University of Alberta

Renewable Diesel Production from Canola and Camelina

by

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Abstract

Hydrogenation-derived renewable diesel (HDRD) is a promising alternative fuel due to its excellent low-temperature properties, cetane number, and similarity to fossil diesel. Using Alberta as a basis, data-intensive techno-economic models and life cycle assessment models were developed to estimate costs and environmental impacts of HDRD produced from canola and camelina. The estimated vegetable oil production costs, total HDRD production costs, greenhouse gas emissions (GHGs), and net energy ratios (NERs) are:

- Canola: $0.55/L, $1.09/L, 33 – 94 g$CO_{2e}$/MJ, 1.2 – 2.2 MJ/MJ
- Camelina: $0.28/L, $0.85/L, 30 – 82 g$CO_{2e}$/MJ, 1.0 – 2.3 MJ/MJ

These costs are for processing and production plants at their economically optimum sizes of 190 million L/year canola oil plant, 120 million L/year camelina oil plant, and 812 million L/year HDRD plant. HDRD appears to be less expensive and more environmentally friendly to produce from camelina than canola. However, if camelina meal cannot be sold, the total camelina-based HDRD production cost rises to $1.37/L, GHGs rise and NER drops, making canola-based HDRD more attractive.

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Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AARD	Alberta Agriculture and Rural Development
AFDP	Agri-Food Discovery Place
Al_2O_3	Alumina
ASTM	American Society for Testing and Materials
Avg	Average
B	Boron
bbl/day	Barrels per day
^oC	Degrees Celsius
C	Carbon
Ca	Calcium
CD	Census division
CEPCI	Chemical engineering plant cost index
CFPP	Cold filter plugging point
CH_4	Methane
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CP	Cloud point
Eq	Equation
FAME	Fatty acid methyl esters
Fe	Iron

g	Gram
GHG	Greenhouse gas emission
GJ	Gigajoule
ha	Hectare
H_2O	Water
HDRD	Hydrogenation-derived renewable diesel
HHV	Higher heating value
HZSM-22	A type of zeolite
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
L	Liter
LCA	Life cycle assessment
LUC	Land use change
m^3	Cubic meters
Max	Maximum
Mg	Magnesium
Min	Minimum
MJ	Megajoule
Mo	Molybdenum

MPa	Megapascal
N	Nitrogen
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NER	Net energy ratio
Ni	Nickel
O&M	Operating and maintenance
PCCI	Power capital cost index
P	Phosphorous
Pd	Palladium
Pt	Platinum
RFS	Renewable fuels standard
S	Sulphur
TAN	Total acid number
US$	United States dollars
yr	Year

1 Introduction

1.1 Background

With increasing concerns over climate change, greenhouse gas (GHG) mitigation has become a key topic of interest for industry, government policy makers, and researchers. In particular, a great deal of research has been dedicated to develop alternatives to fossil fuels, such as nuclear, wind, solar, hydro, and biomass to reduce GHGs. Nuclear, wind, solar, and hydro technologies have great potential in the electricity generation sector but cannot directly replace liquid fuels derived from fossil fuels. Biomass, on the other hand, can be directly converted to a variety of liquid fuels (i.e. biofuels) with similar properties to conventional gasoline and diesel.

Liquid fuels used in the transportation sector are especially important to consider because they produce approximately 13.5% of the world's GHGs (United Nations Environment Programme, 2010). Although alternatives to liquid vehicle fuels such as electricity and fuel cells are available, liquid fuels are difficult to replace because they have a high energy density and extensive infrastructure already in place for distribution and consumption. Since liquid fuels are so convenient, many governments have developed policies to promote biofuels, which can be blended with conventional gasoline and diesel and used in unmodified engines (Environment Canada, 2011; Cordonnier, 2009; U.S. Environmental Protection

Agency, 2010). Some of the most common biofuels in use today are ethanol (a gasoline substitute), biodiesel, and renewable diesel (diesel substitutes).

To help meet Canada's national GHG reduction targets by 2020, the Canadian Government recently legislated an average renewable fuel content requirement of two percent in diesel and heating oil (Environment Canada, 2011). Similarly, in the Province of Alberta, a Renewable Fuels Standard (RFS) was recently implemented by the government, which requires two percent of all diesel sold to be either biodiesel or renewable diesel (Government of Alberta, 2011). Alberta's RFS also specifies that any renewable fuel used to satisfy the RFS can generate up to a maximum of 75% of the GHGs of generated by the equivalent petroleum fuel (Government of Alberta, 2011).

Both biodiesel and renewable diesel are derived from vegetable oils (e.g. canola oil, camelina oil, sunflower oil, soy oil, and palm oil), but are produced using different processes. Biodiesel is composed of fatty acid methyl esters (FAME) and is produced via transesterification, which consists of reacting the triglycerides in the vegetable oil with an alcohol (usually methanol) in the presence of a homogeneous alkaline or acid catalyst (Kubickova & Kubicka, 2010). Renewable diesel (also known as green diesel) can be produced via hydroprocessing, in which triglycerides in the vegetable oil react with hydrogen under high pressure, high temperature conditions in the presence of a heterogeneous catalyst to form primarily n-alkanes (Wells, 2011); if hydroprocessing is used, the end-product is usually referred to as hydrogenation-derived renewable diesel (HDRD) (Thuen, 2011). Several different processes and catalysts can be used to produce HDRD and these are discussed in detail in Chapter 3 of this thesis.

Due to differing compositions, biodiesel and HDRD have significantly different fuel properties. A key concern with biodiesel is poor low temperature properties (i.e. pour point and cloud point) (Canakci and Sanli, 2008), which makes biodiesel undesirable for northern climates like Alberta's. HDRD can have much better low temperature properties, is very similar in chemical composition to conventional diesel, and has a high cetane number (Kalnes et al., 2009; Kubickova and Kubicka, 2010; Šimáček et al., 2010), making it a more desirable blending component than biodiesel. However, HDRD production in North America is very limited and energy companies in Canada have a poor understanding of the cost structure to produce it (Kemp, 2011).

In Alberta, the main oilseed crop available for HDRD production is canola (B*rassica rapa, Brassica napus L*), which was developed from rapeseed but has lower glucosinolate and erucic acid content than rapeseed. Canada is the world's largest exporter of canola oil (Statistics Canada, 2009) and the majority of Canada's canola production comes from the prairies in Western Canada. Alberta produces over a third of Canada's canola, with an average production of 2.7 million tonnes per year from 1997 to 2008 (Statistics Canada, 2006; Alberta Agriculture and Rural Development, 2008). Although canola is readily available, other crops may be better options for HDRD production. Camelina (*Camelina sativa*) is a promising crop for renewable fuels production because compared to canola, it requires less fertilizer and water, can grow on marginal lands, has a shorter growing season (less than 100 days), and has better cold and insect tolerance (Zubr, 1997; Lafferty et al., 2009). Another advantage of camelina is that it does not compete with food, but unfortunately camelina meal is not widely accepted as animal feed, limiting its economic and environmental viability.

For this study, canola and camelina were selected as crops for HDRD production in Alberta. Despite Canada's highly developed agriculture and energy industries, no techno-economic or life cycle analysis (LCA) studies were available in literature for HDRD production in Canada. Most of the literature for renewable fuels from oilseeds is dedicated to biodiesel (Bernesson, 2004; Haas et al., 2006; Saville and Canola Council of Canada, 2006; Edwards et al., 2007; Marchetti et al., 2008; Rustandi, 2010; S&T Consultants Inc, 2010; Krohn and Fripp, 2012). A few environmental and economic studies are available for HDRD from canola/rapeseed (Marker, 2005; Kalnes et al., 2009; Arvidsson et al., 2011) and camelina (Shonnard and Williams, 2010) but these studies are based in the Europe or the United States. This study was an effort to fill this gap in the literature.

1.2 Objective of the study

The overall objectives of this research were to evaluate the economic and environmental sustainability of producing HDRD from canola and camelina. The data used for this study were specific to the Province of Alberta. To evaluate the economic sustainability of HDRD, the following specific objectives were established:

- Determine the cost of producing vegetable oil from canola and camelina in Alberta from two different oil extraction technologies – press extraction and solvent extraction;
- Estimate the economically optimum size of oil extraction plant by evaluating the change in vegetable oil production cost with oil extraction plant size. The optimum size occurs when the production cost is minimized;
- Identify viable locations for vegetable oil extraction plants in Alberta;
- Determine the cost of converting vegetable oil to HDRD via hydroprocessing;
- Estimate the economically optimum size of HDRD plant by evaluating the change in HDRD production cost with HDRD plant size;
- Ascertain the impact on production costs for key variables such as yield, meal (co-product) price, solvent losses, solvent price, farming (field) cost, capital cost, operating cost, and transportation cost.

To evaluate the environmental sustainability of HDRD, the following specific objectives were established:

- Estimate the life cycle GHGs from producing HDRD and compare these to the GHGs for conventional diesel;

- Estimate the net energy ratio, that is, the ratio of output energy to fossil fuel input energy, (NER) for HDRD production. NER is a commonly used measure for sustainability of energy sources;
- Identify the variables that have the greatest impact on life cycle GHGs and NER for HDRD production.

1.3 Scope and limitations of the study

To complete the research objectives, this study was broken into three phases:

1) Economics of producing canola and camelina oil (Chapter 2);
2) Economics of converting canola and camelina oil to HDRD (Chapter 3);
3) Sustainability of the life cycle of producing HDRD (Chapter 4).

Detailed techno-economic and life cycle analysis models were developed for these phases, which required data from many sources, including literature, vendors, industry experts, vegetable oil producers, HDRD producers, government databases, and other researchers. In some cases, the data had to be adjusted for year, currency type, and location. The study used Alberta specific data including location specific data inputs particularly those in the farming stage (e.g. yield, fertilizer inputs, soil emissions etc.)

Although both press extraction and solvent extraction technologies were evaluated in Chapter 2, solvent extraction was the technology used for subsequent chapters because it is the technology commonly used in large-scale vegetable oil production plants. As noted in Section 1.1, several different technologies are available for hydroprocessing; in this study, the hydroprocessing reactions used were based on experimental work completed by Alberta Agriculture and Rural Development (Wells, 2011). Aspen Plus® software was used to simulate the reactions and build chemical process models for various unit operations involved in an HDRD plant. These models were then used to size the process equipment, and to estimate energy use, capital costs, and operating costs for the plant. For different hydroprocessing technologies (i.e. catalyst type, solvent type, reaction temperatures and pressures), the costs and energy use for HDRD production would change.

For the LCA part of the study, only direct inputs to HDRD production were considered. That is, energy (e.g. diesel and electricity) and chemicals (e.g. fertilizers) consumed during HDRD production were considered direct inputs and were included in the LCA but other inputs such as the energy required to build the HDRD processing plant were considered indirect inputs and were not included in the LCA unless otherwise indicated. Accurate data for indirect inputs was very difficult to obtain, and based on other studies, the impact of indirect inputs is usually insignificant. The greenhouse gases considered in the LCA were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

1.4 Organization of the thesis

In this thesis, there are five chapters:

- Chapter 1 provides background of this research, defines the research objectives, and outlines the scope and limitations of the study;
- Chapter 2 discusses the techno-economic models that were developed to estimate the economic optimum size and minimum costs of production for vegetable oil extraction plants in Western Canada. This chapter compares the techno-economics for different feedstocks (canola vs. camelina), and extraction technologies (press vs. solvent);
- Chapter 3 reviews different technologies for HDRD production and describes the chemical process models that were developed to simulate HDRD production. This chapter also discusses the techno-economic models used to estimate total HDRD production costs from canola and camelina. These cost estimates were developed using input data from Chapter 2, as well as capital and operating cost data from the Aspen Plus® models.
- Chapter 4 evaluates the environmental sustainability of HDRD from canola and camelina by calculating the GHGs and NER for several HDRD production scenarios. The scenarios considered were selected in order to account for variables (i.e. yield and field N_2O emissions) and methodological assumptions (i.e. co-products, allocation methods, and land-use changes) that could significantly impact the LCA results. Detailed data is provided for all of the key stages of HDRD production: (i) oilseed farming, (ii) transportation of oilseeds to the oil extraction plant,

(iii) oil extraction, (iv) transportation of oil to the HDRD plant, (v) HDRD production, and (vi) transportation of HDRD to the consumer.

- Chapter 5 provides a synthesis of the key conclusions in Chapters 2 to 4, and recommends future research that could be done to expand on this study.

These chapters are a consolidation of papers and each chapter is intended to be read independently, which results in repetition of some data and concepts. Appendices provided at the end of this thesis contain additional details regarding the techno-economic models and chemical process models developed in the study.

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2 Techno-Economics of Producing Vegetable Oil from Canola and Camelina*

2.1 Introduction

The role of greenhouse gas emissions (GHGs) in climate change has become an increasingly important issue in the world today. Biofuels reduce GHGs because these are absorbed from the atmosphere as plants grow and use solar energy to convert carbon dioxide to starches. Biofuels can also reduce GHGs because they typically burn more efficiently than fossil fuels due to a higher octane number in the case of ethanol fuels, and a higher cetane number in the case of biodiesel or hydrogenation-derived renewable diesel (HDRD) fuels (Goldemberg et al., 2004; Brady et al., 2007; Canakci and Sanli, 2008).

Biodiesel and HDRD are fuels that can be derived from feedstocks such as soybean, sunflower, palm, and canola. Biodiesel is produced via transesterification and is made up of long-chain alkyl esters, whereas HDRD is produced via hydroprocessing and has a chemical composition similar to conventional diesel. In Western Canada, the primary feedstock for biodiesel production is canola but there has also been growing interest in the use of camelina due to its low field costs compared to canola (Frohlich and Rice, 2005). Energy companies are becoming attracted to producing HDRD over biodiesel

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because HDRD can have better cold flow properties and can be produced using existing petroleum upgrading equipment (Šimáček et al., 2011). Some studies have been done to evaluate the economics of biodiesel or HDRD production (Saville and Canola Council of Canada, 2006; Marchetti et al., 2008; Kalnes et al., 2009; Knothe, 2010) but these studies assume a fixed feedstock cost/unit, and do not examine the effect of plant scale on production cost.

The Province of Alberta has recently legislated a Renewable Fuels Standard (RFS), which requires all diesel fuel sold in Alberta to contain 2% biodiesel or renewable diesel (Government of Alberta, 2011). The RFS will increase the demand for renewable fuels in Alberta, so there will be a corresponding increase in the demand for vegetable oil as a feedstock for production. The existing canola oil extraction plants in Alberta (Bunge – Fort Saskatchewan, Canbra – Lethbridge, and ADM – Lloydminster (Saville and Canola Council of Canada, 2006)) may not be able to keep up with the increased demand, so new plants may be built. Many studies address the economics of canola and oilseed oil extraction plants in North America (Weber, 1993; Center for Agribusiness and Economic Development, 2000; Reaney et al., 2006; Schumacher, 2007; Jaeger and Siegel, 2008; Fore et al., 2011). However, none of these studies estimate the optimum scale of the feedstock processing plants at which the cost of production is minimum. This study was an effort to fill a significant gap in the literature and assessed the economic optimum size of a feedstock processing plant for HDRD production.

In this study, canola oil and camelina oil were assessed as feedstocks for HDRD production. The specific objectives of the study are given below.

- Estimate the economic optimum size and the minimum cost of production for an oil extraction plant using canola and camelina as feedstocks;
- Compare the techno-economics for canola and camelina oil extraction plants;
- Determine the economic sensitivity to yield and co-product (meal) price, as well as capital, operating, field, and transportation costs;
- Study viable locations for an oil extraction plant in the Province of Alberta as a case study.

To complete these objectives, data-intensive techno-economic models were developed for vegetable oil production plants operating for 30 years. The models include detailed cost estimates for all aspects of vegetable oil production: seed harvesting, collection, handling, transportation and storage, as well as oil extraction capital and operating costs and the technical characteristics of the plants. All costs in this study are in 2008 United States dollars (US$) unless otherwise indicated.

2.2 Methodology

2.2.1 Feedstock characteristics

Canola (*Brassica napus L. and Brassica rapa*.) is a type of rapeseed developed in Canada that has low erucic acid and glucosinolate content. Winter and Spring Canola are grown primarily in Western Canada, but some portions are planted in Ontario and in the north central and southeastern United States. Canada is the world's largest producer of canola and most of the canola oil produced is exported to foreign countries such as the USA, Japan, Mexico, China, and Pakistan (Statistics Canada, 2009; Canola Council of Canada, 2010a). In 2009, the amount of canola produced in Canada was 12.4 million tonnes. Canola seed used for domestic purposes such as human food, seed production, and industrial use was 5.0 million tonnes. Approximately 7.1 million tonnes was exported to other countries.

Camelina (*Camelina sativa*) is an oilseed crop that comes from the *Brassicacae* family but it is not used to produce edible oil. The main advantages of camelina over canola are that it has a short growing season (less than 100 days) and it can survive in drought and cold weather better than canola. Camelina has few insect problems, can compete with weeds, and no herbicide is required during growth. Compared to other oilseeds, camelina requires less fertilizer, pesticides, and water, which can reduce its production cost substantially. A conservative estimate of 30% oil content for camelina was used in this study (Abramovic and Abram, 2005) although an earlier study reported that camelina oil content can be as high as 38% (Budin et al., 1995). Camelina meal is comparable to soybean meal in terms of fiber and protein content. Western Canada has little experience growing camelina, though field trials have been conducted (Agriculture and Agri-Food Canada, 2009).

2.2.2 Processes for canola oil and camelina oil production

Canola and camelina seeds can go through several steps to have the oil extracted: cleaning, preparation, pressing, solvent extraction, and degumming. A continuous screw press is usually used for the pressing stage and additional oil can be extracted by using a solvent (typically hexane) to absorb residual oil from the oilseed meal (Mag, 2011). Degumming removes phosphatides from the oil, which can separate to form a sludge during storage (Mag, 2011). Camelina seeds produce different gums than canola seeds, so camelina oil extraction requires a slightly different degumming process (Sandroni, 2010), such as different chemicals to initiate precipitation of the phosphatides. However, the cleaning, preparation, pressing, and solvent extraction steps for canola and camelina are the same (Sandroni, 2010). A detailed description of the oil extraction process for canola can be found in literature (Mag, 2011).

Canola oil is generally divided into three quality grades: crude oil, crude degummed oil, and crude super degummed oil. The main difference between the grades is the phosphorous content (50 ppm max for crude super degummed oil, and 200 ppm max for crude degummed oil). Biodiesel producers who use canola oil normally require crude degummed oil, and sometimes use crude super degummed oil to produce biodiesel that meets the ASTM D6751 requirements (Stone, 2010). Renewable diesel producers who use hydroprocessing also generally require crude degummed canola oil as a feedstock (Halonen, 2010). In this study, the processing plant costs are based on producing crude degummed oil.

Oil extraction plants normally fit into two categories – press plants and solvent extraction plants. Small oil extraction plants normally only use pressing, while large oil extraction plants use a combination of pressing and solvent extraction. Press plants have lower capital costs and can normally achieve oil extraction efficiencies of up to 75% (Nesbitt, 2010). Greater extraction efficiencies can be achieved with press plants, however extra equipment is required to recycle the meal, which adds to capital costs (The EDA University Center at Washington State University, 2003). Solvent extraction plants require higher up-front capital costs but can achieve oil extraction efficiencies of up to 97% (Reaney et al., 2006; Mag, 2011), which reduces overall feedstock costs.

2.2.3 Feedstock yield and availability

The yield and regional availability of canola and camelina are important parameters to determine the appropriate capacity and location of an oil extraction facility because these parameters strongly affect production cost. Yield data for different census divisions and regional locations within Alberta was collected from the 2006 and 2008 Alberta Agricultural Statistics Yearbook and the 2006

Census of Agricultural Crop Data available through Statistics Canada (Alberta Agriculture and Rural Development, 2006, 2008; Statistics Canada, 2006). Gross yield depends on many factors including species, location, climate, and time of harvest. To determine the net yield, losses that occur due to dockage, handling, transportation, and storage must be taken into account.

2.2.3.1 Gross yield

In Alberta the total average production of canola over the last twelve years (1997-2008) was 2.7 million tonnes/yr (Statistics Canada, 2006; Alberta Agriculture and Rural Development, 2008). This is approximately 34% of the total canola production in Canada. The average, minimum, and maximum gross canola yields in Alberta are 1.66 green tonnes/ha, 1.21 green tonnes/ha, and 2.12 green tonnes/ha, respectively. Alberta has on average about 1.64 M ha of cropland available for canola production.

Camelina is grown on a very limited basis in Alberta and the production data is not available in the public domain. Therefore, the camelina yield data used for this study is the data for the trial basis presented by Agriculture and Agri-food Canada (Agriculture and Agri-Food Canada, 2009). In trials, the average, minimum, and maximum camelina gross yields (green tonnes/ha) were 2.25, 1.52 and 4.15, respectively (Agriculture and Agri-Food Canada, 2009).

2.2.3.2 Net yield

Untimely harvesting, inappropriate harvesting techniques, and improper handling and storage are the main causes of losses in yield and in quality of oilseeds (Alberta Agriculture and Rural Development, 2009). To determine the net yield of canola and camelina, the following factors have been taken into consideration:

- Dockage, handling, transport, and storage losses;
- The fraction of seeds that a harvesting machine is capable of removing;
- Seed moisture content.

Dockage is defined under the Canada Grain Act as "any material intermixed with a parcel of grain, other than kernels of grain of a standard quality fixed by or under the Act for a grade of that grain, that must and can be separated from the parcel of grain before that grade can be assigned to the grain" (Canola Council of Canada, 2010b). The dockage removal process is described in detail in the Official Grain Grading Guide of the Canadian Grain Commission (Canadian Grain Commission, 2011). The amount of dockage in farm deliveries of canola to elevators in Western Canada over the years has averaged 9% (Manitoba Agriculture, 1980; Canola Council of Canada, 2010b).

The harvest loss in the field considered by Alberta Agriculture and Rural Development is 56 to 112 kg/ha (Alberta Agriculture and Rural Development, 2009). Gulden et al. reported average yield losses of 107 kg/ha or 5.9% of the crop seed yield (Gulden et al., 2003). The average harvest loss range for Ontario is far less than the range for Western Canada; Ontario's harvest loss varies from

10 – 50 kg/ha (Ontario Ministry of Agriculture Food and Rural Affairs, 2009). Based on the available data, a conservative estimate of 100 kg/ha was used for harvest loss in this study. The storage and transportation loss considered for the analysis was 2% based on previous studies and the assumed moisture content of the canola and camelina was 8.5%.

To develop the data intensive techno-economic models, three yield cases were considered: average yield, maximum yield, and minimum yield. The average net yield of canola after all deductions is shown by year and by census division in Table 2-1. The data shown for each census division is the 12-year average for 1997 – 2008.

Table 2-1: Yield and availability of canola in Alberta by year and by census division

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Average
Yield													
Gross yield (green tonnes/ha)	1.32	1.42	1.63	1.46	1.53	1.21	1.66	1.92	2.12	1.89	1.68	2.07	1.66
Net yield (green tonnes/ha)	1.09	1.18	1.36	1.22	1.28	0.99	1.40	1.62	1.81	1.60	1.41	1.76	1.39
% loss	17.6	17.1	16.3	16.9	16.6	18.2	16.2	15.5	15.0	15.5	16.1	15.1	16.3
Production													
Total production (000 green tonnes)	2109	2472	2971	2189	1656	1225	2223	2926	3651	3425	3402	4323	2714
Net production (000 green tonnes)	1737	2048	2485	1816	1379	986	1861	2466	3101	2892	2852	3667	2274

Census Division (CD)	1	2	3	4	5	6 &15	7	8	9	10	11	12	13	14	16	17	18	19	Alberta
Yield																			
Gross yield (green tonnes/ha)	1.68	1.93	1.60	1.02	1.62	1.72	1.45	1.96	1.61	1.64	2.09	1.72	2.04	2.06	0.87	1.38	1.54	1.46	1.66
Net yield (green tonnes/ha)	1.41	1.63	1.34	0.82	1.36	1.45	1.20	1.66	1.35	1.37	1.79	1.44	1.73	1.75	0.69	1.14	1.29	1.22	1.39
% loss	16.1	15.4	16.4	19.6	16.3	16.2	17.0	15.4	16.4	16.3	15.1	16.0	15.2	15.1	21.1	17.3	16.6	16.9	16.2
Production																			
Total production (000 green tonnes)	35	117	44	21	280	130	272	160	2	524	274	79	187	6	2	188	23	370	2714
Net production (000 green tonnes)	29	99	37	16	235	109	226	135	1	439	233	67	159	5	2	155	19	308	2274

2.2.4 Input data and assumptions for techno-economic models

The cost to produce canola oil and camelina oil can be broken down into four parts:

1) Field cost - to grow and harvest the seeds;
2) Storage cost – to store the seeds on-farm and in elevators;
3) Transportation cost – to transport the seeds from the field to the plant;
4) Oil extraction cost – to store and process the seeds once they have been delivered to the plant. These costs include capital costs and operating costs.

These cost categories are discussed in more detail in the following sections. In this study, all cost data is given in US$, with a base year of 2008 unless otherwise indicated. Using the cost data discussed in this section, techno-economic models for canola and camelina oil production were developed and used in determining the optimum processing plant size and minimum cost of oil production. Key assumptions used in developing the techno-economic models are given in Table 2-2.

Table 2-2: Key assumptions used to develop the techno-economic models

Factor	Value	Source
Plant Lifetime (years)	30	a,b,c
Inflation	2.0%	a,b,c
Internal rate of return	10%	-
Base year	2008	-
Plant startup profile		
Year 1	80%	c
Year 2+	90%	d,e,f,g
Spread of construction costs		a,b,c
Year 1	20%	
Year 2	35%	
Year 3	45%	
Site reclamation cost as % of capital cost	10%	c
Other cost (tax, insurance etc.) as % of capital cost	0.5%	a
Bulk density of vegetable Oil (kg/L)	0.915	h
Canola seed oil content	44%	i
Camelina seed oil content	30%	j
Press plant oil extraction efficiency	75%	e
Solvent plant oil extraction efficiency	97%	k,l

Table 2-2 Sources:
[a](Sultana et al., 2010)
[b](Sarkar and Kumar, 2009)
[c](Kumar et al., 2003)
[d](Reaney et al., 2006)
[e](Nesbitt, 2010)
[f](Risner, 2010)
[g](Takeda, 2010)
[h](Przybylski, 2010)
[i](Trimark Engineering Ltd., 2007)
[j](Abramovic and Abram, 2005)
[k](Reaney et al., 2006)
[l](Mag, 2011)

2.2.4.1 Field cost

The field cost for oilseed production consists of the cost of seed harvesting, collection and on-farm storage. Summaries of the field costs used in this study for canola and camelina are shown in Table 2-3 and Table 2-4 respectively. Note that the field cost of canola is much higher than the field cost of camelina. The higher cost for canola is mainly due to the high cost of seeds and higher use of pesticide and farm chemicals.

Table 2-3: Field costs for canola[a]

Item	Cost ($/tonne) Average Yield	Cost ($/tonne) Max Yield	Cost ($/tonne) Min Yield
Operating Inputs			
Seed			
Canola	35.71	27.91	48.97
Fertilizer			
Urea (46-0-0)	49.55	38.72	67.95
Diammonium phosphate (18-46-0)	8.93	6.98	12.24
Ammonium sulphate (21-0-0-24S)	4.91	3.84	6.73
Fertilizer application	8.93	6.98	12.24
Herbicides			
Glyphosate	12.32	9.63	16.89
Ammonium sulfate (AMS)	0.74	0.58	1.02
Herbicide application	14.88	11.63	20.40
Insecticides			
Warrior (1 out 3 Fall)	5.95	4.65	8.16
Warrior spring	17.86	13.95	24.49
Aerial application	9.89	7.73	13.57
Custom & Consultants			
Aerial application for capture	8.93	6.98	12.24
Hauling cost	2.23	1.74	3.06
Other			
Overhead	8.30	6.49	11.39
Crop insurance	18.60	14.54	25.51
Fuel	17.19	13.43	23.57
Lubricants	2.75	2.15	3.77
Machinery repairs	18.60	14.54	25.51
Machinery labor	24.64	19.26	33.79
Other labor	1.61	1.26	2.20
Operating interest	8.57	6.70	11.75
Total operating costs	**281.09**	**219.68**	**385.46**
Fixed Costs			
Machinery depreciation	15.13	11.83	20.75
Machinery interest	6.59	5.15	9.04
Machinery insurance	3.09	2.42	4.24
Machinery taxes	8.09	6.33	11.10
land investment	23.73	18.55	32.54
Total fixed costs	**56.65**	**44.27**	**77.68**
Total costs	**337.74**	**263.95**	**463.14**

[a]Derived from: (Malhi and Gill, 2004, 2006; Havlin et al., 2005; Karamanos et al., 2005; Reaney et al., 2006; Frier and Rother, 2006; Alberta Agriculture and Rural Development, 2007; Jaeger and Siegel, 2008; Painter et al., 2009; Agriculture and Agri-Food Canada, 2010; DeVuyst et al., 2010)

Table 2-4: Field costs for camelina[a]

Item	Cost ($/tonne) Avg yield	Cost ($/tonne) Max yield	Cost ($/tonne) Min yield
Operating Inputs			
Seed (Camelina)	3.56	1.93	5.26
Herbicides	27.01	14.66	39.91
Insecticides	0.00	0.00	0.00
Custom harvest	18.09	9.82	26.72
Fertilizer			
Ammonium phosphate (16-20-0)	9.87	5.35	14.58
Ammonium sulfate	6.36	3.45	9.39
Other			
Overhead, crop insurance	33.57	18.22	49.59
Fuel	15.78	8.56	23.31
Machinery repairs	10.69	5.80	15.79
Machinery labor	7.96	4.32	11.76
Operating interest	6.31	3.43	9.33
Total operating costs	**139.20**	**75.53**	**205.65**
Fixed Costs			
Equipment	47.03	25.52	69.48
Land investment	17.49	9.49	25.83
Total fixed costs	**64.52**	**35.01**	**95.32**
Total costs	**203.72**	**110.54**	**300.97**

[a]Derived from: (Jaeger and Siegel, 2008; Willamette Biomass Processors, 2010)

The main inputs to field costs are the cost of seeds, fertilizer, farm chemicals, and other costs such as machinery, land, labor, and insurance. Certified seeds, which are produced under stringent conditions to make them free of disease and weed contamination, are normally used and can be bought from seed growers and seed companies (Reaney et al., 2006). Nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) fertilizers are the most important inputs during growth of canola. Canola plants also benefit from other nutrients such as calcium (Ca), magnesium (Mg), iron (Fe), and boron (B) (Havlin et al., 2005) but producers rarely apply these nutrients in their fields. A high N fertilizer application rate increases the yield and protein content of canola but decreases the oil content (Malhi and Gill, 2004). This study considers the average price of fertilizer over 5 years. The price of the fertilizer considered for urea is $815/tonne, diammonium phosphate is $485/tonne and sulphate is $310/tonne (Agriculture and Agri-Food Canada, 2009b).

2.2.4.2 Storage cost

From harvesting to the vegetable oil processing plant, storage cost is incurred in two places: on-farm and local elevator storage. The on-farm storage cost is equal to 67 cents per tonne per month (or $8.05/tonne/year) based on capital and estimated costs of the storage capacity. The elevator storage cost of 96 cents/tonne/month (or $11.54/tonne/year) is based on the quoted elevator grain storage rate (Reichert and Vachal, 2003).

2.2.4.3 Transportation cost

It is assumed in this analysis that the area from which feedstock is drawn is circular. The center of the circular area is where the oil extraction plant is located. The oilseed yield distribution is considered uniform within the circular area. This assumption is a limitation of the model; however, there are concentrated areas of canola production in Alberta, such as Census Division 10 (CD10), which produce enough canola to support a 190 million L/year solvent extraction plant. It is further assumed that canola is transported through existing publicly maintained roads and trucks are used for transportation from the field to the oil extraction plant.

The average radius to any point within a circular area is $r_{av} = \frac{2}{3}r$, where r is the length of the radius within the circular area. Since not all transportation is in a straight line, a winding factor of 1.27 was used in this study (Overend, 1982; Sarkar and Kumar, 2009). Perlack and Turhollow considered a winding factor of 1.3 (Perlack et al., 2002). For the Province of Alberta, the fraction of the total harvest area used to grow canola to total harvest area is 25% (Alberta Agriculture and Rural Development, 2008).

The transportation cost has two components irrespective of its mode, i.e. truck, rail or ship. The fixed component of the cost of truck transportation is the loading and unloading cost ($/tonne). The variable component of the cost of truck transportation includes costs of wages for the driver, fuel, and maintenance ($/tonne/km). These variable costs are proportional to the distance travelled. The typical loading and unloading cost for truck transportation in North America is $3.26/green tonne (Reichert and Vachal, 2003). The variable transportation cost for a truck is $0.10/green-tonne/km (Reichert and Vachal, 2003). The total cost of transport of oilseeds ($/tonne) is expressed in Equation 2-1:

Eq (2-1): $TC = C_1 + C_2X$

Where:
TC = transportation cost of oilseeds ($/tonne)
C_1 = fixed cost parameter ($/tonne)
C_2 = distance-dependent cost parameter ($/tonne/km)
X = round trip distance (km)

The size of the processing plant determines the seed collection area. Thus, the total cost of transportation increases as processing plant capacity increases. Figure 2-1 shows the variation of the delivered seed cost (field cost plus transportation cost) with plant capacity. The transportation distance is proportional to the square root of the capacity of the plant and this is reflected by the curves in Figure 2-1.

