the location, technology, and feedstock used. This study conducted a full LCA analysis of the selected biojet pathways using the GHGenius model.

Canadian biojet is expected to meet existing global sustainability standards and emerging aviation approaches to sustainability. Many of the feedstocks that would be processed into biojet are already in compliance with major sustainability certification regimes used in both regulated and voluntary markets. The biojet supply chains analyzed for both the 2020 and 2025 deployment scenarios would likely qualify for at least a baseline level of sustainability performance (under a global meta-standard for biojet sustainability); most pathways would be able to positively differentiate themselves (e.g., by superior GHG reductions), should there be a tiered approach to sustainability distinctions of biojet fuels. The existing and potential sustainability certification pathways for biojet are illustrated in Figure E-6.

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[1] Boeing conducted a successful test flight in December 2014 to demonstrate the functionality of a 15% HDRD/fossil jet blend.

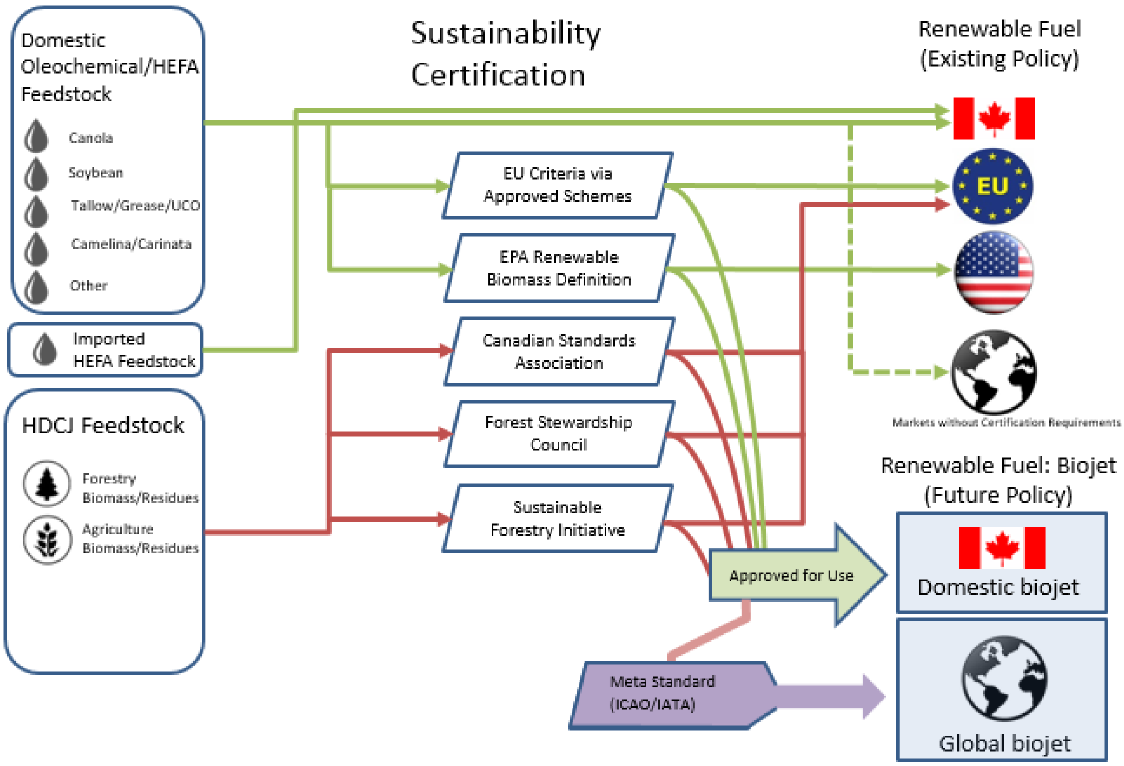

Figure E-6: Sustainability certification

Analysis results: biojet costs more than fossil jet, but the gap can decrease

Techno-economic models were built to assess the economic viability of the supply chain and to identify key parameters that influence biojet viability.

