



Study of Hydrogenation Derived Renewable Diesel as a Renewable Fuel Option in North America

Final Report

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Executive Summary

As of 2011, 27 national governments and 29 state/province governments have implemented policies that mandate the use of a minimum amount of renewable alternatives to diesel, including Europe, six South American countries, six Asian countries, Canada, the United States, Costa Rica and the Dominican Republic.

On June 29, 2011, the government of Canada registered regulations amending the *Renewable Fuels Regulations* which were then published on July 20, 2011¹. These amendments stated that the coming into force date of the 2% requirement of renewable content in diesel and heating oil would be July 1st, 2011. Under the *Renewable Fuels Regulations*, both ester-based biodiesel and hydrogenation-derived renewable diesel (HDRD) are admissible as renewable content that can be used to meet the requirements of the Regulations. While biodiesel is the most widely available diesel fuel alternative, there has been increasing interest by the regulated parties in using HDRD to meet the requirements, even though HDRD is currently only produced in Europe, Southeast Asia and the United States^{2,3}. The purpose of this study is to evaluate the potential for HDRD production and use in Canada.

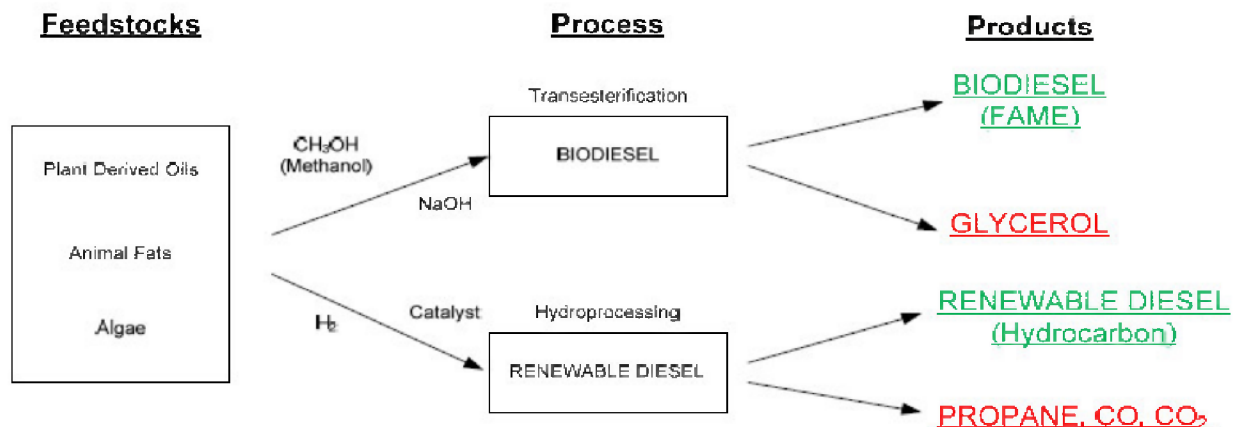
Biodiesel and HDRD can be made from the same feedstocks and yet their chemical composition and physical properties are quite different. This is due to the different processing pathways that are used for their production. Figure I illustrates the difference between biodiesel and HDRD production pathways and by-products. Biodiesel is produced via transesterification with glycerol as a by-product and HDRD is produced via hydroprocessing with propane, carbon monoxide (CO) and carbon dioxide (CO₂) as by-products.

¹ Canada Gazette (2011). *Regulations amending the renewable fuels regulations*. Published July 20, 2011.

² ÉcoRessources Consultants (2010). *National Renewable Diesel Initiative Infrastructure Project*. Prepared for Natural Resources Canada, May 2010.

³ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

FIGURE I – BIODIESEL AND HDRD FEEDSTOCKS, PRODUCTION PATHWAYS AND PRODUCTS



Source: Hoekman, S. K., Gertler, A., Brock, A., Robbins, C. (Desert Research Institute) and Natarajan, M. (Marathon Petroleum Company) (2010). *Production and Properties of Biodistillate Transportation Fuels*. Presentation at the AWMA International Speciality Conference: Leapfrogging Opportunities for Air Quality Improvement, May 2010, China.

HDRD can be produced from virtually any type of bio-based renewable feedstock. The most common feedstocks are animal fats and vegetable oils, which are made up mostly of triglycerides and are the types of feedstocks that are traditionally used for biodiesel production. However, HDRD can be produced from a wider range of feedstocks than biodiesel. There are two principal reasons for this: 1) the degree of unsaturation of the feedstock molecules is not a consideration since hydroprocessing results in paraffinic hydrocarbons that are fully saturated and are not susceptible to oxidative instability in the way that unsaturated methyl esters found in biodiesel can be^{4,5}; and 2) during hydroprocessing to produce HDRD, free fatty acids (FFA's) are easily converted to paraffins, whereas in biodiesel production they can react with the alkali catalysts to produce soaps. Therefore FFA content of the feedstock is not a concern for HDRD production⁶.

HDRD can also be produced from lignocellulosic feedstocks such as those derived from agricultural and pulp and paper residues, but additional processing must be carried out prior to hydrotreatment. No existing HDRD production facilities currently use lignocellulosic biomass as a feedstock, however there is significant research currently being conducted in order to optimize the use of these more diverse feedstocks that also do not compete with food crops⁷.

⁴ It should be noted that transesterification can be followed by a hydrogenation step to saturate the double bonds in biodiesel. This additional processing step can be added to allow for the use of a greater diversity of feedstocks for biodiesel production and to improve product stability.

⁵ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Biodistillate Transportation Fuels 1. Production and Properties*. SAE Int. J. Fuels Lubr., 2(2):185.

⁶ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

⁷ Holmgren, J., Gosling, C., Couch, K., Kalnes, T., Marker, T., McCall, M. And Marinangeli, R. (UOP-Honeywell, 2007). *Refining Biofeedstock Innovations*. Petroleum Technology Quarterly, Q3, 2007.

The most commonly used feedstocks for HDRD production in Europe are palm oil, rapeseed oil, tallow, yellow grease, jatropha oil and camelina oils. In Southeast Asia palm oil is used exclusively and in the United States tallow is currently used exclusively, but soy may also be used. In Canada, existing biodiesel feedstocks such as canola, soy, tallow and yellow grease could be used for HDRD production.

One of the advantages of the HDRD production process is that it makes use of existing refining technology. Hydrotreatment units are already used in conventional refineries in order to desulfurise fractional distillates, including diesel oil. As such, this same technology can be applied to the hydrotreatment of renewable oils to produce HDRD. This can be done either by co-processing the renewable feed with the conventional diesel oil feed or by constructing a stand-alone hydrotreatment unit used exclusively for producing HDRD. The advantage of co-processing is the large savings in capital costs, since the renewable feed can be processed in the existing hydrotreater. However, it requires reactor shutdown when switching between modes of operation and it to make necessary changes in the catalyst bed and operating conditions. In addition, due to the higher hydrogen requirements and the highly exothermic nature of hydroprocessing renewable feeds, co-feed blends above 10%-15% can be more challenging, although regular co-processing of feeds of up to 30% have been achieved successfully^{8,9} and even higher blends can be achieved with the proper operating conditions.

There is an additional concern related to co-processing that is specific to the United States market: HDRD that is produced as a blend with conventional diesel via co-processing cannot be used to generate valuable D4 Renewable Identification Number (RIN) credits for Type B biomass-based biofuels under the US Renewable Fuels Standard (RFS2)¹⁰. For HDRD to be eligible for D4 RIN's, it must be processed independently from a conventional diesel feed (as well as other RFS2 requirements, such as those related to environmental performance).

Stand-alone units for hydroprocessing renewable feedstocks have the advantage of being tailor-made and optimised for HDRD production. They can be built as add-ons to existing refineries in order to make use of existing hydrogen generation capacity and to streamline the management of recycle gases. The HDRD can also be blended with conventional diesel after processing on-site at the refinery before distribution to the terminals, or it can be kept separate for distribution and sale as a neat product. The blend percentage can be determined at short notice according to changing market conditions without changes to operating conditions.

However, the obvious disadvantage of a stand-alone production facility are the high capital costs for the construction of the required additional infrastructure. In order for the construction of such a facility to be economic, the operator must take advantage of economies of scale by producing renewable diesel in large volumes. Co-processing allows the refiner to blend small volumes of HDRD with less capital investment (mostly related to the receipt, storage and handling of the feedstock).

⁸ Egeberg, R., Michaelsen, N. and Skyum, L. (Haldor Topsøe, date unknown). *Novel Hydrotreating Technology for Production of Green Diesel*.

⁹ Personal Communications.

¹⁰ Co-processed HDRD is eligible for D5 RIN's in the Type A advanced biofuels category, but these RIN's are currently trading at about half the price of D4 RIN's.

The choice of producing HDRD via co-processing or in a stand-alone facility will depend greatly on local conditions. In the United States context, however, co-processing is unlikely to be the method of choice in the near to medium term due to unfavourable RIN prices relative to HDRD produced in a stand-alone unit under the RFS2 regulations.

Table I provides a comparison of some of the properties of Ultra Low Sulphur Diesel (ULSD), biodiesel and HDRD. The oxygen content in ULSD and HDRD is zero, whereas it is about 11 weight% for biodiesel. Correspondingly, the carbon content by weight of biodiesel is lower and consequently, the energy content by weight is lower. As can be seen in the table, the energy content of biodiesel is approximately 39 MJ/kg, while it is closer to 43-44 MJ/kg for ULSD and HDRD. However, HDRD is also less dense than biodiesel, which means that the energy content by volume is only slightly higher than that of biodiesel (~121,000-122,000 BTU/gal or ~32,000 BTU/litre), which is less than that of ULSD (~130,000 BTU/gal or ~34,000 BTU/litre). It can also be seen in the table that the cetane number of HDRD is significantly higher than that of ULSD or biodiesel.

TABLE I – PROPERTIES OF ULSD, BIODIESEL AND HDRD (RENEWABLE DIESEL)

Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
T ₉₀ , °C	300-330	330-360	290-300
Viscosity, mm ² /sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Source: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

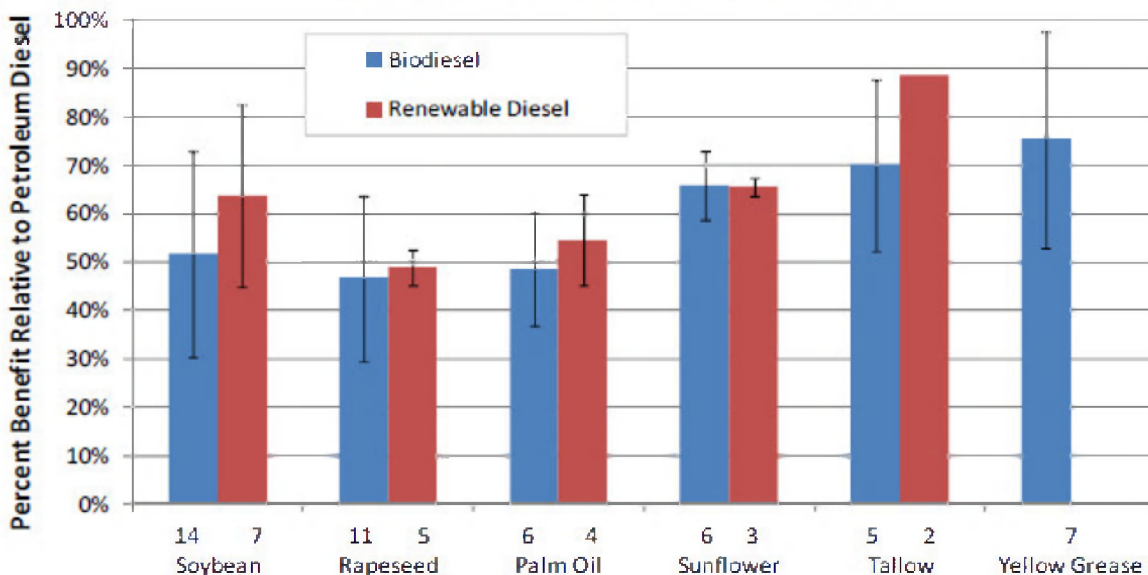
Currently, there are no fuel standards that have been developed uniquely for HDRD, neat or blended. HDRD is comprised of the same types of hydrocarbons as conventional diesel and therefore is subject to the same fuel standards as No. 2 diesel or ULSD: CGSB 3.517 in Canada, ASTM D975 in the United States and EN 590 in Europe¹¹. Since HDRD is a fuel that is fully fungible with ULSD, infrastructure

¹¹ Source: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

requirements for blending HDRD with ULSD are minimal and are mostly related to inventory management^{12,13}. No significant vehicle equipment compatibility issues have been found either^{14,15,16}.

Figure II presents the greenhouse gas (GHG) emissions benefits of biodiesel and HDRD from different feedstocks, relative to fossil diesel (these analyses did not include indirect land use changes). As can be seen in the figure, HDRD from tallow has the greatest GHG benefit of all feedstock types. It should be noted that there are very few studies on the GHG impacts of HDRD relative to the number of studies carried out for biodiesel. As the use of HDRD grows and more studies are carried out, a more accurate picture of the GHG benefits (or dis-benefits) associated with the use of HDRD relative to diesel (or biodiesel) will develop.

FIGURE II – GHG BENEFITS FOR BIODIESEL AND HDRD FROM DIFFERENT FEEDSTOCKS, RELATIVE TO DIESEL



Note: The numbers under each bar indicate the number of studies whose results were averaged to produce the data bar.
 Source: Hoekman, S. K., Broch, A., Robbins, C., Cenicerros, E. (Coordinating Research Council – CRC, 2011). Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality. CRC Report No. AVFL-17a. Published February 2011.

Both the United States and Canada have policies in place that support the use of renewable fuels. In July 2011, the government of Canada implemented a portion of its *Renewable Fuels Regulations* requiring fuel producers and importers in Canada to blend an annual average of 2% renewable content

¹² ÉcoRessources Consultants (2010). *National Renewable Diesel Initiative Infrastructure Project*. Prepared for Natural Resources Canada, May 2010.
¹³ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.
¹⁴ Rilett, J., Gagnon, A., (Climate Change Central, 2008). *Renewable Diesel Characterization Study*. Published August 2008.
¹⁵ Climate Change Central (2009). *Alberta Renewable Diesel Demonstration*. Published February 2009.
¹⁶ Neste Oil (2009). *Pilot test shows: Less CO2 emissions with new diesel from renewable energy sources*. Press release, published June 9, 2009.

into their diesel and heating oil fuel pool. This corresponds to about 400 million litres in 2012 (not including Quebec, the Territories and the Atlantic Provinces¹⁷). This increases with demand to approximately 900 million litres in 2035^{18,19}. Assuming an average HDRD production yield of 80% by mass (75% for winter HDRD, 85% for summer HDRD)²⁰, it would require approximately 390,000 tonnes of feedstock in order to produce 400 million litres (312,000 tonnes) of HDRD. The production yield does not vary significantly by feedstock type²¹. For the purposes of comparison, total production of canola and soybean oil in the 2010/2011 crop year in Canada was 2.7 million tonnes and 270,000 tonnes, respectively²², and about 400,000 tonnes of tallow is produced annually²³.

Each November, the United States Environmental Protection Agency (EPA) sets the standards for the required volumes of different types of biofuels for the following year, under the RFS2. In 2012, 4.5 billion litres of HDRD could be used to meet the requirements of the advanced biofuels category of the RFS2^{24,25,26,27}. Using the same average HDRD production yield of 80%, 4.5 billion litres of HDRD would require approximately 4.78 million tonnes of feedstock. Existing and planned HDRD production in the United States makes use of tallow as the feedstock, although these plants could also use soybean oil as a feedstock. In 2010, 815,000 tonnes of rendered tallow and 8.6 million tonnes of soybean oil were produced in the US.

Tables II and III below summarize existing and proposed capacity for production of HDRD worldwide in both stand-alone and co-processing facilities. As can be seen in the tables, current global capacity is at 2.8 billion litres per year (2,525 ML/yr for stand-alone facilities and 300 ML/yr for co-processing), which will increase to 3.3 billion litres per year when the Valero/Darling plant comes online at the end of 2012. The majority of this capacity exists outside of North America. Including the Valero/Darling plant, by the end of 2012 total North American capacity will be 800 million litres per year.

¹⁷ The Territories and Newfoundland and Labrador are permanently exempted from the Regulations. Quebec and the remaining Atlantic provinces are temporarily exempted until December 31, 2012.

¹⁸ For a full explanation of how predicted demand volumes have been calculated, see Section 3.3.1 of: ÉcoRessources Consultants (2010). *Updating the cost-benefit analysis of the proposed 2% renewable fuels regulation*.

¹⁹ Natural Resources Canada (NRCAN, 2006) *Canada's Energy Outlook: The Reference Case*.

²⁰ Personal communications.

²¹ Personal communications.

²² Canadian Oilseed Processors Association (COPA, 2012). *COPA Monthly: December 2011/January 2012*.

²³ Asia-Pacific Economic Co-operation (APEC, 2012). *APEC Biofuels – Canada Biofuels Activities*. Website consulted February 12, 2012. http://www.biofuels.apec.org/me_canada.html

²⁴ In 2012, the RFS2 requirement for advanced biofuels is 7.6 billion litres (2 billion gallons, see note 25). HDRD has an energy equivalence value of 1.7 as accorded by the EPA (see note 26) so only 4.5 billion litres of HDRD would be required to meet the 7.6 billion litre requirement.

²⁵ United States Environmental Protection Agency (US EPA, 2011). *Regulatory Announcement: EPA Finalizes 2012 Renewable Fuel Standards*. EPA-420-F-11-044, published December 2011.

²⁶ United States Environmental Protection Agency (US EPA, 2010). *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program*. [EPA-HQ-OAR-2005-0161; FRL-9112-3] Published in the Federal Register, Vol. 75, No. 58, March 26, 2010.

²⁷ It should be noted that Under RFS2, each of the four new fuel categories must meet GHG emission reduction criteria, relative to 2005 levels for petroleum fuels: a minimum of 20% reduction for Type R fuels in general, 50% reduction for Types A and B and 60% reduction for Type C.

TABLE II – SUMMARY EXISTING AND PROPOSED COMMERCIAL-SCALE HDRD STAND-ALONE PLANTS*

Company	Location of facility	Status	Start date	Capital costs (USD)	Principal feedstocks used	Capacity (ML/yr)	Source
Neste Oil	Porvoo, Finland	Operational	2007	\$130 million	Palm oil Animal fats Rapeseed oil	215	[1]
Neste Oil	Porvoo, Finland	Operational	2009	\$130 million	Palm oil Animal fats Rapeseed oil	215	[1]
Neste Oil	Tuas, Singapore	Operational	2011	\$725 million	Palm oil	906	[2]
Neste Oil	Rotterdam, Netherlands	Operational	2010	\$1 billion	Palm oil Animal fats Rapeseed oil	906	[3]
Dynamic Fuels (Syntroleum and Tyson Foods joint venture)	Geismar, Louisiana	Operational	2010	\$150 million	Animal fats Soybean oil	283	[4]
TOTAL EXISTING CAPACITY						2,525 ML/yr	
Valero and Darling joint venture	Norco, Louisiana	Under construction	Estimated start date: Q4 2012	\$330 million	Animal fats Soybean oil	509	[5]
TOTAL EXISTING + FUTURE CAPACITY (FIRM)						3,034 ML/yr	
UPM biofuels	Lappeenranta, Finland	Construction begins summer 2012	Estimated start date: 2014	\$200 million	Tall oil (pine)	117	[6]
TOTAL EXISTING + FUTURE CAPACITY (POSSIBLE)						3,151 ML/yr	

*This is a list of known plants and is not exhaustive.

¹Schill, S. R. (2007). *Heeding Hydrogenation*. Biodiesel Magazine, published online March 15, 2007.

²Nest Oil (2011). *Neste Oil celebrates the grand opening of its ISCC-certified renewable diesel plant in Singapore*. Press release, 8 March 2011.

³Green Car Congress (2008). *Neste Oil to Build \$1B NExBTL Renewable Diesel Plant in Rotterdam*. Published online 13 June, 2008.

⁴Syntroleum (2011). *Syntroleum Announces Third Quarter Results and October Production Update*. Press release, published November 8, 2011.

⁵Stuckey, M. (2011). *Valero begins construction of \$330 million renewable diesel plant in Norco*. Published in St Charles Herald Guide, October 6, 2011.

⁶UPM (2012). *UPM to build the world's first biorefinery producing wood-based biodiesel*. Press release, 1 February, 2012.

TABLE III – EXISTING AND PROPOSED COMMERCIAL-SCALE HDRD CO-PROCESSING FACILITIES*

Company	Location of facility	Status	Co-processing max%	Principal feedstocks used	Capacity (ML/yr)	Source
ConocoPhillips	Cork, Ireland	Operational	Unknown	Soybean oil Animal fats	57	[1]
CEPSA	Algeciras, Spain	Operational	5%	Vegetable oil	90	[2]
Preem Petroleum	Göteborg, Sweden	Operational	30%	Tall oil	153	[2]
TOTAL EXISTING CO-PROCESSING CAPACITY					300 ML/yr	
Eni (UOP license)	Livorno, Italy	Technology licensed, construction not yet begun	Unknown	Soybean oil	368	[3]
Galp Energia	Sines, Portugal	Technology licensed, construction not yet begun	Unknown	Soybean oil	368	[3]
Undisclosed refiner	Australia	Unknown	5%	Animal fat	25	[2]
Undisclosed refiner	California, USA	Unknown	10%	Tallow	23	[2]
Undisclosed refiner	Europe	Unknown	5%	Animal fat	62	[2]
Undisclosed refiner	Texas, USA	Unknown	5%	Vegetable oil	180	[2]
TOTAL EXISTING AND PROPOSED CO-PROCESSING CAPACITY					1,326 ML/yr	

*This is a list of known plants and is not exhaustive.

¹ConocoPhillips (2006). *ConocoPhillips Begins Production of Renewable Diesel Fuel at Whitegate Refinery in Cork, Ireland*. Press release, published December 19, 2006.

²Personal Communications.

³Argonne National Laboratory (2008). *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Published March 12, 2008.

In terms of the Canadian context, just one Porvoo-sized plant (215 ML/yr) would be able to account for 30% of Canada's requirement for renewable alternatives to diesel and heating oil from 2013 onwards. Adding another plant of the same size would account for 48% of the projected requirements in 2035. 215 ML/yr is considered about the minimum capacity for which a stand-alone new HDRD production facility

could be considered profitable²⁸. Alternatively, a Rotterdam-sized plant (906 ML/yr) would provide 30% more than the total Canadian federal requirements in the short term, allowing for potential exports to the US, and in 2035 would account for 100% of the projected requirements.

It would make sense for a stand-alone plant to be located close to existing refinery infrastructure, for instance in Edmonton or Sarnia.

Table II also presents the capital costs (in USD) expended for each of the facilities. Based on the six existing commercial plants and two hypothetical plants (\$36 - \$42 million for a 500 barrel per day (bpd) plant and \$75 - \$85 million for a 2,500 bpd plant²⁹), the unit capital cost is high for very small and very large plants (\$45,000 - \$85,000 per bpd capacity), but approximately the same for the rest (\$30,000 - \$40,000 per bpd capacity). In contrast, the average capital costs for a petroleum refinery are \$15,000 - \$20,000 per bpd capacity³⁰. Typical petroleum refineries can have capacities in the tens to hundreds of thousands of bpd. For a biodiesel plant the capital costs are \$20,000 - \$30,000 per bpd capacity for plant sizes around 2,000 bpd, which is considered large (i.e. around 114 million litres/year)³¹.