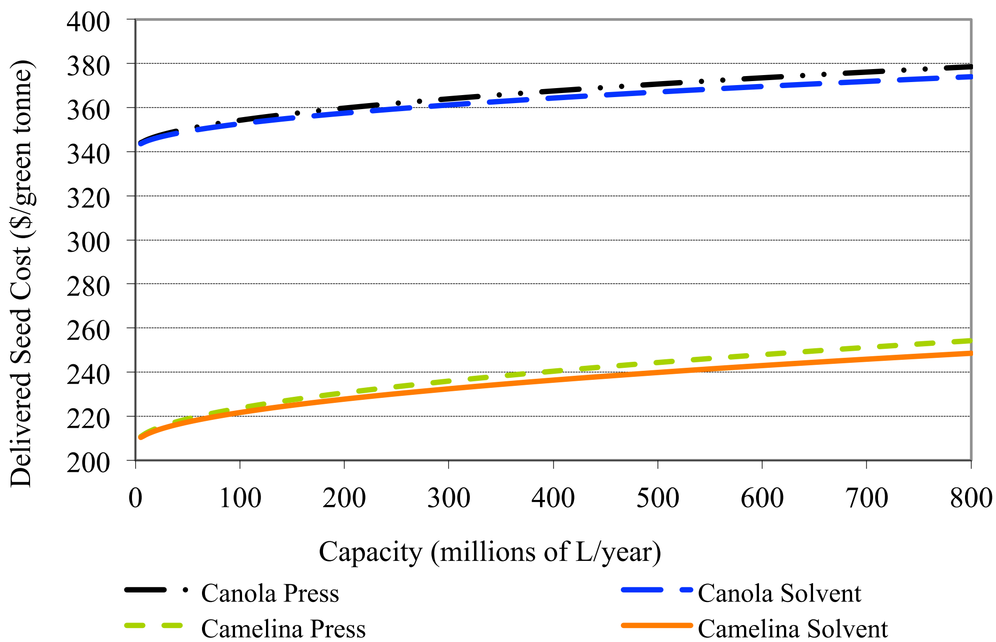


Figure 2-1: Delivered cost of seed as a function of processing plant capacity

2.2.4.4 Oil extraction capital and operating costs

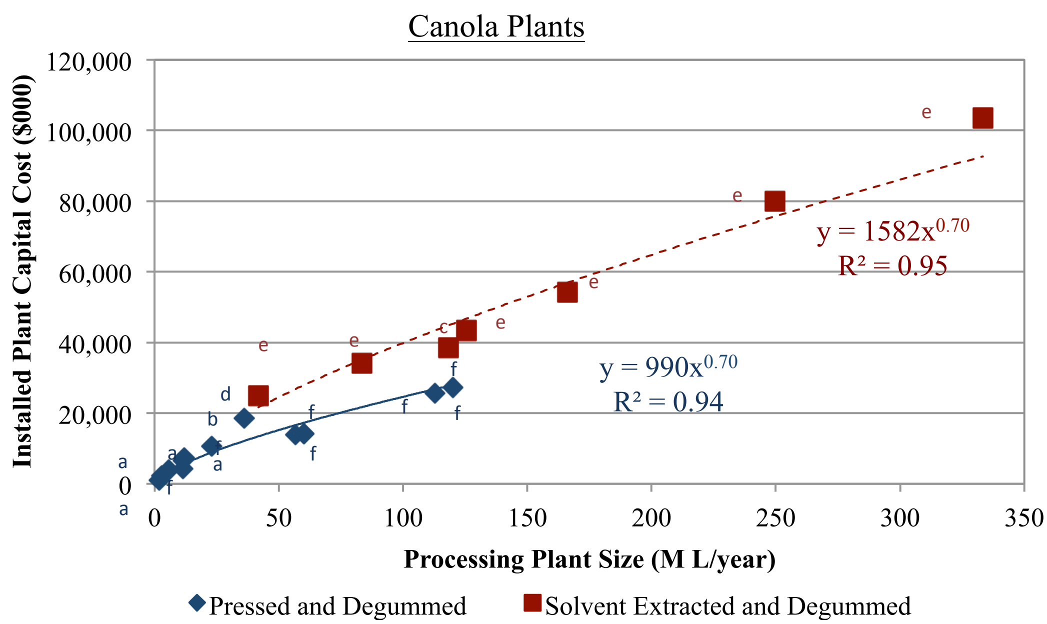
Capital cost will vary depending on process type (press plant or solvent plant), vendor, location, and current economic conditions. In this study, capital cost estimates for press plants and solvent plants were collected from a variety of sources including literature, industry vendors, industry experts, and through modeling. The capital costs are based on producing crude, degummed oil. Some data from literature was excluded because the facilities in the studies included processing equipment for oil refining or for processing soybeans (Center for Agribusiness and Economic Development, 2000; Schumacher, 2007). Also, some cost data from industry vendors in Asia was excluded because the estimates were extremely low compared to the other estimates collected in literature and from North American vendors. All of the capital cost data collected was for canola processing plants. There is very little data available for camelina processing plant capital costs.

The cost estimates were scaled to 2008 US dollars using the IHS Power Capital Cost Index (PCCI) (IHS Inc., 2010). The PCCI combines time varying data such as equipment cost, material cost, and labor cost so that capital costs can be scaled up or down depending on economic conditions of the base year and at the time of the cost estimate. The PCCI is based on power plants but also provides reasonable scaling for biomass processing facilities. The PCCI (without nuclear) data was used to scale the data for this study. Using the PCCI data, a capital cost estimate from the year 2003 could be scaled to 2008 as follows:

2008 Estimate = (2003 Estimate) X (189/116)

It is important to note that the PCCI peaked in 2008 at 189, so the capital costs presented in this report are likely higher than current capital costs. The estimates in this report can be scaled down to a 2010 estimate by multiplying by 0.931 (or 176/189).

Installation cost estimates collected from vendors ranged from approximately 30 – 70% of the capital equipment cost. Based on the authors' personal experience and consultation with industry experts (Takeda, 2010), an installation cost equal to 100% of the capital cost was used to estimate the installed capital cost for data obtained from vendors. The developed capital cost estimates for canola and camelina press plants and solvent plants at various scales are shown in Figure 2-2.



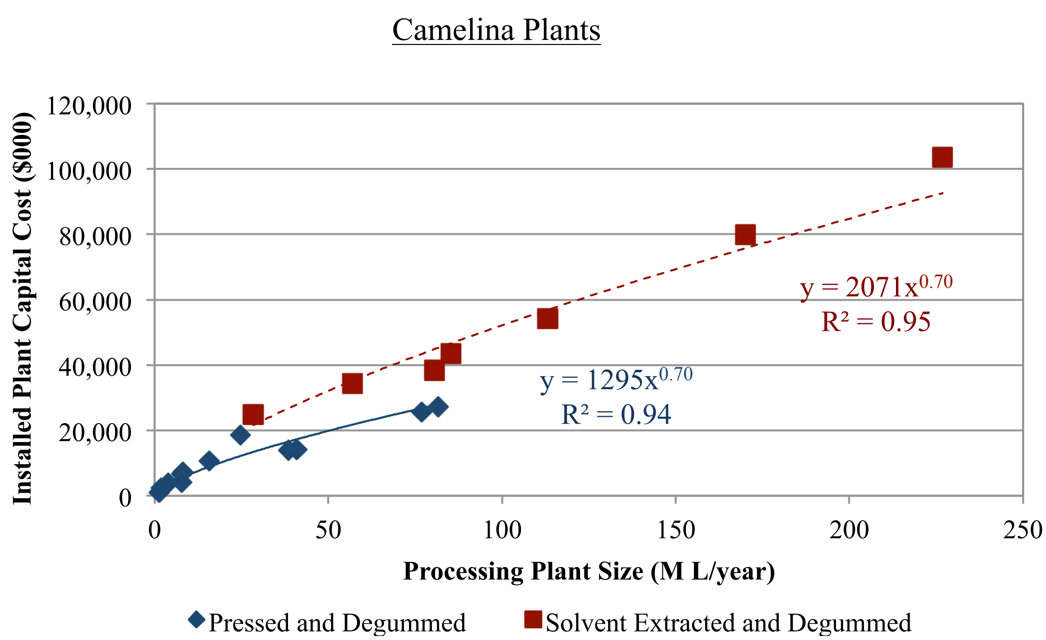


Figure 2-2: Developed capital cost estimates for oil extraction plants

Figure 2-2 sources:
[a](Nesbitt, 2010)
[b](Risner, 2010)
[c](Confidential Industry Vendor, 2010)
[d](The EDA University Center at Washington State University, 2003)
[e](Saville and Canola Council of Canada, 2006)
[f](Reaney et al., 2006)

It is clear from Figure 2-2 that press plants are typically smaller in terms of capacity compared to solvent plants. The difference in size is due to the lower oil extraction efficiency and lower capital cost of press plants. An important parameter shown in Figure 2-2 is the scale factor for the press plants and solvent plants. The scale factor is the exponent of the regression equations shown in Figure 2-2. The scale factor can be used to adjust costs from one capacity to another (Kumar et al., 2003) as shown in Equation 2-2:

Eq (2-2): $$\text{Cost 2} = \text{Cost 1} \times (\text{Capacity 2}/\text{Capacity 1})^{\text{Scale Factor}}$$

In this case, the scale factors are very close to 0.7. Typical scale factors for biomass processing facilities often range from 0.6 – 0.8 (Sultana et al., 2010). In terms of capital cost by category, approximately 58% of the costs are for major process equipment (seed presses, pressure vessels, pumps, contactors etc.), 7% are for seed storage and handling, 6% are for meal storage and handling, 1% are for oil storage and handling, 8% are for degumming, and 20% are for the motor control centers and control systems.

Although there is little data available for capital costs of camelina processing plants, the technology used for processing is nearly identical (Sandroni, 2010). Therefore, the capital cost estimates developed for canola processing plants were scaled using the difference in seed oil content between canola and camelina to develop capital cost estimates for camelina plants. The capacity of most equipment in canola processing plants is rated in terms of tonnes per day of raw feedstock. Since camelina seeds contain less oil than canola seeds, a larger camelina processing plant is required to produce the same volume of oil as a smaller canola processing plant. Based on seed oil content, the capital cost for a camelina processing plant of a given oil volume capacity will be 47% higher than the capital cost for a canola processing plant that produces the same volume of oil.

In this study, operating cost data was developed for canola press extraction and solvent extraction plants using data found in literature (Center for Agribusiness and Economic Development, 2000; Reaney et al., 2006; Saville and Canola Council of Canada, 2006) and from vendor estimates (Confidential Industry Vendor, 2010; Nesbitt, 2010; Risner, 2010). The operating costs can be divided into two parts: energy costs and labor costs. Energy costs consist of components such as steam, natural gas, electricity, water, chemicals, solvent, and water treatment. These costs were assumed to be constant on a $/L basis regardless of plant capacity. The labor costs generally decline on a $/L basis with increasing plant capacity because the plant capacity increases more rapidly than the number of people required to run the plant (Saville and Canola Council of Canada, 2006). Using the literature data and input from vendors, Table 2-5 was developed to determine the labor cost at various plant scales.

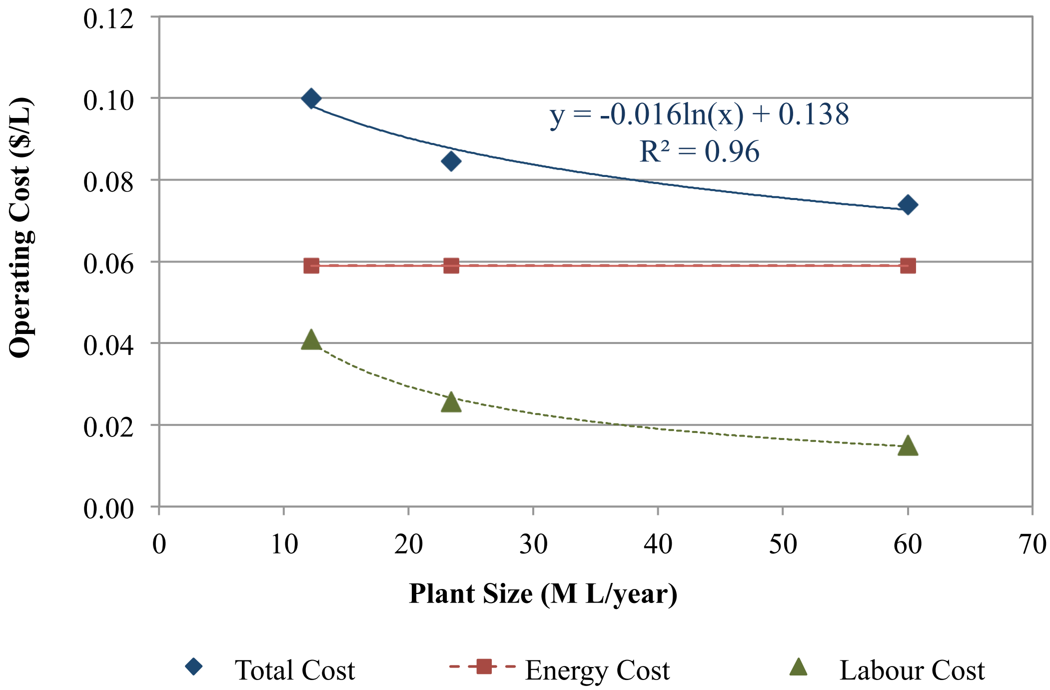
Table 2-5: Canola plant labor cost at various capacities

Plant Capacity (ML/year)	12 (Press)	23 (Press)	42 (Solvent)	60 (Press)	84 (Solvent)	125 (Solvent)	166 (Solvent)	208 (Solvent)	249 (Solvent)	333 (Solvent)
Plant manager	1	1	1	1	1	1	1	1	1	1
Quality control Manager	0	0	0	0	0	0	1	1	1	1
Controller	0	0	0	0	0	0	0	0	1	1
Administrative assistant	1	1	1	1	1	1	1	1	1	1
Shift team leader	0	0	1	0	1	1	1	1	1	1
Shift operator	2	2	4	4	4	4	4	5	5	6
Yard labor	0	0	0	0	0	1	1	1	1	1
Maintenance manager	0	0	0	1	1	1	1	1	1	1
Boiler operator	0	0	0	0	1	1	1	1	1	1
Maintenance worker	1	1	1	1	1	2	2	2	3	3
Electrician	0	1	1	1	1	1	1	1	1	2
Instrument technician	0	0	0	0	0	0	1	1	1	1
Total employees	5	6	9	9	11	13	15	16	18	20
Total labor cost	$500k	$600k	$900k	$900k	$1,100k	$1,300k	$1,500k	$1,600k	$1,800k	$2,000k
Labor cost ($/L)	0.041	0.026	0.022	0.015	0.013	0.010	0.009	0.008	0.007	0.006

The labor cost for a solvent plant of a given capacity was estimated to be slightly higher than the labor cost for a press plant because solvent plants use a more complex extraction process and generally use more process equipment. An average employee cost (including salary and benefits) of $100,000 per year was used.

When the energy and labor costs are combined, the overall operating cost on a $/L basis can be determined. The overall operating costs for a canola press plant and a canola solvent plant are shown in Figure 2-3. To determine the overall operating cost for the camelina processing plants, the costs for the canola plants were scaled using the ratio of seed oil content. This was the same method used to scale the capital costs; therefore the operating costs for camelina plants on a $/L basis are 147% of the operating costs for canola plants.

Canola Press Plant



Canola Solvent Plant

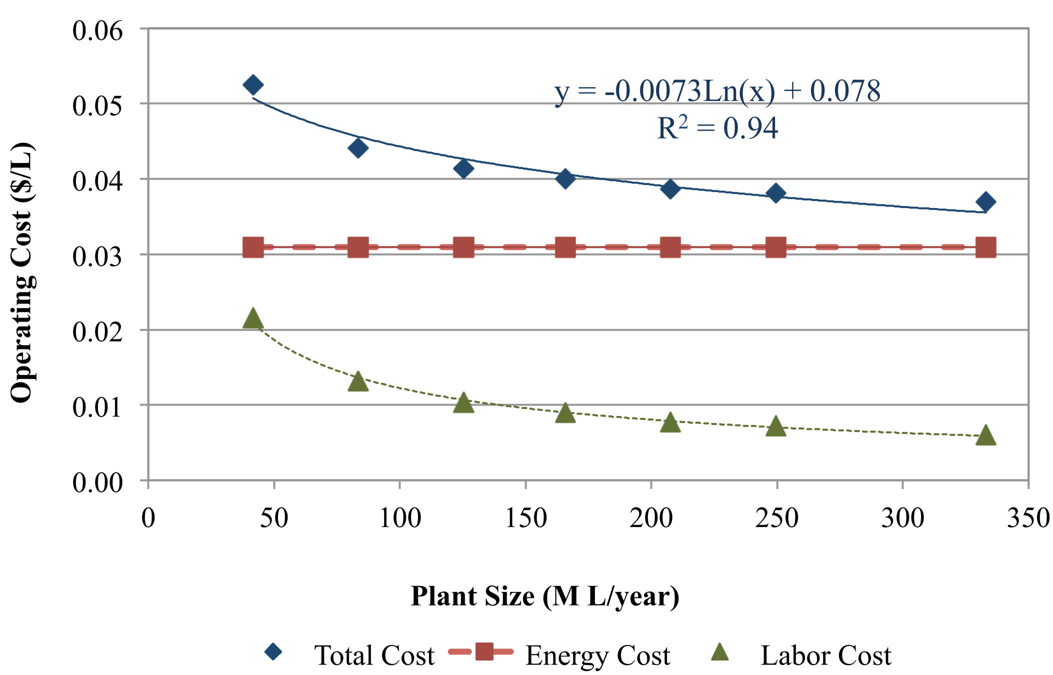


Figure 2-3: Operating costs for canola oil extraction plants

2.2.4.5 Co-products

Canola meal is commonly used as feed for a variety of livestock such as beef and dairy cattle, swine, and poultry (CanolaInfo, 2007). Camelina meal has recently been introduced as animal feed in the United States, but has only been approved by the US Food and Drug Administration for use for up to 10% of feed by weight for beef cattle and broiler chickens (Schill, 2010). There are primarily two companies in the US working to increase the approval percentages for camelina use as feed – Great Plains and Sustainable Oils (Schill, 2009). In this study, two scenarios for meal price have been examined. In one scenario, the assumed price of meal for both canola and camelina meal is $0.26/kg, which is the average price of canola meal in 2008 and 2009 (Canola Council of Canada, 2010c). In the other scenario, canola meal is sold at $0.26/kg but the camelina meal is assumed to be worthless.

2.3 Results and discussion

2.3.1 Probable location of processing plant

Based on the twelve-year average net production data in Table 2-1, the highest production areas of canola in Alberta are census divisions 10, 19, 5, 11, and 7, with census division 10 being highest and 7 being lowest of these divisions.

2.3.2 Optimum sizes and minimum oil production cost

Like most field-sourced biomass processing facilities, canola and camelina oil extraction plants exhibit interesting economic behavior as the size of the processing plant is increased. Initially as the size of the plant is increased, the cost of oil production decreases due to the economy of scale benefit associated with the capital costs. As the size of the plant is increased further, the seed transportation cost has an increasingly strong influence on the overall cost of oil production. The transportation cost per tonne of seeds increases rapidly as the plant capacity is increased because the collection area for the seeds increases, which increases the average distance that the seeds must be transported to the processing plant. Therefore, a point is reached at which the oil production cost is at a minimum. This point is where the plant size is economically optimal. The change in cost of oil production for canola and camelina oil extraction plants at various sizes is shown in Figure 2-4. The optimum sizes and minimum costs of production are also indicated on the graph. In Figure 2-4, the average yield is used and it is assumed that both canola and camelina meal can be sold for \$0.26/kg. The discounted cash flow sheets for canola and camelina oil extraction plants at their optimum sizes are given in Appendix A.

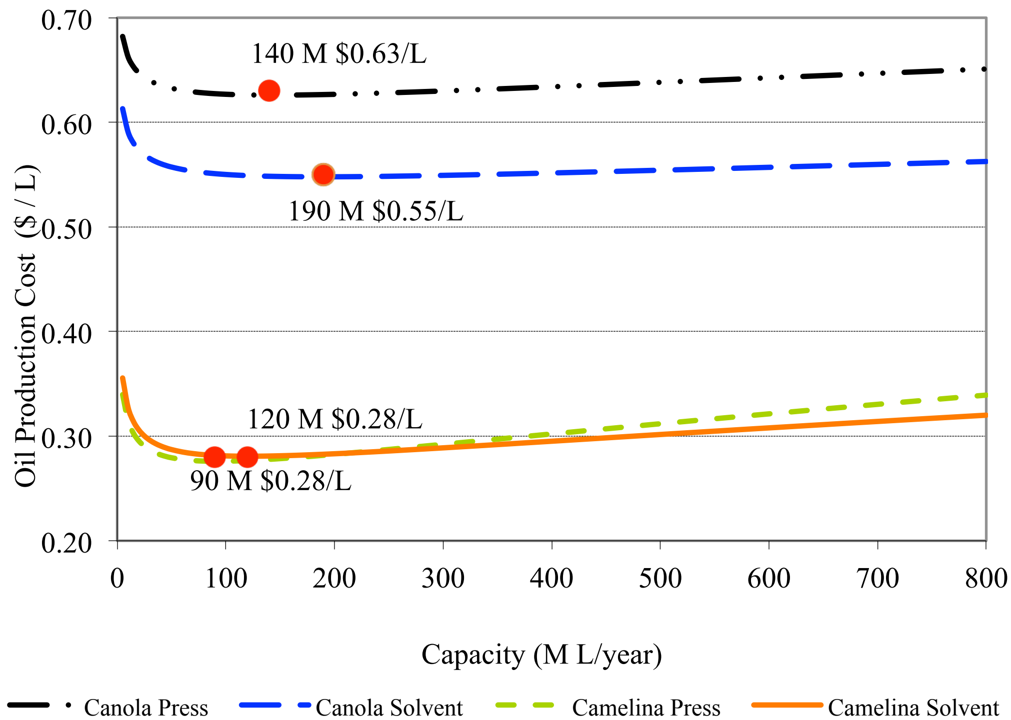


Figure 2-4: Change in vegetable oil production cost with processing plant capacity (average yield, meal price of $0.26/kg)

Although there is an economically optimal size of oil extraction plant for canola and for camelina, a range of plant sizes could be built without significantly impacting the total oil production cost. The flatness of the curves in Figure 2-4 shows that the size of the oil extraction plants can be increased beyond the optimum plant size by 100 million L/year, without increasing the total production cost by more than $0.01 per liter. Note that the slope of the curves for the camelina plants is greater than the slope for the canola plants due to the lower oil content of camelina. A lower oil content means greater quantities of seeds are required to produce a given oil volume, which results in transportation costs increasing faster for camelina plants as plant size is increased.

For canola oil extraction plants, field cost is the largest cost component, which makes up approximately 85% of the total oil cost, followed by transportation cost (9.1-10.3%), operating and maintenance cost (2.6-3.4%), and capital recovery (1.7-3.1%). For camelina oil extraction plants the field cost is also the largest cost component at approximately 75%, followed by transportation cost (16.5-18.7%), operating and maintenance cost (3.8-4.9%), and capital recovery (1.8-3.6%). Due to the additional processing equipment required for solvent extraction plants, the capital cost and the operating and maintenance cost for solvent plants contribute more to the overall cost of production than they do for press plants.

Yield per unit area is a very important factor in the processing plant economics. As yield increases, the field cost per tonne of seed and the feedstock collection area decreases for an extraction plant of a given size. Therefore, a higher yield results in a larger optimum plant size and a lower cost of production. Table 2-6 summarizes the optimum plant sizes, minimum costs of production, and feedstock collection areas for the four processing plants examined in this study at average, maximum, and minimum yield.

Table 2-6: Optimum plant sizes and minimum costs of production

	Average Yield	Maximum Yield	Minimum Yield
Canola Press Plant			
Yield (green tonne/ha)	1.66	2.12	1.21
Optimum Size (M L/year)	140	170	100
Minimum Cost of Production ($/L)	0.63	0.41	0.98
Feedstock Collection Area (km^2)	10,942	10,257	10,980
Meal Price ($/kg)	0.26	0.26	0.26
Canola Solvent Plant			
Yield (green tonne/ha)	1.66	2.12	1.21
Optimum Size (M L/year)	190	210	130
Minimum Cost of Production ($/L)	0.55	0.38	0.83
Feedstock Collection Area (km^2)	11,482	9,796	11,036
Meal Price ($/kg)	0.26	0.26	0.26
Camelina Press Plant			
Yield (green tonne/ha)	2.25	4.15	1.53
Optimum Size (M L/year)	90	160	60
Minimum Cost of Production ($/L)	0.28	-0.13	0.69
Feedstock Collection Area (km^2)	7,483	7,069	7,538
Meal Price ($/kg)	0.26	0.26	0.26
Camelina Solvent Plant			
Yield (green tonne/ha)	2.25	4.15	1.53
Optimum Size (M L/year)	120	190	90
Minimum Cost of Production ($/L)	0.28	-0.03	0.60
Feedstock Collection Area (km^2)	5,786	5,466	5,828
Meal Price ($/kg)	0.26	0.26	0.26

In general, it is much cheaper to produce camelina oil than it is to produce canola oil. In fact, in the maximum yield case, the minimum oil production cost is negative for both the camelina press plant and the camelina solvent plant. Although this may seem strange at first, the negative cost means that the processing plant makes so much money from selling meal that the plant could afford to pay to have the oil taken away and the plant would still earn a 10%

internal rate of return. However, since camelina meal is not commonly used in Alberta for animal feed, it is also important to examine the scenario in which camelina meal cannot be sold. Figure 2-5 shows the optimum plant sizes and minimum costs of production when canola meal can be sold for \$0.26/kg and camelina meal cannot be sold.

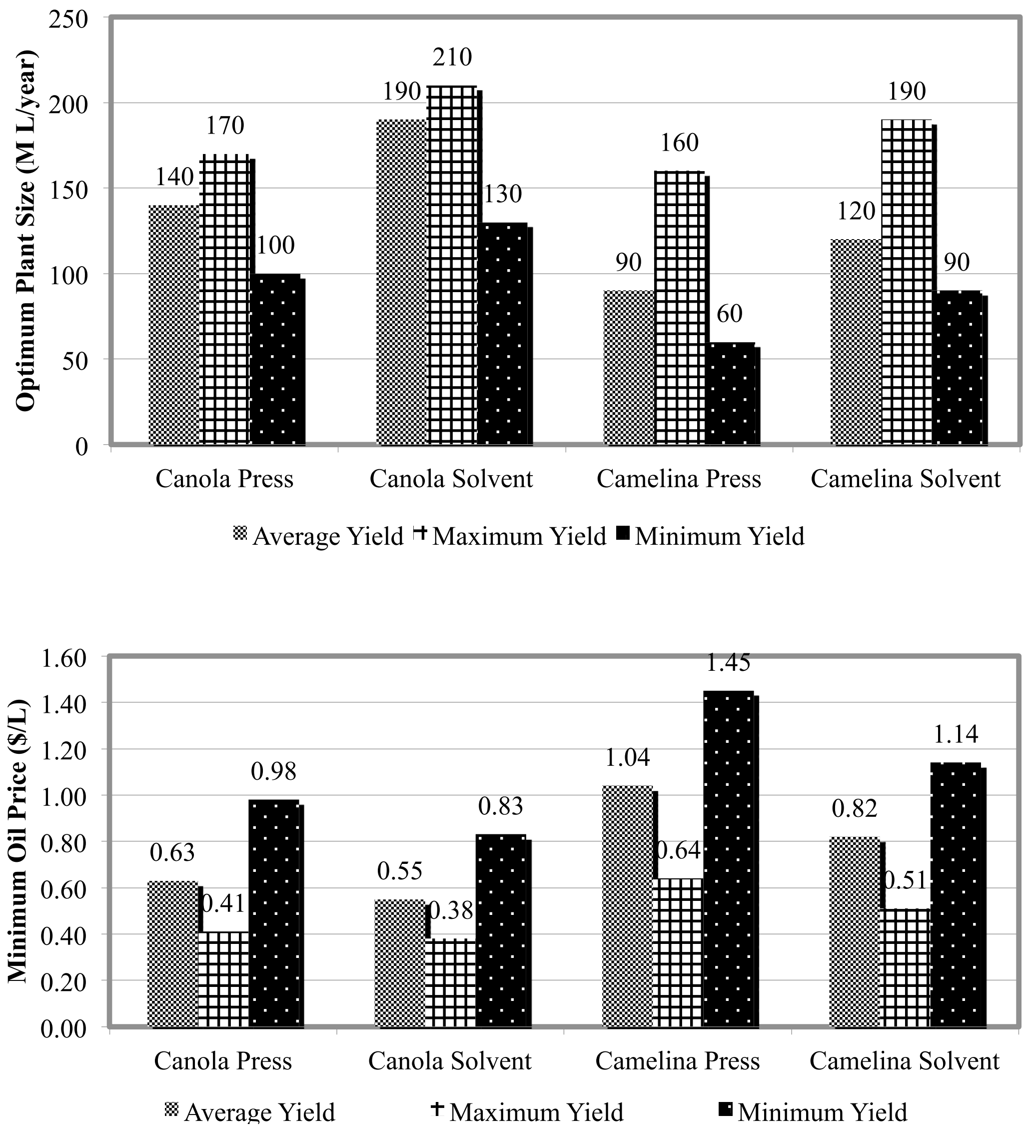


Figure 2-5: Optimum plant sizes and minimum costs of oil production (canola meal \$0.26/kg, camelina meal \$0/kg)

Clearly, both the ability to sell meal and the yield per unit area have a significant impact on the economics for oil extraction plants. If camelina meal can be sold for the same price as canola meal, the economics for camelina oil extraction plants are far better than the economics for canola oil extraction plants. However, if camelina meal cannot be sold, then it is cheaper to produce canola oil.

2.3.3 Comparison of results with existing plants in Alberta

The optimum plant sizes developed in this study match well with existing plants in Canada and in Alberta. In Canada, there are 13 large-scale canola oil extraction plants, which produce approximately 1.8 billion liters of canola oil each year (Canola Council of Canada, 2010a). Assuming that all plants are of the same size, that works out to about 137 million liters of production per year per plant. Using a 90% capacity factor, the average plant size would be approximately 152 million L/year. There are no large-scale camelina oil extraction plants in Canada – likely due to a lack of demand since camelina oil is not used for food and camelina meal has not been widely accepted as animal feed.

In the Province of Alberta there are 3 major canola oil extraction facilities owned by Bunge, ADM, and Canbra (Richardson), located in Fort Saskatchewan, Lloydminster, and Lethbridge respectively (Saville and Canola Council of Canada, 2006). The capacity of the Bunge plant is estimated as 120 million L/year based on a study done by the Canadian Bioenergy Corporation that looked at building a 114 million L/year biodiesel plant adjacent to the plant (Kelwin

Management Consulting and Government of Manitoba, 2006). The Canbra plant capacity is approximately 130 million L/year (BFuel Canada Corp., 2009) and data showing the capacity of the ADM plant was unavailable. Both the Bunge and the Canbra plant are smaller than the optimum size identified in this study, but the Canbra plant may expand to approximately 208 million L/year, which is much closer to the optimum size for Alberta.

2.3.4 Comparison with past oil prices

The minimum cost of canola oil production developed in this study also matches well with historical canola oil prices. The trend of canola oil prices in Canada since 1990 generally fluctuates between \$0.40 to \$0.90/L and has an average of \$0.67/L (Canola Council of Canada, 2010c). This price range makes sense because the range of prices developed in this study for canola solvent extraction plants is similar: from \$0.41 - \$0.89/L with a minimum cost of \$0.59/L in the average yield case.

2.3.5 Implications for renewable fuels standards in Canada

The amount of diesel fuel sold in Alberta from 2006 to 2010 has averaged approximately 3.5 billion L/year (Statistics Canada, 2011). In order to meet the 2% RFS, 71 million liters of HDRD or biodiesel is required annually. This demand corresponds to 74 million liters of vegetable oil, based on a 95% conversion efficiency, which is less than one optimum sized canola oil solvent extraction plant. Canada as a whole uses approximately 16.6 billion L/year of diesel fuel annually (Statistics Canada, 2011), which corresponds to a vegetable oil demand of approximately 350 million liters - nearly 2 optimum sized canola solvent extraction plants.

If all of Alberta's canola production was converted to oil, approximately 1.1 billion liters of oil could be produced. Therefore, Alberta is capable of supplying enough canola for up to a 6% RFS across Canada. However, since the majority of canola currently produced in Alberta is dedicated to food production, directing all of Alberta's canola towards fuel production would likely add upward pressure to worldwide canola prices.

2.3.6 Sensitivity analysis

In any techno-economic analysis, there are many variables that can affect the model outputs. In this study, the main variables that had an impact on optimum plant size and minimum cost of oil production are shown in Figure 2-6 and Figure 2-7 respectively. All of the sensitivities considered compare the change in optimum plant size or minimum oil production cost for the average yield case.