The average fossil jet price in the past three years has been approximately $0.782/L (all figures exclude tax). Based on the techno-economic analysis in this report, the minimum fuel selling price (MFSP), inclusive of financial impacts of co-products and market-based instruments, is estimated at $1.56/L for HEFA and $0.812/L for HDCJ. In the TEA analysis, the MFSP represents the aggregate revenue required for economically feasible biojet production. The cost scenarios for blended biojet fuel are illustrated below:

Table 3: Biojet premium on a blended basis

Biojet Blend Rate (%)	Fossil Jet Reference Price ($/L)	HEFA Biojet		HDCJ Biojet	
		Blended Selling Price ($/L)	Premium ($/L)	Blended Selling Price ($/L)	Premium ($/L)
0%	$ 0.782	$ 0.782	$ -	$ 0.782	$ -
1%	$ 0.782	$ 0.789	$ 0.008	$ 0.782	$ 0.000
2%	$ 0.782	$ 0.797	$ 0.016	$ 0.782	$ 0.001
3%	$ 0.782	$ 0.805	$ 0.023	$ 0.783	$ 0.001
4%	$ 0.782	$ 0.813	$ 0.031	$ 0.783	$ 0.001
5%	$ 0.782	$ 0.821	$ 0.039	$ 0.783	$ 0.001
6%	$ 0.782	$ 0.828	$ 0.047	$ 0.783	$ 0.002
7%	$ 0.782	$ 0.836	$ 0.054	$ 0.784	$ 0.002
8%	$ 0.782	$ 0.844	$ 0.062	$ 0.784	$ 0.002
9%	$ 0.782	$ 0.852	$ 0.070	$ 0.784	$ 0.003
10%	$ 0.782	$ 0.859	$ 0.078	$ 0.785	$ 0.003

For example, at a 10% blend rate, the cost premium over the reference fossil jet price of $0.782/L ranges from 0.3¢/L to 7.8¢/L between the HDCJ-jet and HEFA-jet fuels, respectively.

The TEA analysis shows that market-based instruments are required to assure that the carbon reduction value of biojet fuels is recognized by the market (whether regulatory, or voluntary). As seen in the road transportation renewable fuel markets, the market-based policy measures both create market access assurance for new, low carbon renewable fuels, and enhance financial returns to levels necessary for investment. Well-designed policy tools can bridge the estimated costs of production of biojet fuel to the future price of fossil jet fuel, inclusive of co-product and carbon reduction values. The TEA estimates show that the production cost of biojet is likely to decrease as technology develops.

The broad results of the LCA, SA, and TEA analyses are shown below:

Table 4: Summary of supply chain assessment for 2020 and 2025

	TEA					LCA	Sustainability	
	Technology readiness	Tech Risk	ASTM	MFSP/ Tonne [4]	Gap (MFSP to Jet) @ 965/Tonne [3]	GHG Reduction [1]	Certifiable	Meta-standard minimum [2]
HEFA 2020 Western	Commercial	Low	Yes	$1,966	$1,001	88%	Yes	Yes
HEFA 2020 Eastern	Commercial	Low	Yes	$1,885	$920	73%	Yes	Yes
HDCJ 2025 Western	Pilot	High	No	$1,020	$55	46%	Yes	Yes
HDCJ 2025 Eastern	Pilot	High	No	$984	$19	64%	Yes	Yes

[1] Compared with fossil jet fuel
[2] Compared with potential IATA meta-standard
[3] Prior to inclusion of biojet market-based instrument adjustments
[4] Minimum fuel selling price, per tonne, for modelled commercial viability

Biojet: a Canadian opportunity?

Canada has the natural capacity to develop a domestic biojet industry. Several identified regions have sufficient certifiably sustainable feedstocks (agricultural and forestry biomass) under globally recognized supply-chain management systems. These feedstocks are compatible with commercially available (HEFA) and emerging technology (HDCJ) platforms. Canada's opportunity to implement a domestic biojet production industry is akin to the leadership opportunities it has successfully deployed in developing unconventional petroleum resources, or establishing itself as a global leader in mining and aluminum smelting.

A domestic biojet industry can provide opportunities for Canada including enhancing energy security, rural economic development, job creation, stimulation of R&D and knowledge harvesting, strengthening existing industries via diversification, and meeting GHG reduction goals.

Policy measures to enable a biojet industry

Biojet supply chain development in Canada will require definition and analysis of specific biojet market-based measures (MBMs). These instruments must set out clear and stable policy, regulatory and/or voluntary commitments, and fiscal measures necessary to create assured market access for biojet fuels. These policy measures can establish competitive investment returns to compel private sector investment in Canada.

The underlying premise for government implementation of MBMs for the biofuel industry is that 'policy' (including derivative regulations and fiscal programs) must address market access and fiscal competitiveness to reduce risks associated with early-adoption investments in the aviation fuels sector. Significant private and public sector investment is needed to construct renewable fuel production capacity and advance new technologies. In the Canadian context, complementary federal and provincial policies are essential to scaling up private capital investment to create a biojet sector.