Operating costs at an HDRD production facility include: renewable feedstock, hydrogen, energy input/utility, water, catalysts, chemicals, management and employee and administrative costs. Operating costs are much more difficult to predict, because feedstock, hydrogen and utility prices, the largest components of production costs, can vary widely depending on local, national and international market conditions. Feedstock costs make up approximately 80% of operating expenses and hydrogen and utilities make up approximately 15%³². Given the important role that feedstock plays in determining production costs, changes in feedstock prices can make or break the profitability of an HDRD operation. This is also why it is advantageous to diversify feedstock supply in order to be able to adapt to changing feedstock prices.

Figure III plots US biofuel feedstock prices from 1995 – 2010, as compared with regular No. 2 diesel wholesale prices³³. As can be seen, aside from baking and frying fats, renewable feedstock prices had a generally inverse relationship relative to diesel oil prices from 1995-2005. As of 2005, renewable feedstock prices began more or less to follow oil prices, although this trend is not expected to continue indefinitely (see Figure IV). Installing or adapting refinery infrastructure in order to be able to accommodate the production or co-feeding of HDRD from a variety of different feedstocks could be seen as a hedge for when oil prices are high relative to renewable feedstock prices.

²⁸ Personal communications. (Note: due to the potentially commercially sensitive nature of some of the information provided in this report, some industry stakeholders that provided information preferred to remain anonymous. In these cases, unfortunately the individual who provided the information and/or the company they represent cannot be given.)

²⁹ Personal communications.

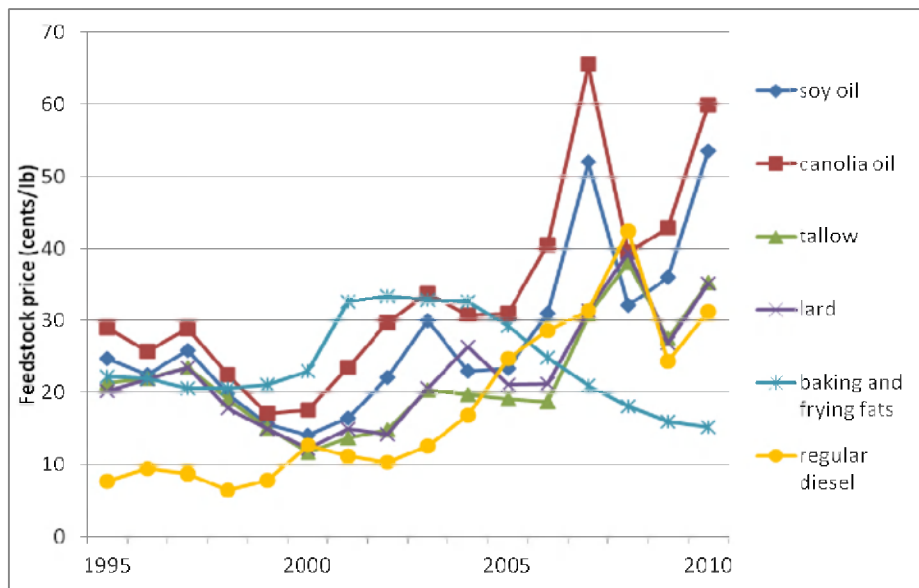
³⁰ United States Energy Information Administration (EIA, 2006). *Annual Energy Outlook 2006*. DOE/EIA-0383, 57-58.

³¹ United States Department of Agriculture (USDA) and Iowa State University (2012). *Biodiesel Profitability*. Excel model, last updated January 10, 2012.

³² Personal communications.

³³ It is important to remember that the equivalent fossil feedstock to vegetable oils and rendered fats is regular (not-desulfurised) diesel oil, not crude oil.

FIGURE III – US BIOFUEL FEEDSTOCK AND REGULAR DIESEL PRICES



Sources: United States Department of Agriculture (USDA, 2011). *Oil Crops Yearbook 2011*. Updated March 2011. United States Energy Information Administration (EIA, 2011). *No.2 Distillate Prices by Sales Type*. Release date: November 1, 2011.

In 2011, Neste Oil estimated that production costs for NExBTL (not including feedstock costs) are approximately USD 220/tonne³⁴. In 2009, Neste Oil estimated that the net cash margin for July 2008 – June 2009 was about USD 225/tonne³⁵. Feedstock prices do not necessarily affect margins because HDRD is typically priced relative to biodiesel prices. The average premium of NExBTL relative to biodiesel in 2007 was 17 US cents/L for product sold in Europe³⁶, in 2008-2009 it was about 21 US cents/L for product sold in Europe³⁷ and in 2010 it was about 30 US cents/L for product sold in Canada³⁸. As demand for HDRD grows, producers can charge a higher premium.

It should be noted that in the United States, HDRD prices are governed primarily by the RIN market. Since HDRD generates 1.7 RIN's per gallon while biodiesel only generates 1.5 RIN's (due to energy equivalence factors), if biodiesel prices increase, the price differential between HDRD and biodiesel will actually increase rather than decrease. Conversely, if production of biodiesel and/or HDRD increases,

³⁴ Source: Lehmus, Matti (Neste Oil, 2011). *Renewable Fuels – Driving Growth and Profitability*. Presentation at Neste Oil Capital Markets Day, 21 September 2011.

³⁵ Source: Honkamaa, J., 2009. *Delivering Future Growth*. Presentation at Neste Oil Capital Markets Day, 29 September, 2009.

³⁶ Honkamaa, J. (Neste Oil, 2007). *Biodiesel*. Presentation at Neste Oil Analyst Day, November 2, 2007.

³⁷ Honkamaa, J. (Neste Oil, 2009). *Delivering Future Growth*. Presentation at Neste Oil Capital Markets Day, September 29, 2009.

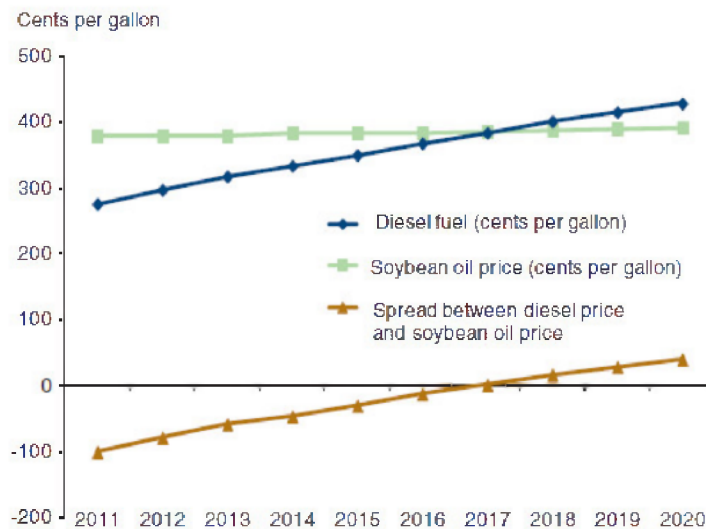
³⁸ The value of US 30 cents/L was calculated as CAD 35 cents/L minus a CAD 5 cents/L transportation cost (CAD was at parity with USD in 2010) from: ÉcoRessources Consultants (2010). *Updating the cost-benefit analysis of the proposed 2% renewable fuels regulation*.

increasing the overall supply of Type B fuels, D4 RIN prices will decrease and the price differential between biodiesel and HDRD will also decrease³⁹.

A recent 2012⁴⁰ study by ÉcoRessources found that in the short-term (i.e. at current HDRD prices), 48% of the federal requirement for renewable alternatives to diesel and heating oil are expected to be met with HDRD. For refiners producing their own HDRD, the infrastructure, energy content and cloud point additive savings are the same, but they are able to save on the HDRD price premium⁴¹ relative to biodiesel, either in their own use or in sales to other customers. This advantage can compensate for the high capital expenditures.

In the long-term, a refiner’s interest in blending with HDRD may not only be in order to meet federal regulations. When oil prices rise, it can become more economical to produce diesel from renewable feedstocks than from crude oil. Of course, this assumes that renewable feedstock prices do not increase at the same rate. According to projections by the US EIA and the USDA, average regular diesel prices are expected to reach parity with average soybean oil prices in 2017, after which diesel prices are expected to continue to grow relative to soybean oil prices (see Figure IV)⁴².

FIGURE IV – PROJECTED US SOYBEAN OIL AND REGULAR DIESEL PRICES, 2011 – 2020



Source: McPhail, L., Westcott, P. and Lutman, H. (USDA, 2011). *The Renewable Identification Number System and U.S. Biofuel Mandates*. Published by the USDA Economic Research Service, November 2011. Original data from EIA, 2011. 2010 Annual Energy Outlook and USDA, 2011. *Agricultural Projections to 2020*.

³⁹ Personal communications.

⁴⁰ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

⁴¹ Currently, HDRD is priced relative to biodiesel prices plus a premium for higher density/energy content, cetane, cold flow properties and branding value.

⁴² McPhail, L., Westcott, P. and Lutman, H. (USDA, 2011). *The Renewable Identification Number System and U.S. Biofuel Mandates*. Published by the USDA Economic Research Service, November 2011. Original data from EIA, 2011. 2010 Annual Energy Outlook and USDA, 2011. *Agricultural Projections to 2020*.

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1. Introduction

As of 2011, 27 national governments and 29 state/province governments have implemented policies that mandate the use of a minimum amount of renewable alternatives to diesel, including Europe, six South American countries, six Asian countries, Canada, the United States, Costa Rica and the Dominican Republic.

In Europe, the European Commission Directorate General for Energy implemented the Renewable Energy Directive, which stipulates that EU Member States must ensure that 10% of energy consumption in transport is from renewable sources.

Under the Renewable Fuels Standard, the United States requires that 3.8 billion litres of biomass-based diesel (such as biodiesel and HDRD) be used in 2012 and this volume can increase annually in future rulings. Four states have independently implemented minimum requirements for renewable alternatives to diesel.

On June 29, 2011, the government of Canada registered regulations amending the *Renewable Fuels Regulations* which were then published on July 20, 2011⁴³. These amendments stated that the coming into force date of the 2% requirement of renewable content in diesel and heating oil would be July 1st, 2011. Under the *Renewable Fuels Regulations*, both ester-based biodiesel and hydrogenation-derived renewable diesel (HDRD) are admissible as renewable content that can be used to meet the requirements of the Regulations.

Although biodiesel has been and continues to be largely the fuel of choice to meet mandates for renewable alternatives to diesel, there has been increasing interest by the regulated parties globally with regards to the use of HDRD in order to meet the requirements. Currently, HDRD is only produced in Europe, Southeast Asia and the United States^{44,45}.

The purpose of this study is to evaluate the potential for HDRD production and use in Canada. More specifically, the objectives of this study are to:

- Provide an overview of the history of HDRD development and current and proposed production plant capacity;
- Describe the HDRD production process, its capital and operating costs, GHG emission impacts and the feedstocks used;

⁴³ Canada Gazette (2011). *Regulations amending the renewable fuels regulations*. Published July 20, 2011.

⁴⁴ ÉcoRessources Consultants (2010). *National Renewable Diesel Initiative Infrastructure Project*. Prepared for Natural Resources Canada, May 2010.

⁴⁵ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

- Describe HDRD fuel properties and the various international standards that they are subject to;
- Discuss the compatibility of HDRD with existing petroleum fuels infrastructure and vehicles;
- Assess the potential market penetration of HDRD in North America (especially Canada) and other market factors such as existing and proposed supply and demand for HDRD, renewable fuels regulations and incentives and fuel prices;
- Describe future developments for other next-generation renewable alternatives to diesel.

2. Historical background

The very first engines and motor vehicles of the late 19th and early 20th century were in fact designed to run on biofuels such as vegetable oils and corn ethanol. However, during the same period, oil exploration was growing rapidly and soon petroleum-based transportation fuels overtook vegetable-based fuels due to their cheap cost and availability. Although biofuels continued to be used in niche applications throughout the 20th century, it was not until the 1970's, following the oil crisis and fossil fuel price spikes, that there was an increase in serious research into biofuel production technologies. Yet contrary to the first diesel engines designed at the turn of the century, modern-day diesel engines had been modified to run on less viscous petroleum diesel and could no longer run on pure vegetable oil due to its higher viscosity. Therefore, researchers began to investigate with new interest a process of transesterification of vegetable oil to produce less viscous fatty acid methyl esters (also referred to as biodiesel). This process was first discovered in 1937 but began to be applied in earnest in the 1980's in response to environmental concerns, agricultural surpluses and energy security. By the late 1990's and early 2000's, in order to achieve emissions reduction objectives and to support rural and agricultural businesses, incentives for biodiesel production were put in place in a number of different countries worldwide, resulting in a dramatic increase in global biodiesel production. In 2010, global biodiesel production reached 19 billion litres, up 12% from 2009^{46, 47, 48}.

As demand for biofuels grew, the need for greater production efficiency and higher quality of the final product resulted in a growing interest in producing biofuels using existing refinery technologies and infrastructure. In addition, as biodiesel was being used in greater volumes and in higher blend concentrations, some issues related to vehicle operability were observed, most notably at low temperatures and high blend concentrations. The most important issue is wax and sediment formation that can block fuel dispensers and vehicle filters. There are a number of different reasons for this wax and sediment formation that depend on the biodiesel feedstock and the production process⁴⁹. These will be described in more detail in Sections 3 and 4.

The combination of these factors led to the development of processes for the conversion of animal fats, vegetable oils and biomass into paraffinic hydrocarbons that could make use of existing pyrolysis, hydrotreatment and cracking technologies that already exist in petroleum refineries. These second-generation processes produce fuels that are made up of paraffins, the same types of molecules found in conventional diesel. These fuels are known collectively as renewable diesel or green diesel. Currently, all renewable diesel commercially produced today is done via hydrotreatment processes and is known as hydrogenation-derived renewable diesel (HDRD). However, other processes of converting renewable

⁴⁶ *History of Biodiesel*. Pacific Biodiesel website. Consulted January 4, 2012.
http://www.biodiesel.com/index.php/biodiesel/history_of_biodiesel_fuel

⁴⁷ Schmidt, C. W. (2007). *Biodiesel : Cultivating Alternative Fuels*. Environ. Health Perspect. 115(2): A86-A91.

⁴⁸ REN21. (2011). *Renewables 2011 – Global Status Report*. Published August 2011.

⁴⁹ Chandler, John Sr. (2011). *Flowability: A Complex Issue*. Biodiesel magazine. Published online January 12, 2011.

feedstocks to renewable diesel via different pathways are also being actively researched and will likely be commercialised in the medium term⁵⁰.

The CanmetENERGY labs at Natural Resources Canada were in fact one of the first to develop technologies for the hydrotreatment of renewable feedstocks to HDRD, with some of the first patents for their SUPERCETANE™ HDRD production technology dating to the early 1990's. Commercialization of HDRD production technologies began in the early to mid- 2000's with Neste Oil's NExBTL and UOP's Ecofining technologies. The first commercial-scale HDRD co-processing plant came online in 2006 in Cork, Ireland, at ConocoPhillips' Whitegate refinery, producing 57 ML/year HDRD. This was followed shortly in 2007 by the startup of a 215 ML/yr stand-alone HDRD facility in Porvoo, Finland, under the operation of Neste Oil. A second plant of the same capacity was built by Neste in Porvoo in 2009. The first North American facility came online in 2010 in Geismar, Louisiana as a joint partnership between Syntroleum and Tyson foods, with a capacity of 280 ML/year. Neste then opened two large-scale HDRD production plants with a capacity of 900 ML/year each, first in Rotterdam in 2010 and then in Singapore in 2011. A second large (500 ML/year) North American plant is under construction in Norco, Louisiana as a joint venture between Valero and Darling, and should be operational by the end of 2012. A number of additional stand-alone and co-processing plants are also under development.

A summary of existing and planned HDRD stand-alone and co-processing plants are given in Tables 15 and 16 in Section 7.

⁵⁰ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Biodistillate Transportation Fuels 1. Production and Properties*. SAE Int. J. Fuels Lubr., 2(2):185.

3. HDRD production

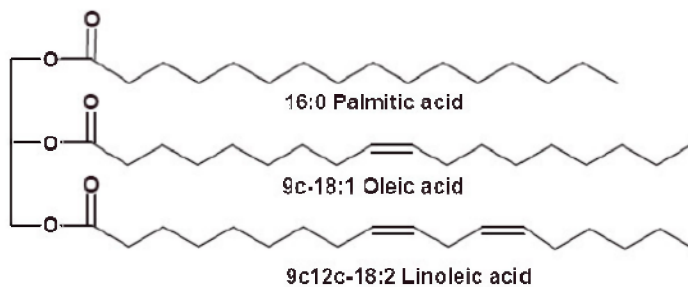
In this section, the types of feedstocks that can be used for HDRD production are discussed and the pathways for the production of HDRD are explained.

3.1 Feedstocks

Vegetable oils and animal fats

HDRD can be produced from virtually any type of bio-based renewable feedstock. The most common feedstocks are animal fats and vegetable oils, which are made up mostly of triglycerides and are the types of feedstocks that are traditionally used for biodiesel production. Triglycerides are chemical compounds made up of a glycerol backbone and three fatty acids (see an example of a triglyceride in Figure 1). Fatty acids are aliphatic (i.e. non-aromatic, or not containing any carbon rings) carbon chains connected to a carboxyl (HO-C=O) group. Each of the three fatty acids connected to the glycerol group on the triglyceride can have a different chain length (i.e. number of carbon atoms) and different degrees of unsaturation (the number of C=C double bonds). For example, as can be seen in Figure 1 below, oleic acid is an unsaturated fatty acid because it contains one double C=C bond. Linoleic acid is also unsaturated and contains two double C=C bonds. Palmitic acid, on the other hand, is fully saturated, as there are no double C=C bonds in the aliphatic chain.

FIGURE 1 – EXAMPLE OF A TRIGLYCERIDE



Source: Egeberg, R., Michaelsen, N. and Skyum, L. *Novel Hydrotreating Technology for Production of Green Diesel*. Haldor Topsoe.

The aliphatic chain length and the degree of saturation of the fatty acids are important as they are the principal determining factors in the physical properties of the final biodiesel or HDRD product, including cold flow properties, fluid density and energy content. The nomenclature for fatty acids includes a number to indicate the chain length and the number of double bonds. For example, in Figure 1, 16:0 palmitic acid has a backbone chain length of 16 carbons and zero double bonds. Different feedstocks

will have different distributions of fatty acids with varying chain lengths and degree of saturation. For instance, animal fats have more saturated fatty acids than vegetable oils⁵¹.

HDRD can be produced from a wider range of feedstocks than biodiesel. There are two principal reasons for this:

- 1) Triglycerides can be converted to biodiesel via transesterification or to HDRD via hydroprocessing (explained in more detail in Section 3.2). Transesterification results in oxygen-containing methyl esters with varying degrees of unsaturation. These products are susceptible to oxidation, which makes the product unstable during periods of storage and transportation. Hydroprocessing of triglycerides to produce HDRD results in paraffinic hydrocarbons which are by nature fully saturated and are therefore not susceptible to oxidative instability. As a result, a greater range of feedstocks can be used for HDRD production relative to biodiesel, since the degree of saturation of the feedstock is not a consideration^{52,53}.
- 2) Biofuel feedstocks can have significant variations in the degree of free fatty acid (FFA) content. FFA's are carboxylic acids that are not bonded to the glycerol backbone of a triglyceride. They can be detrimental to the biodiesel production process because they react with the alkali catalyst (typically sodium hydroxide) to form soaps, which have no value as a fuel. Some feedstocks can contain up to 15% FFA's by weight, so if they are not converted to a combustible fuel, this represents significant loss. During hydroprocessing to produce HDRD, however, FFA's are easily converted to paraffins and therefore FFA content of the feedstock is not a concern for HDRD production⁵⁴.

Table 1 below lists the vegetable oil sources used for biodiesel and HDRD production in North America. The most commonly used sources are soy and canola. Fats and greases are also commonly used, including waste animal fats from the meat processing industry (also known as tallow) as well as waste greases from the food processing and restaurant industries (yellow grease and brown grease). Tallow, yellow and brown greases are desirable feedstocks because they are produced from waste products and therefore are cheaper than cultivated feedstocks such as canola and soy. However, their chemical composition can vary widely and they can contain many impurities. This is less of an issue for HDRD production for the reasons discussed above, yet the properties of the feedstock must nevertheless be taken into account when adjusting pre-treatment and hydroprocessing operational parameters^{55,56}.

⁵¹ Robert O. Dunn (2011). *Improving the Cold Flow Properties of Biodiesel by Fractionation*. Soybean - Applications and Technology. Published April 2011.

⁵² It should be noted that transesterification can be followed by a hydrogenation step to saturate the double bonds in biodiesel. This additional processing step can be added to allow for the use of a greater diversity of feedstocks for biodiesel production and to improve product stability.

⁵³ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Biodistillate Transportation Fuels 1. Production and Properties*. SAE Int. J. Fuels Lubr., 2(2):185.

⁵⁴ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

⁵⁵ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009

The dominant feedstock for biodiesel and renewable diesel production in Europe is rapeseed oil (a close relative of canola oil), soybean oil and tallow in North America and palm oil Southeast Asia. HDRD plants currently in operation today make use of palm, rapeseed/canola, jatropha and camelina oils as well tallow and yellow and brown greases.

TABLE 1 – VEGETABLE OIL FEEDSTOCKS USED FOR BIODIESEL AND HDRD PRODUCTION IN NORTH AMERICA

NORTH AMERICA	
Reported Feedstock	Edible
Algae	No*
Beech	No
Camelina	Yes
Corn Oil	Yes
Cottonseed Oil	Yes
Jatropha	No
Lesquerella	No
Linseed	Yes
Rape Seed	Yes
Safflower	Yes
Soapnut Oil	No
Soybean	Yes
Spruce	No
Sunflower Oil	Yes
Walnut	Yes

*Some algae, or portions of algae, are edible.

Source: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. SAE Int. J. Fuels Lubr., 2(2):185.

The production pathways for transesterification and for hydroprocessing will be discussed in more detail in Section 3.2.

Table 1 also indicates which feedstocks are edible for human consumption. As demand for biofuels grows, there is concern that global food supply may suffer as a result of agricultural producers either selling their food crops for fuel production rather than for human consumption, or crop switching from a food-crop to a non-food crop in order to satisfy biofuel demand. The fact that HDRD can be produced from a wider range of feedstocks is an advantage, since feedstocks that do not compete with food crops can be used, thus minimizing public opposition. Indeed, in North America, the Dynamic Fuels HDRD plant and the Valero/Darling plant currently under construction both make use of tallow, a meat

⁵⁶ Holmgren, J., Gosling, C., Couch, K., Kalnes, T., Marker, T., McCall, M. And Marinangeli, R. (UOP-Honeywell) (2007). *Refining Biofeedstock Innovations*. Petroleum Technology Quarterly, Q3.

processing industry waste product, as their principal feedstock. Issues of feedstock availability will be discussed in Section 7.4.