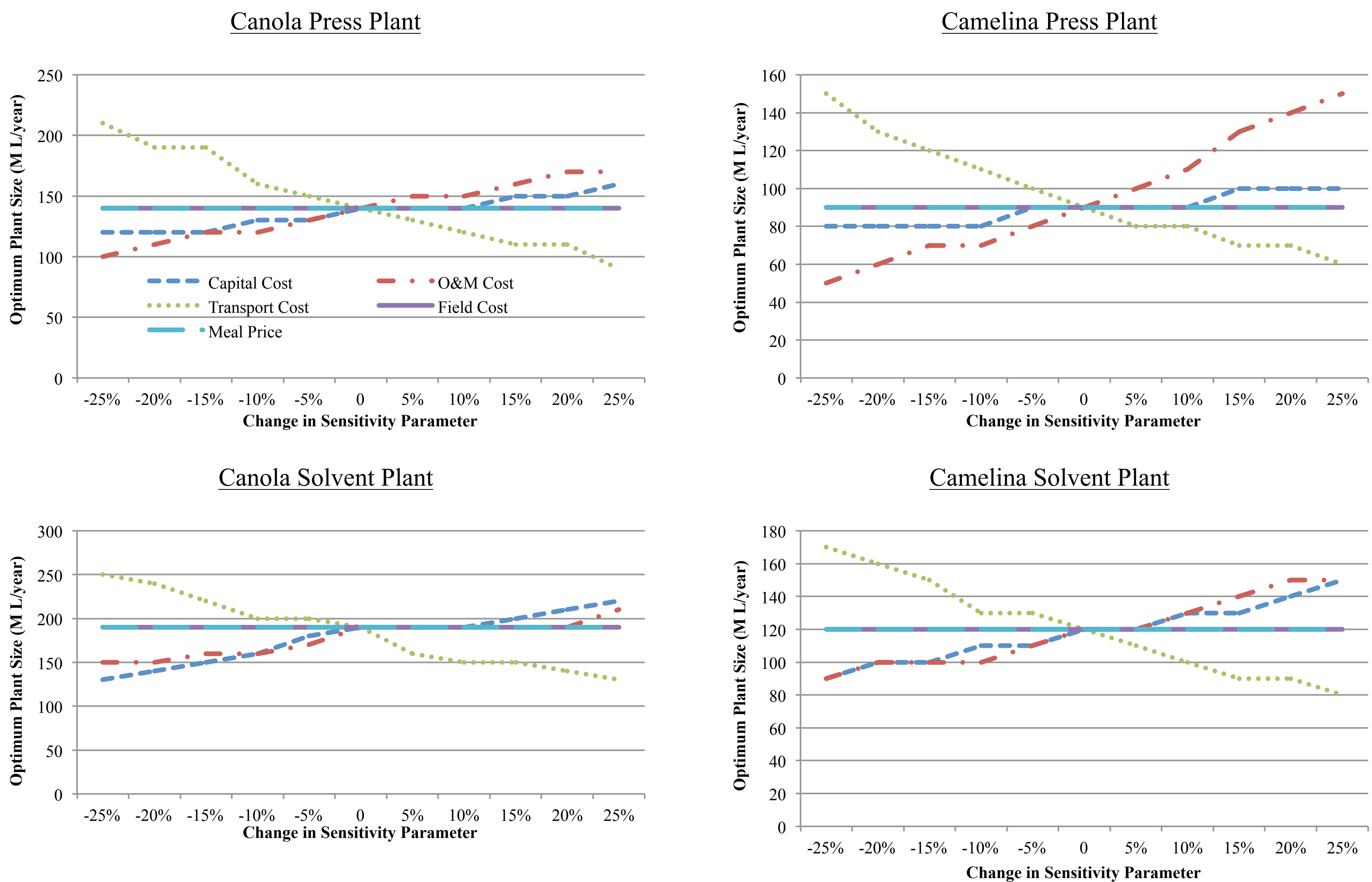


Figure 2-6: Sensitivity of optimum plant size

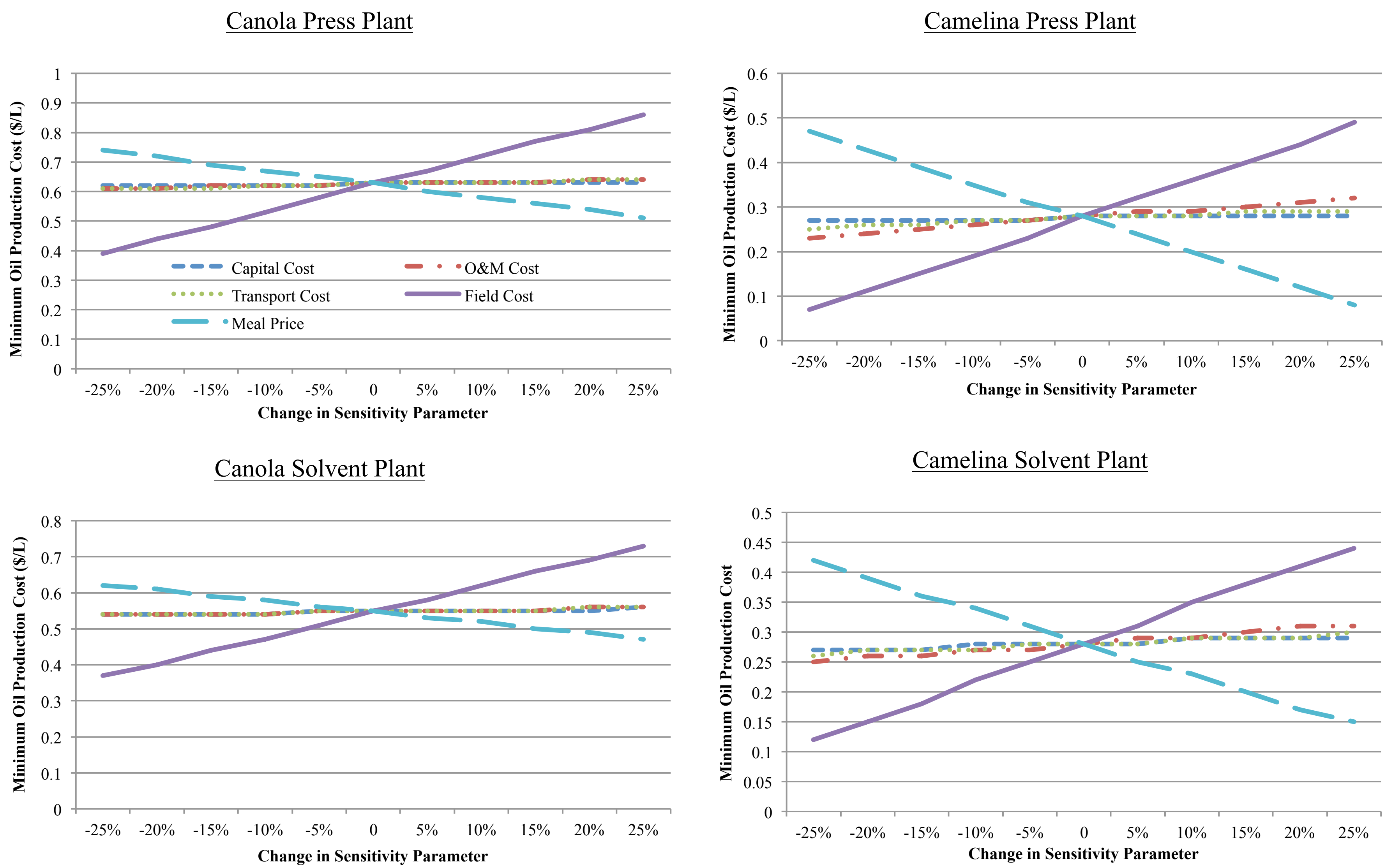


Figure 2-7: Sensitivity of minimum oil production cost

Some key observations from the sensitivity analysis are as follows:

- Changes in capital, operating and maintenance (O&M), and transportation cost have a large effect on optimal size but a very small effect on minimum cost of oil production. For a canola solvent plant, a 25% change in these parameters only changes the oil production cost by a few cents per liter but result in an optimum size range from 130-250 million liters per year.
- Changes in meal price and field cost do not impact optimal plant size but have a large impact on minimum cost of oil production. For a canola solvent plant, a 25% change in field cost results in an oil production cost range of \$0.37-\$0.73/L and a 25% change in meal price results in an oil production cost range of \$0.47-\$0.62/L. Camelina plant oil production cost is especially sensitive to changes in meal price because for a given volume of oil production, camelina seeds produce more meal than canola seeds.
- For O&M cost changes, the optimal size sensitivity is greater for press plants and the minimum cost sensitivity is greater for camelina plants.
- Camelina plant optimal size is more sensitive to transportation cost changes than canola plant optimal size.

2.4 Conclusions

The study estimated the optimum size of feedstock processing plants for production of HDRD in Western Canada. For the average yield case, the optimum plant sizes and minimum costs of oil production are 140 million L/year and \$0.63/L (canola-press), 190 million L/year and \$0.55/L (canola-solvent), 90 million L/year and \$0.28/L (camelina-press), and 120 million L/year and \$0.28/L (camelina-solvent). The cost of camelina oil is much lower than the cost of canola oil unless camelina meal cannot be sold. Field cost contributes most to overall oil cost (75-85%), followed by transportation cost (9-19%), O&M cost (3-5%), and capital recovery (2-4%). The sensitivity analyses conducted determined that the oil cost is most sensitive to field cost and meal price, while optimum plant size is most sensitive to transportation cost, capital cost, and O&M cost.

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3 Techno-Economics of Converting Canola Oil and Camelina Oil to Renewable Diesel

3.1 Introduction

Over the past decade, governments and environmental groups have pushed energy companies towards energy sources that are more sustainable than fossil fuels. However, when it comes to transportation fuels, fossil fuels are hard to displace because they are extremely convenient to use. It is very difficult to replace all of the processing facilities, pipelines, fueling stations, and vehicles that already exist to produce, distribute, and consume fossil fuels. In order to smooth the transition to sustainable energy, people have started to turn to biofuels, which can make use of the infrastructure already in place for fossil fuels like gasoline and diesel. Biofuels have lower greenhouse gas (GHG) footprints over their life cycles compared to fossil fuels and are produced from biomass, which is a renewable feedstock; the amount of CO_2 released during biomass combustion is nearly the same as that taken up by the plants during their growth. In addition, biomass is the only renewable resource that can be used to produce liquid fuels directly.

Two main types of diesel can be produced from biomass and can substitute for fossil resource-based diesel: biodiesel, and renewable diesel (Knothe, 2010). These fuels are typically blended with petroleum diesel and burned in unmodified diesel engines. The term ‘renewable diesel’ has been used in literature to refer to several types of renewable diesel but most commonly refers to hydrogenation-derived renewable diesel (HDRD), which is the focus of this thesis. Both biodiesel and HDRD can be produced from vegetable oils such as canola oil, camelina oil, sunflower oil, soy oil, or palm oil to name a few (Kalnes et al., 2007; Wells, 2011a; Šimáček et al., 2010).

The differences between biodiesel and HDRD lie in the processing methods and final product composition. Biodiesel is composed of fatty acid methyl-esters and is produced via transesterification, which consists of reacting the triglycerides in the vegetable oil with an alcohol (usually methanol) in the presence of an alkaline or acid catalyst (Kubickova and Kubicka, 2010). On the other hand, HDRD is generally composed of n-alkanes, which can be produced by reacting the triglycerides in the vegetable oil with hydrogen under high pressure, high temperature conditions in the presence of a catalyst (Wells, 2011a) – a process commonly referred to as hydroprocessing. Several different catalysts and processing methods can be used for HDRD production and are discussed later in this chapter. Energy companies are becoming increasingly interested in producing HDRD rather than biodiesel because HDRD's chemical composition is much closer to that of petroleum diesel and HDRD can have better cold flow properties than biodiesel (Kalnes et al., 2007; Guzman et al., 2010; Šimáček et al., 2011).

Although the use of biodiesel and HDRD is not yet widespread in North America, production is growing. Production growth for these fuels is mostly due to recently implemented renewable fuel standards legislation, such as the legislation in the Province of Alberta, Canada, which requires diesel sold to contain two percent biodiesel or HDRD (Government of Alberta, 2011). At this point in time in Canada, production growth of biodiesel and HDRD must be driven by legislation because these fuels are more expensive to produce than conventional diesel. Many studies have been completed on the cost of producing biodiesel (Haas et al., 2006; Saville and Canola Council of Canada, 2006; Marchetti et al., 2008) but fewer authors have looked into the cost of producing HDRD.

Some of the economic studies in literature include the cost of producing HDRD from bio-oil (Jones et al., 2009; Sadhukhan and Ng, 2011), the cost of producing Fischer-Tropsch liquids (Wright and Brown, 2007), and the cost of co-processing bio-feedstocks with petroleum feedstocks in oil refineries (Marker, 2005). Kalnes et al. (2009) and Marker (2005) examined the economics of producing HDRD from vegetable oil but did not analyze the impact of processing plant size on production cost and did not quote overall HDRD production costs. Wright and Brown (2007) analyzed the influence of processing plant size on the production cost of various alcohols, hydrogen, and Fischer-Tropsch liquids but did not include HDRD. There is also very limited research in Canada for production of HDRD. This study is an effort to fill a significant gap in the literature by estimating the cost of production of HDRD from canola or camelina oil at various production plant sizes through development of data-intensive techno-economic models, and by identifying the factors that have the greatest influence on production cost.

3.2 Background

3.2.1 Biodiesel vs. Renewable Diesel

The terms “biodiesel” and “renewable diesel” (HDRD) are often used interchangeably by the public to describe diesel fuel substitutes derived from biomass. However, there are many important distinctions between the two fuel types. The most notable difference is that the chemical compounds in biodiesel contain oxygen, whereas the chemical compounds in HDRD do not. The presence of oxygen in biodiesel causes a reduction in heating value (Marker, 2005) and a reduction in fuel stability compared to HDRD (Kalnes et al., 2007, 2009). In terms of general fuel properties, biodiesel and HDRD fall under different standards. In North America, the ASTM standard D6751 is used for biodiesel. However, since the composition of HDRD is so similar to petroleum diesel, the ASTM standard D975 for petroleum diesel can also be used for HDRD. Some of the main requirements of each standard are shown in Table 3-1 below. Note that although the minimum cetane number for ASTM D975 is 40, the cetane number of HDRD is much higher (Kalnes et al., 2009; Kubickova and Kubicka, 2010; Šimáček et al., 2010), thereby increasing its value with refiners as a blending component.

Table 3-1: ASTM Standards for Biodiesel and HDRD

Requirement	ASTM D6751 Biodiesel	ASTM D975 No. 2 Diesel
Kinematic Viscosity (at 40°C)	1.9 – 6.0 mm^2/s	1.9 – 4.1 mm^2/s
Cetane Number	47 min	40 min
Flash Point	130°C min	52°C min
Cloud Point	Report	Report
Pour Point	-	Report
Phosphorous Content	10 mg/kg max	-
Oxidative Stability (at 110°C)	3 hours	-
Distillation Temperature	360°C max	282 – 338°C

For geographic regions with cold climates, the most important difference between biodiesel and HDRD is the difference in low temperature properties. Low temperature properties of concern include cold filter plugging point (CFPP) and cloud point (CP). CFPP is "the lowest temperature at which fuel will still flow through a specific filter" and CP is the temperature at which the fuel begins to appear cloudy due to wax crystallizing (British Petroleum, 2002).

For biodiesel, the CFPP can range from -40°C to -7°C and the CP can range from -4°C to 13°C (Canakci and Sanli, 2008) - likely not acceptable for northern climates. For HDRD, the low temperature properties are highly dependent on processing conditions. If HDRD is produced at higher temperatures, greater proportions of i-alkanes and short chain n-alkanes are produced, which improves the fuel's low temperature properties (Šimáček et al., 2009, 2011). Unfortunately, at higher temperatures, undesirable aromatics also tend to form (Šimáček et al., 2011). If the production process includes an isomerization step, the low temperature properties can be drastically improved (Kalnes et al., 2007; Šimáček et al., 2011). NESTE, a major producer of HDRD in Finland, uses an isomerization step in its process and can vary the CP of its HDRD from -5^{o}C to -30^{o}C (Brady et al., 2007; Šimáček et al., 2009). This flexibility in low temperature properties for HDRD is very beneficial for producers in climates with wide temperature variations such as Canada.

In addition to advantageous fuel properties, HDRD also has some economic advantages over biodiesel. First, biodiesel production creates a co-product called glycerol, and as biodiesel production increases it is likely that the price of glycerol will drop, which will negatively impact biodiesel economics. HDRD is not sensitive to co-product prices because the co-product from HDRD production is propane (Marker, 2005; Guzman et al., 2010), which does not need to be sold; propane can be used as fuel gas at the production plant or steam-reformed to provide hydrogen for the HDRD production process. Second, current biodiesel production technology uses a homogeneous catalyst (usually NaOH), which is consumed in the process and must be repurchased. HDRD uses one of several heterogeneous catalysts that are not consumed in the process and can be re-used. Recent research has shown that in terms of investment cost, HDRD is comparable to biodiesel (Kalnes et al., 2007, 2009; Guzman et al., 2010) and overall production cost for HDRD could be less than biodiesel (Marker, 2005). The superior fuel properties of HDRD may also allow it to command a price premium as a diesel-blending component (Kalnes et al., 2009).

From an environmental perspective, HDRD appears to have advantages as well. Biodiesel production consumes significant quantities of methanol, which is usually derived from natural gas and the methanol production process is energy-intensive (Marker, 2005). Thus, methanol consumption usually increases the life-cycle greenhouse gas emissions (GHGs) for biodiesel production (Marker, 2005). Biodiesel advocates might counter with the fact that HDRD production requires hydrogen, which is also typically derived from natural gas. However, the propane produced in HDRD production could be re-formed to provide more than enough hydrogen to run the process (Kalnes et al., 2007). Therefore, from a life-cycle perspective, some researchers claim that life-cycle GHGs are lower for HDRD than biodiesel (Marker, 2005; Kalnes et al., 2007, 2009). A detailed assessment of GHG emissions in the production of HDRD is discussed in Chapter 4 of this thesis.

3.2.2 Commercial Renewable Diesel Production

Renewable diesel is produced commercially by a variety of companies. Some of the major producers are Neste, ConocoPhillips, Petrobras, and Syntroleum. Further details regarding each company's plant size and location are shown in Table 3-2.

Table 3-2: Commercial Renewable Diesel Producers

Company	Plant Location	Capacity (bbl/day)	Capacity (M L/year)	On-Stream	Reference
Neste	Porvoo, Finland	~3,400	~197	2007	Neste Oil, 2008
Neste	Naantali, Finland	~3,400	~197	2009	Neste Oil, 2008
Neste	Tuas, Singapore	~16,000	~929	2010	Neste Oil, 2010
Neste	Rotterdam, Netherlands	~16,000	~929	2011	Neste Oil, 2011
ConocoPhillips	Cork, Ireland	1,000	~58	2006	ConocoPhillips, 2007
ConocoPhillips	Borger, USA	Suspended	Suspended	2007	ConocoPhillips, 2008
Petrobras	Quixada, Brazil	~1,000*	~58*	2008	Petrobras, 2009; Global Energy, 2008; Green Car Congress, 2010
Petrobras	Candeias, Brazil	~1,000*	~58*	2008	Petrobras, 2009; Green Car Congress, 2010
Petrobras	Montes Claros, Brazil	~1,000*	~58*	2009	Petrobras, 2009; Green Car Congress, 2010; Biofuels Digest, 2009
Syntroleum	Geismar, USA	~5,000	~290	2010	Syntroleum, 2010

*Production capacity may have been increased in 2009 to ~110 million L/year (1,900 bpd)

3.2.3 Renewable Diesel Production Methods

The Renewable Diesel Subcommittee in the United States defines renewable diesel as "any of several diesel fuel substitutes, produced from renewable feedstocks, that chemically are not esters and thus are distinct from biodiesel" (Brady et al., 2007). Based on this definition, there are a number of different chemical processes that can be used to create a product that meets the criteria for renewable diesel. Each process uses reactions between the triglycerides in vegetable oil and hydrogen to form a primary product of n-alkanes and a smaller proportion of i-alkanes, aromatics and cycloalkanes (Šimáček et al., 2011). The reactions take place in the presence of a catalyst at high temperature and high pressure, and can use of a variety of vegetable oil feedstocks such as canola oil, camelina oil, palm oil, sunflower oil, or soy oil. Common reaction steps that occur are: saturating double bonds between carbon atoms with hydrogen (hydrotreating), removing oxygen as H_2O, CO, or CO_2 (hydrodeoxygenation or hydrodecarboxylation), breaking long hydrocarbon chains into short chains (hydrocracking), and re-arranging the atoms in hydrocarbon chains to form isomers (isomerization). Hydrotreating and oxygen removal usually take place but hydrocracking and isomerization occur to varying degrees depending on the process. The catalyst type used for production influences all of these reactions.

Kubickova and Kubicka (Kubickova and Kubicka, 2010) reviewed a range of catalysts that can be used for HDRD production. In their paper, the catalysts for HDRD production are broken into two broad categories: supported metal sulfide catalysts, and supported noble metal catalysts. Topsoe et al. (1996) noted that supported metal sulfide catalysts are commonly used for hydrotreating and hydrocracking petroleum but require a source of sulfur to keep their activity level high. Sulfur is not present in vegetable oil so an external source of sulfur is needed for HDRD production with metal sulfide catalysts. These catalysts include $NiMo/Al_2O_3$, $CoMo/Al_2O_3$, Ni/Al_2O_3, or Co/Al_2O_3 and are typically used for HDRD production in a temperature range of 250-360^oC and pressure range of 0.7-15 MPa (Kubickova and Kubicka, 2010).

Supported noble metal catalysts are also used for hydrotreating, hydrocracking, and isomerization (Rigutto et al., 2007); these catalysts have shown great promise for HDRD production because they have a high selectivity to alkanes and consume less hydrogen than metal sulfide catalysts (Kubickova and Kubicka, 2010). Supported noble metal catalysts include Pd/C, Pt/C, Pd/Al_2O_3, and Pt/Al_2O_3, which are often used in a temperature range of 300-400^oC and pressure range of 1.5-4.2 MPa (Kubickova and Kubicka, 2010). Activated carbon is usually preferred over Al_2O_3 as the support for noble metal catalysts (Kubickova and Kubicka, 2010) because Pt and Pd on Al_2O_3 tend to form an undesirable symmetrical ketone (Snåre et al., 2006). Pd is also typically preferred over Pt because Pd is more active (Kubickova and Kubicka, 2010). If isomerization is included in the HDRD production process, it is usually accomplished using a separate catalyst (Luo et al., 2010), such as $Pt/HZSM\text{-}22/Al_2O_3$, which has been used to isomerize hydrotreated sunflower oil (Hancsok et al., 2007). In this paper, the reactions for hydroprocessing are based on using a Pd/C catalyst to convert canola oil and camelina oil to HDRD without using an isomerization step.

3.2.4 Feedstock Characteristics

Canola (*Brassica Rapa or Brassica Napus*) and camelina (*Camelina Sativa)* are the two feedstocks considered in this study for HDRD production. Canola was developed in Canada from rapeseed, and has a low erucic acid content compared to traditional rapeseed. Canola was selected because it is readily available in Western Canada, where it serves as a major supply of edible oil and animal feed. Camelina, on the other hand, is not widely grown in Western Canada but has been tested on a trial basis (Agriculture and Agri-Food Canada, 2009) and shows great promise as a feedstock for HDRD production. The United States has also recognized the potential of camelina for biofuel production; there have been trials in Montana, Wyoming, Colorado and Nebraska (Lafferty et al., 2009), and the U.S. Navy has used camelina bio-jet fuel for some aircraft (Brink, 2012).

Compared to canola, camelina does not compete with food and has a shorter growing season, better cold weather tolerance, and requires less fertilizer, pesticides, and water. However, a major drawback of camelina is that camelina meal has not been approved for animal feed in Canada, and has only been approved by the US Food and Drug Administration for up to 10% by weight for beef cattle and broiler chickens (Schill, 2010). If meal cannot be sold as animal feed, a major revenue stream for the oilseed producers is lost, which drives up the overall vegetable oil production cost.

Canola oil and camelina oil are typically produced by crushing the seeds to extract the oil, separating the oil from the meal, then using a solvent (hexane) to extract residual oil from the meal (Mag, 2011). Small scale oil extraction plants may only crush the seeds, which results in a lower capital cost but also lower oil extraction efficiency and higher overall oil production cost (Miller et al., 2012). Further details regarding the oil extraction process can be found in literature (CanolaInfo, 2007; Mag, 2011). After extraction, the oil is normally degummed in order to meet the quality requirements of HDRD producers (Halonen, 2010). Previous work (Miller et al., 2012) has shown that the production cost for vegetable oil in Western Canada is approximately \$0.55/L for canola oil and \$0.28/L for camelina oil and has been discussed in detail in Chapter 2. These production costs are for oil extraction plants at their economically optimal sizes and use a meal price of \$0.26/kg. If camelina meal cannot be sold, the production cost for camelina oil is approximately \$0.82/L.

Although the oil extraction processes for canola and camelina are similar, the compositions of the oils are significantly different (Labs-Mart Inc., 2010a, 2010b). As with other vegetable oils, canola oil and camelina oil are primarily made up of fatty acids linked by glyceride backbones (triglycerides). The fatty acid profiles of canola oil and camelina oil are shown in Table 3-3.

Table 3-3: Fatty Acid Profiles (w/w %) for Canola Oil and Camelina Oil

Fatty Acid	Canola[a]	Camelina[b]
16:0 Palmitic	3.9	5.4
18:0 Stearic	2.0	2.5
18:1 Oleic	67.9	17.3
18.2 Linoleic	18.2	20.5
18:3 Linolenic	7.2	28.0
20:1 Eicosenoic	-	19.0
20:2 Eicosadienoic	-	2.0
20:4 Arachidonic	-	3.7
Polyunsaturated	25.4	54.2

[a](Labs-Mart Inc., 2010a)

[b](Labs-Mart Inc., 2010b)

3.2.5 Vegetable Oil Hydroprocessing

If a Pd/C catalyst is used for vegetable oil hydroprocessing, triglycerides react with hydrogen to form a primary product of n-alkanes, as well as carbon dioxide (CO_2) and propane (Wells, 2011a). This process occurs via hydrotreating, decarboxylation, and hydrocracking. During hydrotreating, hydrogen saturates the double bonds between carbon atoms in the fatty acids; vegetable oils with higher proportions of polyunsaturated fatty acids (e.g. camelina oil) require more hydrogen for this step than vegetable oils with lower proportions of polyunsaturated fatty acids (e.g. canola oil). During decarboxylation, the glyceride backbone is separated from the fatty acids and is converted to CO_2 and propane. Once hydrotreating and decarboxylation are complete, the fatty acid strands are n-alkanes with one fewer carbon atom than the original fatty acid. For example, with canola oil, the primary n-alkane product is heptadecane (C_{17}), since the majority of the fatty acids present in canola oil contain 18 carbon atoms (Labs-Mart Inc., 2010a). Other alkanes can also form due to hydrocracking, in which the long-chain alkanes are broken into shorter chain alkanes.

It is important to ensure that sufficient hydrogen is available during hydroprocessing because hydrogen is needed to fill the bonding sites that become available on carbon atoms during decarboxylation and hydrocracking. If hydrogen is not available to cap the carbon atoms, hydrocarbon chains may couple together to form long-chain alkanes (C_{30} – C_{42} for canola and camelina oil) (Wells, 2011b); long chain alkanes are undesirable in HDRD because they worsen the low-temperature properties of the fuel. Hydrogen also helps to prevent catalyst fouling and deactivation (Mäki-Arvela et al., 2007).

Hydroprocessing reactions can be aided by the presence of a solvent such as supercritical hexane. The low mass-transport resistance and high alkane-solubility of supercritical hexane serves two main functions: to increase contact between the catalyst and reactants (Randolph et al., 1994; Han et al., 2010), and to improve desorption of alkanes from the catalyst surface, which prevents alkyl intermediates from coupling to form undesirable long-chain alkanes (Han et al., 2010). The use of hexane adds to processing costs but most of the hexane can be recycled. It may be possible to reduce operating costs by using a recycled product stream as a solvent instead of hexane, but this option requires further study and experimentation (Wells, 2011b).

The two major process areas of an HDRD plant are the hydroprocessing unit and the distillation unit. In the hydroprocessing unit, vegetable oil can be converted to alkanes, propane, and CO_2 using a counter-current flow reactor with multiple catalyst beds. Downstream of the reactor, a typical refinery distillation train can be used to separate the product components. Alkanes would be sent to product storage, hexane and heavy components would be recycled to the front-end of the process, CO_2 would be blended with the fuel gas or captured, and propane would be used as fuel gas or re-formed to produce hydrogen. A simple process flow diagram for HDRD production is shown in Figure 3-1.

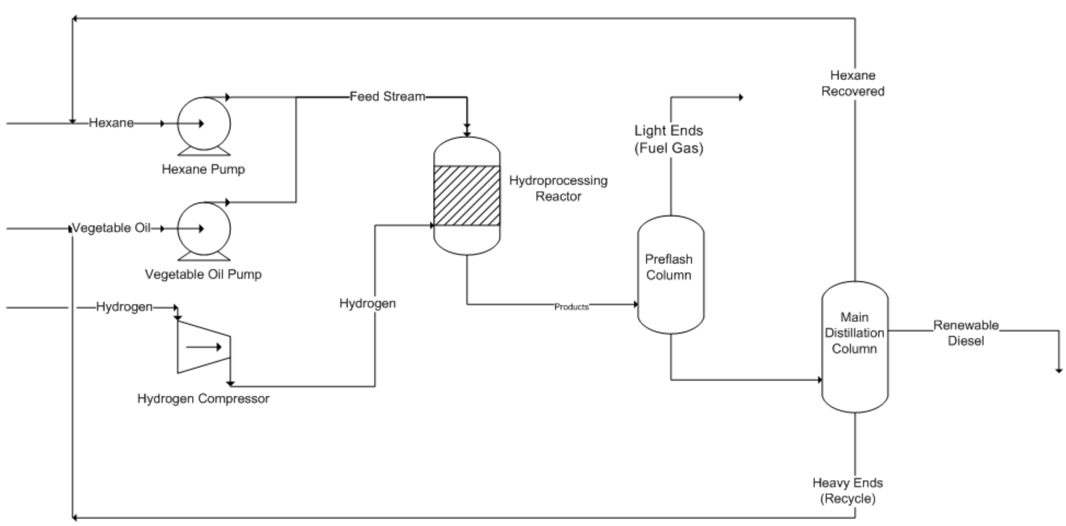

Figure 3-1: Process Flow Diagram for HDRD Production

3.3 Methodology

3.3.1 Model Development with Aspen Plus®

Aspen Plus® is a software package that can be used to model a variety of chemical processes such as oil refining (Aspen Technology Inc., 2009), coal combustion (Aspen Technology Inc., 2010a), and hydrogen production from biomass (Sarkar and Kumar, 2010). In Aspen Plus®, process flowsheets are built by connecting energy and material streams to unit operation blocks such as separators, reactors, heat exchangers, pumps, compressors, and fractionation columns. Using the integrated economics built into Aspen Plus®, the unit operation blocks can be sized and mapped to actual pieces of equipment based on the heat and material balances in the model. The integrated economics functionality of Aspen Plus® is very versatile because it can retrieve capital cost estimates for equipment from the Aspen Icarus™ database and it uses built-in algorithms to estimate engineering costs, operating costs, and installation costs. These algorithms are data-intensive and take into account factors like plant location, site environmental conditions, recent labor costs, and process complexity.

In this study, process models were developed using Aspen Plus® for HDRD production from canola oil and camelina oil based on the experimental results from a study conducted by Alberta Agriculture and Rural Development (AARD) (Wells, 2011a). In AARD's study, the triglycerides in the vegetable oil were converted to alkanes in a bench-scale batch reactor using a Pd/C catalyst. A temperature of 400°C, pressure of approximately 15.2 MPa, and residence time of

6 hours were used for both canola oil and camelina oil. Table 3-4 shows the distribution of products from hydroprocessing canola oil and camelina oil.

Table 3-4: Product Distribution (w/w %) from Hydroprocessing (Wells, 2011a)

Alkane	Canola	Camelina
C9	1.70	1.02
C10	2.45	1.67
C11	2.69	1.95
C12	2.68	2.13
C13	2.63	2.19
C14	2.56	2.19
C15	4.60	5.13
C16	2.47	2.56
C17	55.17	46.72
C18	6.80	5.02
C19	1.21	11.03
C20	0.23	1.02
C21	1.70	1.94
C22	0.00	0.43
Heavier	13.10	15.00

The models developed in this study use fired heaters to increase the reactants' temperature to 400^{o}C and use compressors and pumps to increase the reactants' pressure to 15.2 MPa. An RYield reactor block simulates the hydroprocessing reactions and several Separator and PetroFrac unit operation blocks are used downstream of the reactor to separate the product components. Heat exchangers are used throughout the model to transfer energy from hot product streams to cooler feed streams. Detailed process flowsheets, as well as heat and material balances are given in the Appendices B and C respectively. The BK-10 property set was used for the models in this study.

3.3.2 Input Data and Assumptions for the Techno-Economic Models

The cost to convert vegetable oil to HDRD can be broken down into three parts:

1) Capital cost – cost incurred to design, purchase, and install the process equipment.
2) Operating cost – cost incurred for energy, labor, and materials needed to run the plant.
3) Feedstock cost - cost incurred to produce vegetable oil and transport the oil to the HDRD plant.

These cost categories are discussed in more detail in the following sections.

In this study, the cost results are given in Canadian dollars, with a base year of 2010. Other cost data quoted in the paper is given with the base year used in the data source, unless otherwise indicated. In the techno-economic model, cost data with different base years has been scaled to the year 2010 using the Chemical Engineering Plant Cost Index (CEPCI), which is provided monthly by the journal *Chemical Engineering* (Chemical Engineering, 2011). The CEPCI is an index that can be used to adjust costs from year to year based on changes in labor cost, capital cost, and inflation (Ulrich and Vasudevan, 2006). Using the cost data discussed in the following sections, techno-economic models for HDRD production from canola oil and camelina oil were developed using a discounted cash flow approach to determine the overall cost of production for HDRD. Key assumptions used to develop the techno-economic models are given in Table 3-5.

Table 3-5: Key Assumptions Used to Develop the Techno-Economic Models

Factor	Value	Reference
Plant Lifetime	30 years	(Sarkar and Kumar, 2010; Sultana et al., 2010)
Inflation	2%	(Sarkar and Kumar, 2010; Sultana et al., 2010)
Internal Rate of Return	12%	Assumed
Base Year	2010	Assumed
Plant Startup Profile		
Year 1	80%	
Year 2+	90%	
Spread of Construction Costs		(Sarkar and Kumar, 2010; Sultana et al., 2010)
Year -2	20%	
Year -1	35%	
Year 0	45%	
Pipe Metallurgy	Carbon Steel	(Risner, 2010)
Reclamation Cost as % of Capital Cost	10%	(Kumar et al., 2003)
Other Cost (Tax, Insurance etc.) as % of Capital Cost	0.5%	(Sultana et al., 2010)

3.3.2.1 Capital Cost

Plant location is one of the key assumptions needed to determine the capital cost for the HDRD plant. In Western Canada, renewable fuels are currently produced on a small scale compared to fossil fuels. Due to renewable fuel standard legislation, oil-refining companies will likely build HDRD plants on the same site as existing refineries to take advantage of infrastructure already in place; hydrogen, steam, fuel gas, cooling water, and electricity are all normally available at oil refineries and taking advantage of these utilities reduces the capital cost required to build an HDRD plant. In this study, it is assumed that the HDRD plant is on the same site as an oil refinery. In this study, it is assumed that the HDRD plant operates in parallel with the oil refinery so co-processing of fossil fuel feedstock with vegetable oil feedstock does not occur.

Capital costs were estimated for each unit operation involved in production of HDRD from canola and camelina. For these unit operations, actual pieces of equipment were sized based on heat and material balances. With the exception of the hydroprocessing reactor, the equipment costs were retrieved from the Aspen Icarus™ cost database. The cost estimates developed in this manner are typically within 30-50% (Aspen Technology Inc., 2010b). The hydroprocessing reactor cost was scaled from data found in literature for a bio-oil hydroprocessing unit (Jones et al., 2009). A breakdown of the capital costs for the base-case HDRD plant (58 million L/year or 1,000 bbl/day) is shown in Figure 3-2.

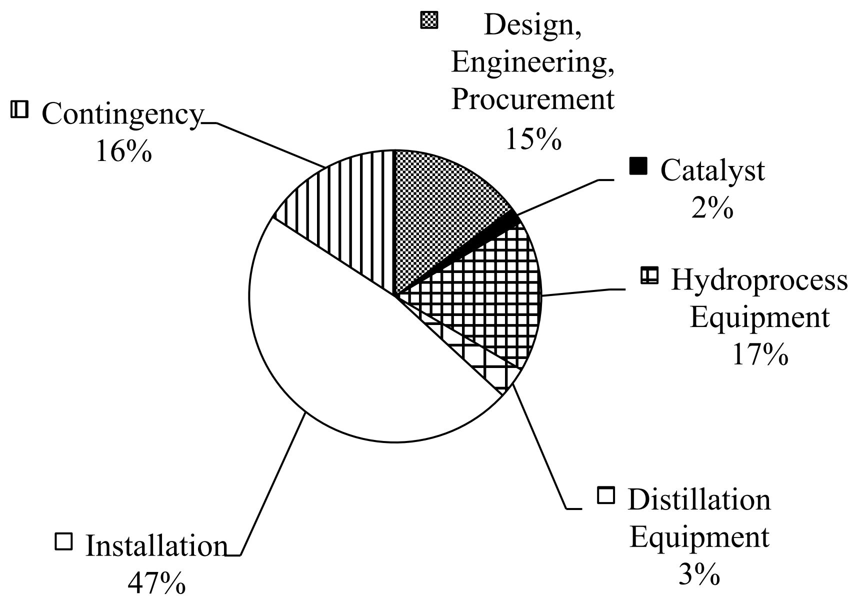

Figure 3-2: Capital Cost Breakdown for Base Case Plant

The plant was designed to have 100% redundancy for all process equipment. By having two identical process trains, the plant does not need to shut down for most maintenance, and the catalyst in one reactor can be regenerated using hydrogen reduction while the other reactor is online. The quantity of catalyst used in this study was scaled-up based on the catalyst loading in AARD's study (Wells, 2011a) and catalyst cost quotes for 10% Pd on activated carbon were obtained from an industry vendor – Johnson Matthey (Stell, 2011). The cost quotes are broken into two components – fabrication cost and Pd cost. The fabrication cost is \$71.85/kg (Stell, 2011) and the Pd cost is based on the current market price of Pd - \$19,754/kg (London Metal Exchange, 2011).