Biojet sector policies must achieve the following:

> *Competitive financial returns* - Some types of renewable energy (e.g., wind, solar, bioenergy, ethanol) are cost competitive or near cost competitive with incumbent (fossil) sources of energy, in part due to reasonably stable and sufficient policy support that enabled economy-of-scale production, infrastructure, and supply-chain development to take hold. Government assistance in sector enablement is not specific to renewable fuels; this level of policy support is similar to what has been provided to past energy technologies (e.g., oilsands) and is still provided to other strategic, non-renewable energy industries.
>
> At this stage of market development (e.g., pre-commercial), it will be necessary to establish conditions that present an opportunity for compelling financial returns in order to attract capital investment in biojet production assets.
>
> *Risk reduction* - Government policies play a key role in reducing risks, particularly for early stage technology deployment in a new manufacturing sector. Reducing risks drives down capital financing costs to unlock the capital necessary to create broad build-out.
>
> Effective and stable policies are required to incentivize private investment. Governments and the private sector have long worked together to create industries which have strategic importance and contribute to national interests or the broader public good. GHG mitigation is considered an activity with substantial public benefits. In the Canadian aviation fuels sector, there is an opportunity to utilize public/private partnerships to align federal, provincial, and private efforts.

Market access – The successful development and expansion of the production and use of renewable fuel alternatives to petroleum gasoline and diesel was largely achieved through regulatory measures that established requirements for blending levels and/or carbon intensity reductions. The global aviation sector is also investigating voluntary commitments to achieve its GHG carbon neutral and deep de-carbonization targets.

Regardless of the mix of regulatory or voluntary measures, biojet fuels must be accorded assured market access in order to penetrate the mature fossil jet fuels marketplace. Petroleum sector concentration in the upstream production, refining, and fuel distribution assets presents a significant barrier to entry for biojet fuels. Renewable fuel standards (RFS) and low carbon fuel standards (LCFS) have been critically important to market access and de-carbonization of the road transportation sector. Biojet implementation will likewise require assured access to de-risk investment in new fuel supply management systems.

The opportunity exists to create a Canadian biojet industry that preserves and even enhances the international competitiveness of the Canadian aviation sector. Based on the viable technology platforms identified (HEFA, emerging HDCJ), a biojet sector in Canada will stimulate new investment in refining transportation fuels (biojet, renewable diesel) and other co-products. In addition to new investments, jobs, and economic growth, a biojet sector will also diversify Canada's transportation fuel supply, providing new options for airlines and Canadians while improving long-term competition amongst fuel supply companies. A biojet sector also provides upstream, stable structural demand to improve the viability of two primary resource sectors in Canada: agriculture and forestry. Strategic investments in innovation and research in agriculture, forestry, and advanced fuels will support long-term competitiveness of these engines of the Canadian economy.

The results of this biojet supply chain feasibility study were used in consultations with expert stakeholders to help create a biojet sector development strategy. Transitioning to an 'established' industry will require coordinated and complementary efforts from the public and private sectors across the supply chain.

Canada has demonstrated successes in creating new, value-added markets for its abundant natural resources that are socially and environmentally responsible. Biojet is positioned now to be one such Canadian success story.

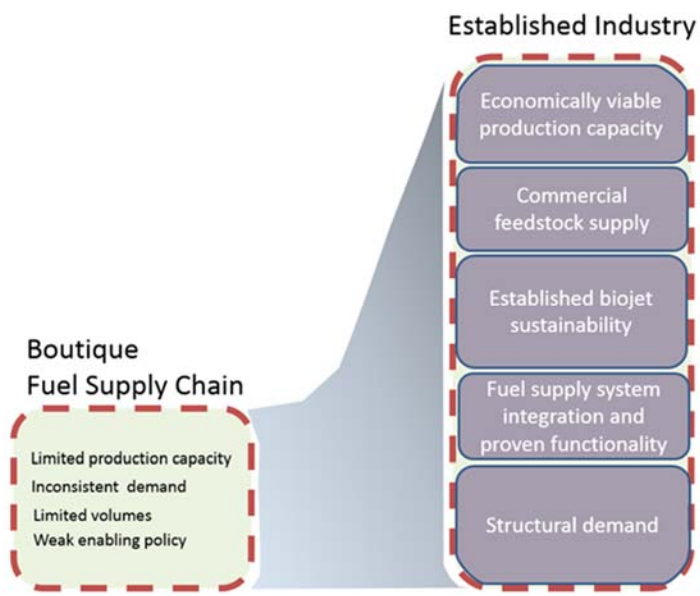

Figure E-7: Transitioning from a boutique to established supply chain