Lignocellulosic feedstocks

HDRD can also be produced from other feedstocks than triglycerides. Lignocellulosic feedstocks such as those derived from agricultural and pulp and paper residues can also be used to produce HDRD (as well as renewable “green gasoline”), but additional processing must be carried out prior to hydrotreatment in order to break down the cellulose, hemicellulose and lignin found in these feedstocks into smaller molecules. This can be done via pyrolysis or by thermal or catalytic depolymerisation to produce bio-oil, which can then be hydrotreated, or by gasification to produce syngas⁵⁷, which can then be synthesized into larger fuel molecules. Biomass can be converted to bio-oil either at the same facility as the hydrotreatment plant or prior to arriving at the hydrotreatment facility (at the pulp and paper mill, for example). No existing HDRD production facilities currently use lignocellulosic biomass or bio-oil as a feedstock, however there is significant research currently being conducted in order to optimize the use of these more diverse feedstocks that also do not compete with food crops⁵⁸.

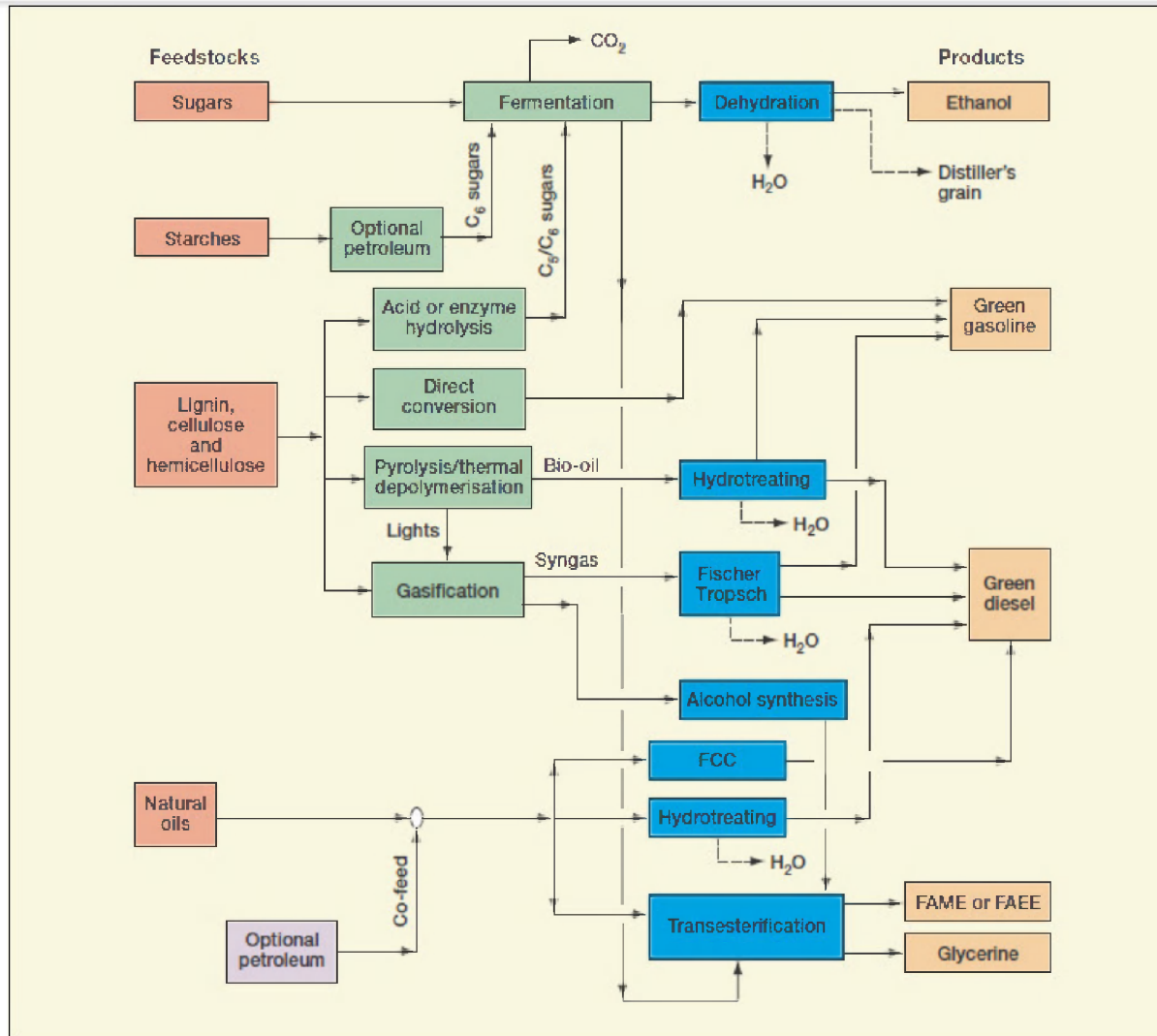
There has also been investigation into the production of renewable diesel from natural oils via fluid catalytic cracking (FCC), which is also a process that can currently be found in existing petroleum refineries.

Figure 2 below provides a schematic of the principal pathways for producing renewable fuels from a variety of different feedstocks. Table 2 presents the advantages and disadvantages of different biodiesel and renewable diesel production technologies. As can be seen in the Table, production of renewable diesel via hydrotreatment remains a favourable option due the wider availability of feedstock options and greater product quality relative to biodiesel, yet lower capital investment costs relative to gasification + Fischer-Tropsch processes. In the following section, the pathways for the production of HDRD are described in more detail.

⁵⁷ The conversion of biomass to paraffinic renewable fuels is known as Fischer-Tropsch gas-to-liquids (GTL) technology.

⁵⁸ Holmgren, J., Gosling, C., Couch, K., Kalnes, T., Marker, T., McCall, M. And Marinangeli, R. (UOP-Honeywell, 2007). *Refining Biofeedstock Innovations*. Petroleum Technology Quarterly, Q3, 2007.

FIGURE 2 – RENEWABLE FUEL PRODUCTION BY FEEDSTOCK TYPE



Note: Fluidized catalytic cracking (FCC) of natural oils is typically used to produce green gasoline and olefins, not green diesel.

Source: Holmgren, J., Gosling, C., Couch, K., Kalnes, T., Marker, T., McCall, M. And Marinangeli, R. (UOP-Honeywell, 2007). *Refining Biofeedstock Innovations*. Petroleum Technology Quarterly, Q3, 2007.

TABLE 2 – COMPARISON OF BIODIESEL AND RENEWABLE DIESEL PRODUCTION TECHNOLOGIES

Large scale production	Process	Product	Feedstocks: Availability and price	Favourable product properties	Capital investments
~ 1995	Esterification	Biodiesel/FAME	-	-	+
2007	Hydrotreating	HDRD	+	+++	-
~ 2015	Gasification + Fischer-Tropsch	Renewable diesel	+++	+++	---

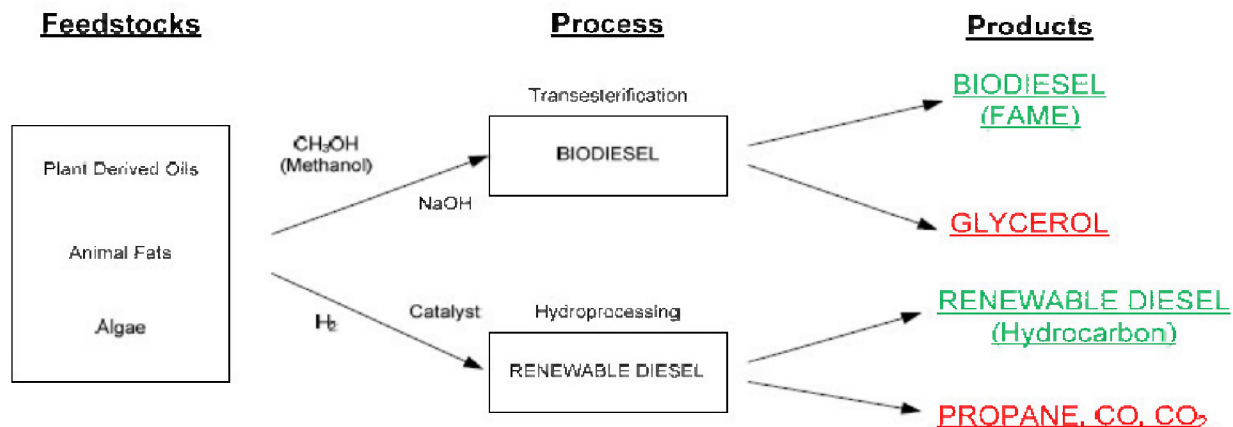
+ sign indicates advantage, - sign indicates disadvantage.

Source: Aatola, H., Larmi, M., Sarjoavaara, T., Mikkonen, S. (2008). *Hydrotreated Vegetable Oil as a Renewable Diesel Fuel: Trade-Off Between NO_x Particulate Emission and Fuel Consumption of a Heavy Duty Engine*. SAE Int. J. Engines 1(1):1251-1262.

3.2 Production pathways

Biodiesel and HDRD are made from the same feedstocks and yet their chemical composition and physical properties are quite different. This is due to the different processing pathways that are used for their production. Figure 3 illustrates the difference between biodiesel and HDRD production pathways and by-products. Biodiesel is produced via transesterification with glycerol as a by-product and HDRD is produced via hydroprocessing with propane, CO and CO₂ as by-products.

FIGURE 3 – BIODIESEL AND HDRD FEEDSTOCKS, PRODUCTION PATHWAYS AND PRODUCTS



Source: Hoekman, S. K., Gertler, A., Brock, A., Robbins, C. (Desert Research Institute) and Natarajan, M. (Marathon Petroleum Company) (2010). *Production and Properties of Biodistillate Transportation Fuels*. Presentation at the AWMA International Speciality Conference: Leapfrogging Opportunities for Air Quality Improvement, May 2010, China.

In this section, the biodiesel production process is briefly discussed, followed by a description the most common pathways used for HDRD production and their advantages and disadvantages. The capital and operating costs of each of these pathways are examined and their environmental impacts discussed.

Transesterification to biodiesel

The production of biodiesel is carried out via transesterification (see Figure 4). In this reaction, the triglyceride is reacted with an alcohol (typically methanol) in the presence of a catalyst (typically a base such as NaOH) to produce three fatty acid methyl esters and the side-product glycerine (or glycerol).

FIGURE 4 – BIODIESEL PRODUCTION VIA TRANSESTERIFICATION OF TRIGLYCERIDES

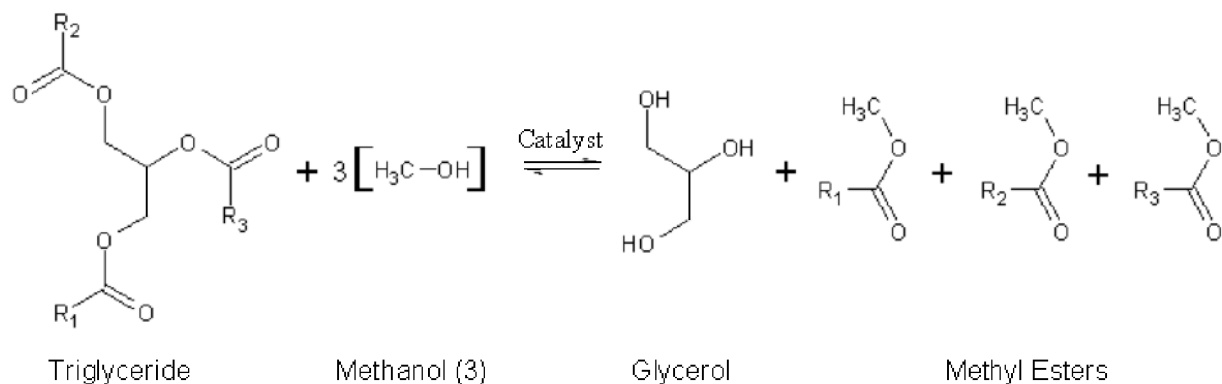


Image source: By E8 (E8) (self-made using ChemSketch10) [GFDL (www.gnu.org/copyleft/fdl.html) or CC-BY-3.0 (www.creativecommons.org/licenses/by/3.0/)], via Wikimedia Commons. Obtained January 19, 2012 at http://commons.wikimedia.org/wiki/File%3ABiodiesel_Reaction2.gif

There are some disadvantages to the production of biodiesel in this way. Firstly, the resulting fuel is made up of esters, not paraffins. Esters contain oxygen and may contain unsaturated double C=C bonds in the aliphatic chain. Paraffins, the types of chemicals found in conventional ULSD, are fully saturated hydrocarbons that contain no oxygen and no double bonds. The higher oxygen content in biodiesel contributes to its lower heating value (lower energy content) relative to ULSD and its varying degrees of unsaturation causes product instability, as these double bonds can be oxidized during extended periods of storage.

It is important to note that the fatty acid chains on the triglyceride are conserved in the resulting methyl esters. These are identified as R₁, R₂, and R₃ in Figure 4. As a result, the fatty acid methyl esters that result from transesterification have the same chain lengths and the same degree of saturation as the fatty acids in the original triglyceride. Therefore, a feedstock with a higher degree of saturated fatty acids in the triglyceride will have a higher degree of saturated methyl esters in the final product. It is these saturated methyl esters that have a higher melting point and can form wax crystals in the biodiesel liquid at temperatures that are higher than desirable and can cause storage, distribution and operability issues. A number of strategies can be implemented to control these undesirable effects, such as blending with

kerosene or the addition of additives, but these solutions are costly and operationally challenging to ensure consistent and predictable product quality and characteristics⁵⁹.

There are some other issues with transesterification. One is the by-product glycerine, which is produced at about 8% volume of the product⁶⁰. The carbons in the glycerine are “lost” as they do not contribute to the yield of the more economically favourable biodiesel fuel. Typically the glycerine that results from transesterification of vegetable oils and animal fats is low-grade and must undergo cleaning and further processing to be able to be sold as a viable by-product.

Hydrotreatment to HDRD

Pre-treatment

Most feedstocks require a pre-treatment step to prepare them for hydroprocessing. Depending on the quality of the feedstock, it may contain varying levels of alkali metals, phospholipids and metallolipids, which can hinder the effectiveness of the hydroprocessing catalysts. Hydrogenation of double bonds in the fatty acid chains may also be carried out in the pre-treatment unit prior to hydrotreatment^{61,62}.

Reaction mechanism

The principal objectives of hydrotreatment of triglycerides are to remove oxygen and to saturate C=C double bonds to produce paraffinic *n*-alkanes in the diesel boiling range. Hydrogen is reacted with the triglycerides under high temperature and pressure in the presence of catalysts to hydrogenate the double bonds in the fatty acid chains in the triglyceride. Next, the glycerol backbone is broken and the oxygen removed, leaving paraffinic *n*-alkanes. There are two principal pathways by which oxygen can be removed from the triglycerides: hydrodeoxygenation (HDO) and decarboxylation (DCO). These two pathways require different inputs and produce different products. They are illustrated in Figure 5 below using rapeseed oil as an example.

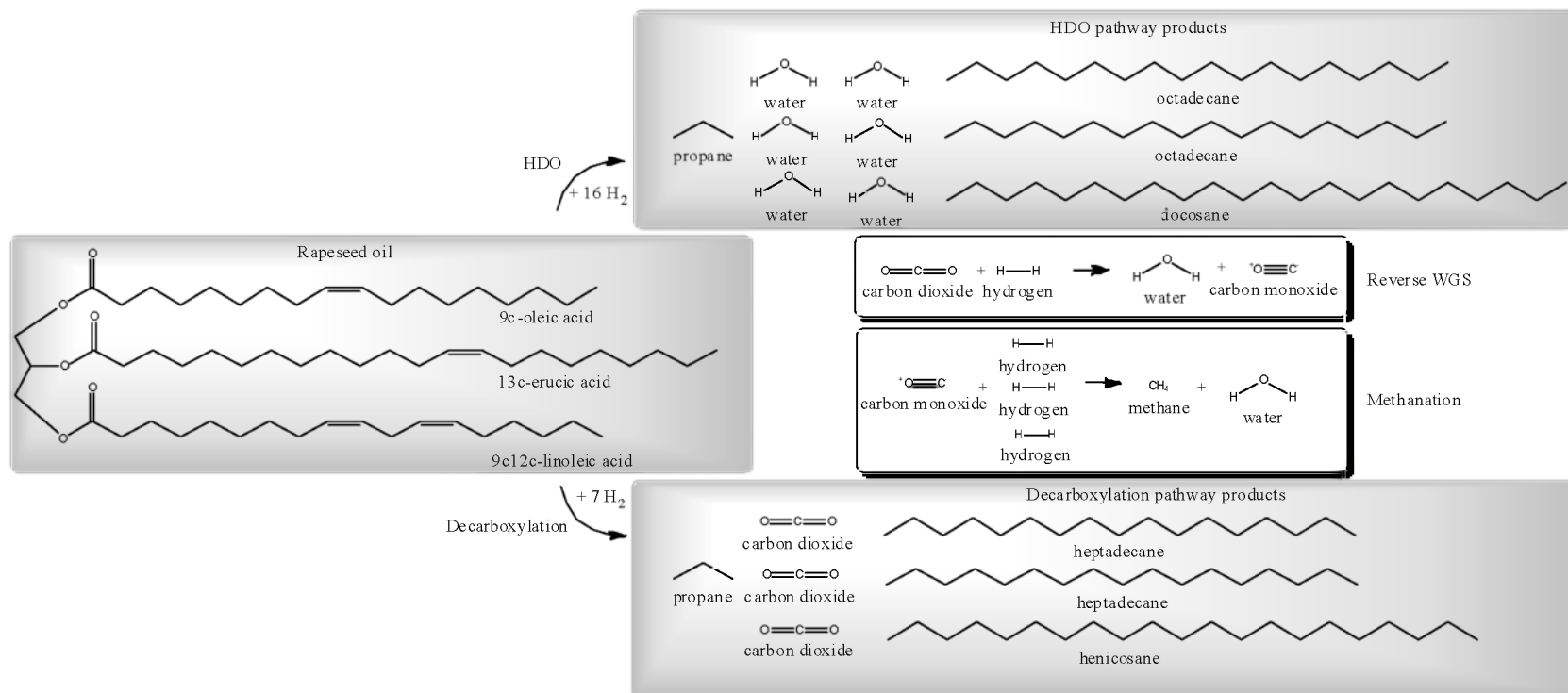
⁵⁹ Natural Resources Canada (2010). Report on the Technical Feasibility of Integrating an Annual Average of 2% Renewable Diesel in the Canadian Distillate Pool by 2011. Published October 2010.

⁶⁰ Marker, T. L., Kokayeff, P., Gosling, C. (UOP), Faraci, G., and Perego, C. (Eni) (2007). Green Diesel Production From Vegetable Oil. Presentation at the American Institute of Chemical Engineers conference, Salt Lake City, USA, November 2007.

⁶¹ Holmgren, J., Gosling, C., Couch, K., Kalnes, T., Marker, T., McCall, M. And Marinangeli, R. (UOP-Honeywell, 2007). *Refining Biofeedstock Innovations*. Petroleum Technology Quarterly, Q3, 2007.

⁶² Egeberg, R., Michaelsen, N. and Skyum, L. (Haldor Topsøe, date unknown). *Novel Hydrotreating Technology for Production of Green Diesel*.

FIGURE 5 – HDO AND DECARBOXYLATION OF RAPESEED OIL



Source: Haldor Topsøe (2010). *Turning over a new leaf in renewable diesel hydrotreating.*

http://www.topsoe.com/business_areas/refining/Hydrotreating/~/_media/PDF%20files/Refining/topsoe_npra_2010_turning_over_a_new_leaf.ashx

As can be seen in Figure 5, HDO of rapeseed oil requires an input of 16 moles of hydrogen and produces one mole of propane and six moles of water in addition to the HDRD hydrocarbons. DCO, on the other hand, requires only seven moles of hydrogen to produce one mole of propane and three moles of CO₂. However, the CO₂ can react further with hydrogen to form first CO (reverse water gas shift (WGS)) and then CH₄ (methanation, see Figure 5), requiring an additional four moles of hydrogen for each mole of CO₂. As a result, DCO can require up to 19 moles of hydrogen overall, depending on the extent of reverse WGS and methanation⁶³.

HDO and DCO produce hydrocarbons of different molecular weight. HDO involves breaking the C-O bonds in the glycerol group and hydrogenating the resulting propyl and fatty acid chains. During DCO, the CO₂ group is separated completely from the propyl group of the glycerol and the aliphatic chains of the fatty acids, which are then hydrogenated. As a result, the paraffinic molecules that result from HDO contain one more carbon atom than those that result from DCO, which in practical terms corresponds to a 5% greater liquid product yield relative to DCO⁶⁴. However, this does not result in any significant differences in fuel properties.

Finally, HDO only produces propane and water as by-products. DCO produces the same amount of propane as the HDO pathway, but it also produces CO₂, CO and water in amounts that depend on the extent of WGS and methanation. Therefore DCO also has a higher potential for GHG emissions.

As can be seen from the previous example, the hydrotreatment reaction pathway can have a significant impact on the processing conditions (notably H₂ input) and on the output products. Catalysts can be used to control the reaction pathways that are followed. For example, it has been found that for the hydrotreatment of soybean oil, nickel-molybdenum catalysts favour the HDO route, while cobalt-molybdenum catalysts favour the DCO pathway⁶⁵.

It is important to remember that in practice, both HDO and DCO will take place during hydrotreatment and cannot be completely controlled, but finding the right balance using catalysts and reactor conditions can help minimize hydrogen input and CO₂ output and maximise liquid product yield.

The catalysts used during the hydroprocessing step can also have an impact on the pour point of the final product. For instance, one study has shown that using a silica-alumina (SiO₂-Al₂O₃) support for a nickel-molybdenum catalyst instead of a silica (SiO₂) support while hydroprocessing a jatropha, palm and canola oil blend results in a lowering of the pour point of the liquid product from 20C to -10C⁶⁶.

⁶³ Haldor Topsøe (2010). *Turning over a new leaf in renewable diesel hydrotreating*. http://www.topsoe.com/business_areas/refinina/Hydrotreating/~media/PDF%20files/Refinina/topsoe_npra_2010_turning_over_a_new_leaf.ashx

⁶⁴ *Ibid.*

⁶⁵ Bambang Veriansyah, Jae Young Han, Seok Ki Kim, Seung-Ah Hong, Young Jun Kim, Jong Sung Lim, Young-Wong Shu, Seong-Geun Oh and Jaehoon Kim (2011). *Production of renewable diesel by hydroprocessing of soybean oil: Effect of catalysts*. Fuel, in press, electronic version of corrected proof available 7 November 2011.

⁶⁶ Liu, Y., Sotelo-Boyas, R., Murata, K., Minowa, T. and Sakanishi, K. (2011). *Hydrotreatment of Vegetable Oils to Produce Bio-Hydrogenated Diesel and Liquefied Petroleum Gas Fuel over Catalysts Containing Sulfided Ni-Mo and Solid Acids*. Energy & Fuels, 25(10), 4675-4685.

As was mentioned previously, the free fatty acid content of the feedstock is an issue for transesterification, but it is not for hydrogenation. FFA's can be easily converted to hydrocarbons via hydrotreatment, whereas transesterification does not always convert all FFA's and indeed in some cases produces FFA's, which negatively affects sediment formation in the final product. As a result, a wider range of feedstocks can be used for hydrotreatment, without affecting final product quality. For example, this allows for the use of tall oil, a by-product of the pulp and paper industry, which contains almost exclusively FFA's (and other molecules) but no triglycerides⁶⁷. It should be noted that feedstocks with very high FFA content (such as tall oil) can cause other issues in a hydrotreater such as acid corrosion, thus in some cases requiring pre-treatment of the feedstock to reduce the FFA content.