Although the catalyst can be regenerated to a certain extent on-site, at some point in time the catalyst will become fouled and must be returned to the manufacturer for re-fabrication (Stell, 2011). The catalyst lifetime is dependent on many factors but one of the important factors is whether a solvent (e.g. supercritical hexane) is used in the hydroprocessing reactor (Zwijnenburg, 2011). With supercritical hexane, the catalyst can be expected to last in this application for approximately 1-2 years; without supercritical hexane, the catalyst may only last 6 months (Zwijnenburg, 2011). In this study, a catalyst lifetime of 1 year is used. When the catalyst is returned to the manufacturer, approximately 96-97% of the Pd is recovered so the HDRD plant would only need to pay for the cost of top-up Pd, fabrication, and shipping (Stell, 2011). The total capital costs for the range of processing plant sizes considered in this study are shown in Figure 3-3 for a plant that uses canola oil as a feedstock.

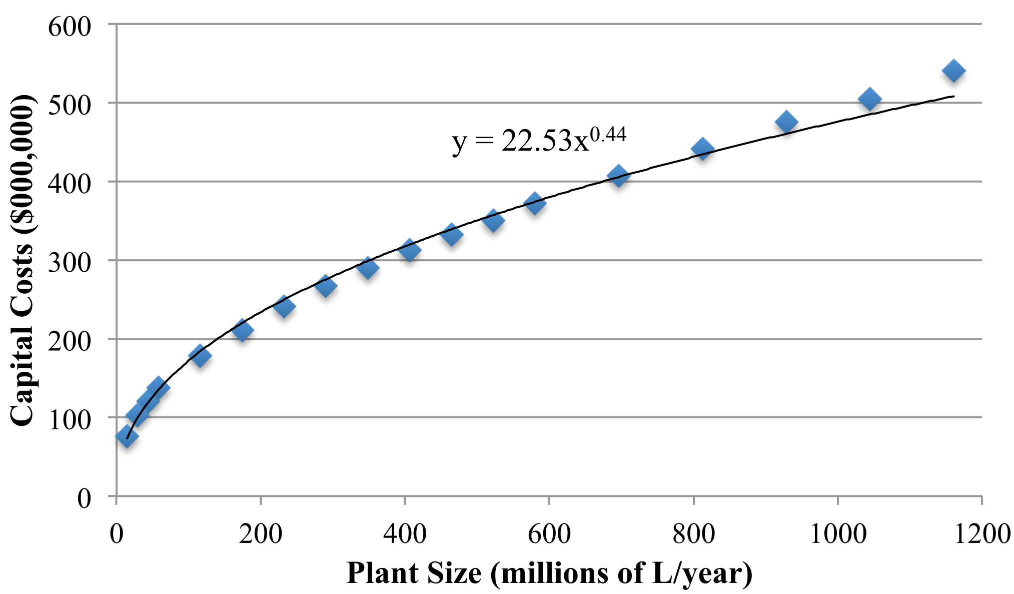

Figure 3-3: Total Capital Cost for Plant Sizes Considered in this Study (Canola Oil Feedstock)

The capital cost estimates developed in this study for a given flow rate of feedstock are much higher than the estimates shown in Jones' study (Jones et al., 2009). If only the costs for feedstock upgrading, hydrocracking, and separation in Jones' study are considered, the installed capital cost estimates developed in this study are approximately 4.5 times greater than Jones' estimates. This difference in cost estimates occurred because a solvent was used in this study but was not used in Jones' study. In this study, the solvent to oil ratio on a mass basis was 7:1. Therefore, when a solvent is used, a much greater volume of material must flow through the front end of the plant before it is separated into individual components. A higher flow rate of material requires larger pumps, reaction vessels, and distillation equipment, which results in greater capital costs compared to a case where there is a lower flow rate of material.

3.3.2.2 Operating Costs

Operating costs were estimated using the heat and material balances in the Aspen Plus® model, as well as the built-in algorithms used for estimating labor and maintenance costs. Unit costs for the energy and material streams needed for HDRD production are shown in Table 3-6 and were estimated based on data from literature, energy distributors[†], and vendor quotes. The calculations done to estimate cooling water unit costs are given in Appendix D.

[†] These energy distributors are based in Alberta, Canada. In this study, it is assumed that the costs would be similar in other jurisdictions of North America.

Table 3-6: Unit Costs for Energy and Material Streams

Cost Component	Units	Cost	Notes	Reference
Hydrogen	$/kg	0.88	SMR[1]	(Chen and Elnashaie, 2005; Blok et al. 1996; McHugh, 2005)
Natural Gas	$/GJ/Day	0.181	Transmission[2]	(ATCO Gas and Pipelines Ltd., 2011)
Natural Gas	$/GJ/Day	0.142	Delivery[2]	(ATCO Gas and Pipelines Ltd., 2011)
Natural Gas	$/GJ	3.707	Consumption[3]	(Alberta Utilities Commission, 2011a)
Cooling Water	$/m^3	0.0678	Consumption	(Ulrich and Vasudevan, 2006)
Electricity	$/kWh	0.0783	Consumption[4]	(Alberta Utilities Commission, 2011b)
Electricity	$/kWh	0.0053	Transmission[5]	(Alberta Utilities Commission, 2011c)
Electricity	$/kW-day	0.1345	Distribution[5]	(Alberta Utilities Commission, 2011c)
Hexane	$/tonne	2,018	Material &Shipping[6]	(Yang, 2011)
Pd/C Catalyst	$/kg	19,754	Pd Cost[7]	(London Metal Exchange, 2011)
Pd/C Catalyst	$/kg	71.85	Fabrication	(Stell, 2011)

[1]Scaled from McHugh (2005) based on $3.707/GJ natural gas price

[2]Current transmission and delivery charges with ATCO Gas North, High Use

[3]Direct Energy Regulated Services North – Total Rider F, 1-year average

[4]EPCOR (Fortis Distribution), Oil and Gas rate in AB, 1-year average

[5]EPCOR (Fortis Distribution), Large General Service rate in AB

[6]Shipping to Edmonton, AB, Canada

3.3.2.3 Feedstock Cost

In this study, the vegetable oil required for HDRD production is purchased from an oil extraction plant located in an area with a high level of canola production. This study uses the specific case of Alberta for assessment of costs and these costs could be adjusted for other jurisdictions. A different approach would be to build an oil extraction facility at the same site as the HDRD plant but this approach would result in farther transportation distances for the oilseeds. Also, the meal produced at the oil extraction facility in that case would need to be transported back to agricultural areas so that it could be sold as animal feed, which would increase the oil production cost.

As discussed earlier in Chapter 2, the purchase cost of the vegetable oil is based on previous work (Miller et al., 2012) - \$0.55/L for canola oil and either \$0.28/L or \$0.82/L for camelina oil. These feedstock purchase prices represent average yield cases for the oilseeds. Two cases need to be considered for camelina because camelina meal is not widely accepted as animal feed in Western Canada, and the ability to sell oilseed meal has a very strong influence on oil production cost (Miller et al., 2012). The \$0.28/L purchase price for camelina oil is based on the assumption that camelina meal can be sold and the \$0.82/L price is based on the assumption that the meal cannot be sold. Sensitivity cases were developed to determine the impact of oilseed yield on production cost of HDRD.

Redwater, which is the location considered in this study for production of HDRD, is located in central Alberta, and is surrounded by multiple areas with dense canola production. The highest canola-producing areas in Alberta are census divisions 5, 7, 10, 11, and 19, with Census division 10 (CD10) producing the most canola of the group – approximately 439,000 green tonnes/year (Alberta Agriculture and Rural Development, 2006; Statistics Canada, 2006; Alberta Agriculture and Rural Development, 2008). These crop production details have been discussed earlier in Chapter 2. A canola solvent-based oil extraction plant at its optimal size of 190 million liters per year would require approximately 400,000 green tonnes of canola per year; thus, all of the canola for the oil extraction plant could be supplied by CD10. In this study, it is assumed that canola oil extraction plants are located in these areas of dense canola production.

The cost to transport vegetable oil in this study is based on transporting the oil from highly concentrated areas of canola production in Alberta to Redwater. A map showing the census divisions in Alberta and the location of Redwater is shown in Figure 3-4. At small HDRD plant sizes, all of the oil is supplied by CD10; the distance from the center of CD10 to Redwater is approximately 130 km. Oil is transported by super B-train trucks, which have an approximate capacity of 60 m^3. The trucking cost has a fixed component (loading and unloading cost) of \$1.193/m^3 and a variable cost (maintenance, labor, fuel) of \$0.048D/m^3, where D is the round-trip transportation distance in kilometers (Sarkar and Kumar, 2010; Transport Canada, 2005). Therefore, the transportation cost for one load (60 m^3) of vegetable oil is approximately $820. Once the HDRD plant size increases beyond 580 million L/year (10,000 bbl/day), the transportation cost for oil increases because the census divisions that are close to Redwater cannot supply enough oil to run the plant so oil must also be sourced from areas of Alberta farther away from Redwater. For HDRD production from camelina, the oil transportation costs on a $/L basis are assumed to be the same as they are for canola oil.

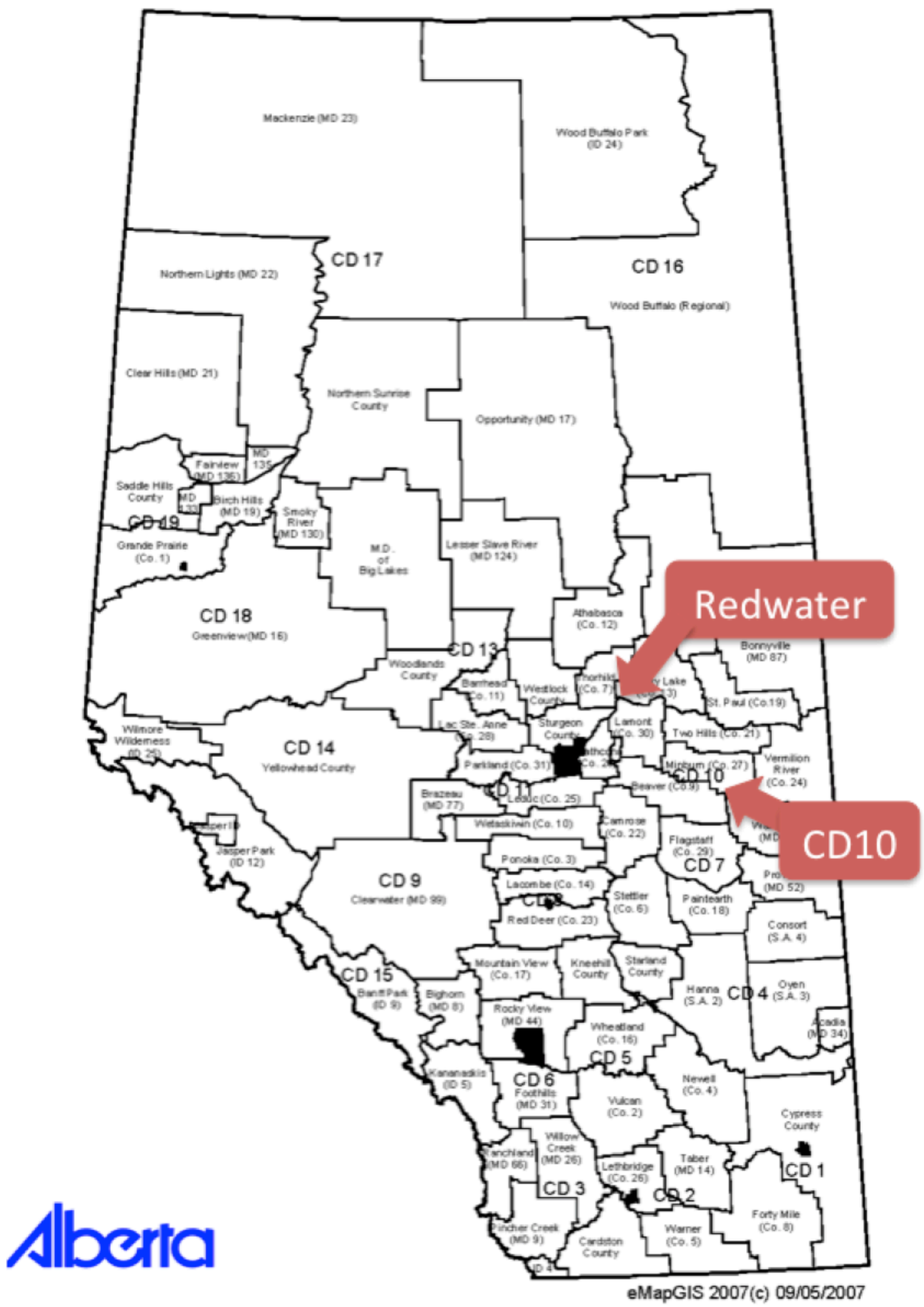

Figure 3-4: Map of Alberta

Derived from (Alberta Agriculture and Rural Development, 2012)

3.3.3 Study Limitations

Although Aspen Plus® is very versatile, there are several limitations of the models built in this study. First, the RYield reactor block is an extremely simple block - it takes a feed stream as input, and outputs a product stream based on a given product distribution (w/w %). Although its simplicity makes the block reliable, it is a disadvantage in terms of economic analysis because the block cannot be sized and mapped to an actual piece of equipment. Therefore, a scaled estimate from literature (Jones et al., 2009) was used to arrive at the installed cost of the hydroprocessing unit. Second, triglycerides are not built into the library of components available in Aspen Plus®. However, during hydroprocessing, the triglycerides break down into fatty acids, CO_2, and propane. These components were used in the feed stream instead of triglycerides, because with the RYield reactor block, only the mass flow rate of the feed is used to calculate the mass flow rate of each product. Third, some of the heavy product components such as C_{34} and C_{38} are not available in the Aspen Plus® component library. C_{32} is the heaviest n-alkane available in Aspen Plus® so it was used to represent any components heavier than C_{32}. Since C_{32} is so much heavier than the other product components, the minor difference in phase behavior between the C_{32} and the heavier components is unlikely to affect the accuracy of the simulation results.

The choice of carbon steel for piping metallurgy is another limitation of the study. The Total Acid Number (TAN) for canola oil and camelina oil is approximately 1-4 (Wells, 2011b) but for carbon steel a TAN greater than 0.5-0.6 (Marker, 2005) could result in higher rates of corrosion. Therefore, some areas of the plant may require more expensive metallurgy but only carbon steel was considered for this study.

3.4 Results and Discussion

3.4.1 Influence of Plant Size on Cost of Production

In this study, cost estimates were developed for HDRD production from canola and camelina oil in Western Canada. It is assumed that the HDRD plant is constructed on the same site as an oil refinery in order to take advantage of existing utilities such as power, hydrogen, fuel gas, and cooling water. As is the case for most field-sourced biomass processing plants (Kumar et al., 2003; Sultana et al., 2010; Sarkar and Kumar, 2010; Miller et al. 2012), the HDRD plants display the characteristic "inverted C-shaped" production cost curve for the range of plant sizes considered. This distinctive curve shape arises because as the plant size is increased, the production cost initially decreases due to economies of scale for capital costs but as the plant size is increased further, the economy of scale benefit is offset by increasing feedstock transportation costs. The transportation costs increase with plant size because for high capacity HDRD plants, the vegetable oil needs to be sourced from locations farther away from the plant compared to low capacity HDRD plants.

Since feedstock cost is a critical variable for overall HDRD production cost, three cases were considered for this study:

1) Canola oil as a feedstock with a purchase price of \$0.55/L

2) Camelina oil as a feedstock with a purchase price of \$0.28/L

3) Camelina oil as a feedstock with a purchase price of \$0.82/L

The production costs of HDRD for these cases for a range of production plant sizes are shown in Figure 3-5.

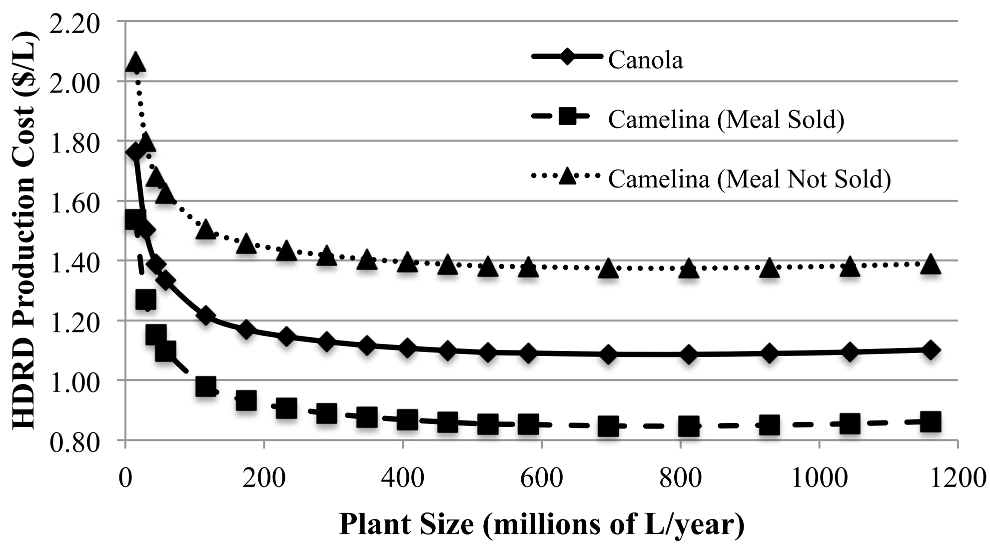

Figure 3-5: HDRD Production Costs for a Range of Production Plant Sizes

Although the curves in Figure 3-5 do display the characteristic "inverted C-shape", the curves become relatively flat beyond a plant size of approximately 290 million L/year (5,000 bbl/day). This flatness means that although vegetable oil transportation cost does counter-balance the economy of scale benefit, transportation cost is not as influential in overall HDRD production cost as it is for overall production cost of other biomass products such as vegetable oil (Miller et al., 2012) and wood for power (Kumar et al., 2003).

The economically optimal plant size in each case was 812 million L/year (14,000 bbl/day) and the minimum costs of production were: \$1.09/L (canola oil feedstock), \$0.85/L (camelina oil feedstock, meal sold), and \$1.37/L (camelina oil feedstock, meal not sold). Detailed discounted cash flow sheets for canola- and camelina-based HDRD plants at their optimal size are given in Appendix E. Since the cost curves are relatively flat beyond a plant size of 290 million L/year (5,000 bbl/day), the economically optimal size of HDRD production plant is really a range of plant sizes (~290 to 1,161 million L/year, or 5,000 to 20,000 bbl/day), rather than a single plant size. Plants at a scale of 290 million L/year could be built to minimize risk, as this is a new technology. At this scale, most of the benefits of economy of scale are achieved. The cost of production of HDRD at 1,161 million L/year is only 2% lower compared to the cost of production of HDRD at 290 million L/year. As shown in Table 3-2, Neste has recently built two HDRD plants within this size range (~929 million L/year, or 16,000 bbl/day).

Based on the curves in Figure 3-5, it is clear that the HDRD production cost in Alberta is lowest for HDRD produced from camelina oil, but only if camelina meal can be sold. If camelina meal cannot be sold, then it is cheaper to produce HDRD from canola oil. The difference in production cost for each case is almost entirely due to the differences in feedstock costs because the other costs involved in converting vegetable oil to HDRD are very similar in magnitude. In order to illustrate how the magnitude of each cost component changes with plant size, a breakdown of the production costs for a 58 million L/year (1,000 bbl/day) and a

290 million L/year (5,000 bbl/day) HDRD plant are shown in Figure 3-6 and Figure 3-7 respectively. In these figures, the HDRD plants use canola oil as a feedstock.

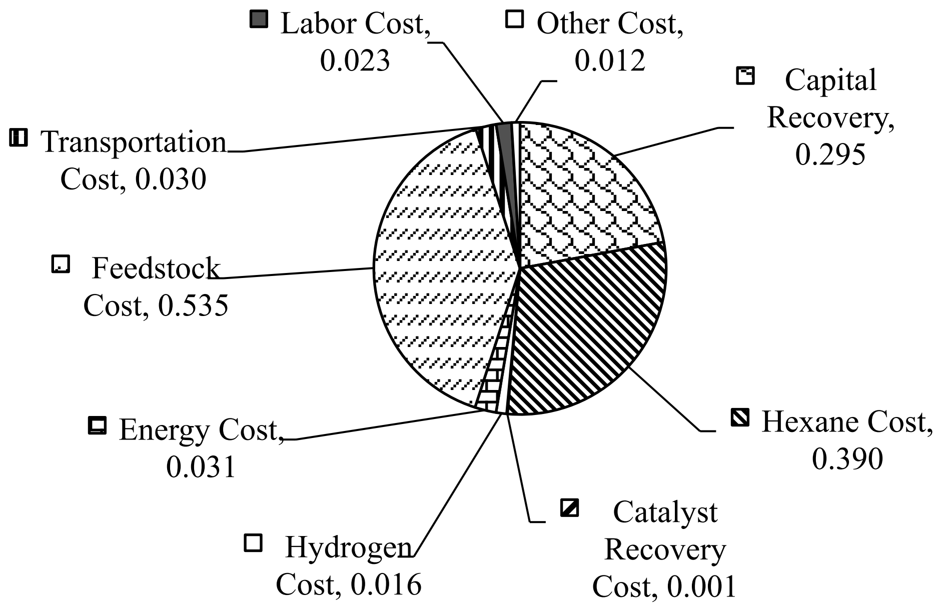

Figure 3-6: Production Cost Breakdown ($/L) for 58 million L/year (1,000 bbl/day) Canola-HDRD Plant (Total Cost $1.33/L)

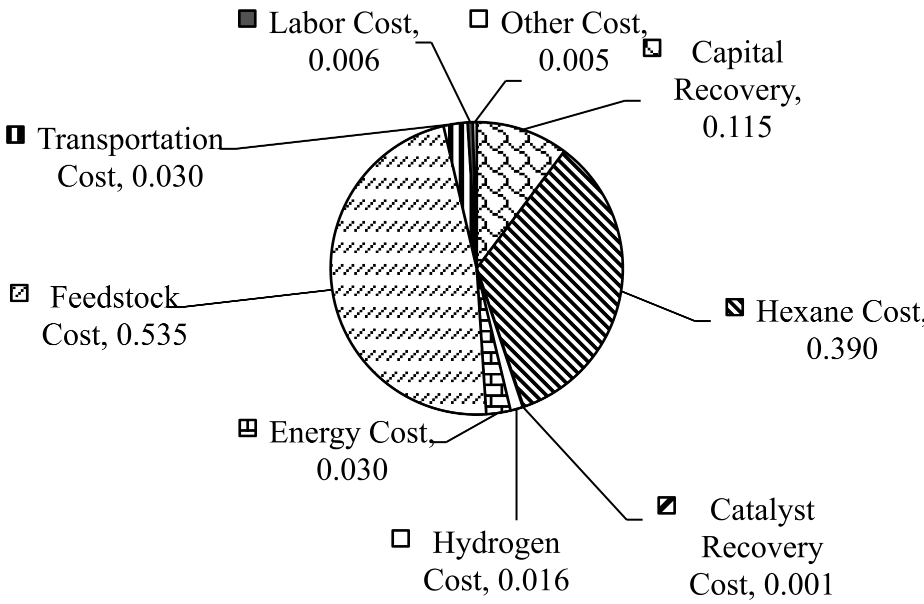

Figure 3-7: Production Cost Breakdown ($/L) for 290 million L/year (5,000 bbl/day) Canola-HDRD Plant (Total Cost $1.13/L)

Figure 3-6 and Figure 3-7 show the factors that have the greatest impact on overall HDRD production. These include feedstock cost, hexane cost, and capital recovery. In this case, the purchase cost of canola oil is $0.526/L of vegetable oil (in 2010 dollars) but contributes $0.535/L of HDRD cost to the overall HDRD production cost. This slight difference in magnitude is due to several factors: mass lost during hydroprocessing in the form of CO_2 and propane, mass gained during hydroprocessing in the form of hydrogen, and differences in density between vegetable oil and HDRD. The hexane cost shown in Figure 3-6 and Figure 3-7 is the “top-up” hexane that must be purchased because not all of the hexane used in the process can be recycled. The process models built in this study showed that approximately 97% of the hexane can be recycled, but 3% is lost with the HDRD product stream and the fuel gas stream that contains the lighter propane and CO_2 components. Although capital recovery is a significant cost factor, its influence on a $/L basis rapidly declines with increasing plant size; for a 58 million L/year (1,000 bbl/day) plant, capital recovery contributes $0.295/L to the overall HDRD production cost but for a 290 million L/year (5,000 bbl/day) plant, capital recovery only contributes $0.115/L to the overall HDRD production cost. However, beyond a plant size of 290 million L/year (5,000 bbl/day), increasing feedstock transportation costs essentially balance any incremental economy of scale benefits for capital costs.

3.4.2 Comparison to Fuel Price Estimates and Actual Fuel Prices

It is difficult to assess the accuracy of the production costs developed in this study because there is little public data available on HDRD production costs and many of the cost factors for HDRD production are location specific. There are currently no large-scale producers of HDRD or biodiesel in Alberta but construction is expected to begin in 2012 for two Alberta-based biodiesel plants (Rubin, 2011; Cooper, 2011). Due to the lack of available data, the costs developed in this study are compared to HDRD production costs for Neste Oil, estimated biodiesel production costs for Western Canada, and average fossil diesel prices in Alberta.

Neste Oil reported a production cost of $220/tonne for HDRD in 2011, not including the cost of vegetable oil feedstock (Maula, 2011). After converting this cost to a volume basis and adding the cost of feedstock (assuming the same feedstock cost used for this study), the production cost for Neste's HDRD in 2011 would have been approximately \$0.75/L if canola oil was used as a feedstock; this production cost is much lower than the cost developed in this study. Although it is not totally clear what Neste includes in its quoted "production cost", the difference in cost can likely be attributed to how solvent is used in Neste's process.

Optimizing solvent use in HDRD production is very important because the solvent affects the hydroprocessing reactions, catalyst life, and two main processing cost components – solvent cost and capital recovery. Neste has been producing renewable diesel for several years and likely has a production process that is more fine-tuned than the process considered in this study. Therefore, the solvent flow rates may be lower in Neste's process, which would reduce the solvent make-up cost. Neste may produce its own solvents, or recycle some of the products for use as a solvent, which would also reduce solvent make-up costs. For lower solvent flow rates, smaller equipment can be used, which results in lower capital costs. Since solvents influence both the chemical reactions and processing costs for HDRD production, solvent type and flow rate are key parameters that should be considered by companies interested in producing HDRD.

In a study commissioned by the Canola Council of Canada (Saville and Canola Council of Canada, 2006), the cost of biodiesel production from canola in Western Canada was estimated for a range of processing plant sizes. For biodiesel plants in the size range of 151 to 303 million liters per year, the estimated cost of biodiesel production was nearly constant at approximately \$0.62/L (2006 dollars) or \$0.68/L (2010 dollars). This production cost includes credits for selling canola meal and glycerol by-products. Other researchers such as Marker (2005), have quoted similar biodiesel production costs - \$0.70/L to \$0.78/L (in 2010 dollars) for biodiesel from soy oil and corn oil respectively. Although these studies suggest that biodiesel is cheaper to produce than canola-HDRD, HDRD typically commands a price premium over biodiesel due to HDRD's superior fuel properties (e.g. cloud point) (Kalnes et al., 2009; Thuen, 2011). This price premium could potentially make up for some of the difference in production cost.

The HDRD production costs developed in this study are in the same neighborhood as the production cost for fossil-diesel in Alberta. From December 2010 to December 2011, the weekly average for the retail diesel price in Edmonton, AB ranged from approximately \$1.00/L to \$1.25/L (Natural Resources Canada, 2011). After subtracting federal and provincial taxes, and marketing costs (Natural Resources Canada, 2010), this retail price range suggests a production cost range of approximately \$0.77/L to \$1.01/L. At this production cost range for fossil diesel, HDRD from canola (\$1.13/L for a 290 million L/year plant) is not competitive but HDRD from camelina (\$0.89/L for a 290 million L/year plant) could be competitive if camelina meal can be sold. Therefore, optimizing solvent use in the production process and promoting widespread acceptance of camelina meal as animal feed are two key steps that could be taken to improve the cost competitiveness of HDRD with fossil diesel in Alberta.

3.4.3 Sensitivity Analysis

In this study, the variables that have the greatest influence on production cost of HDRD are: capital costs, operating costs, vegetable oil price, hexane price, and hexane recovery. A sensitivity analysis for these variables for the case of HDRD produced from canola oil is shown in Figure 3-8 and Figure 3-9. In the sensitivity analysis, operating costs are defined as costs for electricity, natural gas, cooling water, hydrogen, catalyst regeneration, and labor. Costs for vegetable oil and hexane were not included under operating costs because vegetable oil and hexane are examined separately. The production costs shown in the sensitivity analysis are for an HDRD production plant at its economically optimal size (typically 812 million L/year, or 14,000 bbl/day), but as discussed earlier it is important to note that the HDRD production cost changes only slightly for plant sizes larger than 290 million L/year (5,000 bbl/day).

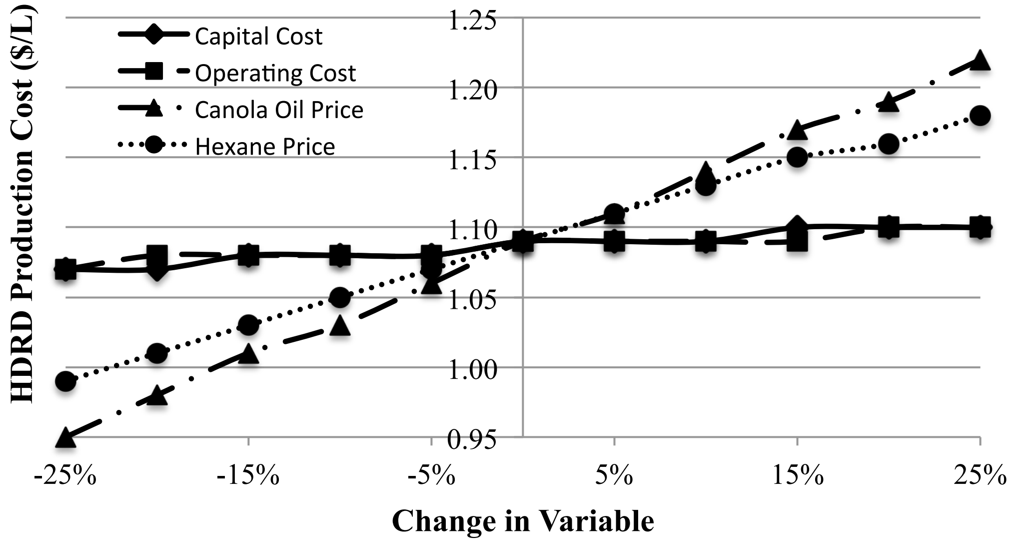

Figure 3-8: Sensitivity of HDRD Production Cost to Capital and Operating Costs, and to Vegetable Oil and Hexane Price

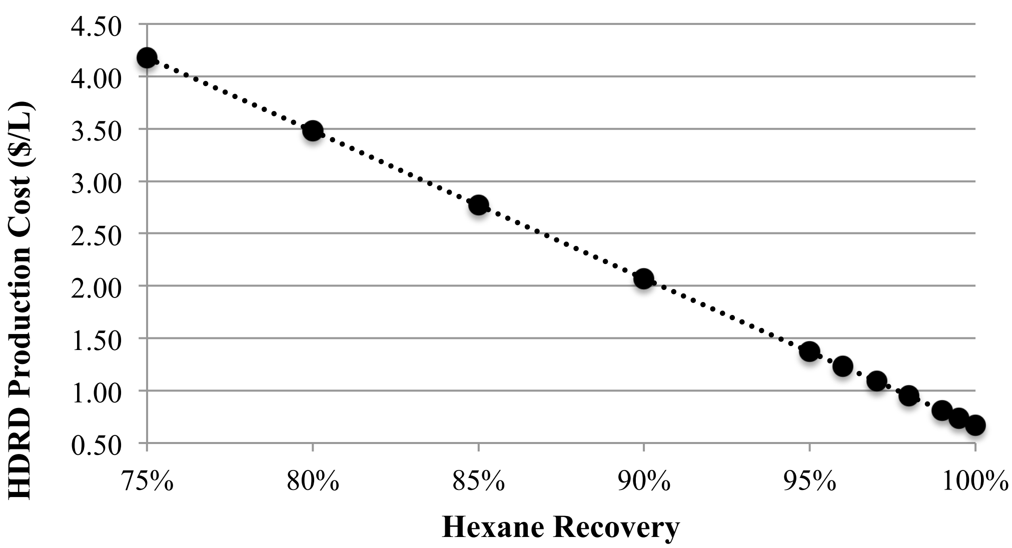

Figure 3-9: Sensitivity of HDRD Production Cost to Hexane Recovery

From Figure 3-8, it is clear that vegetable oil price and hexane price have a major impact on HDRD production cost – much more so than operating costs and capital costs. However, decreasing the capital cost was the only sensitivity case that resulted in a change in the optimal plant size – from 812 million L/year (14,000 bbl/day) to 696 million L/year (12,000 bbl/day), which occurred in the variable range of -25% to -10%. Although a variable change of -25% to +25% was shown for vegetable oil price in Figure 3-8, the canola oil price in Alberta could realistically vary from -31% to +51% ($0.36/L to $0.79/L), based on the historical minimum and maximum yields of canola in Alberta. For this price range of canola oil, the HDRD production cost ranges from $0.92/L to $1.36/L for a 812 million L/year (14,000 bbl/day) plant. Therefore, companies interested in producing HDRD will likely need to consider securing a long-term supply of vegetable oil at a fixed price to avoid significant variations in HDRD production cost.

The sensitivity analysis in Figure 3-9 indicates that hexane recovery would be a critical variable to monitor in the HDRD production plant because it has such a strong impact on HDRD production cost. In this study, hexane is purchased for approximately $1.27/L ($1932/tonne in 2010 dollars); a small portion of the hexane that is not recycled flows out of the plant with the comparable value HDRD product stream but most of it flows out of the plant with the low value fuel gas stream. For the base case, approximately 97% of hexane used in the process is recovered and recycled to the hydroprocessing reactor. Close monitoring of the composition of the fuel gas stream and the HDRD product stream is required to detect process upsets that would cause a decrease in hexane recovery and resultant increase in HDRD production cost. The high sensitivity of production cost to hexane recovery also highlights the need for further experimentation to optimize hexane recovery and the flow rate of hexane used. Hexane flow rate should be optimized so that the hydroprocessing reactions occur to completion but catalyst lifetime is not significantly reduced.

3.5 Conclusion

This study estimated the cost of producing HDRD from canola oil and camelina oil in Western Canada using Pd/C as a catalyst and supercritical hexane as a solvent. A wide range of production plant sizes was considered and for both feedstock types, the minimum cost of production occurred at a plant size of 812 million L/year (14,000 bbl/day). However, there is little variation in production cost for plant sizes in the range of 290 to 1,161 million L/year (5,000 to 20,000 bbl/day). The minimum cost of production was approximately $1.09/L for HDRD from canola oil and $0.85/L for HDRD from camelina oil – assuming that camelina meal can be sold for the same price as canola meal. If camelina meal cannot be sold, the purchase price of camelina oil would increase, which results in a minimum cost of production of HDRD from camelina oil of $1.37/L. At these production costs, only HDRD from camelina (if camelina meal is sold) is cost competitive with fossil diesel or biodiesel. However, the superior fuel properties of HDRD compared to fossil diesel and biodiesel could offset some of the difference in production cost.

Several additional cases were developed to examine the sensitivity of HDRD production cost to operating cost, capital cost, vegetable oil price, solvent price, and solvent recovery. These cases showed that HDRD production cost is not very sensitive to capital and operating costs, but is highly sensitive to vegetable oil price, solvent price, and solvent recovery. Therefore, producers of HDRD should consider long-term, fixed price vegetable oil supply contracts to minimize fluctuations in HDRD production cost. Further research could also be conducted to optimize solvent type, flow rate, and recovery.

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4 Environmental Sustainability of Producing HDRD from Canola Oil and Camelina Oil

4.1 Introduction

Due to growing concerns over climate change and energy sustainability, many governments are creating policies to encourage development of alternative fuel sources. These policies often promote the use of biofuels (e.g. ethanol, biodiesel, and renewable diesel) as alternative fuels in the transportation sector because biofuels can be easily blended with conventional gasoline or diesel, and burned in unmodified engines. Since carbon contained in biofuels is originally derived from CO_2 in the atmosphere, biofuels are often said to be nearly carbon-neutral, that is, they contribute very little to the build-up of greenhouse gas emissions (GHGs) in the atmosphere.

Although biofuels are generally considered to be more sustainable than fossil fuels, there are three primary issues to consider if agricultural crops are used to produce fuel. First, the GHGs and energy inputs required to produce biofuels vary greatly with crop type and growing location (De Klein et al., 2006; West, 2002; Krohn and Fripp, 2012). Second, if food crops are used to make biofuels, food prices can increase dramatically (World Bank, 2007). Third, increased demand for a particular crop can result in GHGs from land use change (LUC), where non-agricultural land (e.g. forest, grassland, or peat) is converted to agricultural land (Searchinger et al., 2008). This conversion releases CO_2 and N_2O into the atmosphere if the agricultural land stores less carbon and nitrogen than the previous land type (Intergovernmental Panel on Climate Change, 2003), which is often the case (Krohn and Fripp, 2012).

Due to these issues, a great deal of recent research has been dedicated to evaluating the sustainability of biofuels. To measure sustainability, life cycle GHGs and net energy ratio (NER) (i.e. the ratio of energy output to fossil-fuel energy input) have been evaluated for a variety of biofuel pathways. For alternatives to fossil diesel, most of the available literature is focused on biodiesel from palm (Pleanjai and Gheewala, 2009; Varanda et al., 2011), soybean (Pradhan et al., 2008; Reijnders and Huijbregts, 2008), or canola/rapeseed (Bernesson, 2004; Edwards et al., 2007; Reijnders and Huijbregts, 2008; Rustandi, 2010; S&T Consultants Inc, 2010; Chen and Chen, 2011). In contrast, very few life cycle assessments (LCAs) have been completed for hydrogenation-derived renewable diesel (HDRD), which can be produced from the same feedstocks as biodiesel, but is closer in composition to fossil diesel and can have better cold flow properties than biodiesel (Kalnes et al., 2007; Guzman et al., 2010; Šimáček et al., 2011).

Some authors have studied the sustainability of HDRD from rapeseed (Arvidsson et al., 2011), soybean (Kalnes et al., 2007), and camelina (Shonnard and Williams, 2010), a promising low-input oilseed, but these studies are based in Europe or the United States. Although Canada is the world's largest exporter of canola oil

(Statistics Canada, 2009), has conducted trials of growing camelina (Agriculture and Agri-Food Canada, 2009), and has implemented renewable fuels standards (Government of Alberta, 2011), no LCAs of HDRD from canola or camelina in Canada are available in literature. This study is an effort to fill a significant gap in the literature by evaluating the life cycle GHGs and NER of HDRD from canola and camelina in the Province of Alberta, Canada.

4.2 Methodology

4.2.1 Scope

4.2.1.1 Goal Definition

The goal of this study was to develop a data-intensive model to evaluate the sustainability of HDRD produced from canola or camelina in Alberta. GHG mitigation is often the key driver behind government policies that promote renewable fuels, but NER (also known as energy output-input ratio or energy return on investment) is also important because it helps in understanding the effectiveness of energy use in producing a particular fuel (Kabir and Kumar, 2011). Therefore, in this study, both life cycle GHGs and NER were estimated in order to quantify the sustainability of HDRD production. The key stages of HDRD production where emissions and energy consumption were estimated include: (i) oilseed farming, (ii) transportation of oilseeds to the oil extraction plant, (iii) oil extraction, (iv) transportation of oil to the HDRD plant, (v) HDRD production, and (vi) transportation of HDRD to the consumer.

Although a variety of LCA models exist in the public domain (e.g. GREET and GHGenius), the authors built a separate model for this study. The main driver to build a separate model was that it is not always clear where data is derived from in the publicly available models or how that data is used to calculate energy and emission impacts. Building a separate model also provided more flexibility to include site-specific data and data for pathway steps that were not available in the public models.

4.2.1.2 System Boundary, Functional Unit, and GHGs

Only direct inputs into each stage of HDRD production were considered for this LCA. That is, energy (e.g. diesel and electricity) and chemicals (e.g. fertilizers) consumed during HDRD production were considered direct inputs and were included in the LCA but other inputs such as the energy required to build the HDRD processing plant were considered indirect inputs and were not included in the LCA unless otherwise indicated. A schematic illustrating the system boundary for the LCA is given in Figure 4-1. The functional unit used in this study is 1 MJ of energy in the renewable diesel produced (higher heating value basis), which is consistent with other studies (Kalnes et al., 2007, 2009; Shonnard and Williams, 2010; Krohn and Fripp, 2012). The three primary gases considered for contribution to global warming were CO_2, CH_4, and N_2O, which have global warming potentials (CO_{2e}) of 1, 25, and 298 respectively based on a 100 year time horizon (Intergovernmental Panel on Climate Change, 2007).

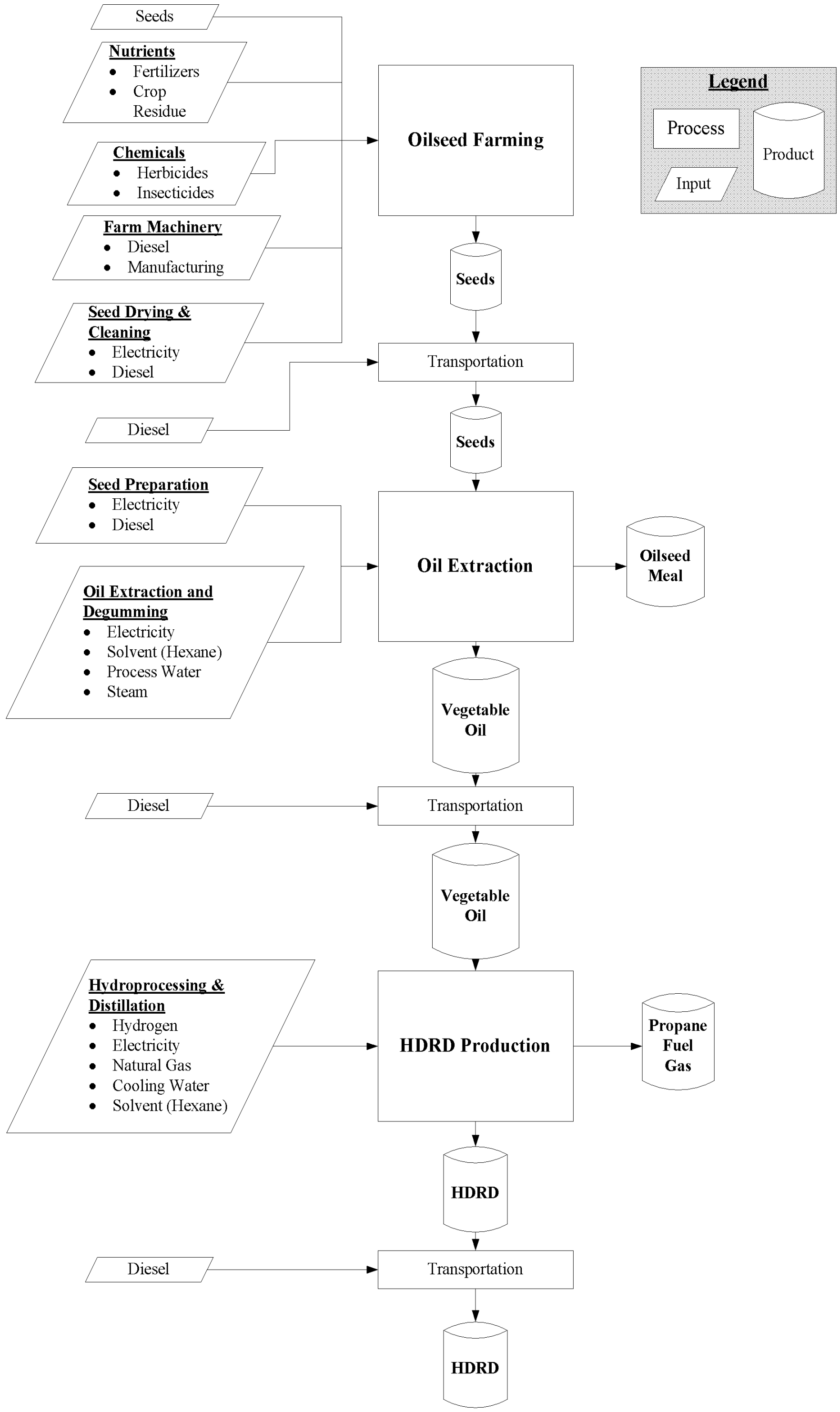

Figure 4-1: System Boundary for this LCA of HDRD Production

4.2.1.3 Scenarios Considered

Canola (*Brassica rapa and Brassica napus L.*) and camelina (*Camelina Sativa*) were selected as feedstocks for this study because canola is widely grown in Western Canada and camelina is an oilseed that is gaining attention as a feedstock for renewable fuel production (Frohlich and Rice, 2005; Jaeger and Siegel, 2008; Shonnard and Williams, 2010; Agusdinata et al., 2011; Krohn and Fripp, 2012). Canola was developed from rapeseed, but has lower erucic acid and glucosinolate content than traditional rapeseed. Camelina's main advantages over canola include a shorter growing season (less than 100 days), lower fertilizer inputs and water use, better cold tolerance, and fewer insect problems (Zubr, 1997; Lafferty et al., 2009; Miller et al., 2012).

Although camelina has clear advantages over canola, unlike canola, the meal produced from camelina as a co-product in the oil extraction stage is not yet widely accepted as animal feed. Camelina has been approved by the US Food and Drug Administration for use as animal feed, but only up to 10% by weight for beef cattle and broiler chickens (Schill, 2010). Inclusion (or exclusion) of camelina meal in energy and emission allocations would have a significant impact on the results of the LCA and therefore thirteen different scenarios were analyzed in this study – shown in Table 4-1. The scenarios considered in this study were selected in order to account for variables (i.e. yield and field N_2O emissions) and methodological assumptions (i.e. co-products, allocation methods, and land-use changes) that could significantly impact the LCA results.

Table 4-1: Scenarios Considered for the LCA

Scenario	Crop	Allocation Method	Products Included	Yield	N_2O Emissions (% of Applied N)	Land Use Change Considered?
Base	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	0.76	No
1	Canola, Camelina	Mass	HDRD, Propane, Meal, Straw	Average	0.76	No
2	Canola, Camelina	Economic Value	HDRD, Propane, Meal	Average	0.76	No
3	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	1	No
4	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	2	No
5	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	3	No
6	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	4	No
7	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	5	No
8	Canola, Camelina	Mass	HDRD, Propane, Meal	Average	0.76	Yes
9	Canola, Camelina	Mass	HDRD, Propane, Meal	Minimum	0.76	No
10	Canola, Camelina	Mass	HDRD, Propane, Meal	Maximum	0.76	No
11	Camelina	Mass	HDRD, Propane	Average	0.76	No
12	Camelina	Economic Value	HDRD, Propane	Average	0.76	No

Although HDRD and meal are the two products typically considered for HDRD LCAs, straw and propane are also produced in the process. Canola straw can be used for animal feed or bedding but has little feed value (Manitoba Agriculture Food and Rural Initiatives, 2004) and decomposes quickly, so it is less effective than wheat straw at preventing erosion if removed from the field (Saskatchewan Ministry of Agriculture, 2006). Therefore, straw was only considered as a co-product in a sensitivity analysis rather than in the base scenario. Propane is produced at the HDRD plant during decarboxylation of the triglycerides in the vegetable oil. Propane can be used as fuel gas in the HDRD plant or steam-reformed to provide hydrogen for the process, thus it was included as a co-product in all of the sensitivity scenarios.

4.2.2 Allocation Method for GHGs and Energy

Allocation method is an important consideration for any LCA and several allocation methods are common in literature: energy allocation, displacement allocation (also known as system expansion), mass allocation, and economic value allocation. Energy allocation is often used for biodiesel or HDRD LCAs if the meal co-product from oil extraction is used as fuel in a boiler, but this practice is not common. Displacement allocation accounts for changes in energy consumption and emissions by replacing equivalent products on the market with co-products (Hoefnagels et al., 2010). In the case of biodiesel or HDRD LCAs in literature, soybean meal is usually the co-product that is displaced but in Western

Canada, soybeans are only grown on a limited basis (Statistics Canada, 2006) so this assumption is not realistic. Therefore, in this study, only mass and economic value allocation methods were used. Additional detail on allocation methods is available in literature (Hoefnagels et al., 2010; Cherubini et al., 2011)

In an effort to make the LCA calculations as transparent as possible, an attributional LCA model structure was used, in which each input to the process has an associated energy or emission co-efficient (Krohn and Fripp, 2012). These co-efficients were obtained from published literature or calculated as indicated in the tables shown later in the study. To calculate the energy or emission impact for a particular input, the energy or emission co-efficient is multiplied by the input quantity and then converted to the functional unit basis.

4.2.3 Inventory Assessment

4.2.3.1 Oilseed Farming

As demonstrated by other studies (Reijnders and Huijbregts, 2008; Arvidsson et al., 2011; Chen and Chen, 2011), the agricultural stage has a significant impact on the life cycle GHGs produced and energy consumed in biodiesel and renewable diesel production. For canola and camelina farming, the main areas to consider include crop nutrients, chemicals, and seeding; machinery and fuel use; seed drying and cleaning; field N_2O emissions; and LUC emissions. The input quantities, energy and emission coefficients, and energy and emission impacts for these areas are summarized in Table 4-2 (canola) and Table 4-3 (camelina). Each area from Table 4-2 and Table 4-3 is discussed in more detail in the following subsections. Whenever possible, data specific to Alberta or Western Canada was used.

Note that all of the energy and emission impacts given in Table 4-2 and Table 4-3 are for the base scenario from Table 4-1, which means that LUC was not included and average yields were used. The minimum, average, and maximum gross and net yields considered for canola and camelina in this study are shown in Table 4-4. For canola, the yields are based on a 12-year average from 1997-2008 (Alberta Agriculture and Rural Development, 2006, 2008; Statistics Canada, 2006) and for camelina, the yields are based on trials conducted by Agriculture and Agri-Food Canada (Agriculture and Agri-Food Canada, 2009).

Table 4-2: Inputs, Energy Coefficients, Emission Coefficients, and Impacts for Canola Farming, Base Scenario

Operation	Input Quantity			Energy Coefficients			Emission Coefficients			Energy Use	Emissions
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	123.0	a	MJ/kg	49.45	i	gCO_{2e}/g	3.58	i	0.220	15.9
Phosphorous	kg/ha	14.5	a	MJ/kg	14.13	i	gCO_{2e}/g	1.07	i	0.007	0.6
Potassium	kg/ha	100.5	a	MJ/kg	8.84	i	gCO_{2e}/g	0.69	i	0.032	2.5
Sulfur	kg/ha	25.0	a	MJ/kg	11.26	j	gCO_{2e}/g	2.70	m	0.010	2.4
Crop residue	tonnes/ha	1.5	b	-	-	-	kgN/tonne	6.00	n	-	-
Herbicide	kg/ha	3.43	c	MJ/kg	267	k	gCO_{2e}/g	17.24	k	0.033	2.1
Insecticide	kg/ha	0.28	d	MJ/kg	285	k	gCO_{2e}/g	18.08	k	0.003	0.2
Seeds	kg/ha	6.55	e	MJ/kg	5.83	g	gCO_{2e}/g	1.19	g	0.001	0.3
Machinery & fuel use (diesel)											
Manufacturing & maintenance	-	-	-	MJ/ha	1456	h	gCO_{2e}/ha	35740	h	0.053	1.3
Sowing	L/ha	10	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.016	1.2
Farm chemical spraying	L/ha	4	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.007	0.5
Spreading fertilizer	L/ha	14	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.023	1.7
Harvesting	L/ha	25	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.041	3.0
Seed transportation	L/ha	8	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.013	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	g,h	MJ/kWh	9.89	l	gCO_{2e}/kWh	880	p	0.005	0.5
Diesel	L/tonne seed	1.2	h	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.003	0.2
Field emissions											
N_2O emissions	-	-	-	-	-	-	% as N_2O-N	0.76	e	-	17.0
Land use change											
N_2O credit	-	-	-	-	-	-	g N_2O/ha	-503	q,r,s	-	-
Change in soil nitrogen	-	-	-	-	-	-	g N_2O/ha	1138	q,t	-	-
Change in soil carbon	-	-	-	-	-	-	kg CO_2/ha	3187	q,t	-	-
Farming Subtotal										**0.47**	**50.4**

Table 4-3: Inputs, Energy Coefficients, Emission Coefficients, and Impacts for Camelina Farming, Base Scenario

Operation	Input Quantity			Energy Coefficients			Emission Coefficients			Energy Use	Emissions
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	92.5	u,v	MJ/kg	49.45	i	gCO_{2e}/g	3.58	i	0.176	12.8
Phosphorous	kg/ha	39.9	u,w	MJ/kg	14.13	i	gCO_{2e}/g	1.07	i	0.022	1.6
Potassium	kg/ha	38.9	u,w	MJ/kg	8.84	i	gCO_{2e}/g	0.69	i	0.013	1.0
Sulfur	kg/ha	0.0	u	MJ/kg	11.26	j	gCO_{2e}/g	2.70	m	0.000	0.0
Crop residue	tonnes/ha	1.5	b	-	-	-	kgN/tonne	6.00	n	-	-
Herbicide	kg/ha	0.7	u	MJ/kg	267	k	gCO_{2e}/g	17.24	k	0.008	0.5
Insecticide	kg/ha	0.0	u	MJ/kg	285	k	gCO_{2e}/g	18.08	k	0.000	0.0
Seeds	kg/ha	8.0	u	MJ/kg	2.35	u	gCO_{2e}/g	0.39	u	0.001	0.1
Machinery & fuel use (diesel)											
Manufacturing & maintenance	-	-	-	MJ/ha	1456	h	gCO_{2e}/ha	35740	h	0.056	1.4
Sowing	L/ha	10	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.017	1.3
Farm chemical spraying	L/ha	4	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.007	0.5
Spreading fertilizer	L/ha	14	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.024	1.8
Harvesting	L/ha	25	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.044	3.2
Seed transportation	L/ha	8	f	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.014	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	g,h	MJ/kWh	9.89	l	gCO_{2e}/kWh	880	p	0.008	0.7
Diesel	L/tonne seed	1.2	h	MJ/L	45.25	l	gCO_{2e}/L	3336	k,o	0.004	0.3
Field emissions											
N_2O emissions	-	-	-	-	-	-	% as N_2O-N	0.76	e	-	13.9
Land use change											
N_2O credit	-	-	-	-	-	-	-	-	-	-	-
Change in soil nitrogen	-	-	-	-	-	-	-	-	-	-	-
Change in soil carbon	-	-	-	-	-	-	-	-	-	-	-
Farming Subtotal										**0.39**	**40.2**

Sources for: Table 4-2 and Table 4-3

[a](Canola Council of Canada, 2003)
[b](Sultana and Kumar, 2011)
[c](Painter et al., 2009)
[d](DeVuyst et al., 2010)
[e](S&T Consultants Inc, 2010)
[f](Baquero et al., 2011)
[g](Bernesson, 2004)
[h](Rustandi, 2010)
[i](Wang, 2011)
[j](Bhat et al., 1994)
[k](West, 2002)
[l](Piringer and Steinberg, 2006)
[m](Ecoinvent, 2004)
[n](Hartman, 2008)
[o](Marano, 2009)
[p](Environment Canada, 2010)
[q](Schmidt, 2007)
[r](Stehfest and Bouwman, 2006)
[s](Bouwman et al., 1993)
[t](Intergovernmental Panel on Climate Change, 2003)
[u](Krohn and Fripp, 2012)
[v](Agriculture and Agri-Food Canada, 2009)
[w](Willamette Biomass Processors, 2010)

Table 4-4: Yields and Loss Factors for Canola and Camelina

Factor	Canola	Camelina	Units	Source
Gross yield (min, avg, max)	1.21, 1.66, 2.12	1.53, 2.25, 4.15	tonnes/ha	Alberta Agriculture and Rural Development, 2006, 2008; Statistics Canada, 2006; Agriculture and Agri-Food Canada, 2009
Harvesting loss	0.1	0.1	tonnes/ha	Miller et al, 2012
Dockage loss	9%	9%	percentage	Canola Council of Canada, 2010; Manitoba Agriculture, 1980
Handling loss	2%	2%	percentage	Miller et al., 2012
Net yields (min, avg, max)	0.99, 1.39, 1.80	1.28, 1.92, 3.61	tonnes/ha	Calculated

4.2.3.1.1 Crop Nutrients, Chemicals, and Seeding

The primary nutrients considered in this study for canola and camelina growth were nitrogen, phosphorous, potassium, and sulfur. The input quantities of these nutrients for canola were provided by the Canola Council of Canada as average application rates in Canada (Canola Council of Canada, 2003). Data regarding nutrient application rates for camelina is more scarce than data for canola and was derived from a few different sources (Agriculture and Agri-Food Canada, 2009; Willamette Biomass Processors, 2010; Krohn and Fripp, 2012). As noted by Sultana and Kumar (2011), “lime is usually applied to acidic soil to neutralize [excess acidity] but only 5% of the total area of Alberta lies in the acidic region”, therefore lime application was not considered here. In general, canola requires more synthetic fertilizers than camelina, which results in higher energy and emission impacts for canola.

Additional nutrients for crop growth are supplied by crop residues left from the previous harvest; canola and camelina can be rotated with cereal crops such as wheat and barley so the quantity of crop residue left on the field was based on typical wheat crop residues for Western Canada. Crop residues do not contribute to energy use but do contribute to N_2O emissions from the field since part of the nitrogen in the crop residues is converted to N_2O as they decompose.

Other chemicals needed for crop growth are herbicides and insecticides. As was the case for synthetic fertilizers, canola requires more herbicides and insecticides than camelina, which results in greater energy use and emissions. The seeding rates for canola and camelina are similar and were taken from previous studies (S&T Consultants Inc, 2010; Krohn and Fripp, 2012).

4.2.3.1.2 Machinery and Fuel Use

Diesel fuel is consumed for farming operations such as sowing, spraying chemicals, spreading fertilizer, harvesting, and seed transportation. Input quantities for each of these operations for canola farming were taken from an earlier LCA study (Baquero et al., 2011). Due to a scarcity of data, the same input quantities (on a per ha basis) were used for camelina and the energy and emission impacts for these inputs were adjusted based on camelina's yield. Since energy and emission parameters were available for farm equipment manufacturing (an indirect input), these were included in the LCA.

4.2.3.1.3 Seed Drying and Cleaning

Before being transported to the oil extraction plant, seeds often go through a preliminary drying and cleaning step, which requires electricity and heat. The energy requirements for drying are based on drying the seed to 8% moisture content (Rustandi, 2010).

4.2.3.1.4 Field N_2O Emissions and Land Use Changes (LUC)

Two of the largest and most contentious sources of emissions for agricultural-based renewable fuels are the emissions that come from soils (field emissions) and the emissions that result from LUC. For field emissions, the main concern is N_2O that is released due to nitrification and denitrification processes in the soil (De Klein et al., 2006). Using the Intergovernmental Panel on Climate Change (IPCC) guidelines (De Klein et al., 2006), direct N_2O emissions can be calculated based on the quantity of nitrogen added to the soil from a variety of sources such as synthetic fertilizers, organic fertilizers, and crop residues. Based on the 2006 IPCC guidelines, Equation 1 shows how direct N_2O emissions were calculated for canola and camelina farming in this study.

Eq (1): $N_2O_{direct}\text{-}N = (F_{SN} + F_{ON} + F_{CR} + F_{SOM})*EF_1$

Where:

N_2O_{direct}-N: annual direct N_2O-N emissions produced from managed soils, kg N_2O-N/yr

F_{SN}: amount of synthetic fertilizer N applied to soils, kg N/yr

F_{ON}: amount of organic N additions applied to soils, kg N/yr (zero for this study)

F_{CR}: annual amount of N in crop residues returned to soils, kg N/yr

F_{SOM}: annual amount of N in mineral soils that is mineralized in association with a loss of soil C as a result of changes to land use or management, kg N/yr (addressed with LUC)

EF_1: emission factor for N_2O emissions from N inputs, kg N_2O-N/kg N input

The default emission factor for the nitrogen added to soil that is evolved as N_2O-N is 1%. However, this emission factor is very site-specific, and can vary significantly depending on climate, type of crop, type of soil, and tillage methods (Edwards et al., 2007; Sultana and Kumar, 2011). In this study, an Alberta-specific emission factor of 0.76% (S&T Consultants Inc, 2010) was used in the base scenario, but some authors have contended that the direct N_2O emission factor can be as high as 5% (Crutzen et al., 2007). Therefore, scenarios 3-7 (see Table 4-1) were developed to account for the variety of emission factor estimates.

The IPCC has also published guidelines regarding methods to calculate soil emissions that result from land use changes (Intergovernmental Panel on Climate Change, 2003). In general, when land changes from one use (e.g. natural grassland) to another (e.g. cropland), the carbon and nitrogen stock (i.e. amount of carbon and nitrogen stored in the soil) gradually changes until a new equilibrium has been established. It can take 20 years or more to establish the new equilibrium and the new equilibrium level depends on initial and final land use types, climate zone, soil management, and input of organic matter (Intergovernmental Panel on Climate Change, 2003). Based on the 2003 IPCC guidelines, Equations 2 and 3 show how changes in soil carbon stock were calculated in this study. After calculating soil carbon stock, soil nitrogen stock was calculated using a carbon to nitrogen ratio of 15 (Intergovernmental Panel on Climate Change, 2003).

Eq (2): $\Delta C = [(SOC_o - SOC_{(o-T)})*A]/T$

Where:

ΔC: annual change in carbon stock, tonnes C/yr

SOC_o: soil organic carbon stock in the inventory year, tonnes C/ha

$SOC_{(o-T)}$: soil organic carbon stock T years prior to the inventory, tonnes C/ha

T: inventory time period, yr (default is 20 years)

A: land area of each parcel, ha

Eq (3): $SOC = SOC_{REF}*F_{LU}*F_{MG}*F_I$

Where:

SOC_{REF}: the reference carbon stock, tonnes C/ha

F_{LU}: stock change factor for land use or land use change type, dimensionless

F_{MG}: stock change factor for management regime, dimensionless

F_I: stock change factor for input of organic matter, dimensionless

When LUC was considered in this study, only the GHGs from canola HDRD were impacted. As noted by other authors (Shonnard and Williams, 2010; Krohn and Fripp, 2012), camelina does not deplete soil nutrients nearly as much as other crops, so camelina could potentially replace the fallow stage in a typical 3 or 4-year crop rotation of oilseeds with cereals. Therefore, if vegetable oil for renewable fuel production comes from camelina, it may not be necessary to convert non-agricultural land to agricultural land, meaning that LUC emissions are not introduced. On the other hand, if canola oil were to be used for large volumes of renewable fuel production, new agricultural land would likely need to be developed because most of the canola oil currently produced in Alberta is used in the food industry.

When including LUC in this study, it was assumed that grassland under natural vegetation was converted to cropland for farming canola. The values used for the parameters in Equations 2 and 3, as well as other factors used in the LUC calculations are given in Table 4-5. Note that although N_2O and CO_2 are released when grassland is converted to cropland, grassland under natural vegetation produces a baseline level of N_2O (Bouwman et al., 1993; Stehfest and Bouwman, 2006; Schmidt, 2007), which can be considered an emissions credit in the LUC calculation (-503 g N_2O/ha for this study).

Table 4-5: Factors Used to Calculate LUC Emissions from Changes in Soil Nitrogen and Carbon Content

Factor	Factor Description	Value	Units	Source	Comments
				Grassland (Natural Vegetation)	
F_{LU}	Land Use Factor	1	N/A	a	Default value
F_{MG}	Management Factor	1	N/A	a	Nominally managed (non-degraded)
F_I	Input Factor	1	N/A	a	Nominal
SOC	Soil Organic Carbon Stock	39	tonnes C/ha	a,b	Average of clay and sandy soils. See IPCC pg 3.117
BOC	Biomass Organic Carbon Stock	4.2	tonnes C/ha	a	Cold temperate, dry and using root to shoot ratio. See IPCC pg 3.109-3.110
TOC	Total Organic Carbon Stock	43.2	tonnes C/ha	Calculated	
C:N	Carbon to Nitrogen Ratio	15.0	N/A	a	See IPCC pg 3.94
TN	Total Nitrogen Stock	2.9	tonnes N/ha	Calculated	
				Canola Cropland	
F_{LU}	Land Use Factor	0.7	N/A	a	Long term cultivated
F_{MG}	Management Factor	1.05	N/A	a,c	Reduced tillage
F_I	Input Factor	0.9	N/A	a	Low
SOC	Soil Organic Carbon Stock	25.8	tonnes C/ha	a,b	Average of clay and sandy soils. See IPCC pg 3.117
BOC	Biomass Organic Carbon Stock	0.0	tonnes C/ha	b	Most vegetation removed, therefore assume zero.
TOC	Total Organic Carbon Stock	25.8	tonnes C/ha	Calculated	
C:N	Carbon to Nitrogen Ratio	15.0	N/A	a	See IPCC pg 3.94
TN	Total Nitrogen Stock	1.7	tonnes N/ha	Calculated	
				Emissions from Change in Carbon Stock	
T	Time Period	20	years	a	Default value
CC	Carbon Conversion	3.67	kg CO_2/kg C	Calculated	Based on molar properties
CO_{2E}	Carbon Dioxide Emissions	3187	kg CO_2/ha yr	Calculated	
				Emissions from Change in Nitrogen Stock	
T	Time Period	20	years	a	Default value
NC	Nitrogen Conversion	1.57	kg N_2O/kg N	Calculated	Based on molar properties
EFN	Nitrous Oxide Emission Factor	1.25	kg N_2O-N/kg N	a	See IPCC pg 3.94
NE	Nitrous Oxide Emissions	1.1	kg N_2O/ha yr	Calculated	

Sources: [a](Intergovernmental Panel on Climate Change, 2003), [b](Schmidt, 2007), [c](Canola Council of Canada, 2010)

4.2.3.2 Transportation of Oilseeds from the Field to the Oil Extraction Plant

After the oilseeds have been harvested, they are transported from the field to the oil extraction plant. In this LCA, it was assumed that seeds are transported from the field to the oil extraction plant by trucks with a capacity of 27 tonnes (Rustandi, 2010), full-load fuel consumption of 0.35 L/km (Mårtensson, 2003), and empty-load fuel consumption of 0.28 L/km (Mårtensson, 2003). The field-to-plant transportation distances are based on previous work done by the authors (Miller et al., 2012) as discussed earlier in Chapter 2, in which they determined the economically optimal sizes of canola and camelina oil extraction plants for Alberta (190 million L/year for canola and 120 million L/year for camelina); these plant sizes were used as the basis for this LCA, which resulted in a round-trip seed transport distance of 164 km for canola and 132 km for camelina. The energy and emission coefficients used for seed transportation were 45.25 MJ/L of diesel (Piringer and Steinberg, 2006) and 3,336 g CO_{2e}/L of diesel (West, 2002; Marano, 2009) respectively. Overall, seed transportation has a very small impact on both energy use (0.004 MJ/MJ for canola, 0.005 MJ/MJ for camelina) and emissions (0.3 g CO_{2e}/MJ for canola, 0.4 g CO_{2e}/MJ for camelina).

4.2.3.3 Vegetable Oil Extraction

At the oil extraction plant the seeds are typically dried and cleaned, then the oil is extracted by crushing the seeds with a press and then using a solvent (hexane) to absorb residual oil from the oilseed meal (Mag, 2011). After extraction, the oil is degummed to remove phosphatides, which prevents sludges from forming during storage (Mag, 2011). Although the degumming stage for camelina is slightly different than it is for canola (e.g. different chemicals used to induce phosphatide precipitation), the preparation, pressing, and solvent-extraction stages are the same for both crops (Sandroni, 2010). Canola seeds contain approximately 44% oil by mass (Trimark Engineering Ltd., 2007), and estimates for camelina seed oil content range from approximately 30% (Abramovic and Abram, 2005) to 38% (Budin et al., 1995). To remain consistent with the authors' previous work (Miller et al., 2012) and as discussed in Chapter 2, an oil content of 30% for camelina was used in this LCA.