It should be noted that although the feedstock used in the production of HDRD is renewable, often the H₂ reagent is not. Hydrogen is typically produced by steam reformation of fossil fuels such as natural gas or coal with steam at high temperatures. In addition to the use of fossil fuels as a feedstock for hydrogen production, the production of steam requires energy input and high temperatures required during the reaction also requiring energy input. Carbon dioxide is also a product of steam reformation reactions, which also increases the GHG emissions of the process (unless the CO₂ is captured and sequestered).

Nevertheless, there are a number of ways in which hydrogen can be produced sustainably and without the use of fossil fuels (albeit at higher costs): electrolysis of water, where the electricity used for the electrolysis is generated by renewable sources; the use of landfill gas as the feedstock for steam reformation; photocatalytic water splitting using solar energy; and fermentative and enzymatic hydrogen generation from organic materials.

Catalytic de-waxing

The melting point of the liquid product of hydroprocessing will depend on the original feedstock composition, the hydrotreatment pathway and the catalysts used during hydroprocessing. In most cases, some long-chain and branched paraffins with high melting points are produced, which form wax solids on cooling. The melting point of the HDRD product can be lowered in three ways: fractionation/distillation, blending with additives and catalytic isomerisation ("de-waxing"). Fractionation and distillation involves the removal of the high melting hydrocarbons but results in lower final HDRD yield. Additives such as kerosene or cloud point suppressants must be blended in high concentrations and are therefore expensive. Catalytic de-waxing involves isomerising and/or hydrocracking high melting hydrocarbons, resulting in a product with a more desirable pour point. The catalytic and processing conditions can be controlled in order to produce HDRD with the required pour point (i.e. summer vs. winter HDRD). It should be noted that due to shorter chain lengths, liquid product yields are slightly lower for winter HDRD (approximately 10%), which contributes to its higher cost relative to summer HDRD⁶⁸. Short-chain naphtha molecules (5-12 carbons) are produced as a co-product of isomerisation. The lower the pour point of the liquid fuel, the higher the naphtha fraction (and consequently lower liquid fraction), which is undesirable since naphtha is less valuable as a fuel than diesel.

⁶⁷ Egeberg, R., Michaelsen, N. and Skyum, L. (Haldor Topsøe, date unknown). *Novel Hydrotreating Technology for Production of Green Diesel*.

⁶⁸ Personal communications.

All HDRD production facilities currently in commercial operation make use of a catalytic de-waxing unit to control the cloud point. Conversely, CanmetENERGY's SUPERCETANE™ process makes use of fractionation/distillation⁶⁹. Both catalytic de-waxing and fractionation/distillation processes allow the cloud point of the final product to be controlled by modifying the operating conditions. In both cases, the lower the cloud point, the lower the product yield (since a greater fraction of molecules must be removed), hence the higher price of low cloud HDRD.

Co-processing vs. stand-alone units

As mentioned previously, one of the advantages of the HDRD production process is that it makes use of existing refining technology. Hydrotreatment units are already used in conventional refineries in order to desulfurise fractional distillates, including diesel oil. As such, this same technology can be applied to the hydrotreatment of renewable oils to produce HDRD. This can be done either by co-processing the renewable feed with the conventional diesel oil feed or by constructing a stand-alone hydrotreatment unit used exclusively for producing HDRD. The advantage of co-processing is the large savings in capital costs, since the renewable feed can be processed in the existing hydrotreater. However, the operating parameters and the catalysts used for diesel oil and for renewable oil can be quite different and it can take time to switch between modes of operation due to necessary changes in the catalyst bed and operating conditions.

The hydrotreatment of oxygen-containing triglycerides, esters and fatty acids, whether by DCO or HDO, is very fast and highly exothermic (i.e. it gives off significant amounts of heat). In fact, once the process is initiated, the heat given off by the reaction can be sufficient to sustain it, with little or no additional energy input. This fast and exothermic reaction creates greater complexity and non-uniformity of temperature and pressure in the reactor bed. If the temperature rises too high too quickly, this can lead to coke formation and clogging in the reactor and catalyst deactivation, lower H₂ partial pressure at the catalyst site (requiring higher H₂ input to compensate) and increased pressure drop. This effect can be controlled by using a graduated catalyst bed comprising of multiple layers of catalysts of different activities that can serve to “guide” the reaction through the reactor bed, ensuring a more uniform distribution of temperature and pressure. The effect of just a few percent of renewable co-feed on a conventional diesel hydrotreater can be seen clearly in Figure 6, which shows the increase in temperature and H₂ requirements as a function of the percentage of renewable co-feed during different modes of operation at the Preem refinery in Gothenburg, Sweden (using tall oil as the renewable feedstock)⁷⁰.

As can be seen in Figure 6, the highly exothermic nature of hydroprocessing oxygen-containing hydrocarbons can have a significant impact on reactor conditions. Existing hydrotreaters can usually handle co-processing low amounts of renewable feed (5-10%) by optimising the catalysts loading, whereas higher amounts will require a revamp of the unit. A hydrotreater revamp to manage high

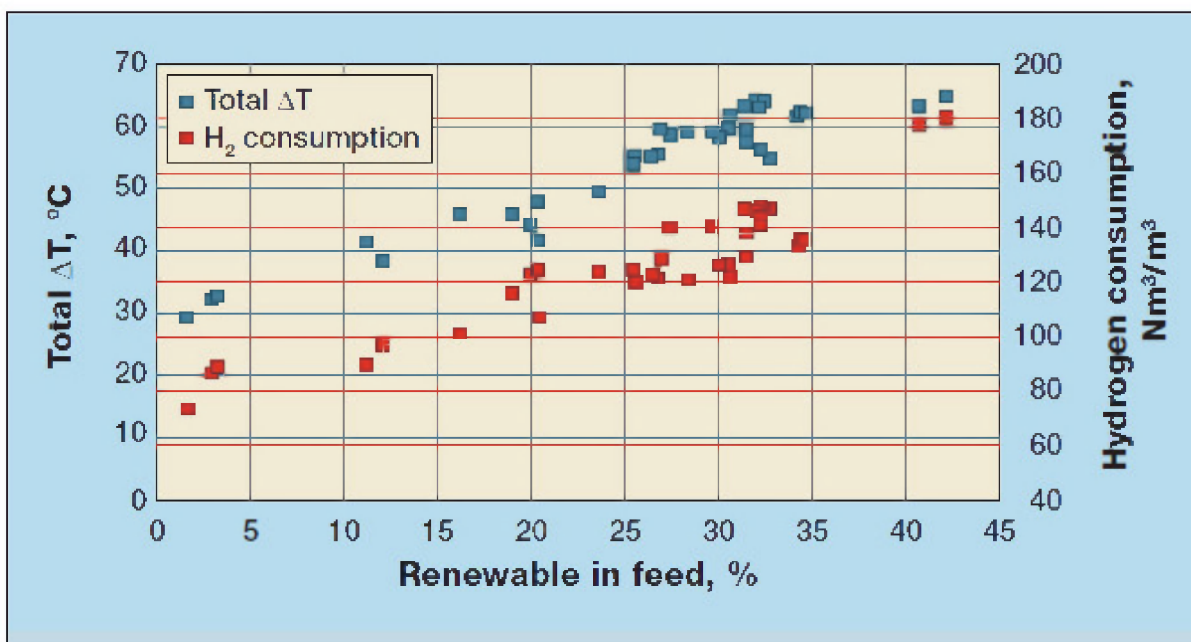
⁶⁹ CanmetENERGY (2008). *CanmetENERGY's SUPERCETANE™ technology*. Website, last modified November 20, 2008. <http://canmetenergy.nrcan.gc.ca/industrial-processes/industrial-energy-systems/publications/342>

⁷⁰Haldor Topsøe (2010). *Turning over a new leaf in renewable diesel hydrotreating*. http://www.topsoe.com/business_areas/refining/Hydrotreating/~media/PDF%20files/Refining/topsoe_npra_2010_turning_over_a_new_leaf.ashx

fractions of co-processing with renewables would involve material selection (heat stress, corrosion issues), the gas loop system to manage CO and CO₂, reactor temperatures (higher exotherm), hydrogen requirements, hydraulic limitations, reactor sizes and any other modifications necessary to handle the new reactions in a safe and reliable manner.

One of the advantages of HDRD is that it can be blended into the conventional diesel pool in very high concentrations, up to 100%, with little or no adverse effects (indeed, with some positive effects, as will be seen in Section 4). Although it is relatively straightforward to optimize reactor conditions for a given percentage of renewable co-feed, these conditions can vary significantly depending on the blend percentage. Batch production of HDRD in a stand-alone facility gives refiners greater flexibility with regards to real-time modifications in the blend percentage^{71,72}.

FIGURE 6 – CHANGES IN TEMPERATURE AND HYDROGEN CONSUMPTION IN A HYDROTREATER CO-FEEDING WITH TALL OIL



Source: Egeberg, R. and Knudsen, K. (Haldor Topsoe); Nyström, S., Grennfelt, E. L. and Efraimsson, K. (Preem) (2011). *Industrial-scale Production of Renewable Diesel*. Petroleum Technology Quarterly, Q3.

As mentioned earlier in this section, hydroprocessing renewable feedstocks requires large amounts of hydrogen – significantly higher than is required for hydroprocessing conventional diesel oil. Consequently, existing capacity for hydrogen generation at a petroleum refinery may not be sufficient to

⁷¹ Egeberg, R., Michaelsen, N. and Skyum, L. (Haldor Topsøe, date unknown). *Novel Hydrotreating Technology for Production of Green Diesel*.

⁷² Personal Communications.

co-process renewable feeds at high percentages. It may not be considered economic to install additional hydrogen generation capacity in order to be able to co-process with renewable feedstocks.

There is an additional concern related to co-processing that is specific to the United States market: under the US Renewable Fuels Standard (RFS2)⁷³, HDRD that is produced as a blend with conventional diesel via co-processing is currently not as valuable as HDRD that is processed independently. This is discussed in more details in section 7.1.

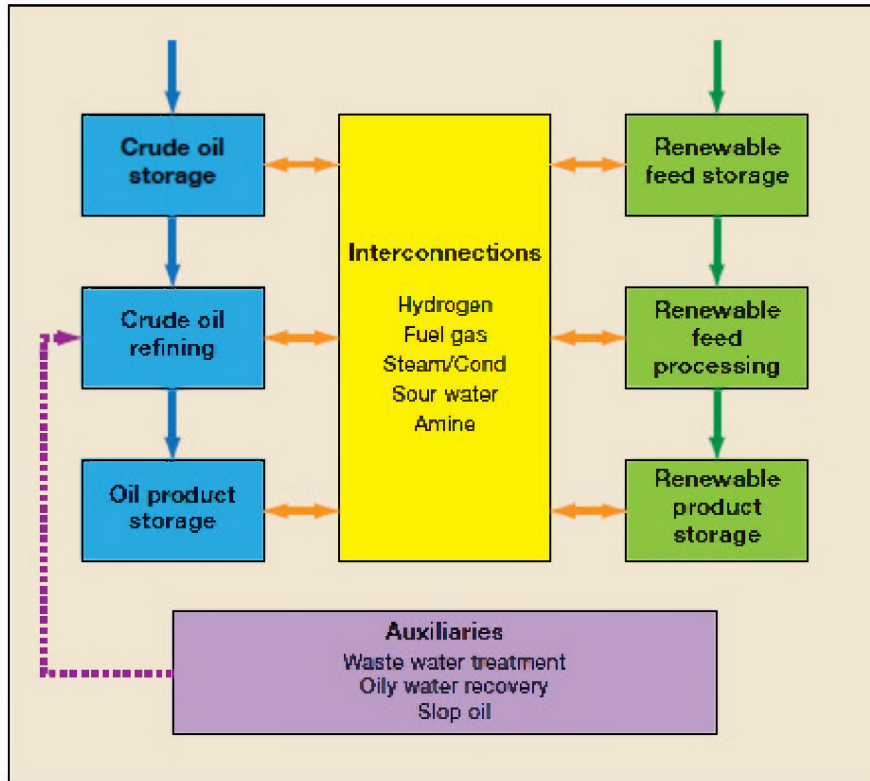
Stand-alone units for hydroprocessing renewable feedstocks have the advantage of being tailor-made and optimised for HDRD production. They can be built as add-ons to existing refineries in order to make use of existing hydrogen generation capacity and to streamline the management of recycle gases. This is illustrated in Figure 7. The HDRD can also be blended with conventional diesel after processing on-site at the refinery before distribution to the terminals, or it can be kept separate for distribution and sale as a neat product. The blend percentage can be determined at short notice according to changing market conditions without complex changes to operating conditions.

However, the obvious disadvantage of a stand-alone production facility is the high capital costs for the construction of the required additional infrastructure. Therefore, in order for the construction of such a facility to be economic, the operator must take advantage of economies of scale by producing renewable diesel in large volumes. Co-processing allows the refiner to blend smaller volumes of HDRD with less capital investment (mostly related to the receipt, storage and handling of the feedstock).

The choice of producing HDRD via co-processing or in a stand-alone facility will depend greatly on local conditions. In the United States context, however, co-processing is unlikely to be the method of choice in the near to medium term due to unfavourable RIN prices relative to HDRD produced in a stand-alone unit under the RFS2 regulations.

⁷³ Co-processed HDRD is eligible for D5 RIN's in the Type A advanced biofuels category, but these RIN's are currently trading at about half the price of D4 RIN's.

FIGURE 7 – INTEGRATION OF A STAND-ALONE HDRD PLANT AT A PETROLEUM REFINERY



Source: Keyriläinen, J. and Koskinen, M. (Neste Jacobs, 2011). Renewable Fuels and Biofuels in a Petroleum Refinery. Petroleum Technology Quarterly, Q1.

3.3 Capital and operating HDRD production costs

3.3.1 Stand-alone plants

Table 3 presents the capital costs and production capacities of each of the HDRD plants in commercial operation today, as well as the estimated costs for hypothetical plants.

Note that in 2006, CanmetENERGY carried out an economic analysis of a potential 8000 bpd plant that makes use of its patented SUPERCETANE™ technology to hydrotreat vegetable oils and animals fats into a paraffinic lubricant wax. The capital costs were estimated to be USD 12.7 million, but this does not include the de-waxing unit that would be used to convert this basestock to HDRD⁷⁴.

TABLE 3 – CAPITAL COSTS OF COMMERCIAL HDRD PRODUCTION FACILITIES

Company	Location of facility	Capacity	Capital costs (USD)	Capital cost per barrel per day capacity	Source
Neste Oil	Porvoo, Finland	190,000 tonnes per year (tpy) 3,800 bpd	\$130 million	\$34,000	[1]
Neste Oil	Porvoo, Finland	190,000 tpy 3,800 bpd	\$130 million	\$34,000	[1]
Neste Oil	Tuas, Singapore	800,000 tpy 16,000 bpd	\$725 million	\$45,000	[2]
Neste Oil	Rotterdam, Netherlands	800,000 tpy 16,000 bpd	\$1 billion	\$63,000	[3]
Dynamic Fuels (Syntroleum and Tyson Foods joint venture)	Geismar, Louisiana	240,000 tpy 5,000 bpd	\$150 million	\$30,000	[4]
Valero and Darling joint venture	Norco, Louisiana	440,000 tpy 9,000 bpd	\$330 million (including \$241 million DOE loan guarantee)	\$36,000	[5]
Hypothetical small-scale plant		500 bpd	\$36- \$42 million	\$72,000-\$84,000	[6]
Hypothetical small-scale plant		2,500 bpd	\$75- \$85 million	\$30,000-\$34,000	[6]

¹Schill, S. R. (2007). *Heeding Hydrogenation*. Biodiesel Magazine, published online March 15, 2007.

²Nest Oil (2011). *Neste Oil celebrates the grand opening of its ISCC-certified renewable diesel plant in Singapore*. Press release, 8 March 2011.

³Green Car Congress (2008). *Neste Oil to Build \$1B NExBTL Renewable Diesel Plant in Rotterdam*. Published online 13 June, 2008.

⁴Syntroleum (2011). *Syntroleum Announces Third Quarter Results and October Production Update*. Press release, published November 8, 2011.

⁵Stuckey, M. (2011). *Valero begins construction of \$330 million renewable diesel plant in Norco*. Published in St Charles Herald Guide, October 6, 2011.

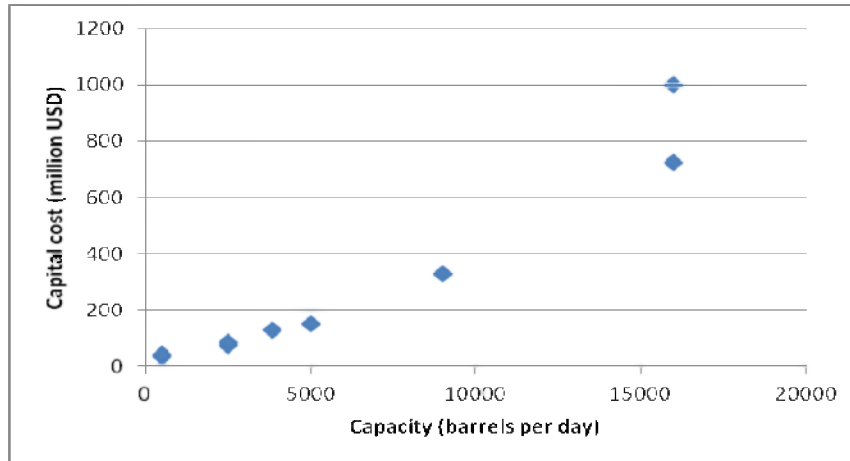
⁶Personal communications.

Figure 8 plots total capital costs as a function of production capacity. This data is based on only six commercial plants and two hypothetical plants so it cannot be taken as fully representative. Also, capital costs can be calculated in a number of different ways and figures can vary depending on what is included, so these are really only rough estimates. However, given the available data, for the moment it

⁷⁴ CanmetENERGY (2008). *CanmetENERGY's SUPERCETANE™ technology*. Website, last modified November 20, 2008. <http://canmetenergy.nrcan.gc.ca/industrial-processes/industrial-energy-systems/publications/342>

appears that economies of scale do not yet apply to the capital costs for new HDRD plant construction, as the relationship appears to be approximately linear.

FIGURE 8 – CAPITAL COSTS AS A FUNCTION OF CAPACITY – SMALL-, MEDIUM- AND LARGE-SCALE HDRD PLANTS

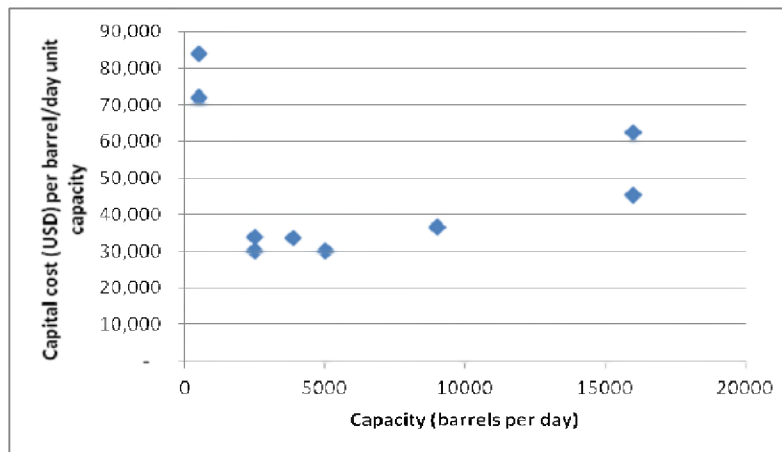


Another way to interpret the data is to analyse the unit capital cost (capital cost bpd of capacity, see Table 3). This is plotted in Figure 9 as a function of plant capacity. As can be seen in the figure, the unit capital cost is high for very small and very large plants (\$45,000 - \$85,000 per bpd capacity), but approximately the same for the rest (\$30,000 - \$40,000 per bpd capacity). In contrast, the average capital costs for a petroleum refinery are \$15,000 - \$20,000 per bpd capacity⁷⁵. Typical petroleum refineries can have capacities in the tens to hundreds of thousands of bpd. For a biodiesel plant they are \$20,000 - \$30,000 per bpd capacity for plant sizes around 2,000 bpd, which is considered a large (i.e. 114 million litres/year)⁷⁶.

⁷⁵ United States Energy Information Administration (EIA, 2006). *Annual Energy Outlook 2006*. DOE/EIA-0383, 57-58.

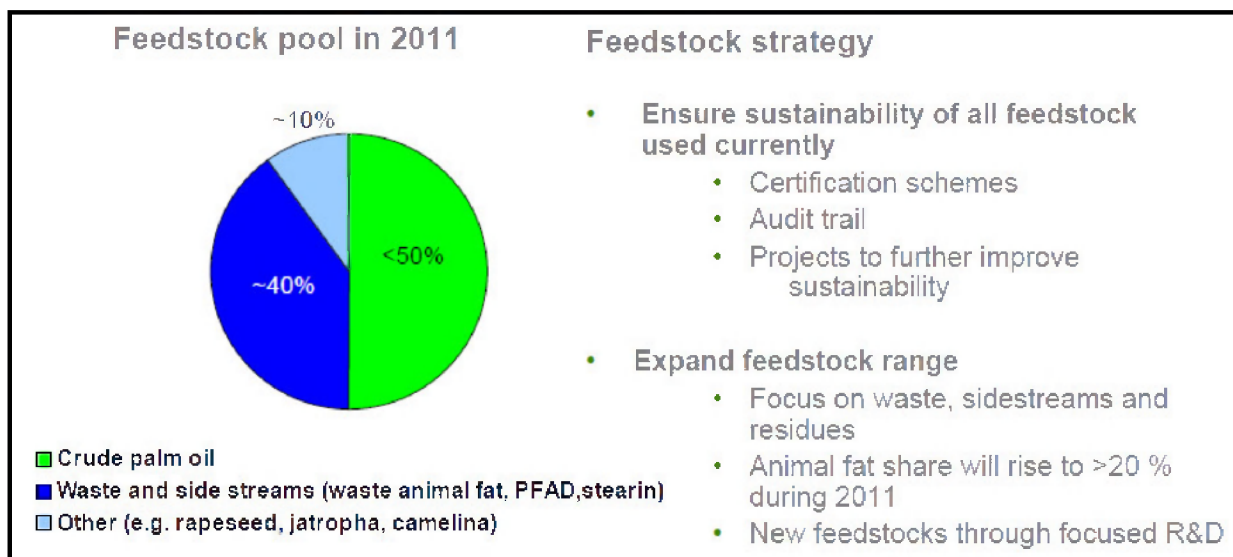
⁷⁶ United States Department of Agriculture (USDA) and Iowa State University (2012). *Biodiesel Profitability*. Excel model, last updated January 10, 2012.