In published literature, detailed input quantity data for canola and camelina oil extraction is very scarce. Of the studies that listed input quantity data (Rustandi, 2010; Shonnard and Williams, 2010; Chen and Chen, 2011; Agusdinata et al., 2011; Krohn and Fripp, 2012), Rustandi's data for canola oil extraction was the most comprehensive so it was used here. Since the canola and camelina oil extraction processes are so similar, Rustandi's data was used for both canola and camelina. A detailed summary of the input quantities, energy coefficients, emission coefficients, and energy and emission impacts for the vegetable oil extraction stage is given in Table 4-6 (canola) and Table 4-7 (camelina).

Table 4-6: Inputs, Energy Coefficients, Emission Coefficients, and Impacts for Canola Oil Extraction, Base Scenario

Operation	Input Quantity			Energy Coefficients			Emission Coefficients			Energy Use	Emissions
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	a	MJ/MJ process heat	3.23	a	gCO_{2e}/MJ process heat	292	a	0.009	0.8
Drying electricity	kWh/tonne seed	13.6	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.007	0.6
Oil extraction											
Electricity*	kWh/tonne seed	40.8*	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.020	1.8
Steam	kg/tonne seed	369	a	MJ process heat/kg	2.00	a	gCO_{2e}/MJ process heat	126	a	0.044	4.7
Cooling water**	kg/tonne seed	14560	a	MJ/kg	0.004	c	gCO_{2e}/kg	0.93	calc.	0.003	0.7
Lost solvent (hexane)***	L/tonne seed	1.94	a	MJ/kg	44.41	d	gCO_{2e}/kg	17710	a	0.003	1.1
*Degumming**** *											
Electricity	kWh/tonne seed	2.2	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.001	0.1
Steam	kg/tonne seed	74.3	a	MJ process heat/kg	2.00	a	gCO_{2e}/MJ process heat	126	a	0.009	0.9
Process water	kg/tonne seed	8.3	a	MJ/kg	0.01	a	gCO_{2e}/kg	2.47	a	0.000	0.0
Oil Extraction Subtotal										**0.09**	**10.7**

*Shonnard's estimate was 8.3 kWh/tonne (Shonnard and Williams, 2010)

**Emission coefficient calculated based on process water and ratio of energy coefficients

***Emission coefficient based on direct release of hexane to the atmosphere

****Assumed half of Rustandi's input quantity estimates (Rustandi, 2010) since they were for degumming plus refining

Table 4-7: Inputs, Energy Coefficients, Emissions Coefficients, and Impacts for Camelina Oil Extraction, Base Scenario

Operation	**Input Quantity**			**Energy Coefficients**			**Emission Coefficients**			**Energy Use**	**Emissions**
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	a	MJ/MJ process heat	3.23	a	gCO_{2e}/MJ process heat	292	a	0.013	1.2
Drying electricity	kWh/tonne seed	13.6	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.010	0.9
Oil extraction											
Electricity*	kWh/tonne seed	40.8*	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.030	2.7
Steam	kg/tonne seed	369	a	MJ process heat/kg	2.00	a	gCO_{2e}/MJ process heat	126	a	0.064	3.4
Cooling water**	kg/tonne seed	14560	a	MJ/kg	0.004	c	gCO_{2e}/kg	0.93	calc.	0.004	1.0
Lost solvent (hexane)***	L/tonne seed	1.94	a	MJ/kg	44.41	d	gCO_{2e}/kg	17710	a	0.004	1.7
*Degumming**** *											
Electricity	kWh/tonne seed	2.2	a	MJ/kWh	9.89	b	gCO_{2e}/kWh	880	e	0.002	0.1
Steam	kg/tonne seed	74.3	a	MJ process heat/kg	2.00	a	gCO_{2e}/MJ process heat	126	a	0.013	1.4
Process water	kg/tonne seed	8.3	a	MJ/kg	0.01	a	gCO_{2e}/kg	2.47	a	0.000	0.0
Oil Extraction Subtotal										**0.14**	**12.3**

*Shonnard's estimate was 8.3 kWh/tonne (Shonnard and Williams, 2010)

**Emission coefficient calculated based on process water and ratio of energy coefficients

***Emission coefficient based on direct release of hexane to the atmosphere

****Assumed half of Rustandi's input quantity estimates (Rustandi, 2010) since they were for degumming plus refining

Sources for: Table 4-6 and Table 4-7

[a](Rustandi, 2010)

[b](Piringer and Steinberg, 2006)

[c](Zhou, 2008) as cited in (Chen and Chen, 2011)

[d](Wang, 2011)

[e](Environment Canada, 2010)

4.2.3.4 Transportation of Vegetable Oil to the HDRD Plant

Once the vegetable oil has been produced, it must be transported to the HDRD plant. It was assumed for this study that the HDRD plant is located in Redwater, Alberta, and that the vegetable oil is sourced from highly concentrated areas of canola production. Redwater is an industrial area of Alberta with nearby canola production and multiple oil and gas processing facilities. For a 290 million L per year (5,000 bbl/day) HDRD plant in Redwater, all of the vegetable oil could be supplied by canola from Census Division (CD) 10 and the round-trip transportation distance for oil from CD 10 to Redwater is approximately 260 km (Miller and Kumar, 2012). Since camelina is not a well-established crop in Alberta, the same transportation distance as canola was assumed for camelina. Super B-train trucks transport the vegetable oil, which have an approximate capacity of 60 m^3, full load fuel consumption of 0.50 L/km (Mårtensson, 2003), and empty-load fuel consumption of 0.31 L/km (Mårtensson, 2003). The energy and emission coefficients used for vegetable oil transportation were the same as those for seed transportation and like seed transportation, vegetable oil transportation has a very small impact on both energy use (0.002 MJ/MJ for both canola and camelina) and emissions (0.1 g CO_{2e}/MJ for both canola and camelina). This transportation distance can be adjusted for other jurisdictions depending on crop yield as appropriate but the methodology can be used around the world directly.

4.2.3.5 HDRD Production

Vegetable oil can be converted to HDRD via hydroprocessing, in which triglycerides in the vegetable oil react with hydrogen to produce primarily n-alkanes, as well as propane and CO_2 (Wells, 2011). This reaction takes place in a high-temperature, high-pressure reactor in the presence of a catalyst. Mixing the vegetable oil with a solvent such as hexane prior to the reaction provides numerous benefits including: increased contact between the catalyst and reactants (Randolph et al., 1994; Han et al., 2010), reduced formation of undesirable long-chain alkanes (Han et al., 2010), and prolonged catalyst life (Zwijnenburg, 2011). Once the reaction is complete, the products can be separated using a typical refinery distillation train into four main streams: a light-cut fuel gas stream containing CO_2, propane, and some hexane; solvent (hexane) to be recycled to the front-end of the process; a mid-cut HDRD product; a heavy-cut stream containing long-chain alkanes that can be recycled to the front-end of the process (Miller and Kumar, 2012).

The input quantities for HDRD production in this study were based on previous work done by the authors (Miller and Kumar, 2012), using an HDRD plant size of 290 million L per year. In the previous work, the authors developed a chemical process model using Aspen Plus® to simulate HDRD production based on experimental work completed by Alberta Agriculture and Rural Development (Wells, 2011). The model simulated converting canola oil and camelina oil to HDRD at a temperature of 400°C, pressure of 15.2 MPa and used palladium-carbon as a catalyst and hexane as a solvent. Based on the model, the primary inputs for HDRD production include: hydrogen consumed in the hydroprocessing reactions, electricity used to drive pumps and compressors, natural gas used for process heat, cooling water used for process cooling, and hexane makeup (i.e. replacement of hexane lost in the light-cut fuel gas stream). These inputs, along with their corresponding energy coefficients, emission coefficients, and energy and emission impacts are shown in Table 4-8 and Table 4-9. For this stage, the inputs and impacts are very similar for canola oil and camelina oil since the product yields from hydroprocessing are similar for both oils.

Table 4-8: Inputs, Energy Coefficients, Emission Coefficients, and Impacts for Converting Canola Oil to HDRD, Base Scenario

Operation	Input Quantity			Energy Coefficients			Emission Coefficients			Energy Use	Emissions
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Hydroprocessing & distillation											
Hydrogen consumption	kg/L HDRD	0.02	a	MJ/kg	217	b	gCO_{2e}/kg	11888	b	0.078	4.3
Electricity	kWh/L HDRD	0.08	a	MJ/kWh	9.89	c	gCO_{2e}/kWh	880	f	0.018	1.6
Natural gas	MJ/L HDRD	5.35	a	-	-	-	gCO_{2e}/MJ	56.59	e	0.118	6.7
Cooling water*	m^3/L HDRD	0.07	a	MJ/kg	0.004	d	gCO_{2e}/kg	0.93	Calc.	0.006	1.5
Hexane makeup**	kg/L HDRD	0.22	a	MJ/kg	44.41	e	gCO_{2e}/kg	3070	Calc.	0.216	15.0
Oil Extraction Subtotal										**0.44**	**29.0**

* Emission coefficient calculated based on process water (from oil extraction stage) and ratio of energy coefficients

**Emission coefficient calculated based on molecular weight and number of carbon atoms, see (Murrells and Derwent, 2007)

Table 4-9: Inputs, Energy Coefficients, Emission Coefficients, and Impacts for Converting Camelina Oil to HDRD, Base Scenario

Operation	Input Quantity			Energy Coefficients			Emission Coefficients			Energy Use	Emissions
	Units	Used Value	Source	Units	Used Value	Source	Units	Used Value	Source	MJ/MJ	gCO_{2e}/MJ
Hydroprocessing & distillation											
Hydrogen consumption	kg/L HDRD	0.02	a	MJ/kg	217	b	gCO_{2e}/kg	11888	b	0.081	4.4
Electricity	kWh/L HDRD	0.09	a	MJ/kWh	9.89	c	gCO_{2e}/kWh	880	f	0.019	1.7
Natural gas	MJ/L HDRD	5.53	a	-	-	-	gCO_{2e}/MJ	56.59	e	0.122	6.9
Cooling water*	m^3/L HDRD	0.07	a	MJ/kg	0.004	d	gCO_{2e}/kg	0.93	Calc.	0.006	1.5
Hexane makeup**	kg/L HDRD	0.21	a	MJ/kg	44.41	e	gCO_{2e}/kg	3070	Calc.	0.205	14.2
Oil Extraction Subtotal										**0.43**	**28.7**

* Emission coefficient calculated based on process water (from oil extraction stage) and ratio of energy coefficients

**Emission coefficient calculated based on molecular weight and number of carbon atoms, see (Murrells and Derwent, 2007)

Sources for: Table 4-8 and Table 4-9

[a](Miller and Kumar, 2012)

[b](Spath and Mann, 2001)

[c](Piringer and Steinberg, 2006)

[d](Zhou, 2008) as cited in (Chen and Chen, 2011)

[e](Wang, 2011)

[f](Environment Canada, 2010)

Note that the emission coefficient used for hexane in this stage of the LCA is much lower than the emission coefficient used for hexane in the oil extraction stage. In the oil extraction stage, hexane is directly released to the environment whereas in the HDRD production stage, the lost hexane would be burned with the light-cut fuel gas stream; when hexane is directly released to the environment, it has a higher global warming potential than when it is combusted directly (Murrells and Derwent, 2007).

4.2.3.6 Transportation of HDRD to the Consumer

In the Province of Alberta from 2006 to 2010, the amount of diesel fuel sold has averaged approximately 3.5 billion L per year (Statistics Canada, 2011). Therefore, a 290 million L per year HDRD plant would satisfy approximately eight percent of the diesel demand in Alberta. Although this supply is greater than the two percent renewable fuels standard recently established in Alberta, it is assumed that all of the HDRD produced at the plant is consumed in the two major cities of Alberta: Edmonton and Calgary. Edmonton is located approximately 65 km south of Redwater and Calgary is located approximately 380 km south of Redwater. If half of the HDRD produced is consumed in Edmonton and half in Calgary, the average round-trip transportation distance from Redwater to the consumer is 445 km and this distance was used in the LCA. This assumption is specific to this study and could adjusted for other jurisdictions.

It was assumed that super B-train trucks transport the HDRD to the consumer. These are the same trucks used for the vegetable oil transportation stage, so the same capacity, fuel consumption rates, energy coefficients, and emission coefficients mentioned earlier also apply for HDRD transportation. As was the case for other transportation stages, the impacts on energy use (0.003 MJ/MJ for canola and camelina) and emissions (0.2 gCO_{2e}/MJ for canola and camelina) are very small for HDRD transportation. Hence, a change in transportation distance in the case of other jurisdictions would not change the overall result significantly.

4.3 Results and Discussion

4.3.1 Base Scenario

In the base scenario, energy and emissions were allocated between the HDRD, propane fuel gas stream, and oilseed meal on a mass basis. Figure 4-2 and Figure 4-3 illustrate the energy and emission inputs for each stage of the LCA, along with allocations to each product for canola-based HDRD and camelina-based HDRD production respectively. Note that the inputs and allocations in these figures have already been normalized using the energy content of HDRD. That is, the inputs and allocations are shown as gCO_{2e} per MJ or MJ per MJ of energy in the fuel, instead of raw gCO_{2e} or MJ amounts. For the base scenario, canola-based HDRD generates 48 gCO_{2e}/MJ with an NER of 1.7 (inverse of energy use) and camelina-based HDRD generates only 38 gCO_{2e}/MJ with an NER of 2.0. Camelina-based HDRD's superior emission and energy performance is mostly due to lower fertilizer use, lower soil N_2O emissions, and higher yield compared to canola.

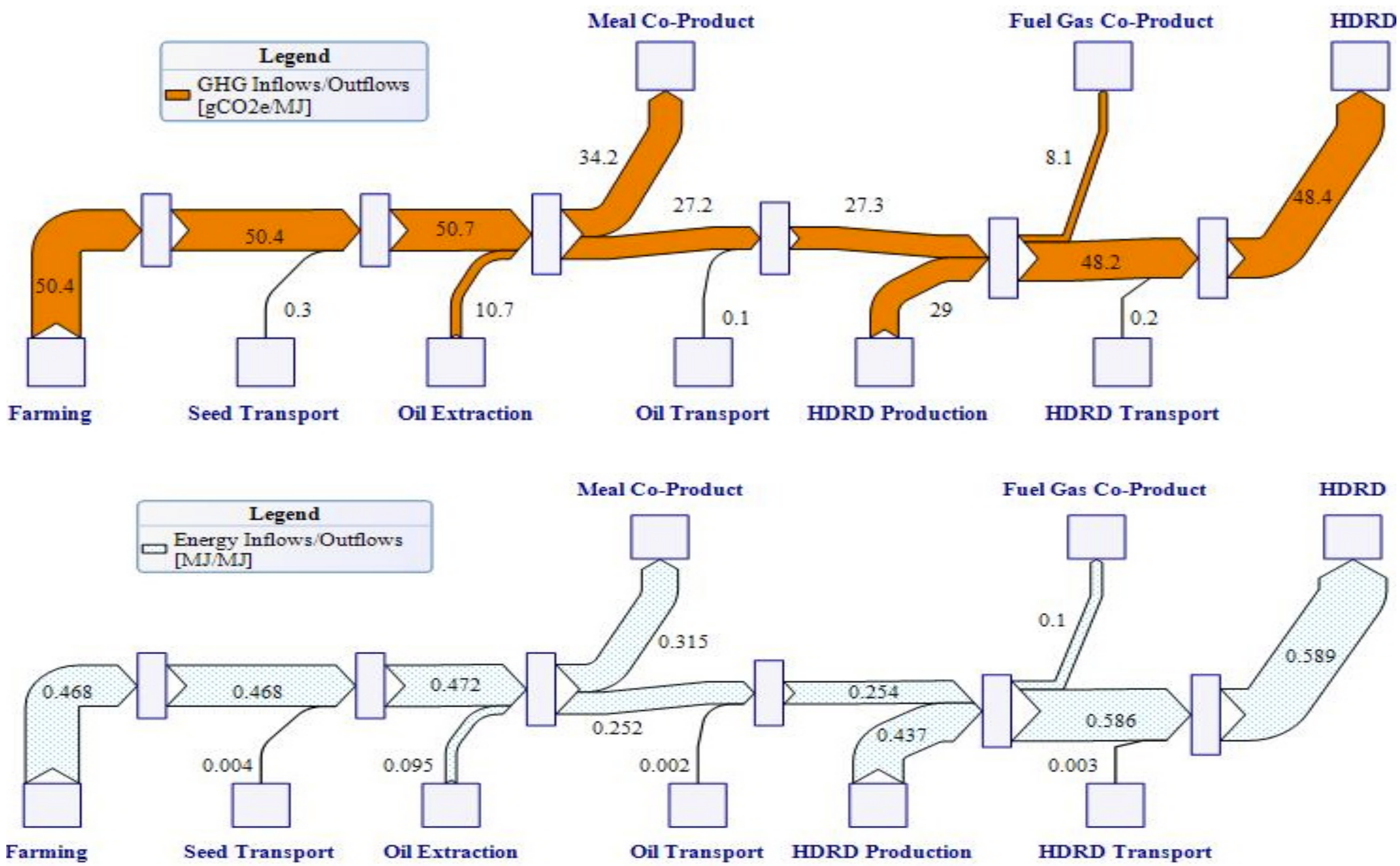

Figure 4-2: Energy and Emission Inflows/Outflows for Canola-Based HDRD

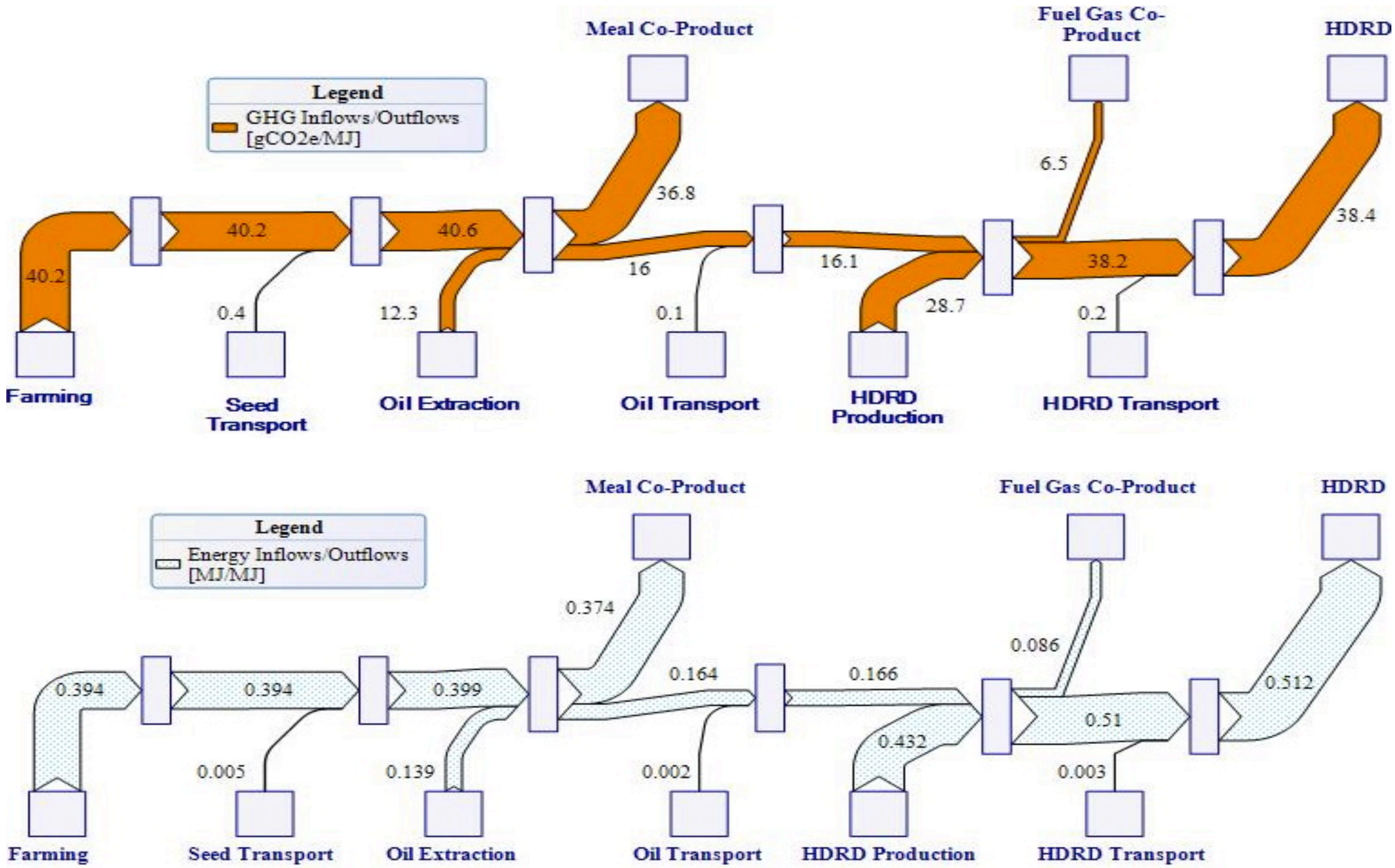

Figure 4-3: Energy and Emission Inflows/Outflows for Camelina-Based HDRD

From Figure 4-2 and Figure 4-3, it is clear that the field stage generates the most emissions, followed by the HDRD production stage, the oil extraction stage, and the transportation stages. In the field stage, the greatest contributors to emissions are fertilizer use and soil N_2O emissions whereas in the HDRD production stage, hexane makeup contributes the most to emissions; in the experiments used as a basis for this study (Wells, 2011), a relatively high solvent to vegetable oil ratio of 7:1 was used but in a real HDRD plant, the solvent to vegetable oil ratio and corresponding hexane makeup rate would likely be lower, resulting in lower emissions than what is shown here. For the oil extraction stage, electricity and steam use generate the most emissions and for all of the transportation stages, the emissions are essentially negligible compared to the other stages.

The relative breakdown of energy use is essentially the same as the breakdown already discussed for emissions. However, unlike the emissions breakdown, the HDRD production stage is slightly more energy intensive than the field stage for camelina-based HDRD. This phenomenon only occurs for camelina-based HDRD because camelina uses less N fertilizer than canola and the input quantity of N fertilizer was used to calculate soil N_2O emissions, which impact total emissions but not energy use. Similar to the emissions breakdown, hexane makeup in the HDRD production stage adds greatly to energy use, so reducing the hexane makeup rate in a real HDRD plant would result in a better NER.

In the co-product allocation, HDRD receives the greatest allocation of emissions and energy use, followed by the oilseed meal, and the propane fuel gas stream. Due to the lower oil content of camelina compared to canola (30% vs. 44%), a higher share of emissions and energy use were allocated to camelina meal compared to canola meal. As discussed in section 4.2.3.3 (Vegetable Oil Extraction), estimates of camelina seed oil content in literature vary significantly. However, increasing the oil content of camelina to 38% (Budin et al., 1995) in the LCA model has essentially no impact on the emissions and NER of camelina-based HDRD; a higher oil content results in lower total emissions and energy use in the oil extraction stage but a greater share of the total emissions and energy use are allocated to the oil and subsequent HDRD. This dynamic between the oil content and allocation results in a balance, but only for the mass allocation method.

4.3.2 Other Scenarios – Sensitivity Analysis

As shown in Table 4-1, many scenarios were analyzed in this study to account for differences in variables (i.e. yield and field N_2O emissions) and methodological assumptions (i.e. co-products, allocation methods, and land-use changes) that could significantly impact the LCA results. The life cycle GHGs and NER for HDRD for each scenario are shown in Figure 4-4 and Figure 4-5 respectively. Note that in Figure 4-5, scenarios 3 to 8 were not included because the NERs for those scenarios are the same as the base scenario NER. The key differences for each scenario compared to the base scenario are as follows (scenarios 11 and 12 apply to camelina only):

- Scenario 1: straw included as a co-product;
- Scenario 2: economic value allocation method;
- Scenario 3: 1% N_2O emission factor;
- Scenario 4: 2% N_2O emission factor;
- Scenario 5: 3% N_2O emission factor;
- Scenario 6: 4% N_2O emission factor;
- Scenario 7: 5% N_2O emission factor;
- Scenario 8: land use change included;
- Scenario 9: maximum yield considered;
- Scenario 10: minimum yield considered;
- Scenario 11: meal not included as a co-product;
- Scenario 12: meal not included as a co-product and economic value allocation.

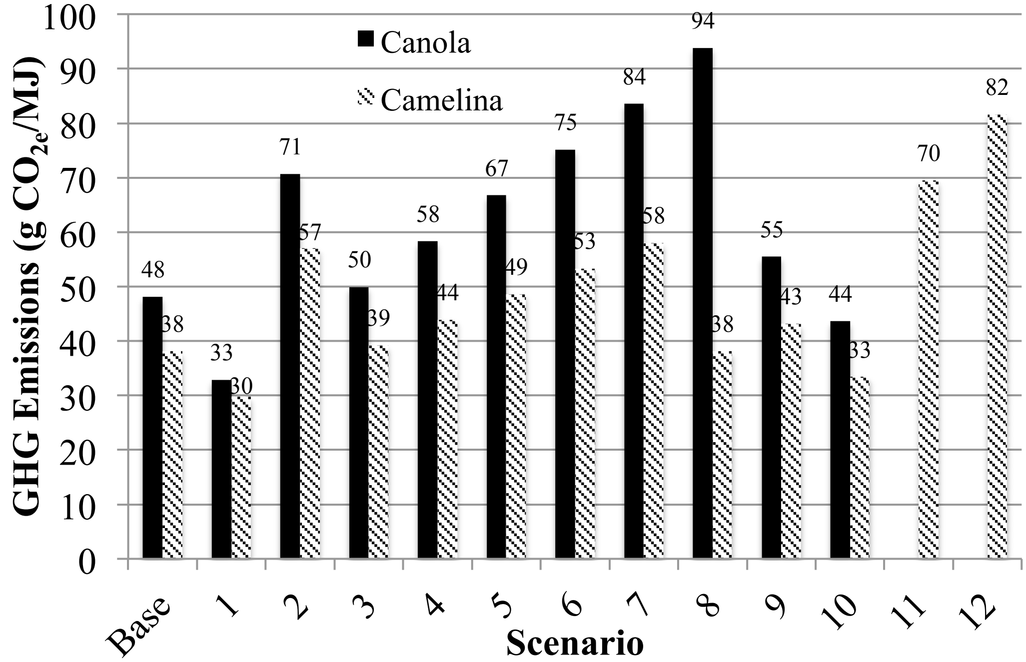

Figure 4-4: Life Cycle GHGs for HDRD for the Scenarios Analyzed

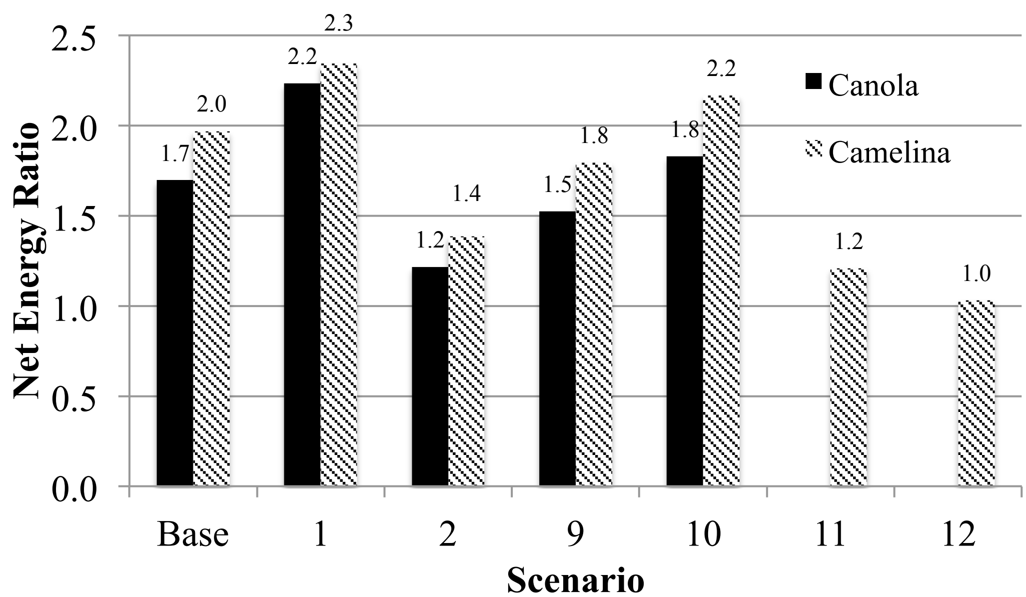

Figure 4-5: NER for HDRD for the Scenarios Analyzed

Some key observations from Figure 4-4 and Figure 4-5 are:

- Including straw in the allocation (scenario 1) significantly reduces the emissions and energy-use allocated to HDRD compared to the base scenario. This reduction occurs because of the high emission and energy intensity of the field stage, coupled with high straw to seed ratios for canola and camelina – 4.1 kg/kg for canola (Malhi and Gill, 2006) and 4.0 kg/kg for camelina (Lošák et al., 2011).
- Changing the allocation method from mass to economic value (scenario 2) increases HDRD emissions by nearly 50% and decreases NER by 30%. Recent canola meal prices in Western Canada were much lower on a mass basis than diesel prices - $0.22/kg (Canola Council of Canada, 2012) vs. $1.35/kg (Natural Resources Canada, 2011) – so for scenario 2 most of the energy and emission burdens go to the HDRD. Since camelina meal price data was not readily available, it was assumed that camelina meal sold for the same price as canola meal.
- Increasing the soil N_2O emission factor from 0.76% to 5% (scenarios 3 to 7), increases the GHGs allocated to HDRD linearly by up to 75% for canola-based HDRD and 53% for camelina-based HDRD. Camelina-based HDRD is less sensitive to changes in the soil N_2O emission factor because less nitrogen fertilizer is used to grow camelina.
- Including land-use changes (scenario 8) nearly doubles the GHGs allocated to canola-based HDRD but has no impact on camelina-based HDRD since camelina could replace the fallow stage in crop rotation.

- Changing the oilseed yield from average to minimum (scenario 9) or to maximum (scenario 10) only changes the GHG allocations by a maximum of 15% and the NERs by a maximum of 11%.
- Removing camelina meal from the co-product allocations has a great impact on the GHGs and NER for camelina-based HDRD. Under mass allocation (scenario 11), GHGs increase by 84% and NER decreases by 39% compared to the base scenario. Under economic value allocation (scenario 12), GHGs increase by 116% and NER decreases by 48%.
- None of the scenarios resulted in an NER less than 1, meaning that in all scenarios, the return on fossil energy invested was positive.

In all direct comparison scenarios, camelina-based HDRD outperforms canola-based HDRD in terms of GHGs and NER. However, if camelina meal cannot be sold (scenarios 11 and 12), canola-based HDRD outperforms camelina-based HDRD. Camelina meal is currently accepted as animal feed on a very limited basis, so at this point in time, canola-based HDRD is more sustainable than camelina-based HDRD based on GHGs and NER. If camelina meal gains greater acceptance as animal feed in the future, camelina will likely be a much better choice from an environmental perspective than canola for renewable fuels production.

4.3.3 Comparison with Literature

Few LCA studies are available in literature for canola- and camelina-based HDRD, but the results in those studies agree reasonably well with the base scenario results in this study. Arvidsson et al. (2011) estimated the life cycle GHGs and NER of rapeseed-based HDRD at approximately 67 gCO_{2e}/MJ and 2.4 respectively. The higher GHGs in that study can be partially explained by Arvidsson's use of a higher emission factor for soil N_2O emissions (1.25% vs. 0.76%). Other differences in emissions and NER are likely due to differences between studies in farming location (Germany vs. Western Canada), allocation method (displacement vs. mass), and energy and emission coefficients.

Shonnard and Williams (2010) used mass allocation, energy allocation, and displacement allocation to estimate the life cycle GHGs and NER of camelina-based HDRD. In that study, the life cycle GHGs were found to be approximately 16 gCO_{2e}/MJ (mass allocation), 18 gCO_{2e}/MJ (energy allocation), or 4 gCO_{2e}/MJ (displacement allocation). Specific NER data was not given for each allocation type, but the general NER given for camelina-based HDRD was approximately 4.0. Shonnard's study suggests much lower energy and emission intensities for camelina-based HDRD than this study, which is likely due to several differences in assumptions. Shonnard's study was based in the United States and used lower fertilizer inputs for the farming stage and lower energy inputs for the oil extraction and HDRD production stages. Since camelina is not widely grown in Canada or the US, the fertilizer inputs are not yet well defined so both studies' estimates may be valid. For the HDRD production stage, Shonnard used data from UOP's commercial HDRD process, so Shonnard's estimates for that stage may be more accurate than this study's, which were based on experimental data and chemical process modeling.

4.3.4 Comparison with Diesel and Biodiesel

Compared to fossil diesel, HDRD from canola or camelina appears to be a more sustainable choice. Estimates in literature for the GHGs and NER for fossil diesel vary from approximately 86 – 94 gCO_{2e}/MJ and 0.79 – 0.85 MJ/MJ respectively (Kalnes et al., 2007; Krohn and Fripp, 2012). Therefore, in the base scenario, canola-based HDRD offers a reduction in GHGs of approximately 47% and more than twice the NER compared to fossil diesel; camelina-based HDRD is even better, with a 58% reduction in GHGs and 2.4 times the NER of fossil diesel. None of the extra scenarios showed that HDRD has an NER less than fossil diesel and only scenarios 7 (canola, 5% N_2O emission factor), 8 (canola, LUC included), and 12 (camelina, meal excluded, economic-value allocation) showed that GHGs from HDRD could fall into the same range as GHGs from fossil diesel.

Many LCAs have been completed on biodiesel from canola/rapeseed (Bernesson, 2004; Edwards et al., 2007; Rustandi, 2010; S&T Consultants Inc, 2010; Chen and Chen, 2011; Krohn and Fripp, 2012) but LCAs are limited for biodiesel from camelina (Krohn and Fripp, 2012). The estimates of GHGs and NER in these studies vary widely, but average at approximately 50 gCO_{2e}/MJ and 2.8 MJ/MJ for canola-biodiesel, and 29 gCO_{2e}/MJ and 2.4 for camelina-biodiesel. These emission levels are very similar to the emission levels found in this study for canola-based HDRD and camelina-based HDRD. However, the NERs in literature for canola- and camelina-based biodiesel are generally slightly higher than those found in this study for HDRD.