FIGURE 9 – UNIT CAPITAL COSTS AS A FUNCTION OF HDRD PRODUCTION CAPACITY



Operating costs at an HDRD production facility include: renewable feedstock, hydrogen, energy input/utility, water, catalysts, chemicals, direct and indirect labour and administrative costs. Operating costs are much more difficult to predict, because feedstock, hydrogen and utility prices, the largest components of production costs, can vary widely depending on local, national and international market conditions. Feedstock costs make up approximately 80% of operating expenses and hydrogen and utilities make up approximately 15%⁷⁷. Given the important role that feedstock plays in determining production costs, changes in feedstock prices can make or break the profitability of an HDRD operation. This is also why it is advantageous to diversify feedstock supply in order to be able to adapt to changing feedstock prices. Figure 10 illustrates Neste’s feedstock diversification strategy:

FIGURE 10 – NESTE OIL FEEDSTOCK DIVERSIFICATION STRATEGY

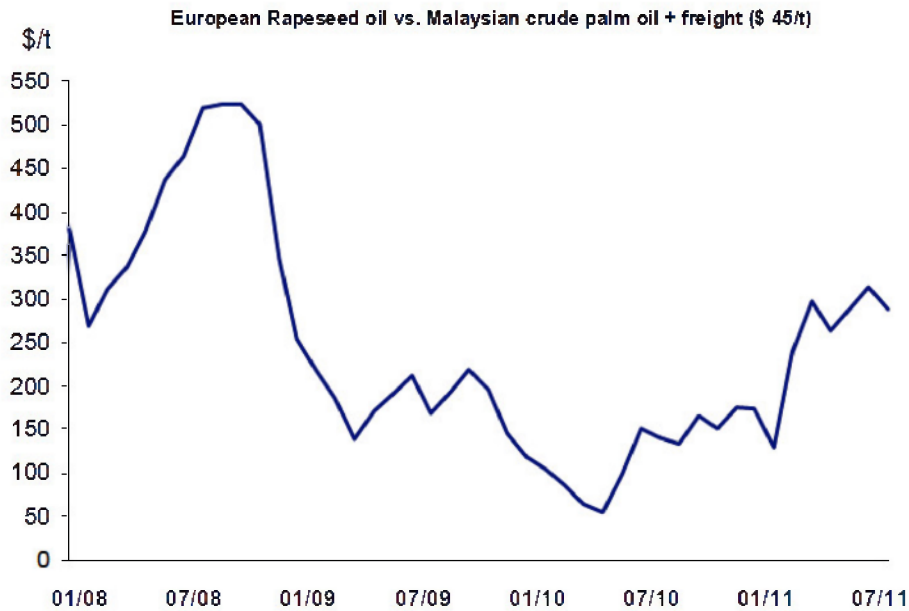


⁷⁷ Personal communications.

Source: Lehmus, Matti (Neste Oil, 2011). *Renewable Fuels – Driving Growth and Profitability*. Presentation at Neste Oil Capital Markets Day, 21 September 2011.

Figure 11 plots the difference in price between rapeseed oil and palm oil from 2008 – 2011. The price differential varied from \$50/t in summer 2010 to \$550/t in summer 2008. This illustrates the importance of feedstock flexibility.

FIGURE 11 – PRICE DIFFERENTIAL BETWEEN EUROPEAN RAPESEED OIL AND MALAYSIAN PALM OIL (INCLUDING FREIGHT TO EUROPE)

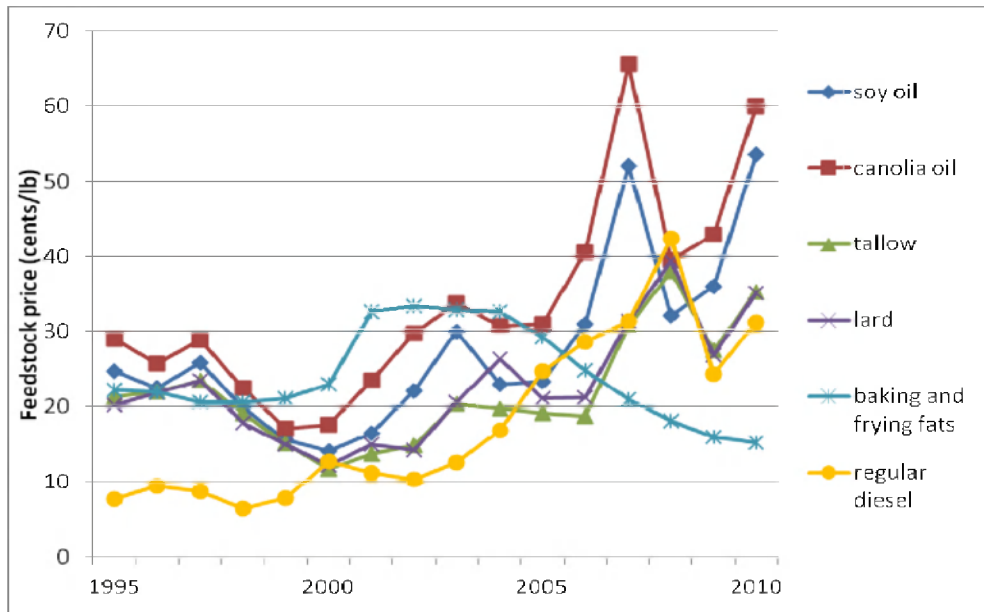


Source: Source: Lehmus, Matti (Neste Oil, 2011). *Renewable Fuels – Driving Growth and Profitability*. Presentation at Neste Oil Capital Markets Day, 21 September 2011.

Figure 12 plots US biofuel feedstock prices from 1995 – 2010, as compared with regular No. 2 diesel wholesale prices⁷⁸. As can be seen, feedstock price volatility has increased dramatically since the early 2000's, due primarily to crude oil price volatility but also due to the development of biofuels markets. Figure 13 plots the price differential of various biofuel feedstocks relative to regular No.2 diesel wholesale prices.

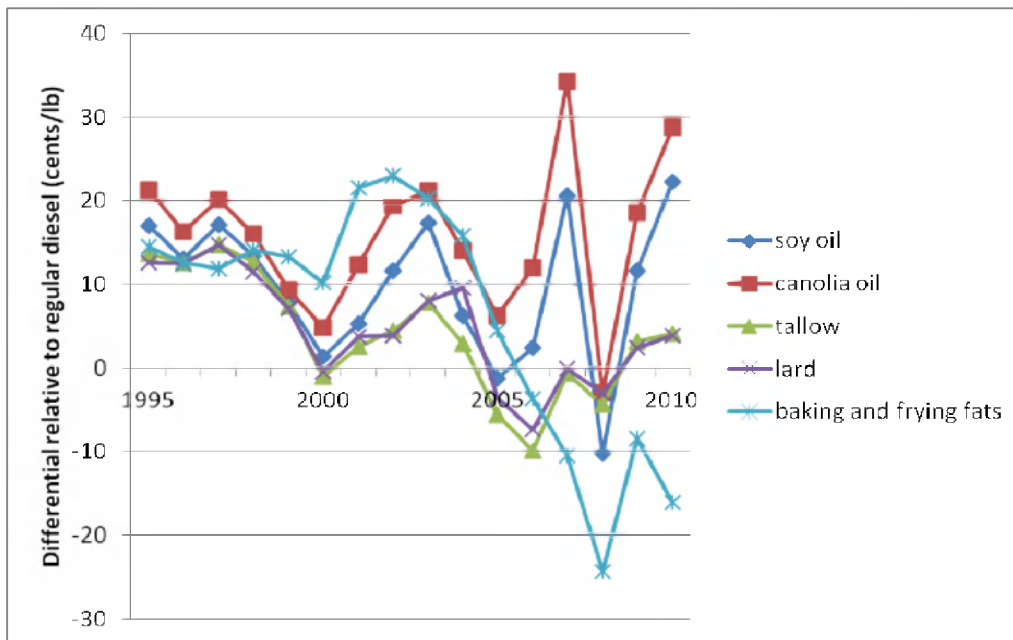
⁷⁸ It is important to remember that the equivalent fossil feedstock to vegetable oils and rendered fats is regular (non-desulfurised) diesel oil (not crude oil). Crude oil is first distilled into a number of fractions of different boiling point ranges and regular diesel is produced from the diesel oil fraction, which is then fed into a hydrotreater for de-sulfurization to ULSD. Therefore the hydrotreater feed for ULSD is regular diesel and the hydrotreater feed for HDRD is vegetable oil or rendered fats (or other suitable renewable feedstocks, such as processed tall oil).

FIGURE 12 – US BIOFUEL FEEDSTOCK AND REGULAR DIESEL PRICES



Sources: United States Department of Agriculture (USDA, 2011). *Oil Crops Yearbook 2011*. Updated March 2011. United States Energy Information Administration (EIA, 2011). *No.2 Distillate Prices by Sales Type*. Release date: November 1, 2011.

FIGURE 13 – PRICE DIFFERENTIAL BETWEEN US BIOFUEL FEEDSTOCKS AND REGULAR DIESEL



Sources: United States Department of Agriculture (USDA, 2011). *Oil Crops Yearbook 2011*. Updated March 2011. United States Energy Information Administration (EIA, 2011). *No.2 Distillate Prices by Sales Type*. Release date: November 1, 2011.

As can be seen, aside from baking and frying fats, renewable feedstock prices had a generally inverse relationship relative to diesel oil prices from 1995-2005. As of 2005, renewable feedstock prices began more or less to follow oil prices, although this trend is not expected to continue indefinitely (see Section 7.3 for a discussion of HDRD prices). Installing or adapting refinery infrastructure in order to be able to accommodate the production or co-feeding of HDRD from a variety of different feedstocks could be seen as a hedge for when regular diesel prices are high relative to renewable feedstock prices. Of course, feedstock supply must be sufficient. This will be discussed in more detail in Section 7.4.

In 2011, Neste Oil published estimated production costs (not including feedstock costs) for their NExBTL process, with a comparison to 2009 estimates. These are shown in Table 4. As can be seen, it is estimated that production costs are approximately 17 US cents/L. This is up from the 2009 estimate of 14 US cents/L, due to increases in utility costs.

TABLE 4 – ESTIMATED NExBTL PRODUCTION MARGIN FOR 2009 AND 2010

US cents/L NExBTL	2009	2010
Fixed Costs	4	4
Hydrogen and utilities	10	13
TOTAL	14	17

Source: Source: Lehmus, Matti (Neste Oil, 2011). *Renewable Fuels – Driving Growth and Profitability*. Presentation at Neste Oil Capital Markets Day, 21 September 2011.

In 2009, Neste Oil also published estimated NExBTL margins for the period July 2008 – June 2009. These are presented in Table 5. As can be seen, the net cash margin for the period was estimated to be about 18 US cents/L. The margin for 2010 was likely somewhat lower, due to the higher utilities costs mentioned earlier. Feedstock prices do not necessarily affect margins because HDRD is typically priced relative to biodiesel prices. More information on HDRD and biodiesel prices will be given in Section 7.3.

TABLE 5 – ESTIMATED NExBTL PRODUCTION MARGIN JULY 2008 - JUNE 2009

	US cents/L NExBTL
Gross margin	31
Utilities and hydrogen	10
Sales margin	21
Fixed costs	4
Net cash margin	18

Source: Honkamaa, J., 2009. *Delivering Future Growth*. Presentation at Neste Oil Capital Markets Day, 29 September, 2009.

3.3.2 Co-processing

In the case of co-processing, the renewable feedstock is co-processed with the petroleum feed using the existing refinery infrastructure, so the marginal capital and operating expenses are minimal. British Petroleum (BP) and Petrobras have both installed co-processing facilities in Australia and Brazil,

respectively, and they have indicated that the marginal capital costs are minimal. The BP plant co-processes up to 2,000 bpd HDRD (up 5% by volume) and Petrobras has adapted four of its existing refineries in Brazil so that each can allow for co-processing of up to 4,000 bpd HDRD. Petrobras has indicated that the marginal capital costs to accommodate co-processing were of the order of USD 5.6 million. Although marginal capital and operating costs are minimal, of course the price of the renewable feedstock relative to the petroleum feed will have a significant impact on the refining margin. For example, Petrobras has not been co-feeding at maximum capacity because of the current high price of renewable feeds relative to regular diesel^{79,80}.

3.4 GHG impacts of HDRD production

The greenhouse gas (GHG) emissions that result from the production and use of HDRD can be calculated using well-to-wheel full lifecycle analysis (LCA). Such an analysis seeks to account for all GHG emissions related to the production and transportation of feedstock and the production, transportation, distribution and combustion of the resulting fuel. This includes feedstock growth and harvesting, fertilizer use (if applicable), direct land use changes (changes in the land used for HDRD production) feedstock processing and oil extraction and HDRD production and distribution, amongst other factors. The combustion stage of the LCA is an important part of the GHG reductions associated with the use of biofuels because typically, the non-fossil based CO₂ emitted during combustion is considered to be zero, since this carbon is considered as having been “recently” sequestered from the environment during the growth of the source organism. Conversely, the CO₂ emitted during the combustion of fossil-based fuels is considered as newly-created and therefore it is accounted for in the LCA. For this reason, there can be lifecycle GHG emission reductions associated with the use of certain biofuels relative to fossil diesel, even if the emissions during the feedstock and fuel production and transportation (“well-to-tank” or WTT) stages are actually higher than they are for fossil diesel. This is illustrated in Table 6, which lists the energy intensity (MJ energy input versus MJ energy produced in the final fuel) of different stages of the WTT LCA for Neste’s NExBTL product, relative to diesel, depending on the feedstock. As can be seen, in this one study, for the rapeseed and palm oil feedstocks, the WTT energy intensity was found to be higher than for diesel⁸¹.

⁷⁹ Murphy, M. (2007). *BP turns animal for renewable diesel production*. The Age, published online April 16, 2007.

⁸⁰ Khalip, A. (Reuters, 2008). *Petrobras H-Bio output on hold due to price*. Published January 16, 2008.

⁸¹ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

TABLE 6 – WELL-TO-TANK ENERGY INTENSITY FOR NEXBTL AND DIESEL

Biofuel chain	MJ/MJ_{NEXBTL} palm oil	MJ/MJ_{NEXBTL} rapeseed oil	MJ/MJ_{NEXBTL} oil from animal waste	Fossil fuel chain	MJ/ MJ_{fossil fuel} fossil fuel reference chain
Cultivation and processing of raw materials	0.02	0.1	0.001	Crude oil production and conditioning at source	0.03
Transport of raw materials	0.1	0.01	0.01	Crude oil transport to markets	0.01
Production of NExBTL	0.07	0.07	0.07	Crude oil refining to diesel	0.10
Transport of final product	0.01	0.01	0.01	Diesel fuel distribution	0.01
Total	0.2	0.19	0.09		0.15

Nikander, S. (Helsinki University of Technology, 2008). *Greenhouse gas and energy intensity of product chain: Case transport fuel*. Master's thesis, published May 2008.

One controversial component of LCA is indirect land use changes (ILUC), i.e. changes in land that occur outside of the biofuel supply chain in question due to market effects. The question of whether or not to include ILUC into the LCA for biofuels can have a significant impact on the results of the analysis⁸². Figure 14 presents the carbon intensity (CI, also known as the GHG emission factor or global warming potential (GWP), gCO₂-equivalent per MJ of energy content in the fuel) of biodiesel and renewable diesel from soy as calculated by a number of different studies, as a function of the year of the study. The data points with large range bars in one direction indicate the difference in the CI depending on whether ILUC have been taken into account⁸³.

⁸² Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

⁸³ Hoekman, S. K., Broch, A., Robbins, C., Ceniceros, E. (Coordinating Research Council – CRC, 2011). *Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality*. CRC Report No. AVFL-17a. Published February 2011.

canola oil and has found all of these feedstocks and processes to meet the 50% and 20% GWP benefit thresholds required (these thresholds are explained in more detail in Section 7.1)⁸⁶. The EPA recently released a Notice of Data Availability on its LCA analysis of biodiesel and renewable diesel produced from palm oil, which finds that they do not meet the minimum 20% threshold, mostly due to the impacts of ILUC⁸⁷. However, this is not the final ruling and once input is received from experts and industry, this determination may change. At this stage, the EPA has not yet ruled on HDRD from canola oil, rapeseed oil, jatropha and other feedstocks that are not commonly used in the United States but that are used internationally.

Another important component of the LCA is the allocation of energy use and emissions to co-products from the feedstock processing and HDRD production stages. The three most common methods are the physical/energy, market and displacement allocation methods. The physical/energy method allocates emissions based on the mass or energy balance of the co-products relative to the products and is typically used when energetic co-products are produced (such as propane produced during hydrotreatment of biofeedstocks). The market method allocates emissions according to the relative market value of the co-products and the products and it is used for processes that produce non-energetic co-products with market value (such as the production of soymeal during soybean processing). The displacement method considers the alternative product(s) that the co-product replaces and subtracts the emissions associated with the displaced products from the overall emissions of the process in question. The choice of the appropriate co-products allocation method will depend on the process in question, the types of co-products produced and the ratio of products to co-products. No method is ideal and the choice of method can make a difference in the overall results of up to 25%-60%^{88,89}.

Figure 15 illustrates the difference in LCA results, depending on the co-products allocation method, for HDRD production using soybean oil via the SUPERCETANE™ and UOP Ecofining™ processes (Renewable Diesel I and II in the diagram, respectively), using the GREET and ASPEN models.

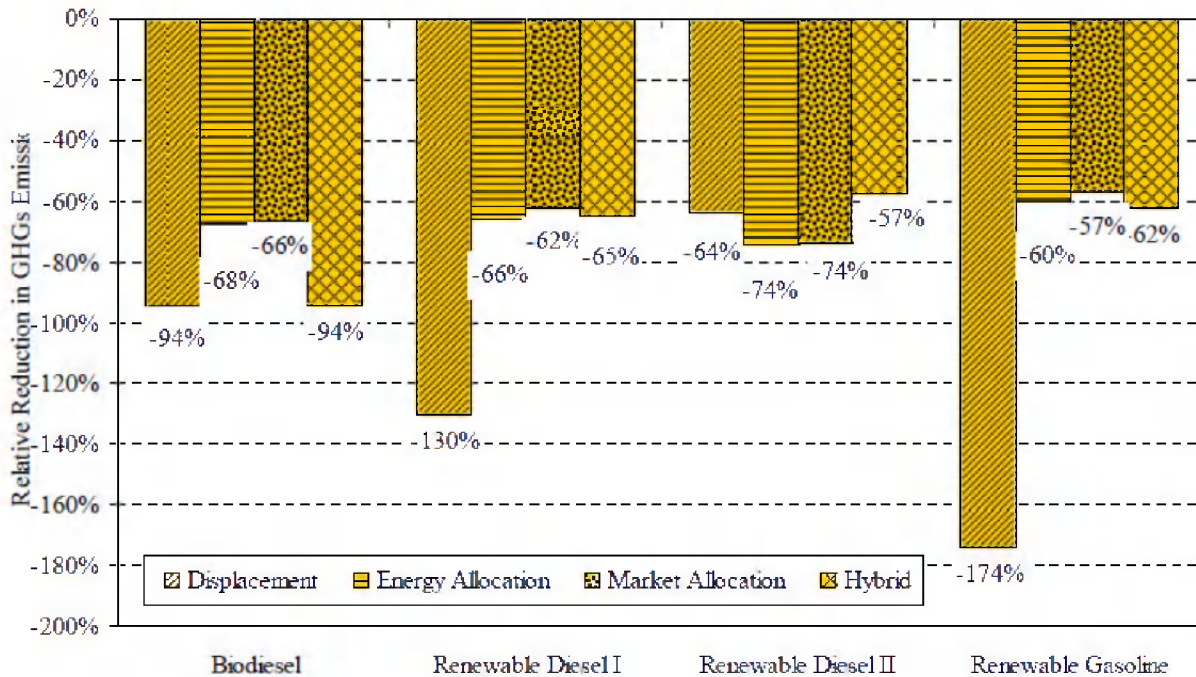
⁸⁶ United States Environmental Protection Agency (EPA, 2010). *Supplemental Determination for Renewable Fuels Produced Under the Final RFS2 Program From Canola Oil*. Final Rule, 40 CFR Part 80, [EPA-HQ-OAR-2010-133; FRL-9207-1], RIN 2060-AQ35. Published in the Federal Register, Vol. 75, No. 187, September 28, 2010.

⁸⁷ United States Environmental Protection Agency (EPA, 2011). *EPA Issues Notice of Data Availability Concerning Renewable Fuels Produced from Palm Oil Under the RFS Program*. Regulatory Announcement, published by the Office of Transportation and Air Quality, EPA-420-F-11-046, December 2011.

⁸⁸ Hoekman, S. K., Broch, A., Robbins, C., Cenicerros, E. (Coordinating Research Council – CRC, 2011). *Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality*. CRC Report No. AVFL-17a. Published February 2011.

⁸⁹ Argonne National Laboratory (2008). *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Published March 12, 2008.

FIGURE 15 – LCA OF HDRD FROM SOY USING DIFFERENT CO-PRODUCT ALLOCATION METHODS



Source: Argonne National Laboratory (2008). *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Published March 12, 2008.

The type of process used to produce HDRD is not the most important factor in the overall emissions. Aside from the LCA methodology used (i.e. the inclusion or exclusion of ILUC and the method used for co-product emissions allocation), the type of feedstock used to produce HDRD has the greatest impact in the overall emissions. For instance, feedstocks like animal fat and waste greases have lower overall emissions because there are no emissions associated with crop cultivation, fertilization use, etc.

Figure 16 presents the GWP of a variety of different biodiesel and HDRD feedstocks. As can be seen, HDRD from tallow has the greatest GWP benefit of all feedstock types. It should be noted that there are very few studies on the GHG impacts of HDRD relative to the number of studies carried out for biodiesel. As the use of HDRD grows and more studies are carried out, a more accurate picture of the GHG benefits (or dis-benefits) associated with the use of HDRD relative to diesel (or biodiesel) will develop.

Figure 17 presents the GWP benefit, or the percentage reduction of GHG emissions due to the use of a given biofuel (biodiesel or HDRD) instead of ULSD, for a variety of different feedstocks.

Table 7 below presents the GHG emission reduction factors for HDRD versus a number of different types of biodiesel, as calculated using the GHGenius LCA model v3.19.

TABLE 7 – EMISSION REDUCTION FACTORS FOR HDRD AND BIODIESEL RELATIVE TO ULSD

Canada canola biodiesel (kg CO ₂ e/L)	3.012
Canada soy biodiesel (kg CO ₂ e/L)	2.704
Canada tallow biodiesel (kg CO ₂ e/L)	3.228
US Soy biodiesel (kg CO ₂ e/L)	2.463
Neste NexBTL palm oil HDRD (kgCO ₂ e/L)	1.470

Source: These emission reduction factors, calculated using GHGenius 3.19, were provided by NRCan to ÉcoRessources in 2010 in the context of a study for Environment Canada entitled: *Updating the Cost-Benefit Analysis of the Proposed 2% Renewable Fuels Regulation*.

Contrary to the data in Figures 16 and 17, emission reductions as calculated by GHGenius appear to be less for HDRD than for biodiesel. However, it should be noted that the emission reduction figures presented in this section are comparing different feedstocks, different pathways, different LCA methodologies, etc. Again, as mentioned above, the way in which co-products are treated in the LCA can also have a significant impact on the results. Most of the more recent studies presented in Figures 16 and 17 have found that biodiesel and HDRD from most of the more commonly-used feedstocks have a GWP benefit of at least 50%, which qualifies them as Type A and B fuels under RFS2. However, these studies did not take into account ILUC, which is included in the EPA LCA calculation for the RFS2. In Canada, renewable fuels used to meet the requirements of the *Renewable Fuels Regulations* are not currently required to demonstrate minimum GHG emission benefits.

4. Fuel properties

As was discussed in the previous section, the chemical properties of HDRD differ significantly from those of biodiesel. HDRD is made up of saturated paraffinic alkanes, whereas biodiesel is comprised of methyl esters. The most important differences are that methyl esters contain oxygen and that the aliphatic chain on the ester can contain various degrees of unsaturation (C=C double bonds). This has a significant impact on the physical properties of the fuel.

Table 8 provides a comparison of some of the properties of ULSD, biodiesel and HDRD. It should be noted that the figures shown in this table are averages and may vary depending on the feedstock and the processing pathway and conditions. As expected, the oxygen content in ULSD and HDRD is zero, whereas it is about 11 weight% (wt%) for biodiesel. As seen previously, this is the reason for the greater oxidative instability of biodiesel relative to ULSD and HDRD. The carbon content by weight of biodiesel is lower and consequently, the energy content by weight is lower. As can be seen in the table, the energy content of biodiesel is approximately 39 MJ/kg, while it is closer to 43-44 MJ/kg for ULSD and HDRD. However, HDRD has a lower specific gravity than biodiesel and ULSD (in part due to its lack of aromatics), which means that the energy content by volume is only slightly higher than that of biodiesel (~121,000-122,000 BTU/gal), which is less than that of ULSD (~130,000 BTU/gal). This means that more biodiesel or HDRD must be used to get the same energy output as ULSD. It can also be seen in the table that the cetane number of HDRD, which is a measure of combustion quality, is significantly higher than that of ULSD or biodiesel (70-90 versus 40-55, respectively). ULSD blended with HDRD will therefore benefit from an improved cetane number.

TABLE 8 – PROPERTIES OF ULSD, BIODIESEL AND HDRD (RENEWABLE DIESEL)

Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
T ₉₀ , °C	300-330	330-360	290-300
Viscosity, mm ² /sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Source: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

It should also be noted that due to the lower content of sulfur and aromatics, the lubricity of HDRD is lower than ULSD and additives must be used in order to ensure that the fuel meets lubricity standards. However, this is not a significant concern since additives must also be used with ULSD anyway in order

for it to meet fuel standards for lubricity. Most HDRD producers will correct the lubricity before sale to ensure that their product sold meets existing fuel standards.

For all diesel fuels, including ULSD, biodiesel and HDRD, the cold flow properties of the fuel are an extremely important parameter. Sediment and wax formation that reduce the flowability of a fuel can occur for a number of reasons. Molecules at the high end of the diesel melting point range formed during the production process will dictate the cloud point of the resulting product. At low temperatures, these high melting point molecules crystallize and eventually aggregate. The cloud point is the temperature at which the crystals become visible (or greater than 0.5 μm), but the fuel may still flow. The pour point is the temperature at which the fuel can no longer flow or be pumped^{90,91}.

As discussed previously, the cloud point of HDRD (and ULSD) can be managed by isomerisation and/or cracking of high melting alkanes. However, these techniques do not work for biodiesel because the cloud point is governed by the concentration of saturated methyl esters, which is determined by the feedstock type. A number of techniques to improve the cold flow properties of biodiesel are currently being investigated, most of which involve some variation of fractionation. Fractionation, while effective, is not ideal as it removes high-melting saturated esters from the blend entirely, lowering product yield. For the moment, the cold flow properties of biodiesel are managed by dilution with kerosene or jet fuel or by the use of additives, both of which are expensive and require monitoring and testing at the blending facility in order to ensure that the blend meets standards specifications. The fact that the cold flow properties of HDRD can be controlled predictably during the production stage is an important advantage.

Another issue that can affect flowability is the oxidative stability of the fuel. Depending on its oxygen content and degree of unsaturation, biodiesel has a tendency to oxidize during storage, transportation and/or distribution. The oxidation products can lead to sediment formation, which can clog filters and cause corrosion. Oxidative stability is not an issue with ULSD and HDRD because they are comprised of fully saturated hydrocarbons⁹².

Finally, the presence of impurities such as monoglycerides, sterol glucosides and glycerine in biodiesel also contribute to flowability problems as they precipitate out of the fuel at lower temperatures. Again, due to the removal of oxygen during the hydrotreatment process, these impurities are not present in ULSD and HDRD.

There are a number of other important properties that have an impact on fuel quality and these will be discussed in the context of fuel standards in the following section.

⁹⁰ Chandler, John Sr. (2011). *Flowability: A Complex Issue*. Biodiesel magazine. Published January 12, 2011.

⁹¹ Dunn, R. O. (2011). *Improving the Cold Flow Properties of Biodiesel by Fractionation*. Soybean - Applications and Technology. April, 2011, page 211. <http://www.intechopen.com/articles/show/title/improving-the-cold-flow-properties-of-biodiesel-by-fractionation>

⁹² ULSD also contains aromatic hydrocarbons, which are carbon rings that are not fully saturated but are very stable and therefore have similar oxidative stability as paraffins.

5. Fuel standards

In North America, fuel standards are governed by ASTM International in the United States and the Canadian General Standards Board (CGSB) in Canada. In Europe, fuel standards are set by the European Committee for Standardization (CEN). In addition, a consortium of automakers and engine makers from the United States, Europe and Japan has also developed their own Worldwide Fuel Charter (WWFC) that aims to provide a uniform standard across jurisdictions. Currently, there are no standards that have been developed uniquely for HDRD, neat or blended. HDRD is comprised of the same types of hydrocarbons as conventional diesel and therefore is subject to the same fuel standards as No. 2 diesel or ULSD: CGSB 3.517 in Canada, ASTM D975 in the United States and EN 590 in Europe⁹³.

The CGSB, ASTM, CEN and WWFC have developed standards specifically for biodiesel and biodiesel blends because of the fact that it is chemically a different type of fuel, being comprised of methyl esters instead of hydrocarbons, and because of the types of impurities that are typically found in biodiesel, but not in ULSD or HDRD. The standards for B100 are ASTM 6751 and CAN/CGSB 3.524-2011⁹⁴ for the United States and Canada, respectively. In addition to the usual tests for ULSD standards, biodiesel standards also include tests for glycerine, mono-, di- and triglycerides, Group I and II metals, phosphorous, polyunsaturated methyl esters, methanol and oxidative stability, amongst others. These differences can be seen in Table 9, which provides a comparison of the fuel standards that govern ULSD (No. 2 diesel), HDRD and biodiesel⁹⁵.

There also exist fuel standards in the United States and Canada for biodiesel blends (CGSB 3.520 and ASTM D975 for B0-B5, CGSB 3.522 and ASTM D7467 for B6-B20). In Europe there is only the EN 14214 for B100^{96,97}.

It should be noted that cloud point is not explicitly defined in CGSB and ASTM standards for ULSD and biodiesel. There are standard testing methods for measuring a fuel's cloud point and the vendor is required to report the cloud point of their product. For example, CGSB 3.517-2007 states that:

“Low-temperature flow properties of the fuel shall be designed to give satisfactory performance at the temperatures indicated by the 2.5% low-end design temperature data for the period and location of intended use. The following shall be reported:

⁹³ Source: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

⁹⁴ This standard is specifically for B100 that is intended to be blended with middle distillate fuels.

⁹⁵ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

⁹⁶ Chandler, John Sr. (2011). *Flowability: A Complex Issue*. Biodiesel magazine. Published January 12, 2011.

⁹⁷ In 2009, CEN published Workshop Agreement CWA 15940, Workshop 38. Although the CWA is not an official standard, but a document agreed upon by a Workshop, CWA 15940 covers paraffinic diesel fuel based on synthesis gas (i.e. FT fuels from natural gas, coal, or biomass) and on hydrotreatment of vegetable or animal oils, and is being used on a voluntary basis as a fuel specification.

- a) The 2.5% low-end temperature to which the fuel is designed;
- b) The test method used to determine the operability temperature:
 - i. Cloud point (ASTM D 2500 or D 5773); or
 - ii. Wax appearance point (ASTM D 3117); or
 - iii. Low-temperature flow test (LTFT) for diesel fuels (CAN/CGSB-3.0 No. 140.1).
- c) The test method result.⁹⁸

Although there are no separate standards for HDRD, in the United States HDRD producers must register their product with the EPA, which can take from six months to a year:

“The Clean Air Act provides EPA with the authority to regulate fuels and fuel additives in order to reduce the risk to public health. The regulations at 40 CFR Part 79 require that each manufacturer or importer of gasoline, diesel fuel, or a fuel additive, have its product registered by EPA prior to its introduction into commerce. Registration involves providing a chemical description of the product and certain technical, marketing and health-effects information. This allows EPA to identify the likely combustion and evaporative emissions. In certain cases, health-effects testing is required for a product to maintain its registration or before a new product can be registered. EPA uses this information to identify products whose emissions may pose an unreasonable risk to public health, warranting further investigation and/or regulation. The registration requirements are organized in a three-tier structure. In general, standard mandatory requirements are contained in the first two tiers, while the third tier provides for additional testing on a case-by-case basis.”⁹⁹

⁹⁸ Canadian General Standards Board (CGSB, 2007). *CAN/CGSB 3.517-2007 – Automotive (on-road) diesel fuel*. Published July 2007.

⁹⁹ Renewable Diesel Subcommittee of the Washington State Department of Agriculture Technical Work Group (2007). *Renewable Diesel Technology*. Published July 25, 2007.

TABLE 9 – CGSB, ASTM AND CEN STANDARDS FOR NO. 2 DIESEL AND B100

Property	Unit	Max/ Min	No. 2 diesel			Biodiesel (B100)		
			CGSB 3.517 - 2007	ASTM 975	EN 590	CGSB 3.524 - 2011	ASTM 6751	EN 14214
Water and sediment	% vol	max	0.05	0.05	0.02 w/w	400 ppm mass water	0.05	0.05 w/w
Total contamination	ppm	max			24	20 mg/L particulates		24
Kinematic viscosity, 40C	mm ² /s		1.7-4.1	1.9 – 4.1	2.0 – 4.5	1.9-6.0	1.9-6.0	3.5-5.0
Flash point, closed cup	C	min	40	52	55	93	93	120
Methanol	weight %	max				0.20	0.20	0.2
Cetane number		min	40	40	51	Report	47	51
Cetane index		min		40	46			
Sulfated ash	weight %	max			0.01		0.02	0.02
Total ash	weight %	max	0.01	0.01	0.01			
Group I metals	mg/kg	max				4	5	5
Group II metals	mg/kg	max				2	5	5
Total sulfur	mg/kg	max	15	15	10	Report	15	10
Phosphorous	mg/kg	max				4	10	10
Acid number	mg KOH/g	max	0.10			0.5	0.5	0.5
Carbon residue	weight %	max	0.15	0.35	0.3	0.05	0.05	0.3
Free glycerin	weight %	max				0.02	0.02	0.02
Total glycerin	weight %	max				0.24	0.24	0.25
Monoglycerides	weight %							0.8
Diglycerides	weight %							0.2
Triglycerides	weight %							0.2

Property	Unit	Max/ Min	No. 2 diesel			Biodiesel (B100)		
			CGSB 3.517 - 2007	ASTM 975	EN 590	CGSB 3.524 - 2011	ASTM 6751	EN 14214
Distillation, 90% recovered	C	max	290	282-338	360 (95% recovery)		360	
Copper strip corrosion	3 hr @ 50C	max	No. 1	No. 3	No. 1		No. 3	No. 1
Oxidation stability	hrs @ 110C	min				8	3	6
Linolenic acid methyl ester	weight %	max						12
Ester content	weight %				0 – 5 (max)			96.5 (min)
Iodine number	glz/100g	max						120
Density	kg/m ³				820 - 845	Report		860-900
Aromatics	% volume	max		35				
Lubricity at 60C	WSD, microns	max		520	460			
Polycyclic aromatic hydrocarbons	weight %	max			11			
Cloud point*	C	max			winter: -5C; summer: 3C			
Cold filter plugging point	C	max			winter: -15C; summer: -5C			country- specific
Cold soak filterability	seconds	max				240	360	
Cold soak filter blocking tendency	CSFBT number	max				1.8		

*Cloud point is not explicitly specified in the ASTM and CGSB fuel standards. See main text for more details.

Sources: Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*. Desert Research Institute, CRC Project number AVFL-17, published June 2009.

Canadian General Standards Board (CGSB, 2007). *CAN/CGSB 3.517-2007 – Automotive (on-road) diesel fuel*. Published July 2007.

Canadian General Standards Board (CGSB, 2011). *CAN/CGSB 3.524-2011 – Biodiesel (B100) for blending with middle distillate fuels*. Published December 2011.

Biofuels Systems Group Ltd (2011). *Biodiesel Standards*. Website consulted February 3rd, 2011. <http://www.biofuelsystems.com/biodiesel/specification.htm>

6. Infrastructure and equipment compatibility

6.1 Infrastructure compatibility

As has been discussed in the previous section, HDRD is a fuel that is fully fungible with ULSD due to its paraffinic physical properties. As a result of its fully fungible properties, there are no distinct fuel property standards for HDRD as there are for biodiesel, since HDRD is governed by the same fuel standards as those for ULSD. As discussed in the previous section, there are no known compatibility, warranty or emissions issues as long as the final HDRD product or blend meets ULSD standards.

The chemical properties of biodiesel and the potential contamination by trace amounts of glycerine can potentially cause storage and operability issues. Refiners that wish to blend ULSD with biodiesel are required to install new storage and blending infrastructure with two main purposes: 1) keep biodiesel separate from other fuel stocks, especially jet fuel and high spec fuels, to prevent contamination; 2) keep biodiesel warm to prevent sediment formation. A 2010 study by ÉcoRessources for NRCan found that the necessary infrastructure required to blend sufficient amounts of biodiesel to meet the 2% requirement of the *Renewable Fuels Regulations* amounted to approximately CAD 180 million (a small amount of these capital costs were for HDRD receipt and storage). This study also found that the estimated annual costs of additional kerosene required for blending with biodiesel (in order to meet cloud point specifications) amounted to CAD 33 million. When blending with HDRD, there is no need for addition of kerosene to meet cloud point specifications (provided winter grade HDRD is used for cold weather use). There is no need for heated transportation and storage infrastructure for HDRD as there is for biodiesel. There is also no need to clean truck, rail and marine tanks each time biodiesel is transported. HDRD could potentially be transported by pipeline without concerns about trailback contamination¹⁰⁰.

Some infrastructure additions or modifications are necessary when handling HDRD, but these are mostly for inventory purposes, such as new receipt and storage facilities. Concerns for cross-product contamination and cold-weather sediment formation during periods of long-term storage are no more of an issue than they are for conventional fuels¹⁰¹.

Of course, if HDRD production is to take place at or near the refinery, there would be a need for additional infrastructure for the HDRD production, as well as facilities for the transportation, receipt and storage of the feedstock. As was seen earlier, the availability of sufficient feedstock is the most important determining factor for an HDRD production facility, as is the ability to transport it efficiently. Again, as was seen, refinery partnerships with feedstock providers are one solution that provides a stable supply of feedstock (minimizing the on-site feedstock storage requirements). Typically, it is the responsibility of the feedstock provider to arrange for transportation of its product – HDRD producers must ensure that sufficient road, rail or marine transportation infrastructure exists and if not that it be put in place.

¹⁰⁰ ÉcoRessources Consultants (2010). *National Renewable Diesel Initiative Infrastructure Project*. Prepared for Natural Resources Canada, May 2010.

¹⁰¹ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

6.2 Equipment compatibility

In general, HDRD has been found to have little or no equipment operability issues. In Canada, the federal government as well as the petroleum and renewable fuels industries worked together on two initiatives that sought to contribute to existing knowledge on the physical and blending characteristics of renewable fuels: the *Renewable Diesel Characterization Study*¹⁰² and the *Alberta Renewable Diesel Demonstration*¹⁰³. The first initiative focused on testing the physical properties of a variety of renewable alternatives to diesel and the second focused on testing the on-the-ground operability of a variety of vehicles using different renewable alternatives to diesel.

The *Renewable Diesel Characterization Study* tested three neat HDRD samples and found the following results: “All three HDRD samples showed quality characteristics similar to petroleum diesel. All three of the HDRD samples tested favourably for all quality parameters, with the exception of electrical conductivity and lubricity... It should be noted that petroleum diesel is normally treated with lubricity and electrical conductivity additives prior to sale and therefore the low lubricity of the HDRD fuel does not signify a failure to meet CAN/CGSB specifications... All were high in Cetane quality. Finally, the isomerized hydrogenation derived renewable diesel sample had the most attractive cold temperature attributes.”¹⁰⁴

For the *Alberta Renewable Diesel Demonstration*, a temporary commercial blending facility was installed at Shell Canada’s Sherwood Marketing Terminal in Edmonton Alberta that would allow rack loading and in-line blending of biodiesel and HDRD at 2% in the winter months and 5% in the summer months. Blended fuels in the amount of 1.6 million litres were dispensed from a variety of participating cardlocks. A fleet of 75 vehicles were used in the test, in which 29 ran on biodiesel, 30 on HDRD and 16 control vehicles ran on ULSD. “The fleet vehicles spanned Class 8 transport trucks with and without exhaust after-treatment technologies (pre- and post 2007 model year units), school buses, a variety of delivery trucks and a group of heavy-duty oilfield services vehicles. All participating vehicles were 2002 model year or later.” The results of the study found no vehicle operability issues with the use of HDRD under the conditions tested.¹⁰⁵

In Germany, Daimler AG, Deutsche Post DHL, the energy group OMV, the Stuttgarter Straßenbahnen AG public transportation company and Neste Oil conducted a year-long pilot project to test the operability of the NExBTL fuel under everyday conditions in Germany. The project involved five medium-duty trucks and 5 heavy-duty trucks operated by Deutsche Post DHL and four city buses operated by Stuttgarter Straßenbahnen AG public transportation company, all Mercedes-Benz vehicles. The vehicles were used in urban, inter-city and long-distance applications and for one year, they were run exclusively on neat NExBTL. After one million kilometers travelled, no vehicle operability issues were encountered. “The results from the first year of testing show that the fuel works perfectly in Mercedes-Benz trucks and buses

¹⁰² Rilett, J., Gagnon, A., (Climate Change Central, 2008). *Renewable Diesel Characterization Study*. Published August 2008.

¹⁰³ Climate Change Central, 2009. *Alberta Renewable Diesel Demonstration*. Published February 2009.

¹⁰⁴ Rilett, J., Gagnon, A., (Climate Change Central, 2008). *Renewable Diesel Characterization Study*. Published August 2008.

¹⁰⁵ Climate Change Central (2009). *Alberta Renewable Diesel Demonstration*. Published February 2009.

and is tolerated very well by the engines,' says Dr. Manfred Schuckert, company strategist at Daimler AG."¹⁰⁶

It is possible that the lower content of aromatics in HDRD relative to ULSD could have an impact on elastomer parts on older engines. Some issues of elastomer shrinking in engines of older vehicles were observed in California when LSD was replaced by ULSD in 2006, since ULSD contains less aromatics than LSD. The pilot test described above using neat HDRD involved mostly newer vehicles. However, no issues have yet been reported regarding elastomer shrinkage in older vehicles due to the use of HDRD.

6.3 Refiner experiences with HDRD

In a recent previous study by ÉcoRessources¹⁰⁷, refiners that had previous experience purchasing, storing, blending, distributing and marketing ULSD blended with HDRD in blends up to 20% indicated that they did not experience any issues and that their customers did not report any issues. As has been seen in previous sections, HDRD can, in principal, be used as a neat fuel with virtually no technical issues related to the storage and transportation of the fuel or of its use in vehicle engines.

However, in practice there are a number of other factors that govern the blend levels or limits refiners may use with HDRD. Blending with HDRD can improve the cetane number of ULSD, but once a certain cetane is reached at a given blend, refiners may find that additional HDRD is unnecessary in order to achieve measurable improved engine performance. In addition, the lower energy content of HDRD requires higher fuel consumption for customers, which may be a motivation to set blending limits. Finally, due to the currently low supply of HDRD relative to global demand, it may not always be possible to secure the volumes required to blend HDRD at high concentrations. In contrast, there is clearly a cost advantage related to blending high percentages of HDRD in the summer months rather than the winter months to meet annual regulatory requirements using the less expensive summer-grade HDRD.

¹⁰⁶ Neste Oil (2009). *Pilot test shows: Less CO2 emissions with new diesel from renewable energy sources*. Press release, published June 9, 2009.

¹⁰⁷ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

7. HDRD markets

7.1 Regulations, policies and incentives

As of 2011, 27 national governments and 29 state/province governments have implemented policies that mandate the use of a minimum amount of renewable alternatives to diesel, including Europe, six South American countries, six Asian countries, Canada, the United States, Costa Rica and the Dominican Republic. Four US states and four Canadian provinces have independently implemented minimum requirements for renewable alternatives to diesel¹⁰⁸.

7.1.1 International policies

In Europe, the European Commission Directorate General for Energy implemented the Renewable Energy Directive, which stipulates that EU Member States must ensure that 10% of energy consumption in transport is from renewable sources¹⁰⁹. A number of European countries have introduced their own national policies mandating the use of renewable alternatives to diesel. These are listed in Table 10 below:

TABLE 10 – MANDATES IN EUROPEAN COUNTRIES FOR THE USE OF RENEWABLE ALTERNATIVES TO DIESEL

Country	Mandate
Belgium	4% minimum renewable content
Czech Republic	B3.5
Finland	5.75% minimum renewable content
Germany	B4.4
Italy	4.5% minimum renewable content (5% in 2014)
Netherlands	4% minimum renewable content
Norway	B3.5
Portugal	B7
Spain	B7
United Kingdom	B3.5

Source: REN21. (2011). *Renewables 2011 – Global Status Report*. Published August 2011.

Table 11 below lists national mandates for renewable alternatives to diesel in Asia, Central and South America and the Caribbean.

¹⁰⁸ REN21. (2011). *Renewables 2011 – Global Status Report*. Published August 2011.

¹⁰⁹ *Ibid.*

TABLE 11 –MANDATES IN ASIAN, CENTRAL AND SOUTH AMERICAN AND CARIBBEAN COUNTRIES FOR THE USE OF RENEWABLE ALTERNATIVES TO DIESEL

Country	Mandate
Asia	
India	B20 by 2017
Pakistan	B5 by 2015
Malaysia	B5
Philippines	B10
South Korea	B2
Thailand	B3
Central + South America and the Caribbean	
Argentina	B5
Bolivia	B2.5
Brazil	B5 by 2013
Columbia	B20
Costa Rica	B3.5
Dominican Republic	B2 by 2015
Paraguay	B5
Peru	B5
Uruguay	B5

Source: REN21. (2011). *Renewables 2011 – Global Status Report*. Published August 2011.

7.1.2 North American policies

Both the United States and Canada have policies in place that support the use of renewable fuels. In July 2011, the government of Canada implemented a portion of its *Renewable Fuels Regulations* requiring fuel producers and importers in Canada to blend an annual average of 2% renewable content into their diesel and heating oil fuel pool. There is no restriction on the production process so biodiesel, HDRD and other advanced renewable fuels can be used to meet the 2% requirement. Unlike the United States, Canada does not currently require the renewable content to meet any criteria related to the lifecycle GHG emissions reductions relative to conventional diesel.

A number of Canadian provinces also have their own renewable fuels requirements. Table 12 below summarizes some requirements of the federal and provincial regulations.