4.4 Conclusion

In this study, data-intensive life cycle assessment models were developed to estimate the NER and GHGs for HDRD produced from canola oil and camelina oil in Western Canada. If camelina meal can be directly substituted for canola meal as animal feed, camelina-based HDRD is environmentally superior to canola-based HDRD due to lower agricultural inputs and higher yields for camelina. However, since there is currently little market demand for camelina meal, it is unrealistic to consider it as a co-product, making canola-based HDRD a more environmentally friendly option at this time. A sensitivity analysis determined that the choice of allocation method, co-products, soil N_2O emission factor, and whether to include LUC could significantly impact the LCA results. However, even in the most extreme scenarios, both canola-based HDRD and camelina-based HDRD appear to be more sustainable than fossil diesel due to lower GHGs and higher NERs. Based on the available literature, GHGs for HDRD production are similar to those for biodiesel, while the NER for HDRD appears slightly lower than the NER for biodiesel.

In producing HDRD, the farming stage and the oil conversion stage (i.e. the HDRD production stage) are the most energy and emission intensive. To improve the sustainability of HDRD, researchers and industry could focus on minimizing nitrogen fertilizer use in farming (while maintaining yield) and optimizing solvent use during hydroprocessing. For camelina specifically, more research is needed to evaluate the viability of camelina meal as animal feed in order to justify including it as a co-product in energy and emission allocations.

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5 Conclusions and Recommendations for Future Work

5.1 Conclusions

With the recently implemented renewable fuels standards in Canada and in Alberta (Environment Canada, 2011; Government of Alberta, 2011), it is important for industry and government policy makers to understand the viability of alternatives to gasoline and diesel. From an environmental perspective, governments need an estimate of the GHG savings for alternative fuels so that they can plan to meet emission reduction targets. From an economic perspective, companies need an estimate of the costs to produce alternative fuels so that they can plan their budgets.

Therefore, the purpose of this research was to investigate the economic and environmental sustainability of producing hydrogenation-derived renewable diesel in Western Canada. Two crops were selected as potential feedstocks for HDRD production – canola because it is readily available in Western Canada, and camelina because compared to canola, it requires less inputs for growth and does not compete with food. Detailed techno-economic and life cycle assessment models were developed to analyze the key stages of HDRD production: farming, vegetable oil extraction, hydroprocessing (i.e. vegetable oil conversion to HDRD), and transportation. These models were used to develop estimates of production costs, optimum processing plant sizes, greenhouse gas emissions, and net energy ratios for HDRD production.

5.1.1 Production costs and optimum plant sizes

In phase 1 of this study (Chapter 2), the cost to produce vegetable oil from canola and camelina was estimated for a wide range of oil extraction plant sizes using either press-based extraction or solvent-based extraction. In the average yield case, the production costs for vegetable oil are \$0.63/L for a canola press plant, \$0.55/L for a canola solvent plant, \$0.28/L for a camelina press plant, and \$0.28/L for a camelina solvent plant. For camelina, these costs are based on selling camelina meal for the same price as canola meal (\$0.26/kg), which is not realistic at this point in time based on the low current demand for camelina meal. If camelina meal cannot be sold, the oil production costs rise dramatically to \$1.04/L for a press plant and \$0.82/L for a solvent plant.

These vegetable oil production costs are for oil extraction plants at their economically optimum sizes (i.e. the plant sizes that result in the minimum production costs): 140 million L/year for a canola press plant, 190 million L/year for a canola solvent plant, 90 million L/year for a camelina press plant, and 120 million L/year for a camelina solvent plant. Although economically optimum sizes for vegetable oil extraction plants do exist, the cost of production increases by only a few cents per L for larger plants, meaning that a range of plant sizes could be built without significantly impacting production cost.

In phase 2 of this study (Chapter 3), the vegetable oil production costs from phase 1 were used as inputs in order to estimate the total production cost of HDRD. As discussed in Chapter 3, Figure 5-1 shows the HDRD production costs that were estimated for a wide range of production plant sizes.

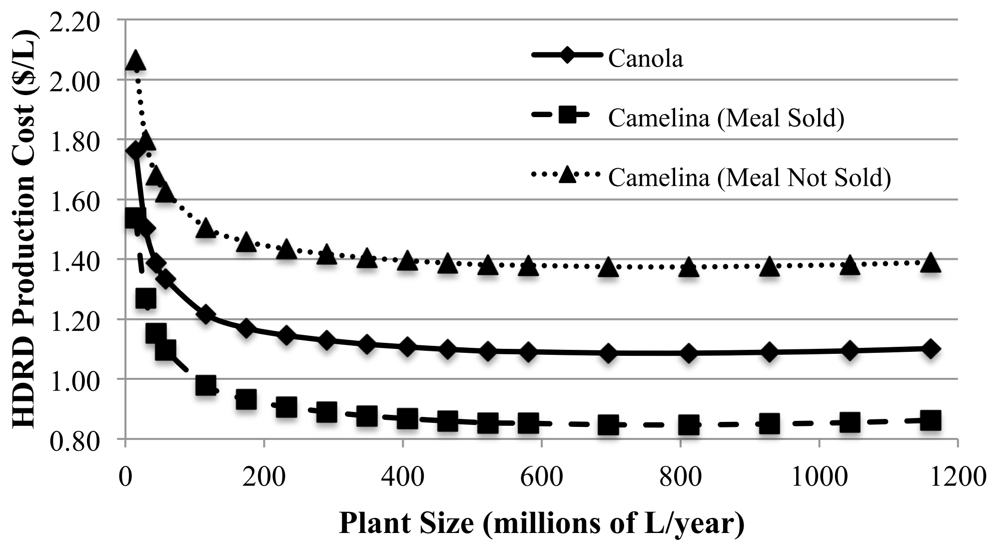

Figure 5-1: HDRD Production Costs for a Range of Production Plant Sizes

Assuming that solvent-based extraction is used to produce the vegetable oil, the total HDRD production costs are $1.09/L from canola, $0.85/L from camelina (if meal can be sold), and $1.37/L from camelina (if meal cannot be sold). Once again, these production costs are for the optimum HDRD plant size – 812 million L/year for both canola and camelina. For HDRD plants, the production cost curves are even flatter than those of oil extraction plants because transportation costs do not increase as rapidly with plant size for HDRD compared to vegetable oil. Therefore, there is little economic advantage in building HDRD plants larger than 290 million L/year. At these production costs, only HDRD from camelina (if camelina meal is sold) could compete economically with fossil diesel or biodiesel.

5.1.2 Greenhouse gas emissions and net energy ratio

In phase 3 of this study (Chapter 4), the frameworks of the models built in phases 1 and 2 were used to develop estimates of the life cycle GHGs and NERs for HDRD produced from canola and camelina. In order to account for different methodological assumptions (i.e. co-products, allocation methods, and land-use changes) and variables (i.e. yield and field N_2O emissions), 12 different scenarios were analyzed. In all scenarios, 1 MJ of energy in the HDRD produced (HHV basis) was used as the functional unit.

For canola based HDRD, the GHGS and NERs range from 33 – 94 gCO_{2e}/MJ and 1.2 – 2.2 MJ/MJ respectively. For camelina based HDRD, the GHGs and NERs range from 30 – 82 gCO_{2e}/MJ and 1.0 – 2.3 MJ/MJ respectively. In the base scenario (mass allocation; oilseed meal and propane fuel gas co-products; average yield; 0.76% N_2O emission factor; LUC ignored), HDRD from camelina (38 gCO_{2e}/MJ, 2.0 MJ/MJ) is environmentally superior to HDRD from canola (48 gCO_{2e}/MJ, 1.7 MJ/MJ) due to lower agricultural inputs and higher yield for camelina than canola. However, if camelina meal is not included as a co-product, the sustainability of camelina-based HDRD decreases substantially (70 gCO_{2e}/MJ, 1.2 MJ/MJ). Considering all of the scenarios examined, HDRD from both crops appears to be more environmentally sustainable than fossil diesel (~90 gCO_{2e}/MJ, ~0.82 MJ/MJ).

5.1.3 Key variables in HDRD production

During HDRD production, the farming and hydroprocessing stages have the greatest influence on production cost, GHGs, and NER. Farming represents approximately 75-85% of the vegetable oil production cost, and the vegetable oil production cost makes up nearly half of the total HDRD production cost (for canola-based HDRD). Similarly, the farming stage generates approximately half of the GHGs and consumes approximately half of the energy used in HDRD production. Fertilizer (particularly nitrogen fertilizer) and other agro-chemical use contribute the most to cost, GHGs, and energy use in the farming stage. If oilseed yield could be maintained with lower rates of fertilizer and agro-chemical use, the viability of HDRD as an alternative to fossil diesel would improve.

In the hydroprocessing stage, solvent use is the most important variable to consider in improving the economic and environmental viability of HDRD. Replacing lost solvent makes up approximately 35% of the production cost, 17% of the GHGs generated, and 21% of the energy used for canola-based HDRD production. In this study, a solvent to vegetable oil ratio of 7:1 (mass basis) was used, and decreasing this ratio would dramatically reduce capital and operating costs for the HDRD plant; with a lower ratio, smaller equipment could be used and less solvent would be lost to other lower value product streams in the distillation process. Since the solvent affects HDRD quality, catalyst life, and production cost, there is an opportunity to optimize solvent flow rates with the goal of balancing these factors.

When considering camelina as an energy crop, the ability to sell meal as a co-product is a crucial factor; including camelina meal as a co-product has an enormous impact on HDRD production cost and the emissions and energy use allocated to HDRD in the LCA. If all other factors are equal, excluding camelina meal from the analysis increases HDRD production cost by \$0.52/L, increases GHGs allocated to HDRD by 32 gCO_{2e}/MJ, and decreases NER for HDRD by 0.8 MJ/MJ. Therefore, for HDRD from oilseeds to be viable, there must be readily available market demand for oilseed meal.

Other important variables examined in this study include transportation cost, capital cost, yield, and N_2O emission factor. Transportation cost proved to be influential in determining the optimum processing plant sizes but was only a substantial cost for vegetable oil production (9–19% of vegetable oil production cost). Capital cost was a relatively small cost component in the economic analysis but was greater for HDRD plants than oil extraction plants – mostly due to large equipment required in the HDRD plants for high solvent flow rates. Changes in yield had a larger impact economically than environmentally; for example, for canola, changing from minimum to maximum yield causes a change in vegetable oil price of \$0.57/L but only changes GHGs allocated to canola-

HDRD by 11 gCO_{2e}/MJ and NER by 0.3 MJ/MJ. The N_2O emission factor selected strongly affected GHGs, resulting in estimates up to 36 gCO_{2e}/MJ higher for canola-based HDRD and 15 gCO_{2e}/MJ higher for camelina-based HDRD compared to the base scenario. Emissions from canola-based HDRD were more sensitive to changes in the N_2O emission factor because canola requires more nitrogen fertilizer than camelina.

5.2 Recommendations for future work

This study focused on the economics and environmental impact of producing HDRD from canola and camelina oilseeds in Western Canada. Although the technology for producing vegetable oil is well understood, hydroprocessing (the technology for converting vegetable oil to HDRD) is used on a limited basis commercially for renewable fuel production. Therefore, other than changing the study location, most of the opportunities for future research lie in changing variables associated with hydroprocessing. Some of these opportunities (in the context of economic and environmental viability) are given below:

- Analyze HDRD production from crops other than canola and camelina (e.g. pennycress). Similar to changing study location, changing the feedstock type will have a substantial impact on farming inputs such as fertilizer and pesticide use;
- Analyze HDRD production from lignocellulosic biomass. This research would include conversion of agricultural biomass such as straw and forest biomass such as forest residues. The focus on lignocellulosic biomass

would help in use of feedstocks that do not have any competing use as food.

- Evaluate HDRD production using different reaction conditions. Changing temperatures, pressures, and catalysts used for hydroprocessing will result in changes to equipment sizing and utility costs for the HDRD plant;
- Develop a case where straw from the oilseeds is burned to provide heat and power for the HDRD plant. This case could reduce the GHG footprint and increase the NER of HDRD;
- Optimize solvent use in hydroprocessing. High solvent flow rates prolong catalyst life but also significantly increase the cost and environmental impact of HDRD production. Therefore, more work could be done to find a balance between these factors by optimizing solvent flow rate, type, and recovery.

In order to accurately complete the research suggested above, experimental work would need to be conducted to determine the hydroprocessing reaction characteristics and products for these scenarios. Without the reaction characteristics and products, it would be very difficult to develop new process models to simulate the processes and subsequently analyze the economics and environmental impacts of these scenarios. Furthermore, the experimental work is necessary to determine if the fuel properties of the end product meet the needs of diesel producers.

This study found that although canola-based HDRD performs much better than fossil diesel environmentally, it is not currently an economically viable alternative. Canola is readily available in Western Canada, but to gain traction as a feedstock for renewable fuel production, costs in the farming stage need to be reduced. It is possible that canola seeds below the quality levels required by the food industry could be used for HDRD production; however, due to low availability and logistical issues in collecting these seeds, oil from these seeds could only supply a small scale HDRD plant.

HDRD from camelina, on the other hand, has the potential to be an economically and environmentally viable alternative to fossil diesel. However, for this potential to mature, camelina meal needs to become widely accepted as animal feed and farmers need to begin growing camelina on a large scale. Therefore, possibilities for supplemental research to accelerate camelina use as an energy crop are:

- Conduct trials of camelina meal as animal feed in Canada. In conjunction with these trials, research effort could be focused on breeding new varieties of camelina with better nutritional characteristics;
- Complete additional trials of growing camelina in Western Canada. More trials will provide farmers with greater confidence in the expected yield of camelina and inputs required for camelina growth.

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Appendices

- **Appendix A: Discounted cash flow sheets for vegetable oil production**
- **Appendix B: Aspen Plus® process flowsheets**
- **Appendix C: Aspen Plus® heat and material balances**
- **Appendix D: Calculation of HDRD plant operating costs**
- **Appendix E: Discounted cash flow sheets for HDRD production**

Appendix A.

Discounted cash flow sheets for vegetable oil production

Tables A-1 and A-2 show the discounted cash flow analyses developed for canola oil and camelina oil extraction plants (solvent-based extraction) at their optimum sizes – 190 million L/year and 120 million L/year respectively. In these tables, costs are given in 2008 US dollars and the average yield was used. Plant construction begins in 2008 with oil production starting in 2011 and ending in 2040 (30 year plant life).

Table A-1: Discounted cash flow analysis for canola oil production at optimum plant size (190 million L/year)

Cost items ($000)/year	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Capital cost	12503	21880	28132	0	0	0	0	0	0	0
Operating & maint. cost				6258	7040	7181	7325	7471	7621	7773
Field cost				119049	133931	136609	139341	142128	144971	147870
Transportation cost				6500	7678	7831	7988	8148	8310	8477
Other costs				313	319	325	332	338	345	352
Total cost	12503	21880	28132	132120	148967	151947	154986	158085	161247	164472
PV of total cost	15129	24068	28132	120109	123113	114160	105857	98159	91020	84400
Oil produced (L)				136800	171000	171000	171000	171000	171000	171000
Meal produced (kg)				184666	207750	207750	207750	207750	207750	207750
Oil price ($/L)				0.58	0.59	0.60	0.62	0.63	0.64	0.65
Meal price ($/kg)				0.26	0.26	0.27	0.27	0.28	0.28	0.29
Oil revenue				79547	101422	103450	105519	107630	109782	111978
Meal revenue				48615	54609	55701	56815	57952	59111	60293
Total revenue				128162	156031	159152	162335	165581	168893	172271
PV of total revenue				116511	128951	119573	110877	102813	95336	88402
Net revenue	-12503	-21880	-28132	-3958	7064	7205	7349	7496	7646	7799

Table A-1 (cont.): Discounted cash flow analysis for canola oil production at optimum plant size (190 million L/year)

Cost items ($000)/year	8	9	10	11	12	13	14	15	16	17
Capital cost	0	0	0	0	0	0	0	0	0	0
Operating & maint. cost	7928	8087	8249	8414	8582	8754	8929	9107	9289	9475
Field cost	150828	153844	156921	160060	163261	166526	169856	173254	176719	180253
Transportation cost	8646	8819	8996	9175	9359	9546	9737	9932	10130	10333
Other costs	359	366	374	381	389	396	404	412	421	429
Total cost	167761	171117	174539	178030	181590	185222	188927	192705	196559	200490
PV of total cost	78262	72570	67292	62398	57860	53652	49750	46132	42777	39666
Oil produced (L)	171000	171000	171000	171000	171000	171000	171000	171000	171000	171000
Meal produced (kg)	207750	207750	207750	207750	207750	207750	207750	207750	207750	207750
Oil price ($/L)	0.67	0.68	0.69	0.71	0.72	0.74	0.75	0.77	0.78	0.80
Meal price ($/kg)	0.30	0.30	0.31	0.31	0.32	0.33	0.33	0.34	0.35	0.35
Oil revenue	114218	116502	118832	121209	123633	126106	128628	131200	133824	136501
Meal revenue	61499	62729	63983	65263	66568	67900	69258	70643	72056	73497
Total revenue	175716	179231	182815	186472	190201	194005	197885	201843	205880	209997
PV of total revenue	81973	76011	70483	65357	60604	56196	52109	48320	44805	41547
Net revenue	7955	8114	8276	8442	8611	8783	8959	9138	9321	9507

Table A-1 (cont.): Discounted cash flow analysis for canola oil production at optimum plant size (190 million L/year)

Cost items ($000)/year	18	19	20	21	22	23	24	25	26	27
Capital cost	0	0	0	0	0	0	0	0	0	0
Operating & maint. cost	9665	9858	10055	10256	10461	10671	10884	11102	11324	11550
Field cost	183858	187535	191286	195112	199014	202994	207054	211195	215419	219727
Transportation cost	10540	10750	10966	11185	11409	11637	11869	12107	12349	12596
Other costs	438	446	455	464	474	483	493	503	513	523
Total cost	204500	208590	212762	217017	221358	225785	230300	234906	239605	244397
PV of total cost	36781	34106	31626	29326	27193	25215	23381	21681	20104	18642
Oil produced (L)	171000	171000	171000	171000	171000	171000	171000	171000	171000	171000
Meal produced (kg)	207750	207750	207750	207750	207750	207750	207750	207750	207750	207750
Oil price ($/L)	0.81	0.83	0.85	0.86	0.88	0.90	0.92	0.94	0.95	0.97
Meal price ($/kg)	0.36	0.37	0.38	0.38	0.39	0.40	0.41	0.41	0.42	0.43
Oil revenue	139231	142015	144856	147753	150708	153722	156796	159932	163131	166394
Meal revenue	74967	76466	77995	79555	81146	82769	84425	86113	87835	89592
Total revenue	214197	218481	222851	227308	231854	236491	241221	246045	250966	255986
PV of total revenue	38525	35723	33125	30716	28482	26411	24490	22709	21057	19526
Net revenue	9697	9891	10089	10291	10497	10706	10921	11139	11362	11589

Table A-1 (cont.): Discounted cash flow analysis for canola oil production at optimum plant size (190 million L/year)

Cost items ($000)/year	**28**	**29**	**30**
Capital cost	0	0	0
Operating & maint. cost	11781	12017	12257
Field cost	224122	228604	233176
Transportation cost	12848	13105	13367
Other costs	534	544	6807
Total cost	249285	254270	265607
PV of total cost	17286	16029	15222
Oil produced (L)	171000	171000	171000
Meal produced (kg)	207750	207750	207750
Oil price ($/L)	0.99	1.01	1.03
Meal price ($/kg)	0.44	0.45	0.46
Oil revenue	169721	173116	176578
Meal revenue	91384	93212	95076
Total revenue	261105	266327	271654
PV of total revenue	18106	16789	15568
Net revenue	11821	12057	6047

Table A-2: Discounted cash flow analysis for camelina oil production at optimum plant size (120 million L/year)

Cost items ($000)/year	-2	-1	0	1	2	3	4	5	6	7
Capital cost	16366	28640	36823	0	0	0	0	0	0	0
Operating & maint. cost				9192	10341	10548	10759	10974	11194	11418
Field cost				105480	118664	121038	123458	125928	128446	131015
Transportation cost				11584	13707	13981	14261	14546	14837	15134
Other costs				409	417	426	434	443	452	461
Total cost	16366	28640	36823	126665	143130	145993	148913	151891	154929	158027
PV of total cost	19802	31504	36823	115150	118289	109686	101709	94312	87453	81093
Oil produced (L)				136800	171000	171000	171000	171000	171000	171000
Meal produced (kg)				335898	377885	377885	377885	377885	377885	377885
Oil price ($/L)				0.30	0.31	0.31	0.32	0.32	0.33	0.34
Meal price ($/kg)				0.26	0.26	0.27	0.27	0.28	0.28	0.29
Oil revenue				41040	52326	53373	54440	55529	56639	57772
Meal revenue				88428	99331	101317	103344	105411	107519	109669
Total revenue				129469	151657	154690	157784	160940	164158	167441
PV of total revenue				117699	125336	116221	107769	99931	92663	85924
Net revenue	-16366	-28640	-36823	2804	8527	8697	8871	9049	9230	9414

Table A-2 (cont.): Discounted cash flow analysis for camelina oil production at optimum plant size (120 million L/year)

Cost items ($000)/year	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Capital cost	0	0	0	0	0	0	0	0	0	0
Operating & maint. cost	11646	11879	12116	12359	12606	12858	13115	13378	13645	13918
Field cost	133635	136308	139034	141815	144651	147544	150495	153505	156575	159707
Transportation cost	15436	15745	16060	16381	16709	17043	17384	17731	18086	18448
Other costs	470	479	489	499	509	519	529	540	551	562
Total cost	161188	164411	167700	171054	174475	177964	181524	185154	188857	192634
PV of total cost	75195	69727	64655	59953	55593	51550	47801	44324	41101	38112
Oil produced (L)	171000	171000	171000	171000	171000	171000	171000	171000	171000	171000
Meal produced (kg)	377885	377885	377885	377885	377885	377885	377885	377885	377885	377885
Oil price ($/L)	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.40	0.40	0.41
Meal price ($/kg)	0.30	0.30	0.31	0.31	0.32	0.33	0.33	0.34	0.35	0.35
Oil revenue	58928	60106	61308	62534	63785	65061	66362	67689	69043	70424
Meal revenue	111863	114100	116382	118710	121084	123505	125976	128495	131065	133686
Total revenue	170790	174206	177690	181244	184869	188566	192338	196184	200108	204110
PV of total revenue	79675	73880	68507	63525	58905	54621	50649	46965	43549	40382
Net revenue	9603	9795	9991	10190	10394	10602	10814	11030	11251	11476

Table A-2 (cont.): Discounted cash flow analysis for camelina oil production at optimum plant size (120 million L/year)

Cost items ($000)/year	18	19	20	21	22	23	24	25	26	27
Capital cost	0	0	0	0	0	0	0	0	0	0
Operating & maint. cost	14196	14480	14770	15065	15367	15674	15987	16307	16633	16966
Field cost	162901	166159	169482	172872	176329	179856	183453	187122	190864	194682
Transportation cost	18817	19193	19577	19968	20368	20775	21191	21615	22047	22488
Other costs	573	584	596	608	620	633	645	658	671	685
Total cost	196487	200417	204425	208513	212684	216937	221276	225702	230216	234820
PV of total cost	35340	32770	30386	28177	26127	24227	22465	20831	19316	17912
Oil produced (L)	171000	171000	171000	171000	171000	171000	171000	171000	171000	171000
Meal produced (kg)	377885	377885	377885	377885	377885	377885	377885	377885	377885	377885
Oil price ($/L)	0.42	0.43	0.44	0.45	0.45	0.46	0.47	0.48	0.49	0.50
Meal price ($/kg)	0.36	0.37	0.38	0.38	0.39	0.40	0.41	0.41	0.42	0.43
Oil revenue	71832	73269	74734	76229	77754	79309	80895	82513	84163	85846
Meal revenue	136360	139087	141869	144706	147600	150552	153564	156635	159767	162963
Total revenue	208192	212356	216603	220936	225354	229861	234459	239148	243931	248809
PV of total revenue	37445	34722	32197	29855	27684	25670	23804	22072	20467	18979
Net revenue	11706	11940	12178	12422	12670	12924	13182	13446	13715	13989

Table A-2 (cont.): Discounted cash flow analysis for camelina oil production at optimum plant size (120 million L/year)

Cost items ($000)/year	28	29	30
Capital cost	0	0	0
Operating & maint. cost	17305	17651	18004
Field cost	198575	202547	206598
Transportation cost	22938	23396	23864
Other costs	698	712	8909
Total cost	239516	244307	257376
PV of total cost	16609	15401	14750
Oil produced (L)	171000	171000	171000
Meal produced (kg)	377885	377885	377885
Oil price ($/L)	0.51	0.52	0.53
Meal price ($/kg)	0.44	0.45	0.46
Oil revenue	87563	89315	91101
Meal revenue	166222	169547	172937
Total revenue	253785	258861	264038
PV of total revenue	17598	16318	15132
Net revenue	14269	14554	6663

Appendix B.
Aspen Plus® process flowsheets

Process flowsheets for the HDRD plant are given in Figures B-1 and B-2. The unit operation blocks with an "X" in their names were not mapped to actual pieces of equipment and were not included in determining the energy used in the plant. These blocks were needed to add flexibility to the model and to supply the feed components at the pressure and temperature that would be observed in the physical plant.

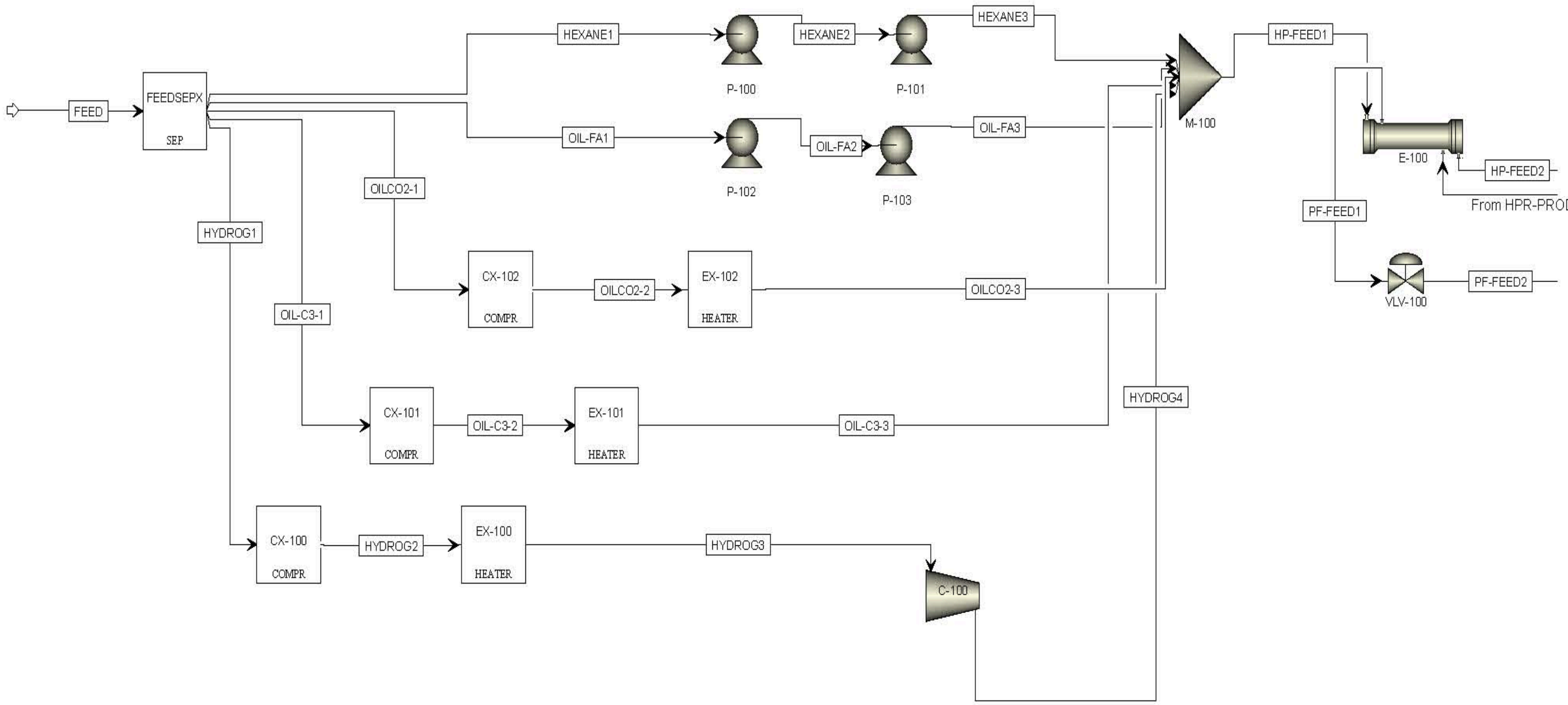

Figure B-1: Process flowsheet 1 of 2 for the HDRD plant

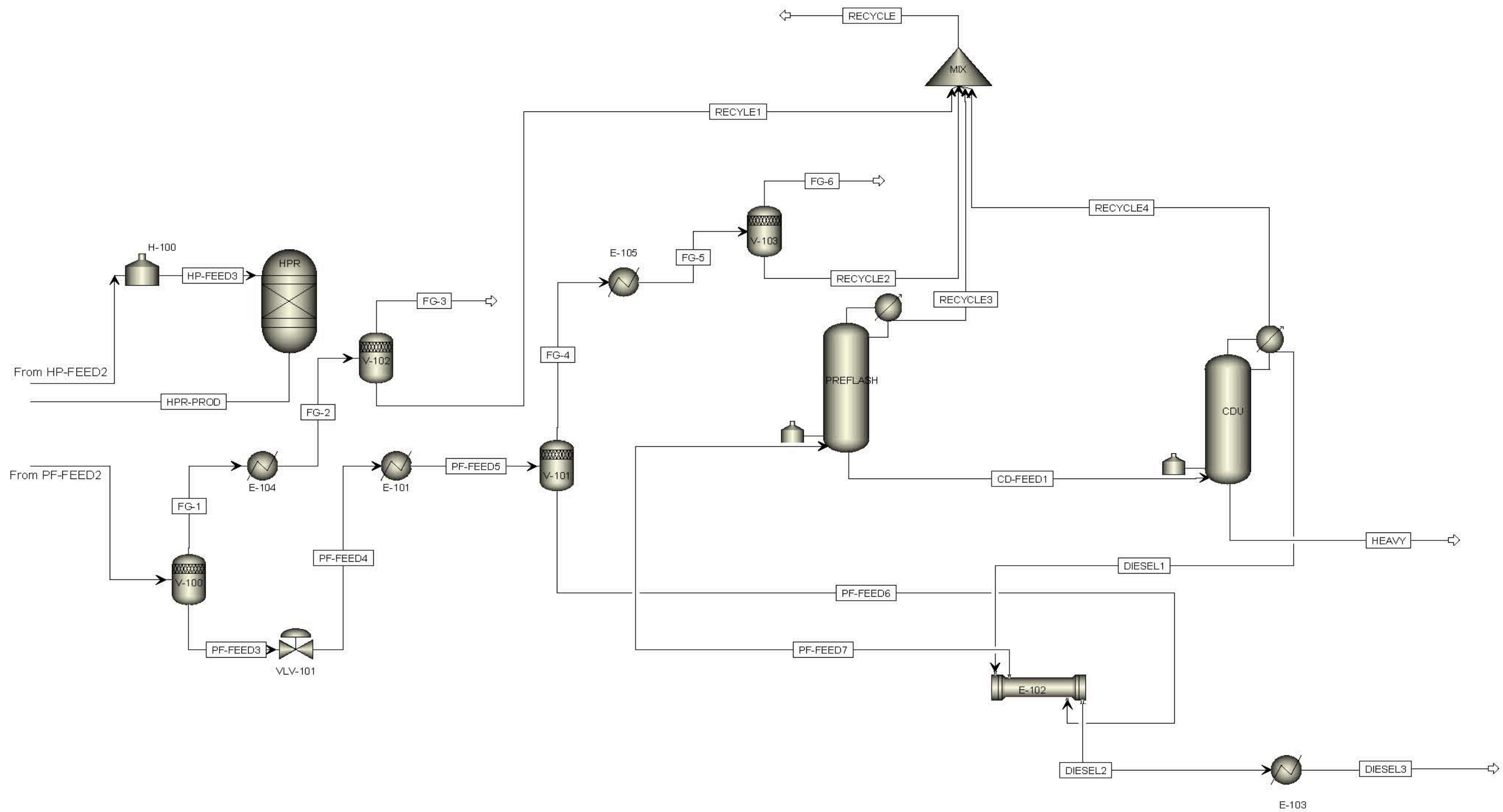

Figure B-2: Process flowsheet 2 of 2 for the HDRD plant

Appendix C.
Aspen Plus® heat and material balances

Tables C-1 and C-2 show the heat and material balances for HDRD plants using canola oil and camelina oil as feedstocks. These plants are at their economic optimum size of 812 million L/year.