Each November, the EPA sets the standards for the required volumes of different types of biofuels for the following year, under the RFS2. In 2010, the EPA established four separate categories of fuels, each with their own standards: the global “renewable fuel” category (Type R) and three additional sub-

categories: cellulosic biofuel (Type C) and biomass-based diesel (Type B) that are sub-categories of advanced biofuel (Type A). HDRD qualifies for the RFS standard as Type A and B but note that co-processed HDRD does not qualify as Type B. In 2012, the Type A requirement is 7.6 billion litres (1.21% of the fuel pool), of which 3.8 billion litres is earmarked for Type B fuels (0.91% in the fuel pool) and 32.7 million litres is for Type C fuels¹¹⁰. Under RFS2, different types of fuels are given energy equivalence values based on their energy content relative to first generation biofuels. HDRD has an energy equivalence value of 1.7 (i.e. 1 litre of HDRD generates RIN credits equivalent to 1.7 litres), therefore only 4.5 billion litres of HDRD would be needed in order to meet the total (non-Type C) requirements for 7.6 billion litres in the Type A category¹¹¹.

Under RFS2, each of the four new fuel categories must meet GHG emission reduction criteria, relative to 2005 levels for petroleum fuels: a minimum of 20% reduction for Type R fuels in general, 50% reduction for Types A and B and 60% reduction for Type C¹¹².

¹¹⁰ United States Environmental Protection Agency (US EPA, 2011). *Regulatory Announcement: EPA Finalizes 2012 Renewable Fuel Standards*. EPA-420-F-11-044, published December 2011.

¹¹¹ It should be noted that Under RFS2, each of the four new fuel categories must meet GHG emission reduction criteria, relative to 2005 levels for petroleum fuels: a minimum of 20% reduction for Type R fuels in general, 50% reduction for Types A and B and 60% reduction for Type C.

¹¹² United States Environmental Protection Agency (US EPA, 2011). *EPA Proposes New Regulations for the National Renewable Fuel Standard Program for 2010 and Beyond*. EPA-420-F-09-023, published May 2009.

TABLE 12 – SOME FEDERAL AND PROVINCIAL RENEWABLE FUELS REGULATIONS

Jurisdiction	Regulation and start date	Enabling legislation	Relevant mandate requirement	HDRD allowable?
Canada	Renewable Fuels Regulations (SOR/ 2010-189) Implemented in 2010 (2011 for the 2% requirement in diesel and heating oil)	Canadian Environmental Protection Act, 1999 (S.C. 1999, c. 33)	2% renewable content in diesel and heating oil	Yes
USA	Renewable Fuels Standard 2 (RFS2, under the EISA P.L. 110-140)* RFS2 implemented in 2009.	Originally enacted in 2005 under the Energy Policy Act (P.L. 109-58), the RFS was expanded in 2007 under the Energy Independence and Security Act (EISA, P.L. 110-140).	In 2012: 9.23% for all renewable fuels 0.91% for sub-category "biomass-based diesel" 1.21% for sub-category "advanced biofuels"	Yes, but co-processed HDRD not admissible as "biomass-based diesel" (Type B) Co-processed HDRD admissible as "advanced biofuels" (Type A) Fuels must meet minimum GHG emission reduction requirements.
British Columbia	Renewable and Low Carbon Fuel Requirements Regulation (B.C. Reg. 394/2008, includes amendments up to B.C. Reg. 77/2011) Implemented in 2008	Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act (SBC 2008, Chapter 16)	4% renewable content in diesel	Yes
Alberta	Renewable Fuels Standard Regulation (AB Reg. 29/2010, including amendments up to AB Reg. 179/2010) Implemented in 2010	Climate Change and Emissions Management Act (Chapter C-16.7 2003)	2% renewable content in diesel	Yes
Manitoba	Biodiesel Mandate for Diesel Fuel Regulation (Reg. 147/2009, including amendments up to Reg. 194/2011) Implemented in 2009	The Biofuels Act (C.C.S.M. c. B40)	2% renewable content in diesel	No

*Note that the US RFS applies to renewable fuels for blending in all transportation fuels, not just middle distillates.

From a market perspective in the United States, an important aspect of the RF2 regulations is the system of allocation, generation and trade of Renewable Identification Numbers (RIN's). A RIN is assigned to each volume of qualifying renewable fuel produced. RIN's can be purchased and/or traded in order for regulated parties to meet their requirements under the mandate. Different types of RIN's are generated depending on the fuel type, each with their own price on the RIN market. For instance, D4 RIN's for Type B fuels are currently trading for around \$1.30, D5 RIN's for Type A fuels are trading at about 70 cents and D6 RIN's for general Type R fuels are trading at just a few cents¹¹³. This fact alone will make it less likely that new HDRD production facilities in the United States will employ co-processing technology (as opposed to building a stand-alone facility) because co-processed HDRD does not qualify as a Type B fuel and therefore can only generate D5 or D6 RIN's and not the much more valuable D4 RIN's¹¹⁴.

In addition, RIN's are allocated per gallon of fuel on the basis of energetic content relative to ethanol. Therefore, a gallon of biodiesel generates 1.5 RIN's whereas a gallon of HDRD generates 1.7 RIN's. This contributes to HDRD's higher price relative to biodiesel in the United States.

Canada's federal *Renewable Fuels Regulations* also include the creation of compliance units (CU), where 1 CU is equal to 1 L of renewable fuel. CU's can only be traded between participants in the trading system. Separate units are created for gasoline or distillates renewable contents. One CU is generated for each litre of qualifying renewable fuel, regardless of the fuel type or the production process. Therefore, in Canada, unlike in the United States, the value of a CU generated by co-processed HDRD is equal to the value of a CU generated in a stand-alone HDRD production facility. Equally, the value of a CU is the same whether it is generated for biodiesel or for HDRD.

There are also some policies and incentives at the local level that can impact the relative competitiveness of HDRD to biodiesel. For example, as shown above, the 2% Biodiesel Mandate in Manitoba applies only to biodiesel – HDRD is not admissible. In Ontario, consumers receive an exemption of the 14.3 cents/L fuel tax for biodiesel, but not for HDRD. At the federal level in Canada, the ecoENERGY for Biofuels Program provides a per-litre incentive for renewable alternatives to diesel produced in Canada. This rate will decline annually until the incentive's expiration in March 2017 (see Table 13). The incentive is applicable to HDRD but there are no HDRD producers in the program.

TABLE 13 – ECOENERGY INCENTIVE RATES* FOR RENEWABLE ALTERNATIVES TO DIESEL (\$/L)

2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017
0.26	0.24	0.20	0.18	0.14	0.10	0.08	0.06	0.04

*By fiscal year, April 1st to March 31st.

Source: Natural Resources Canada Office of Energy Efficiency (2012). *About the Incentive*. Website consulted January 28th, 2012. <http://oee.nrcan.gc.ca/transportation/alternative-fuels/programs/ecoenergy-biofuels/2411>

¹¹³ Personal Communications.

¹¹⁴ McMartin, C. and Noyes, G. (2010). *America Advances to Performance-Based Biofuels – The Advanced Renewable Fuels Standard/RFS2*. White Paper, Published by Clean Fuels Clearinghouse, February 2010.

The federal *Renewable Fuels Regulations* and ecoENERGY Biofuels Program are two of four components of the Canadian government's Renewable Fuels Strategy. The other two components include financial support to agricultural producers seeking to build or expand biofuel production facilities (the ecoAGRICULTURE Biofuels Capital Initiative and the Biofuels Opportunities for Producers Initiative), as well as additional funding to Sustainable Development Technology Canada for investment in large-scale commercial projects for the production of biofuels from non-food feedstocks¹¹⁵.

7.2 Potential HDRD markets in North America due to regulations

The potential market for HDRD in North America is significant. The requirements of the RFS2 stipulate a minimum requirement of 1 billion gallons (3.8 billion litres) annually of Type B fuel until 2023 and possibly beyond. The Type B volumes could be significantly higher in future rulings. HDRD can also be used to meet Type A and Type R fuel requirements. The volumes required for these fuels are shown in Table 14. It should be noted that these volumes are reviewed and stipulated annually every November for the following calendar year. For instance, at the end of 2011 the Type C fuel requirement was reduced from 0.5 billion gallons (1.9 billion litres) to 32.7 million litres.

¹¹⁵ The Government of Canada (2012). *ecoENERGY Renewable Fuels Strategy*. Website consulted January 28th, 2012. <http://ecoaction.gc.ca/ecoenergy-ecoenergie/renewablefuels-carburantsrenouvelables-eng.cfm>

TABLE 14 – RENEWABLE FUEL VOLUME REQUIREMENTS UNDER RFS2 (BILLION GALLONS)*

	Type C	Type B	Type A	Type R
	Cellulosic Biofuel Requirement	Biomass-Based Diesel Requirement	Advanced Biofuel Requirement	Total Renewable Fuel Requirement
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.5	1.0	2.0	15.2
2013	1.0	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0
2023+	b	b	b	b

a To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.

b To be determined by EPA through a future rulemaking.

*Note: These volumes are reviewed and stipulated annually every November for the following calendar year. For instance, at the end of 2011 the Type C fuel requirement was reduced from 0.5 billion gallons (1.9 billion litres) to 32.7 million litres.

Source: McMartin, C. and Noyes, G. (2010). *America Advances to Performance-Based Biofuels – The Advanced Renewable Fuels Standard/RFS2*. White Paper, Published by Clean Fuels Clearinghouse, February 2010.

As can be seen in Table 14, in 2012 there is a potential market for 1 billion gallons (3.8 billion litres) of renewable diesel in the United States under RFS2, which can go up to 2 billion gallons (7.6 billion litres) if the requirements of the Type A fuel category are also included (not including the volumes earmarked for Type C cellulosic fuels). The volume requirements increase significantly each year, climbing by an order of magnitude in 10 years. In Canada under the *Renewable Fuels Regulations*, the potential market for HDRD starts at 400 million litres in 2012 (taking into account the exemption for Quebec and Maritime provinces) and increases to 900 million by 2035¹¹⁶. It is important to note that in the United States, the volumes of renewable fuels required under the RFS2 are set each year by a ruling by the EPA that takes into account feedstock availability, technological feasibility and other factors. In Canada, the volumes

¹¹⁶ For a full explanation of how predicted demand volumes have been calculated, see Section 3.3.1 of: ÉcoRessources Consultants (2010). *Updating the cost-benefit analysis of the proposed 2% renewable fuels regulation*.

required are determined as a 2% annual average of the diesel and heating oil pools of refiners and importers.

Table 15 below shows the projected requirements for renewable alternatives to diesel under the Canadian *Renewable Fuels Regulations*.

TABLE 15 – PROJECTED DIESEL AND HEATING OIL DEMAND VOLUMES AND REQUIREMENTS FOR RENEWABLE ALTERNATIVES TO DIESEL UNDER THE CANADIAN RENEWABLE FUELS REGULATIONS (ML)*

ML	2012**	2015	2020	2025	2030	2035
Diesel and heating oil demand						
West	13,026	13,802	15,212	16,783	18,536	20,493
Ontario	7,600	8,008	8,737	9,532	10,400	11,347
East	0	9,851	10,329	10,837	11,376	11,950
Canada	20,626	31,661	34,278	37,152	40,312	43,790
Requirements for renewable alternatives to diesel (2%)						
Canada	404	633	686	743	806	876

* Newfoundland and Labrador and the Territories are exempt from the Regulations, therefore the demand volumes for these regions have not been included.

**A temporary exemption of the 2% requirement from July 1, 2011 to December 31, 2012 has been granted to Quebec and the Atlantic provinces, so these volumes have been removed from the 2012 numbers.

Sources:

ÉcoRessources Consultants (2010). *Updating the cost-benefit analysis of the proposed 2% renewable fuels regulation*.

Statistics Canada (2010). *The Supply and Disposition of Refined Petroleum Products in Canada*. Catalogue 45-004.

<http://www.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=45-004-X&chprog=1&lang=eng>

Natural Resources Canada (NRCAN, 2006) *Canada's Energy Outlook: The Reference Case*.

http://www.nrcan.gc.ca/inter/publications/peo_e.html

7.3 Existing and potential HDRD production capacity in North America

Tables 16 and 17 below summarize existing and proposed capacity for production of HDRD worldwide in both stand-alone and co-processing facilities. As can be seen in the tables, current global capacity is at 2.8 billion litres per year (2525 ML/yr for stand-alone facilities and 300 ML/yr for co-processing), which will increase to 3.3 billion litres per year when the Valero/Darling plant comes online at the end of 2012. The majority of this capacity exists outside of North America. Including the Valero/Darling plant, by the end of 2012 total North American capacity will be 800 million litres per year.

Current global capacity of 2.8 billion litres per year is equivalent to seven times the current requirement for the Canadian federal regulations or 125% of the current RFS2 Type B fuel requirements (or 62% of the Type A requirement)¹¹⁷.

The vast majority of Neste Oil's product is currently sold in Europe, although some is also being sold in Canada. They are currently are not selling product in the United States. Neste's Porvoo and Singapore plants are approved foreign RIN generators for the RFS2, but HDRD from palm oil has not yet been found by the EPA to meet the minimum GHG reduction requirements of 20%. Just one of Neste's 900 ML/yr plants would account for up to 20% of the Type B fuel requirements¹¹⁸.

Taking into account the Dynamic Fuels plant, the Valero plant and assuming Neste contributes 1 billion litres to the US market, this makes a total of 1.8 billion litres being produced and/or marketed in the US as of 2013, which is equivalent to 3.1 billion litre RIN's when the energy equivalence value of 1.7 for HDRD is taken into account. This corresponds to 52% of the Type B fuel category requirement of 5.7 billion litres in 2013. This means that there is the potential for an additional 2.6 billion litre RIN's for Type B fuels, which corresponds to 1.5 billion physical litres of HDRD, which is equivalent to less than two Rotterdam-sized plants. The potential under the Type A category is even greater; since the total Type A requirement is 10.5 billion litre RIN's in 2013, this means there is a potential for 7.4 billion litre RIN's or 4.3 billion physical litres of HDRD, equivalent to almost five Rotterdam-sized plants.

¹¹⁷ Taking into account the energy equivalence of 1.7 for HDRD under RFS2.

¹¹⁸ United States Environmental Protection Agency (US EPA, 2011). *Regulatory Announcement: EPA Finalizes 2012 Renewable Fuel Standards*. EPA-420-F-11-044, published December 2011.

TABLE 16 – SUMMARY EXISTING AND PROPOSED COMMERCIAL-SCALE HDRD STAND-ALONE PLANTS*

Company	Location of facility	Status	Start date	Principal feedstocks used	Principal markets served	Capacity (ML/yr)	Source
Neste Oil	Porvoo, Finland	Operational	2007	Palm oil Animal fats Rapeseed oil	Europe Canada	215	[1]
Neste Oil	Porvoo, Finland	Operational	2009	Palm oil Animal fats Rapeseed oil	Europe Canada	215	[1]
Neste Oil	Tuas, Singapore	Operational	2011	Palm oil	Europe Canada	906	[2]
Neste Oil	Rotterdam, Netherlands	Operational	2010	Palm oil Animal fats Rapeseed oil	Europe Canada	906	[3]
Dynamic Fuels (Syntroleum and Tyson Foods joint venture)	Geismar, Louisiana	Operational	2010	Animal fats Soybean oil	USA	283	[4]
TOTAL EXISTING CAPACITY						2,525 ML/yr	
Valero and Darling joint venture	Norco, Louisiana	Under construction	Estimated start date: Q4 2012	Animal fats Soybean oil	USA Canada	509	[5]
TOTAL EXISTING + FUTURE CAPACITY (FIRM)						3,034 ML/yr	
UPM biofuels	Lappeenranta, Finland	Construction begins summer 2012	Estimated start date: 2014	Tall oil (pine)	Europe	117	[6]
TOTAL EXISTING + FUTURE CAPACITY (POSSIBLE)						3,151 ML/yr	

*This is a list of known plants and is not exhaustive.

¹Schill, S. R. (2007). *Heeding Hydrogenation*. Biodiesel Magazine, published online March 15, 2007.

²Nest Oil (2011). *Neste Oil celebrates the grand opening of its ISCC-certified renewable diesel plant in Singapore*. Press release, 8 March 2011.

³Green Car Congress (2008). *Neste Oil to Build \$1B NExBTL Renewable Diesel Plant in Rotterdam*. Published online 13 June, 2008.

⁴Syntroleum (2011). *Syntroleum Announces Third Quarter Results and October Production Update*. Press release, published November 8, 2011.

⁵Stuckey, M. (2011). *Valero begins construction of \$330 million renewable diesel plant in Norco*. Published in St Charles Herald Guide, October 6, 2011.

⁶UPM (2012). *UPM to build the world's first biorefinery producing wood-based biodiesel*. Press release, 1 February, 2012.

⁷Personal Communications.

TABLE 17 – EXISTING AND PROPOSED HDRD CO-PROCESSING FACILITIES*

Company	Location of facility	Status	Co-processing max%	Principal feedstocks used	Principal markets served	Capacity (ML/yr)	Source
ConocoPhillips	Cork, Ireland	Operational	Unknown	Soybean oil Animal fats	Europe	57	[1]
CEPSA	Algeciras, Spain	Operational	5%	Vegetable oil	Europe	90	[2]
Preem Petroleum	Göteborg, Sweden	Operational	30%	Tall oil	Europe	153	[2]
TOTAL EXISTING CO-PROCESSING CAPACITY					300 ML/yr		
Eni (UOP license)	Livorno, Italy	Technology licensed, construction not yet begun	Unknown	Soybean oil	Europe	368	[3]
Galp Energia	Sines, Portugal	Technology licensed, construction not yet begun	Unknown	Soybean oil	Europe	368	[3]
Undisclosed refiner	Australia	Unknown	5%	Animal fat	Australia	25	[2]
Undisclosed refiner	California, USA	Unknown	10%	Tallow	USA	23	[2]
Undisclosed refiner	Europe	Unknown	5%	Animal fat	Europe	62	[2]
Undisclosed refiner	Texas, USA	Unknown	5%	Vegetable oil	USA	180	[2]
TOTAL EXISTING AND PROPOSED CO-PROCESSING CAPACITY					1,326 ML/yr		

*This is a list of known plants and is not exhaustive.

¹ConocoPhillips (2006). *ConocoPhillips Begins Production of Renewable Diesel Fuel at Whitegate Refinery in Cork, Ireland*. Press release, published December 19, 2006.

²Personal Communications.

³Argonne National Laboratory (2008). *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*. Published March 12, 2008.

It is important to remember that the RFS2 has minimum GHG emission reduction requirements for each type of admissible renewable fuel under the mandate: 20% reduction for Type R fuels and 50% reduction for Type B and A fuels¹¹⁹. Recently, the EPA published a notice of data availability indicating that their analysis of the lifecycle GHG impacts of biodiesel and renewable diesel from palm oil did not meet the minimum 20% GHG reduction requirements¹²⁰. A similar experience occurred in 2009 with the GHG profile of soybean oil in which the EPA's draft LCA found that soy-based biodiesel only achieved 22% GHG reduction¹²¹. After feedback from the industry and other LCA experts, in 2010 GHG reductions were found to exceed 50% and soy-based biodiesel and renewable diesel were finally accepted as admissible fuels¹²². Some in the industry expect the same to occur for palm oil¹²³. Either way, the EPA's process of arriving on a final ruling on the LCA impacts of palm oil could delay Neste's entry into the US market either in the short-term while a final ruling is decided or in the medium- to long-term if a negative ruling requires Neste to arrange new feedstock sourcing to accommodate the EPA GHG requirements.

In terms of the Canadian context, just one Porvoo-sized plant (215 ML/yr) would be able to account for about one-third of Canada's total requirement for renewable alternatives to diesel and heating oil from 2013 onwards. Adding another plant of the same size would account for 48% of the projected requirements in 2035. As mentioned in Section 3, a Porvoo-sized plant is considered about the minimum capacity for which a stand-alone new HDRD production facility could be considered profitable¹²⁴.

Alternatively, a Rotterdam-sized plant (906 ML/yr) would provide 30% more than the total Canadian federal requirements in the short term, allowing for potential exports to the US, and in 2035 would account for 100% of the projected requirements.

It would make sense for a stand-alone plant to be located close to existing refinery infrastructure, for instance in Edmonton or Sarnia. See Table 18 for a list of existing refineries in Canada and their capacities.

¹¹⁹ McMartin, C. and Noyes, G. (2010). *America Advances to Performance-Based Biofuels – The Advanced Renewable Fuels Standard/RFS2*. White Paper, Published by Clean Fuels Clearinghouse, February 2010.

¹²⁰ United States Environmental Protection Agency (EPA, 2011). *EPA Issues Notice of Data Availability Concerning Renewable Fuels Produced from Palm Oil Under the RFS Program*. Regulatory Announcement, published by the Office of Transportation and Air Quality, EPA-420-F-11-046, December 2011.

¹²¹ United States Environmental Protection Agency (EPA, 2009). *EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels*. Technical Highlights, published by the Office of Transportation and Air Quality, EPA-420-F-09-024, May 2009.

¹²² United States Environmental Protection Agency (EPA, 2010). *EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels*. Regulatory Announcement, published by the Office of Transportation and Air Quality, EPA-420-F-10-006, February 2010.

¹²³ Personal communications.

¹²⁴ Personal communications.

TABLE 18 - REFINERIES IN CANADA: LOCATION, TYPE AND PRODUCTION CAPACITIES, 2008

Refinery	Location	Refinery type	Million litres / day	ML/yr
Imperial Oil	Dartmouth, NS	Cracking	13.0	4628
Irving Oil	Saint-John, NB	Cracking	47.7	16,981
North Atlantic Refining	Come-by-Chance, NF	Cracking	18.3	6515
Total Atlantic			79.0	28,124
Suncor	Montreal, QC	Cracking	20.7	7369
Ultramar	Saint-Romuald, QC	Cracking	42.1	14,988
Total Quebec			62.8	22,357
Imperial Oil	Nanticoke, ON	Cracking	17.8	6337
Imperial Oil	Sarnia, ON	Coking	19.1	6800
Shell	Sarnia, ON	Cracking	11.9	4236
Suncor	Sarnia, ON	Hydrocracking	13.5	4806
Nova Chemicals	Sarnia, ON	Topping	12.4	4414
Total Ontario			74.7	26,593
Co-op Newgrade	Regina, SK	Hydrocracking/coking	15.9	5660
Husky	Lloydminster, AB	Topping Asphalt	4.5	1602
Imperial Oil	Edmonton, AB	Cracking	29.7	10,573
Suncor	Edmonton, AB	Coking	21.5	7654
Shell	Scotford, AB	Hydrocracking/coking	15.9	5660
Total Prairies			87.5	31,150
Chevron	Burnaby, BC	Cracking	8.7	3097
Husky Oil	Prince George, BC	Cracking	1.9	676
Total British Colombia			10.6	3,774
Total Canada			314.6	111,998

Source: Canadian Petroleum Products Institute (CPPI, 2012). *About the Industry – Refinery Operations – Refining Sites and Capacities*. Website consulted February 10, 2012. Source data from company websites.

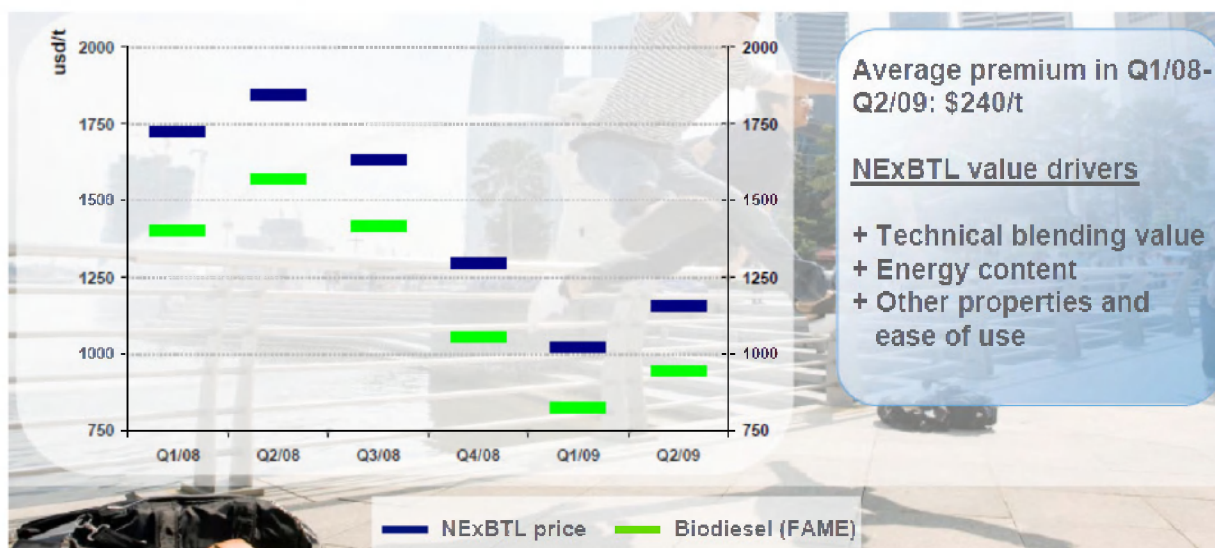
http://www.cppei.ca/index_e.php?p=65

7.4 HDRD prices

The decision between stand-alone production and co-processing HDRD depends on a number of factors. In both cases, it makes sense to make use of existing refinery infrastructure for hydrogen, fuel gas, amine wash, storage, etc., and therefore for HDRD production to take place either solely by, or in partnership with, existing refiners in Canada.

Currently, HDRD is priced relative to biodiesel prices plus a premium for higher density/energy content, cetane, cold flow properties and branding value. The average premium of NExBTL relative to biodiesel in 2007 was 17 US cents/L for product sold in Europe¹²⁵, in 2008-2009 it was about 21 US cents/L for product sold in Europe¹²⁶ and in 2010 it was about 30 US cents/L for product sold in Canada¹²⁷. As demand for HDRD grows, producers can charge a higher premium. Figure 18 shows how NExBTL prices tracked biodiesel prices from Q1 2008 – Q2 2009.

FIGURE 18 – NEXBTL PRICES RELATIVE TO BIODIESEL PRICES, 2008 – 2009



Source: Honkamaa, J. (Neste Oil, 2009). *Delivering Future Growth*. Presentation at Neste Oil Capital Markets Day, September 29, 2009.

Figure 19 below shows how the value of HDRD is determined for customers that are purchasing the product to comply with government biofuel mandates. There is the price of biodiesel as the base component, as well as the difference in density (energy content) between biodiesel and HDRD. There is also a component related to the cost savings for not having to purchase biodiesel blending infrastructure. The final component is the premium for favourable properties (cetane, cloud point). The favourable cloud

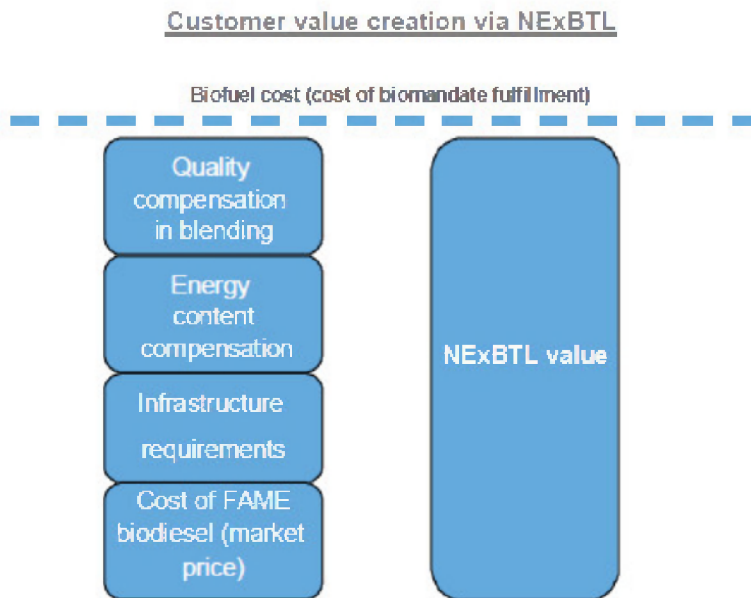
¹²⁵ Honkamaa, J. (Neste Oil, 2007). *Biodiesel*. Presentation at Neste Oil Analyst Day, November 2, 2007.

¹²⁶ Honkamaa, J. (Neste Oil, 2009). *Delivering Future Growth*. Presentation at Neste Oil Capital Markets Day, September 29, 2009.

¹²⁷ The value of US 30 cents/L was calculated as CAD 35 cents/L minus a CAD 5 cents/L transportation cost (CAD was at parity with USD in 2010) from: ÉcoRessources Consultants (2010). *Updating the cost-benefit analysis of the proposed 2% renewable fuels regulation*.

point of HDRD can lead to significant savings in kerosene or fuel additive expenditures when blending with low-cloud biodiesel. For some customers, the cost savings with regards to biodiesel infrastructure, kerosene, additives and the favourable physical characteristics of the product make it “worth” the extra cost premium. A recent 2012¹²⁸ study by ÉcoRessources found that in the short-term (i.e. at current HDRD prices), 48% of the federal requirement for renewable alternatives to diesel and heating oil would be met with HDRD. This increases to about 55% in the medium- to long-term and most refiners indicated that the proportion would increase if the price differential between biodiesel and HDRD was reduced. However, given that there is currently no shortage of demand for HDRD, the price premium relative to biodiesel is not likely to decrease in the near term.

FIGURE 19 – NExBTL VALUE FOR USE UNDER BIOFUEL MANDATES



Source: Lehmus, M. (Neste Oil, 2011). *Renewable fuels – Driving growth and profitability*. Presentation at Neste Oil Capital Markets Day, 21 September, 2011.

The margins for HDRD are determined by feedstock price differentials, the biodiesel margin (relative to diesel) and the price premium¹²⁹. Given that biodiesel and HDRD are produced from similar feedstocks and that their production costs are about equal (see Section 3.3), the price premium for HDRD is a strong advantage.

For refiners producing their own HDRD, the infrastructure, energy content and cloud point additive savings are the same, but they are able to save on the HDRD price premium relative to biodiesel, either

¹²⁸ Lambert, N. (ÉcoRessources Consultants, 2012). *An Update on Renewable Diesel Infrastructure in Canada*. Final report submitted March 12, 2012, not yet made public.

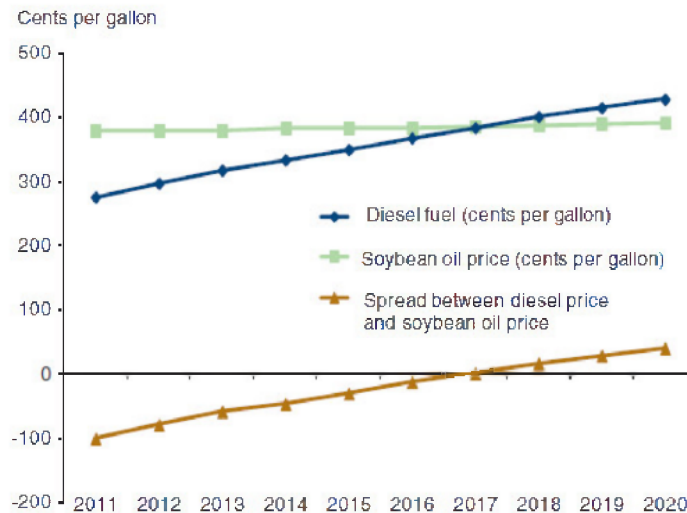
¹²⁹ Lehmus, M. (Neste Oil, 2011). *Renewable fuels – Driving growth and profitability*. Presentation at Neste Oil Capital Markets Day, 21 September, 2011.

in their own use or in sales to other customers. This advantage can compensate for the high capital expenditures.

It should be noted that in the United States, HDRD prices are governed primarily by the RIN market. Since HDRD generates 1.7 RIN's per gallon while biodiesel only generates 1.5 RIN's (due to energy equivalence factors), if biodiesel prices increase, the price differential between HDRD and biodiesel will actually increase rather than decrease. Conversely, if production of biodiesel and/or HDRD increases, increasing the overall supply of Type B fuels, D4 RIN prices will decrease and the price differential between biodiesel and HDRD will also decrease¹³⁰.

However, in the long-term, a refiner's interest in blending with HDRD may not only be in order to meet federal regulations. When oil prices rise, it can become more economical to produce diesel from renewable feedstocks than from crude oil. Of course, this assumes that renewable feedstock prices do not increase at the same rate. According to projections by the US EIA and the USDA, average regular diesel prices are expected to reach parity with average soybean oil prices in 2017, after which diesel prices are expected to continue to grow relative to soybean oil prices (see Figure 20).

FIGURE 20 – PROJECTED US SOYBEAN OIL AND REGULAR DIESEL PRICES, 2011 – 2020



Source: McPhail, L., Westcott, P. and Lutman, H. (USDA, 2011). *The Renewable Identification Number System and U.S. Biofuel Mandates*. Published by the USDA Economic Research Service, November 2011. Original data from EIA, 2011. *2010 Annual Energy Outlook* and USDA, 2011. *Agricultural Projections to 2020*.

¹³⁰ Personal communications.

7.5 Feedstock availability

The extent to which it will be economical to expand the biofuels market in North America and globally will depend directly on the availability of suitable feedstocks. As was seen in the previous section, in 2012 there is a potential market for 2.2 billion physical litres of HDRD¹³¹ (3.8 billion litre RIN's) in the United States under RFS2, which can go up to 4.5 billion physical litres (7.6 billion litre RIN's) if the requirements of the Type A fuel category are also included (not including Type C fuel requirements). The volume requirements increase significantly each year, climbing by an order of magnitude in 10 years. In Canada under the *Renewable Fuels Regulations*, the potential market for HDRD starts at 400 million litres and increases to 900 million by 2035. It is important to note that in the United States, the volumes of renewable fuels required under the RFS2 are set each year by a ruling by the EPA that takes into account feedstock availability, technological feasibility and other factors. In Canada, the volumes required are determined as a 2% annual average of the diesel and heating oil pools of refiners and importers.

Assuming an average HDRD production yield of 80% by mass (75% for winter HDRD, 85% for summer HDRD)¹³², it would require approximately 390,000 tonnes of feedstock in order to produce 400 million litres (312,000 tonnes) of HDRD to meet the Canadian regulatory requirements. The production yield does not vary significantly by feedstock type¹³³. It would require 2.3 million tonnes of feedstock to meet the RFS2 requirement for 2.2 billion physical litres of HDRD.

Table 19 presents the supply and disposition of canola oil and soybean oil in Canada for the crop years 2009/2010 and 2010/2011. As can be seen in the table, total production of canola and soybean oil in 2010/2011 was 2.7 million tonnes and 270,000 tonnes, respectively. 128,000 tonnes of canola oil was imported and 2.4 million tonnes (81% of total supply) was exported. 58,000 tonnes of soybean oil was imported and 72,000 tonnes (22% of total supply) was exported. Domestic use of canola and soybean oil was 453,000 tonnes and 252,000 tonnes, respectively. Exports and imports of these oils are primarily to/from the United States.

Currently, domestic use of soybean oil is almost exclusively for food use. Industrial (primarily energy) use of canola oil is predicted by the USDA to increase from 7% in 2009/2010 to 16% in 2010/2011¹³⁴.

¹³¹ Taking into account the energy equivalence value of 1.7 for HDRD under RFS2.

¹³² Personal communications.

¹³³ Personal communications.

¹³⁴ United States Department of Agriculture (2011). *Canada: Oilseeds and products annual outlook 2011/2012*. Published by the Global Agricultural Information Network of the USDA Foreign Agricultural Service, April 2011.

TABLE 19 – SUPPLY AND DISPOSITION OF CANOLA OIL AND SOYBEAN OIL IN CANADA

	CANOLA OIL			SOYBEAN OIL		
	09/10	10/11	11/12	09/10	10/11	11/12
	'000 tonnes					
SUPPLY						
Opening stocks	31	71	82	3	4	3
Production	2 107	2 768	3 000	232	265	260
Imports	201	128		75	58	
TOTAL	2 339	2 967		310	327	
DISPOSITION						
Exports	1 819	2 432		51	72	
Domestic use	449	453		255	252	
Closing stocks	71	82		4	3	
TOTAL	2 339	2 967		310	327	

¹Canadian Oilseed Processors Association (COPA, 2012). *COPA Monthly: December 2011/January 2012*.

About 400,000 tonnes of tallow and yellow grease is produced annually in Canada, mostly for the oleochemical and animal feed industries. The Canadian Canola Growers' Association estimated that the capacity for biodiesel production in Canada could increase to 500 million litres: 160 million litres from tallow, 80 million litres from yellow grease, 220 million litres from canola and 40 million litres from soy. These same estimates could also apply to HDRD production, as production yields are similar¹³⁵.

In the United States, the large majority of biodiesel is made from soy. Approximately 70 million acres of land is used for soybean crops, of which 8% was used for biodiesel production in 2006-2007. It is estimated that in order to produce 3 billion gallons of biodiesel, 30 million acres of cropland would be necessary for oilseed crops like soy¹³⁶. Existing and planned HDRD production in the United States makes use of tallow as the feedstock. In 2010, 815,000 tonnes of rendered tallow and 8.6 million tonnes of soybean oil were produced in the US.

In order for the biofuels production industries to continue to grow in North America while using North American feedstocks, it may be necessary to improve feedstock crop yields, either through advances in genetic engineering or by switching to more productive crops. Table 20 below presents the yields of a variety of different feedstocks. There is increasing interest in jatropha and algal feedstocks because of their very high yields and the fact that they do not compete with food use. Palm oil also has very high production yields and it is the primary feedstock for NExBTL production, although its GHG emissions performance is controversial due to the potentially high impacts of indirect land use changes on the overall lifecycle emissions.

¹³⁵ Asia-Pacific Economic Co-operation (APEC, 2012). *APEC Biofuels – Canada Biofuels Activities*. Website consulted February 12, 2012. http://www.biofuels.apec.org/me_canada.html

¹³⁶ Hoekman, S. K., Gertler, A. W., Broch, A., and Robbins, C. (2009). *Biodistillate Transportation Fuels 1. Production and Properties*. SAE Int. J. Fuels Lubr., 2(2):185

TABLE 20 – BIOFUEL FEEDSTOCK YIELDS

Feedstock	Potential Yield, gallons/acre
Corn	18
Soybean	40-55
Canola (Rapeseed)	110-145
Sunflower	102
Safflower	83
Cotton	35
Mustard	60-140
Jatropha	175-200
Coconut	290
Palm Oil	600-650
Algae	>5000

Source: Hoekman, S. K., Gertler, A., Brock, A., Robbins, C. (Desert Research Institute) and Natarajan, M. (Marathon Petroleum Company) (2010). *Production and Properties of Biodistillate Transportation Fuels*. Presentation at the AWMA International Speciality Conference: Leapfrogging Opportunities for Air Quality Improvement, May 2010, China.

8. Other next-generation renewable alternatives to diesel

Future renewable alternatives to diesel will make use of alternative feedstocks and alternative production processes. Aside from hydrotreatment technologies, the next-generation technology that is most likely to be commercialized in the medium-term is biomass-to-liquids (BTL). This process involves gasification of biomass at very high temperatures under controlled levels of oxygen to produce syngas, which is a mixture of CO, hydrogen and some CO₂. This syngas is then converted to a liquid fuel via the Fischer-Tropsch process, in which CO and H₂ are reacted in the presence of catalysts under controlled temperature and pressure conditions in order to produce hydrocarbon chains of various lengths. The process conditions and choice of catalyst will determine which hydrocarbon chain lengths will be favoured and therefore which products will result (from fuel gas to paraffinic wax). The advantage of this process is that any type of organic feedstock can be used, notably forest and agricultural residues, which are in large supply and currently at low cost¹³⁷.

There are no BTL plants currently in commercial operation. Choren Industries has probably come the closest to commissioning a commercial-scale plant in Freiberg, Germany, although the scale-up and commissioning process was much longer than expected and since the project was entirely privately funded, many investors backed out and the company is now facing bankruptcy. Choren successfully ran a 1 MWth pilot plant from 1998 to 2004 and began construction of a scaled-up 45 MWth plant in 2003. From 2005 to 2007 Shell, Daimler and Volkswagen became investors, amongst others. Construction took longer than expected and in 2009 the gasification unit was commissioned and began testing. Since it was the first of its kind on that scale, a number of technical issues had to be ironed out, notably the ideal gasification conditions to ensure that the product CO/H₂ ratio is suitable for the F-T step that follows and that yields are maximized (i.e. minimizing the production of CO₂). Eventually it became clear that although none of the technical issues were irresolvable, the time it would take to resolve them would be costly and difficult to predict, and therefore investors pulled out¹³⁸. In October 2011 a new investor was announced and new investors are being sought out to take the project forward¹³⁹.

Other BTL demonstration or pilot-plants are planned or in operation^{140,141}:

- BioTfuel demonstration project: Two demonstration plants are being built in France that incorporate all stages of the BTL process, including drying and crushing of the biomass, torrefaction, gasification, syngas purification and Fischer-Tropsch fuel synthesis. The project budget is 112.7 million euros and the plants are expected to begin operation at the end of 2012.

137 Rapiet, R. (2009). *Renewable Diesel Primer*. Article published on Consumer Energy Report website, January 17, 2009.

138 Rapiet, R. (2011). *What Happened At Choren?* Article published on Consumer Energy Report website, July 8, 2011.

139 European Biofuels Technology Platform (date unknown). *Biomass to Liquids*. Website consulted February 15, 2012. <http://www.biofuelstp.eu/btl.html>

140 European Biofuels Technology Platform (date unknown). *Biomass to Liquids*. Website consulted February 15, 2012. <http://www.biofuelstp.eu/btl.html>

141 Gust, S. (Neste Oil, 2009). *Neste Oil – Stora Enso BTL Joint Venture*. Presentation at the 2nd Stakeholders' Plenary Meeting, January 22, 2009.

- CEA pilot plant: The Atomic and Alternative Energy Commission in France announced in 2009 the construction of a BTL pilot plant in Bure Saudron, France using 75,000 tonnes of forest and agricultural residues to produce 23,000 tonnes/year of biofuels.
- Neste Oil and Stora Enso BTL joint venture: HDRD producer Neste Oil and paper, packaging and forestry products company Stora Enso began a joint venture in 2006 to build a demonstration plant employing BTL technology to produce paraffin wax from forest biomass, which would then be upgraded to HDRD at Neste's biorefinery. The 12 MW plant has been successfully operational since 2009 and a second demonstration phase to expand production capacity is now planned. Commercial-scale production and global expansion is the goal of the third phase of the project, projected for 2015.
- Karlsruhe pilot plant: Forschungszentrum Karlsruhe GmbH is building a BTL pilot plant in partnership with LURGI GmbH for operation in 2016.
- The Dutch Biorefinery Initiative: A 10 MWth BTL demonstration facility will be built in the Port of Rotterdam by WUR and ECN with support from the Dutch government.

These examples illustrate that the technology is still in its nascent stages of scale-up from pilot and demonstration plants to commercial operability and it will take at least five years before commercial-scale BTL plants will be operating regularly. As a result, capital costs for BTL plants are still quite high, with 2006 estimates ranging from US \$120,000 – \$140,000 per bpd production (as compared with \$15,000 - \$20,000 for a petroleum refinery and \$30,000 - \$85,000 for HDRD plants, as seen in Section 3.3)¹⁴².

Aside from alternative technologies, alternative feedstocks are also being actively pursued, both to improve yields per hectare and to avoid conflicts with food crops. As seen in the previous section, jatropha, coconut, palm and algae feedstocks produce very high yields per hectare relative to vegetable oil crops. Waste-based microbial oil is a new renewable fuel feedstock that makes use of fungi to break down industrial waste and agricultural residues into sugars that feed the microbes and subsequently produce oil. This process can be carried out in bioreactors used by brewers and biotechnology companies. A US \$10.4 million pilot plant for microbial oil production is currently being built by Neste Oil and should be online by the end of 2012¹⁴³.

¹⁴² Rapier, R. (2009). *Renewable Diesel Primer*. Article published on Consumer Energy Report website, January 17, 2009.

¹⁴³ Green Car Congress (2011). *Neste Oil building pilot plant to produce waste-based microbial oil for NExBTL renewable diesel fuel; commercial production possible by 2015*. Published December 15, 2011.

9. Conclusions and future perspectives

In this study it was shown that HDRD is a renewable alternative to diesel with favorable physical properties that allow it to be blended with ULSD with less of the additional storage and blending infrastructure required for biodiesel and less kerosene requirements for cold-weather blending. It has a high cetane number and a higher energy content than biodiesel. Due to the chemistry of the hydrotreatment process, HDRD can be made from a wider variety of feedstocks than biodiesel without compromising the final product quality.

The capital costs for building a stand-alone HDRD production facility within an existing refinery are still quite high. The unit capital cost is high for very small and very large plants \$45,000 - \$85,000 per bpd capacity, but approximately the same for the rest (\$30,000 - \$40,000 per bpd capacity). In contrast, the average capital costs for a petroleum refinery are \$15,000 - \$20,000 per bpd capacity and \$20,000 - \$30,000 per bpd capacity large biodiesel plants (of course, because petroleum plants typically have very large capacities, the total capital costs of their construction are much higher than for smaller-capacity HDRD or biodiesel plants).

Operating costs for HDRD production are similar to those for biodiesel, where approximately 80% of operating costs are feedstock costs.

Conversely, the capital costs for adapting an existing refinery hydrotreatment unit for co-processing are much smaller, as are the marginal operating costs.

Currently there exist six operational commercial-scale HDRD production plants with a combined capacity totalling 2.5 billion litres per year. One of these plants is located in the United States, four in Europe and one in Southeast Asia. By the end of 2012, a second plant will be operational in the United States to give a total capacity in North America of 900 million litres per year.

The volume of renewable alternatives to diesel required for the Canadian and American renewable fuels mandates are 400 million litres and 3.8 billion litres in 2012, respectively (7.6 billion litres in the US if total non-cellulosic Type A advanced fuel requirements are considered). It would require 400,000 tonnes and 2.3 million tonnes of feedstock to meet Canadian and US requirements, respectively. Total production of canola oil in 2010/2011 in Canada was 2.7 million tonnes, 270,000 tonnes for soy oil and 400,000 tonnes of tallow. In the US in 2010, 815,000 tonnes of rendered tallow and 8.6 million tonnes of soybean oil were produced. Although current feedstock production capacity is largely sufficient to meet the Canadian and US federal requirements, dynamics related to existing food usage (and other uses) and export revenues must also be considered when evaluating the available feedstock capacity, which was out of the scope of the current study.

In the Canadian context, one 215 ML/yr plant would be able to account for 30% of Canada's current total requirement for renewable alternatives to diesel and heating oil. Adding another plant of the same size would account for 48% of the projected requirements in 2035. Alternatively, a 906 ML/yr plant would provide 33% more than the total Canadian federal requirements in the short term, allowing for potential exports to the US, and in 2035 would account for 100% of the projected requirements.