Table C-1: Heat and material balance (canola, 812 M L/year)

Stream Name	CD-FEED1	DIESEL1	DIESEL2	DIESEL3	FEED	FG-1	FG-2	FG-3	FG-4	FG-5	FG-6	HEAVY
From Equipment	PREFLASH	CDU	E-102	E-103		V-100	E-104	V-102	V-101	E-105	V-103	CDU
To Equipment	CDU	E-102	E-103		FEEDSEPX	E-104	V-102		E-105	V-103		
Temperature (C)	233	215	170	65	25	230	200	200	150	100	100	341
Pressure (PSIA)	45	16	16	15	15	320	320	320	60	60	60	25
Vapor Fraction	0.00	0.00	0.00	0.00	0.16	1.00	0.35	1.00	1.00	0.03	1.00	0.00
Mass Enthalpy (KCAL/KG)	-349	-363	-393	-456	-605	-575	-622	-820	-458	-554	-843	-256
Enthalpy Flow (GCAL/HR)	-36	-26	-28	-33	-456	-20	-21	-9	-257	-312	-12	-7
Total Standard Volume Flow (BBL/DAY)	20303	13998	13998	13998	170894	7654	7654	2321	127764	127764	3180	4915
Total Mass Flow (KG/DAY)	2499270	1724190	1724190	1724190	18091700	815483	815483	250601	13500300	13500300	342752	621747
Component Mass Flow (KG/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	78	5	5	5	485306	95308	95308	62260	390254	390254	81753	0
H2	0	0	0	0	36352	0	0	0	0	0	0	0
C18:3	0	0	0	0	187734	0	0	0	0	0	0	0
C18:2	0	0	0	0	474550	0	0	0	0	0	0	0
C18:1	0	0	0	0	1770440	0	0	0	0	0	0	0
C18:0	0	0	0	0	52149	0	0	0	0	0	0	0
C16:0	0	0	0	0	101690	0	0	0	0	0	0	0
C3	31	2	2	2	161769	29547	29547	18932	131620	131620	25714	0
C6	138364	36565	36565	36565	14821700	687759	687759	169326	12851400	12851400	235204	1184
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	5607	3245	3245	3245	0	600	600	42	27246	27246	48	106
C10	15070	10315	10315	10315	0	535	535	23	27997	27997	22	368
C11	26812	20507	20507	20507	0	385	385	10	21277	21277	8	852
C12	37446	30753	30753	30753	0	250	250	4	13468	13468	2	1539
C13	45948	39324	39324	39324	0	159	159	2	7867	7867	1	2445
C14	52403	45748	45748	45748	0	101	101	1	4380	4380	0	3587
C15	105405	92090	92090	92090	0	119	119	0	4455	4455	0	9394
C16	60777	52315	52315	52315	0	42	42	0	1349	1349	0	7029
C17	1412310	1184320	1184320	1184320	0	616	616	1	17512	17512	0	207131
C18	175887	142078	142078	142078	0	51	51	0	1278	1278	0	32176
C19	30623	23492	23492	23492	0	6	6	0	127	127	0	6955
C20	5414	3871	3871	3871	0	1	1	0	12	12	0	1525
C21	45170	29904	29904	29904	0	4	4	0	56	56	0	15175
C22	0	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	12664	1248	1248	1248	0	0	0	0	0	0	0	11416
C32	329266	8402	8402	8402	0	1	1	0	2	2	0	320864
Component Std Volume Flow (BBL/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	1	0	0	0	3715	730	730	477	2987	2987	626	0
H2	0	0	0	0	6075	0	0	0	0	0	0	0
C18:3	0	0	0	0	1294	0	0	0	0	0	0	0
C18:2	0	0	0	0	3319	0	0	0	0	0	0	0
C18:1	0	0	0	0	12603	0	0	0	0	0	0	0
C18:0	0	0	0	0	373	0	0	0	0	0	0	0
C16:0	0	0	0	0	723	0	0	0	0	0	0	0
C3	0	0	0	0	2011	367	367	235	1636	1636	320	0
C6	1314	347	347	347	140782	6533	6533	1608	122067	122067	2234	11
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	49	28	28	28	0	5	5	0	238	238	0	1
C10	129	89	89	89	0	5	5	0	240	240	0	3
C11	227	174	174	174	0	3	3	0	180	180	0	7
C12	314	258	258	258	0	2	2	0	113	113	0	13
C13	381	326	326	326	0	1	1	0	65	65	0	20
C14	431	376	376	376	0	1	1	0	36	36	0	29
C15	861	752	752	752	0	1	1	0	36	36	0	77
C16	493	424	424	424	0	0	0	0	11	11	0	57
C17	11391	9552	9552	9552	0	5	5	0	141	141	0	1671
C18	1412	1140	1140	1140	0	0	0	0	10	10	0	258
C19	245	188	188	188	0	0	0	0	1	1	0	56
C20	43	31	31	31	0	0	0	0	0	0	0	12
C21	359	238	238	238	0	0	0	0	0	0	0	121
C22	0	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	98	10	10	10	0	0	0	0	0	0	0	89
C32	2555	65	65	65	0	0	0	0	0	0	0	2490

Table C-1 (cont.): Heat and material balance (canola, 812 M L/year)

Stream Name	HEXANE1	HEXANE2	HEXANE3	HP-FEED1	HP-FEED2	HP-FEED3	HPR-PROD	HYDROG1	HYDROG2	HYDROG3	HYDROG4
From Equipment	FEEDSEPX	P-100	P-101	M-100	E-100	H-100	HPR	FEEDSEPX	CX-100	EX-100	C-100
To Equipment	P-100	P-101	M-100	E-100	H-100	HPR	E-100	CX-100	EX-100	C-100	M-100
Temperature (C)	25	25	31	25	237	400	400	25	594	25	333
Pressure (PSIA)	15	180	2200	2200	2200	2200	2200	15	315	315	2200
Vapor Fraction	0.00	0.00	0.00	0.01	0.05	0.08	0.00	1.00	1.00	1.00	1.00
Mass Enthalpy (KCAL/KG)	-551	-550	-544	-603	-470	-341	-320	0	1982	1	1088
Enthalpy Flow (GCAL/HR)	-340	-340	-336	-454	-354	-257	-241	0	3	0	2
Total Standard Volume Flow (BBL/DAY)	140782	140782	140782	170894	170894	170894	167703	6075	6075	6075	6075
Total Mass Flow (KG/DAY)	14821700	14821700	14821700	18091700	18091700	18091700	18091700	36352	36352	36352	36352
Component Mass Flow (KG/DAY)											
H2O	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	485306	485306	485306	490285	0	0	0	0
H2	0	0	0	36352	36352	36352	0	36352	36352	36352	36352
C18:3	0	0	0	187734	187734	187734	0	0	0	0	0
C18:2	0	0	0	474550	474550	474550	0	0	0	0	0
C18:1	0	0	0	1770440	1770440	1770440	0	0	0	0	0
C18:0	0	0	0	52149	52149	52149	0	0	0	0	0
C16:0	0	0	0	101690	101690	101690	0	0	0	0	0
C3	0	0	0	161769	161769	161769	162825	0	0	0	0
C6	14821700	14821700	14821700	14821700	14821700	14821700	14822500	0	0	0	0
C7	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	45229	0	0	0	0
C10	0	0	0	0	0	0	63321	0	0	0	0
C11	0	0	0	0	0	0	70558	0	0	0	0
C12	0	0	0	0	0	0	70558	0	0	0	0
C13	0	0	0	0	0	0	68748	0	0	0	0
C14	0	0	0	0	0	0	66939	0	0	0	0
C15	0	0	0	0	0	0	121214	0	0	0	0
C16	0	0	0	0	0	0	65130	0	0	0	0
C17	0	0	0	0	0	0	1443720	0	0	0	0
C18	0	0	0	0	0	0	177299	0	0	0	0
C19	0	0	0	0	0	0	30756	0	0	0	0
C20	0	0	0	0	0	0	5428	0	0	0	0
C21	0	0	0	0	0	0	45229	0	0	0	0
C22	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	12664	0	0	0	0
C32	0	0	0	0	0	0	329269	0	0	0	0
Component Std Volume Flow (BBL/DAY)											
H2O	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	3715	3715	3715	3753	0	0	0	0
H2	0	0	0	6075	6075	6075	0	6075	6075	6075	6075
C18:3	0	0	0	1294	1294	1294	0	0	0	0	0
C18:2	0	0	0	3319	3319	3319	0	0	0	0	0
C18:1	0	0	0	12603	12603	12603	0	0	0	0	0
C18:0	0	0	0	373	373	373	0	0	0	0	0
C16:0	0	0	0	723	723	723	0	0	0	0	0
C3	0	0	0	2011	2011	2011	2024	0	0	0	0
C6	140782	140782	140782	140782	140782	140782	140790	0	0	0	0
C7	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	395	0	0	0	0
C10	0	0	0	0	0	0	544	0	0	0	0
C11	0	0	0	0	0	0	598	0	0	0	0
C12	0	0	0	0	0	0	591	0	0	0	0
C13	0	0	0	0	0	0	570	0	0	0	0
C14	0	0	0	0	0	0	550	0	0	0	0
C15	0	0	0	0	0	0	990	0	0	0	0
C16	0	0	0	0	0	0	528	0	0	0	0
C17	0	0	0	0	0	0	11645	0	0	0	0
C18	0	0	0	0	0	0	1423	0	0	0	0
C19	0	0	0	0	0	0	246	0	0	0	0
C20	0	0	0	0	0	0	43	0	0	0	0
C21	0	0	0	0	0	0	359	0	0	0	0
C22	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	98	0	0	0	0
C32	0	0	0	0	0	0	2555	0	0	0	0

Table C-1 (cont.): Heat and material balance (canola, 812 M L/year)

Stream Name	OIL-C3-1	OIL-C3-2	OIL-C3-3	OIL-FA1	OIL-FA2	OIL-FA3	OILCO2-1	OILCO2-2	OILCO2-3
From Equipment	FEEDSEPX	CX-101	EX-101	FEEDSEPX	P-102	P-103	FEEDSEPX	CX-102	EX-102
To Equipment	CX-101	EX-101	M-100	P-102	P-103	M-100	CX-102	EX-102	M-100
Temperature (C)	25	221	25	25	25	29	25	639	25
Pressure (PSIA)	15	2200	2200	15	180	2200	15	2200	2200
Vapor Fraction	1.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
Mass Enthalpy (KCAL/KG)	-568	-509	-653	-663	-663	-657	-2136	-1982	-2198
Enthalpy Flow (GCAL/HR)	-4	-3	-4	-71	-71	-71	-43	-40	-44
Total Standard Volume Flow (BBL/DAY)	2011	2011	2011	18312	18312	18312	3715	3715	3715
Total Mass Flow (KG/DAY)	161769	161769	161769	2586560	2586560	2586560	485306	485306	485306
Component Mass Flow (KG/DAY)									
H2O	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	485306	485306	485306
H2	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	187734	187734	187734	0	0	0
C18:2	0	0	0	474550	474550	474550	0	0	0
C18:1	0	0	0	1770440	1770440	1770440	0	0	0
C18:0	0	0	0	52149	52149	52149	0	0	0
C16:0	0	0	0	101690	101690	101690	0	0	0
C3	161769	161769	161769	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0
C7	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0
C13	0	0	0	0	0	0	0	0	0
C14	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0
C16	0	0	0	0	0	0	0	0	0
C17	0	0	0	0	0	0	0	0	0
C18	0	0	0	0	0	0	0	0	0
C19	0	0	0	0	0	0	0	0	0
C20	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0
C22	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	0	0	0
C32	0	0	0	0	0	0	0	0	0
Component Std Volume Flow (BBL/DAY)									
H2O	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	3715	3715	3715
H2	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	1294	1294	1294	0	0	0
C18:2	0	0	0	3319	3319	3319	0	0	0
C18:1	0	0	0	12603	12603	12603	0	0	0
C18:0	0	0	0	373	373	373	0	0	0
C16:0	0	0	0	723	723	723	0	0	0
C3	2011	2011	2011	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0
C7	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0
C13	0	0	0	0	0	0	0	0	0
C14	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0
C16	0	0	0	0	0	0	0	0	0
C17	0	0	0	0	0	0	0	0	0
C18	0	0	0	0	0	0	0	0	0
C19	0	0	0	0	0	0	0	0	0
C20	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0
C22	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	0	0	0
C32	0	0	0	0	0	0	0	0	0

Table C-1 (cont.): Heat and material balance (canola, 812 M L/year)

Stream Name	PF-FEED1	PF-FEED2	PF-FEED3	PF-FEED4	PF-FEED5	PF-FEED6	PF-FEED7	RECYCLE	RECYCLE2	RECYCLE3	RECYCLE4	RECYCLE1
From Equipment	E-100	VLV-100	V-100	VLV-101	E-101	V-101	E-102	MIX	V-103	PREFLASH	CDU	V-102
To Equipment	VLV-100	V-100	VLV-101	E-101	V-101	E-102	PREFLASH		MIX	MIX	MIX	MIX
Temperature (C)	232	226	230	164	150	150	162	66	100	104	215	200
Pressure (PSIA)	2200	320	320	60	60	60	60	16	60	40	16	320
Vapor Fraction	0.00	0.00	0.00	0.90	0.87	0.00	0.17	0.33	0.00	0.00	1.00	0.00
Mass Enthalpy (KCAL/KG)	-453	-453	-441	-441	-451	-427	-414	-540	-546	-505	-349	-534
Enthalpy Flow (GCAL/HR)	-341	-341	-317	-317	-325	-67	-65	-341	-300	-27	-2	-13
Total Standard Volume Flow (BBL/DAY)	167703	167703	160049	160049	160049	32286	32286	143289	124583	11982	1390	5333
Total Mass Flow (KG/DAY)	18091700	18091700	17276200	17276200	17276200	3775950	3775950	15152400	13157500	1276670	153340	564882
Component Mass Flow (KG/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	490285	490285	394976	394976	394976	4723	4723	346266	308500	4645	73	33048
H2	0	0	0	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	0	0	0	0	0	0	0	0	0
C18:2	0	0	0	0	0	0	0	0	0	0	0	0
C18:1	0	0	0	0	0	0	0	0	0	0	0	0
C18:0	0	0	0	0	0	0	0	0	0	0	0	0
C16:0	0	0	0	0	0	0	0	0	0	0	0	0
C3	162825	162825	133278	133278	133278	1658	1658	118177	105907	1627	29	10615
C6	14822500	14822500	14134800	14134800	14134800	1283400	1283400	14380200	12616200	1145040	100615	518433
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	45229	45229	44630	44630	44630	17383	17383	41788	27198	11776	2255	558
C10	63321	63321	62786	62786	62786	34789	34789	52593	27975	19719	4387	512
C11	70558	70558	70173	70173	70173	48895	48895	49181	21270	22084	5453	375
C12	70558	70558	70308	70308	70308	56840	56840	38258	13466	19393	5154	246
C13	68748	68748	68589	68589	68589	60722	60722	26977	7866	14775	4178	158
C14	66939	66939	66838	66838	66838	62458	62458	17604	4380	10055	3069	100
C15	121214	121214	121095	121095	121095	116640	116640	19730	4455	11235	3921	119
C16	65130	65130	65088	65088	65088	63739	63739	5786	1349	2962	1433	42
C17	1443720	1443720	1443100	1443100	1443100	1425590	1425590	52263	17512	13283	20854	615
C18	177299	177299	177248	177248	177248	175970	175970	3045	1278	84	1633	51
C19	30756	30756	30750	30750	30750	30623	30623	308	127	0	175	6
C20	5428	5428	5427	5427	5427	5414	5414	31	12	0	18	1
C21	45229	45229	45225	45225	45225	45170	45170	151	56	0	92	4
C22	0	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	12664	12664	12664	12664	12664	12664	12664	0	0	0	0	0
C32	329269	329269	329268	329268	329268	329266	329266	3	2	0	0	1
Component Std Volume Flow (BBL/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	3753	3753	3023	3023	3023	36	36	2650	2361	36	1	253
H2	0	0	0	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	0	0	0	0	0	0	0	0	0
C18:2	0	0	0	0	0	0	0	0	0	0	0	0
C18:1	0	0	0	0	0	0	0	0	0	0	0	0
C18:0	0	0	0	0	0	0	0	0	0	0	0	0
C16:0	0	0	0	0	0	0	0	0	0	0	0	0
C3	2024	2024	1657	1657	1657	21	21	1469	1316	20	0	132
C6	140790	140790	134257	134257	134257	12190	12190	136589	119833	10876	956	4924
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	395	395	390	390	390	152	152	365	238	103	20	5
C10	544	544	539	539	539	299	299	452	240	169	38	4
C11	598	598	594	594	594	414	414	417	180	187	46	3
C12	591	591	589	589	589	476	476	320	113	162	43	2
C13	570	570	569	569	569	504	504	224	65	123	35	1
C14	550	550	550	550	550	514	514	145	36	83	25	1
C15	990	990	989	989	989	953	953	161	36	92	32	1
C16	528	528	528	528	528	517	517	47	11	24	12	0
C17	11645	11645	11640	11640	11640	11498	11498	422	141	107	168	5
C18	1423	1423	1423	1423	1423	1412	1412	24	10	1	13	0
C19	246	246	246	246	246	245	245	2	1	0	1	0
C20	43	43	43	43	43	43	43	0	0	0	0	0
C21	359	359	359	359	359	359	359	1	0	0	1	0
C22	0	0	0	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	98	98	98	98	98	98	98	0	0	0	0	0
C32	2555	2555	2555	2555	2555	2555	2555	0	0	0	0	0

Table C-2: Heat and material balance (camelina, 812 M L/year)

Stream Name	CD-FEED1	DIESEL1	DIESEL2	DIESEL3	FEED	FG-1	FG-2	FG-3	FG-4	FG-5	FG-6	HEAVY
From Equipment	PREFLASH	CDU	E-102	E-103		V-100	E-104	V-102	V-101	E-105	V-103	CDU
To Equipment	CDU	E-102	E-103		FEEDSEPX	E-104	V-102		E-105	V-103		
Temperature (C)	237	215	170	65	25	230	200	200	150	100	100	346
Pressure (PSIA)	45	16	16	15	15	320	320	320	60	60	60	25
Vapor Fraction	0.00	0.00	0.00	0.00	0.16	1.00	0.35	1.00	1.00	0.03	1.00	0.00
Mass Enthalpy (KCAL/KG)	-344	-362	-392	-455	-598	-573	-620	-819	-457	-554	-842	-252
Enthalpy Flow (GCAL/HR)	-38	-26	-28	-33	-465	-22	-24	-10	-264	-319	-12	-8
Total Standard Volume Flow (BBL/DAY)	21215	14002	14002	14002	176306	8757	8757	2625	131013	131013	3157	5928
Total Mass Flow (KG/DAY)	2619310	1727870	1727870	1727870	18674300	932854	932854	283410	13840000	13840000	340194	750296
Component Mass Flow (KG/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	78	5	5	5	504188	108201	108201	70262	396823	396823	80884	0
H2	0	0	0	0	37520	0	0	0	0	0	0	0
C18:3	0	0	0	0	758482	0	0	0	0	0	0	0
C18:2	0	0	0	0	555318	0	0	0	0	0	0	0
C18:1	0	0	0	0	468634	0	0	0	0	0	0	0
C18:0	0	0	0	0	67722	0	0	0	0	0	0	0
C16:0	0	0	0	0	146278	0	0	0	0	0	0	0
C3	31	2	2	2	168063	33718	33718	21472	134531	134531	25560	0
C6	136347	37186	37186	37186	15299000	788380	788380	191614	13209400	13209400	233698	1393
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	3310	1945	1945	1945	0	414	414	28	16939	16939	29	74
C10	10203	7048	7048	7048	0	422	422	18	19951	19951	15	290
C11	19117	14684	14684	14684	0	318	318	8	15913	15913	6	702
C12	29755	24438	24438	24438	0	229	229	4	11172	11172	2	1404
C13	38936	33203	33203	33203	0	154	154	2	6922	6922	1	2362
C14	45887	39784	39784	39784	0	100	100	1	3961	3961	0	3553
C15	118522	102493	102493	102493	0	152	152	1	5148	5148	0	11860
C16	63918	54260	54260	54260	0	50	50	0	1451	1451	0	8238
C17	1227750	1011780	1011780	1011780	0	600	600	1	15480	15480	0	198942
C18	133330	105460	105460	105460	0	43	43	0	983	983	0	26712
C19	295584	221177	221177	221177	0	63	63	0	1239	1239	0	72829
C20	27940	19402	19402	19402	0	4	4	0	65	65	0	8450
C21	52213	33455	33455	33455	0	5	5	0	65	65	0	18660
C22	11195	6546	6546	6546	0	1	1	0	8	8	0	4637
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	22407	2251	2251	2251	0	0	0	0	0	0	0	20156
C32	382782	12748	12748	12748	0	1	1	0	2	2	0	370034
C20H4-01	0	0	0	0	669090	0	0	0	0	0	0	0
Component Std Volume Flow (BBL/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	1	0	0	0	3859	828	828	538	3037	3037	619	0
H2	0	0	0	0	6270	0	0	0	0	0	0	0
C18:3	0	0	0	0	5228	0	0	0	0	0	0	0
C18:2	0	0	0	0	3884	0	0	0	0	0	0	0
C18:1	0	0	0	0	3336	0	0	0	0	0	0	0
C18:0	0	0	0	0	484	0	0	0	0	0	0	0
C16:0	0	0	0	0	1040	0	0	0	0	0	0	0
C3	0	0	0	0	2089	419	419	267	1672	1672	318	0
C6	1295	353	353	353	145316	7488	7488	1820	125468	125468	2220	13
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	29	17	17	17	0	4	4	0	148	148	0	1
C10	88	61	61	61	0	4	4	0	171	171	0	2
C11	162	124	124	124	0	3	3	0	135	135	0	6
C12	249	205	205	205	0	2	2	0	94	94	0	12
C13	323	275	275	275	0	1	1	0	57	57	0	20
C14	377	327	327	327	0	1	1	0	33	33	0	29
C15	968	837	837	837	0	1	1	0	42	42	0	97
C16	518	440	440	440	0	0	0	0	12	12	0	67
C17	9903	8161	8161	8161	0	5	5	0	125	125	0	1605
C18	1070	846	846	846	0	0	0	0	8	8	0	214
C19	2361	1767	1767	1767	0	1	1	0	10	10	0	582
C20	222	154	154	154	0	0	0	0	1	1	0	67
C21	415	266	266	266	0	0	0	0	1	1	0	148
C22	89	52	52	52	0	0	0	0	0	0	0	37
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	174	17	17	17	0	0	0	0	0	0	0	157
C32	2971	99	99	99	0	0	0	0	0	0	0	2872
C20H4-01	0	0	0	0	4799	0	0	0	0	0	0	0

Table C-2 (cont.): Heat and material balance (camelina, 812 M L/year)

Stream Name	HEXANE1	HEXANE2	HEXANE3	HP-FEED1	HP-FEED2	HP-FEED3	HPR-PROD	HYDROG1	HYDROG2	HYDROG3	HYDROG4
From Equipment	FEEDSEPX	P-100	P-101	M-100	E-100	H-100	HPR	FEEDSEPX	CX-100	EX-100	C-100
To Equipment	P-100	P-101	M-100	E-100	H-100	HPR	E-100	CX-100	EX-100	C-100	M-100
Temperature (C)	25	25	31	25	238	400	400	25	594	25	333
Pressure (PSIA)	15	180	2200	2200	2200	2200	2200	15	315	315	2200
Vapor Fraction	0.00	0.00	0.00	0.01	0.05	0.08	0.00	1.00	1.00	1.00	1.00
Mass Enthalpy (KCAL/KG)	-551	-550	-544	-595	-463	-335	-320	0	1982	1	1088
Enthalpy Flow (GCAL/HR)	-351	-351	-347	-463	-360	-260	-249	0	3	0	2
Total Standard Volume Flow (BBL/DAY)	145316	145316	145316	176306	176306	176306	173030	6270	6270	6270	6270
Total Mass Flow (KG/DAY)	15299000	15299000	15299000	18674300	18674300	18674300	18674300	37520	37520	37520	37520
Component Mass Flow (KG/DAY)											
H2O	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	504188	504188	504188	509758	0	0	0	0
H2	0	0	0	37520	37520	37520	0	37520	37520	37520	37520
C18:3	0	0	0	758482	758482	758482	0	0	0	0	0
C18:2	0	0	0	555318	555318	555318	0	0	0	0	0
C18:1	0	0	0	468634	468634	468634	0	0	0	0	0
C18:0	0	0	0	67722	67722	67722	0	0	0	0	0
C16:0	0	0	0	146278	146278	146278	0	0	0	0	0
C3	0	0	0	168063	168063	168063	169919	0	0	0	0
C6	15299000	15299000	15299000	15299000	15299000	15299000	15298300	0	0	0	0
C7	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	28009	0	0	0	0
C10	0	0	0	0	0	0	44814	0	0	0	0
C11	0	0	0	0	0	0	52283	0	0	0	0
C12	0	0	0	0	0	0	57885	0	0	0	0
C13	0	0	0	0	0	0	59752	0	0	0	0
C14	0	0	0	0	0	0	59752	0	0	0	0
C15	0	0	0	0	0	0	138176	0	0	0	0
C16	0	0	0	0	0	0	69088	0	0	0	0
C17	0	0	0	0	0	0	1258520	0	0	0	0
C18	0	0	0	0	0	0	134442	0	0	0	0
C19	0	0	0	0	0	0	296892	0	0	0	0
C20	0	0	0	0	0	0	28009	0	0	0	0
C21	0	0	0	0	0	0	52283	0	0	0	0
C22	0	0	0	0	0	0	11203	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	22407	0	0	0	0
C32	0	0	0	0	0	0	382785	0	0	0	0
C20H4-01	0	0	0	669090	669090	669090	0	0	0	0	0
Component Std Volume Flow (BBL/DAY)											
H2O	0	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	3859	3859	3859	3902	0	0	0	0
H2	0	0	0	6270	6270	6270	0	6270	6270	6270	6270
C18:3	0	0	0	5228	5228	5228	0	0	0	0	0
C18:2	0	0	0	3884	3884	3884	0	0	0	0	0
C18:1	0	0	0	3336	3336	3336	0	0	0	0	0
C18:0	0	0	0	484	484	484	0	0	0	0	0
C16:0	0	0	0	1040	1040	1040	0	0	0	0	0
C3	0	0	0	2089	2089	2089	2112	0	0	0	0
C6	145316	145316	145316	145316	145316	145316	145309	0	0	0	0
C7	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	245	0	0	0	0
C10	0	0	0	0	0	0	385	0	0	0	0
C11	0	0	0	0	0	0	443	0	0	0	0
C12	0	0	0	0	0	0	485	0	0	0	0
C13	0	0	0	0	0	0	496	0	0	0	0
C14	0	0	0	0	0	0	491	0	0	0	0
C15	0	0	0	0	0	0	1128	0	0	0	0
C16	0	0	0	0	0	0	560	0	0	0	0
C17	0	0	0	0	0	0	10151	0	0	0	0
C18	0	0	0	0	0	0	1079	0	0	0	0
C19	0	0	0	0	0	0	2372	0	0	0	0
C20	0	0	0	0	0	0	223	0	0	0	0
C21	0	0	0	0	0	0	415	0	0	0	0
C22	0	0	0	0	0	0	89	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	174	0	0	0	0
C32	0	0	0	0	0	0	2971	0	0	0	0
C20H4-01	0	0	0	4799	4799	4799	0	0	0	0	0

Table C-2 (cont.): Heat and material balance (camelina, 812 M L/year)

Stream Name	OIL-C3-1	OIL-C3-2	OIL-C3-3	OIL-FA1	OIL-FA2	OIL-FA3	OILCO2-1	OILCO2-2	OILCO2-3
From Equipment	FEEDSEPX	CX-101	EX-101	FEEDSEPX	P-102	P-103	FEEDSEPX	CX-102	EX-102
To Equipment	CX-101	EX-101	M-100	P-102	P-103	M-100	CX-102	EX-102	M-100
Temperature (C)	25	221	25	25	25	29	25	639	25
Pressure (PSIA)	15	2200	2200	15	180	2200	15	2200	2200
Vapor Fraction	1.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
Mass Enthalpy (KCAL/KG)	-568	-509	-653	-611	-611	-606	-2136	-1982	-2198
Enthalpy Flow (GCAL/HR)	-4	-4	-5	-68	-68	-67	-45	-42	-46
Total Standard Volume Flow (BBL/DAY)	2089	2089	2089	18772	18772	18772	3859	3859	3859
Total Mass Flow (KG/DAY)	168063	168063	168063	2665520	2665520	2665520	504188	504188	504188
Component Mass Flow (KG/DAY)									
H2O	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	504188	504188	504188
H2	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	758482	758482	758482	0	0	0
C18:2	0	0	0	555318	555318	555318	0	0	0
C18:1	0	0	0	468634	468634	468634	0	0	0
C18:0	0	0	0	67722	67722	67722	0	0	0
C16:0	0	0	0	146278	146278	146278	0	0	0
C3	168063	168063	168063	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0
C7	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0
C13	0	0	0	0	0	0	0	0	0
C14	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0
C16	0	0	0	0	0	0	0	0	0
C17	0	0	0	0	0	0	0	0	0
C18	0	0	0	0	0	0	0	0	0
C19	0	0	0	0	0	0	0	0	0
C20	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0
C22	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	0	0	0
C32	0	0	0	0	0	0	0	0	0
C20H4-01	0	0	0	669090	669090	669090	0	0	0
Component Std Volume Flow (BBL/DAY)									
H2O	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	0	3859	3859	3859
H2	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	5228	5228	5228	0	0	0
C18:2	0	0	0	3884	3884	3884	0	0	0
C18:1	0	0	0	3336	3336	3336	0	0	0
C18:0	0	0	0	484	484	484	0	0	0
C16:0	0	0	0	1040	1040	1040	0	0	0
C3	2089	2089	2089	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0	0
C7	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0
C13	0	0	0	0	0	0	0	0	0
C14	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0
C16	0	0	0	0	0	0	0	0	0
C17	0	0	0	0	0	0	0	0	0
C18	0	0	0	0	0	0	0	0	0
C19	0	0	0	0	0	0	0	0	0
C20	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0
C22	0	0	0	0	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0
C30	0	0	0	0	0	0	0	0	0
C32	0	0	0	0	0	0	0	0	0
C20H4-01	0	0	0	4799	4799	4799	0	0	0

Table C-2 (cont.): Heat and material balance (camelina, 812 M L/year)

Stream Name	PF-FEED1	PF-FEED2	PF-FEED3	PF-FEED4	PF-FEED5	PF-FEED6	PF-FEED7	RECYCLE	RECYCLE2	RECYCLE3	RECYCLE4	RECYLE1
From Equipment	E-100	VLV-100	V-100	VLV-101	E-101	V-101	E-102	MIX	V-103	PREFLASH	CDU	V-102
To Equipment	VLV-100	V-100	VLV-101	E-101	V-101	E-102	PREFLASH		MIX	MIX	MIX	MIX
Temperature (C)	232	226	230	164	150	150	161	66	100	103	215	200
Pressure (PSIA)	2200	320	320	60	60	60	60	16	60	40	16	320
Vapor Fraction	0.00	0.00	0.00	0.90	0.87	0.00	0.17	0.33	0.00	0.00	1.00	0.00
Mass Enthalpy (KCAL/KG)	-453	-453	-440	-440	-450	-426	-412	-541	-546	-506	-351	-533
Enthalpy Flow (GCAL/HR)	-352	-352	-326	-326	-333	-69	-67	-351	-307	-27	-2	-14
Total Standard Volume Flow (BBL/DAY)	173030	173030	164273	164273	164273	33260	33260	147318	127856	12045	1285	6132
Total Mass Flow (KG/DAY)	18674300	18674300	17741500	17741500	17741500	3901440	3901440	15572600	13499800	1282130	141138	649445
Component Mass Flow (KG/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	509758	509758	401558	401558	401558	4735	4735	358606	315939	4657	73	37938
H2	0	0	0	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	0	0	0	0	0	0	0	0	0
C18:2	0	0	0	0	0	0	0	0	0	0	0	0
C18:1	0	0	0	0	0	0	0	0	0	0	0	0
C18:0	0	0	0	0	0	0	0	0	0	0	0	0
C16:0	0	0	0	0	0	0	0	0	0	0	0	0
C3	169919	169919	136202	136202	136202	1671	1671	122885	108971	1639	29	12246
C6	15298300	15298300	14510000	14510000	14510000	1300580	1300580	14834500	12975700	1164240	97768	596766
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	28009	28009	27595	27595	27595	10655	10655	25932	16911	7345	1291	386
C10	44814	44814	44392	44392	44392	24441	24441	37443	19935	14238	2864	405
C11	52283	52283	51965	51965	51965	36052	36052	36883	15907	16935	3731	310
C12	57885	57885	57656	57656	57656	46484	46484	32037	11170	16729	3913	225
C13	59752	59752	59597	59597	59597	52676	52676	24185	6921	13740	3371	153
C14	59752	59752	59651	59651	59651	55690	55690	16413	3961	9803	2550	100
C15	138176	138176	138025	138025	138025	132877	132877	23823	5148	14354	4170	151
C16	69088	69088	69038	69038	69038	67587	67587	6590	1451	3669	1420	50
C17	1258520	1258520	1257920	1257920	1257920	1242440	1242440	47796	15480	14694	17022	599
C18	134442	134442	134399	134399	134399	133416	133416	2270	983	86	1158	43
C19	296892	296892	296829	296829	296829	295590	295590	2886	1239	6	1578	63
C20	28009	28009	28005	28005	28005	27940	27940	156	65	0	88	4
C21	52283	52283	52278	52278	52278	52213	52213	168	65	0	98	5
C22	11203	11203	11203	11203	11203	11195	11195	21	8	0	13	1
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	22407	22407	22407	22407	22407	22407	22407	1	0	0	0	0
C32	382785	382785	382785	382785	382785	382782	382782	4	2	0	1	1
C20H4-01	0	0	0	0	0	0	0	0	0	0	0	0
Component Std Volume Flow (BBL/DAY)												
H2O	0	0	0	0	0	0	0	0	0	0	0	0
CO2	3902	3902	3074	3074	3074	36	36	2745	2418	36	1	290
H2	0	0	0	0	0	0	0	0	0	0	0	0
C18:3	0	0	0	0	0	0	0	0	0	0	0	0
C18:2	0	0	0	0	0	0	0	0	0	0	0	0
C18:1	0	0	0	0	0	0	0	0	0	0	0	0
C18:0	0	0	0	0	0	0	0	0	0	0	0	0
C16:0	0	0	0	0	0	0	0	0	0	0	0	0
C3	2112	2112	1693	1693	1693	21	21	1527	1355	20	0	152
C6	145309	145309	137821	137821	137821	12353	12353	140903	123248	11058	929	5668
C7	0	0	0	0	0	0	0	0	0	0	0	0
C9	245	245	241	241	241	93	93	227	148	64	11	3
C10	385	385	381	381	381	210	210	322	171	122	25	3
C11	443	443	440	440	440	305	305	312	135	143	32	3
C12	485	485	483	483	483	389	389	268	94	140	33	2
C13	496	496	494	494	494	437	437	201	57	114	28	1
C14	491	491	490	490	490	458	458	135	33	81	21	1
C15	1128	1128	1127	1127	1127	1085	1085	195	42	117	34	1
C16	560	560	560	560	560	548	548	53	12	30	12	0
C17	10151	10151	10146	10146	10146	10021	10021	386	125	119	137	5
C18	1079	1079	1079	1079	1079	1071	1071	18	8	1	9	0
C19	2372	2372	2371	2371	2371	2361	2361	23	10	0	13	1
C20	223	223	223	223	223	222	222	1	1	0	1	0
C21	415	415	415	415	415	415	415	1	1	0	1	0
C22	89	89	89	89	89	89	89	0	0	0	0	0
C23	0	0	0	0	0	0	0	0	0	0	0	0
C30	174	174	174	174	174	174	174	0	0	0	0	0
C32	2971	2971	2971	2971	2971	2971	2971	0	0	0	0	0
C20H4-01	0	0	0	0	0	0	0	0	0	0	0	0

Appendix D.
Calculation of HDRD plant operating costs

<u>General Approach</u> (Ulrich and Vasudevan, 2006)

$$C_{s,u} = (a * CEPCI) + (b * C_{s,f})$$

where: $C_{s,u}$ ≜ utility cost ($/unit)

a ≜ inflation dependent cost coefficient

CEPCI ≜ chemical engineering plant cost index = 550.8 (Anonymous, 2011)

b ≜ energy dependent cost coefficient

$C_{s,f}$ ≜ fuel cost ($/GJ) = $3.71/GJ for natural gas

<u>Cooling Water (Based on process module coefficients)</u>

$$a = 0.001 + [(3.0E - 5) * q^{-1}]$$

$$b = 0.003$$

where: q ≜ cooling water demand = assume at least 10 m^3/s for main refinery/upgrader

$$\therefore C_{s,u} = \$0.0678/m^3$$

Appendix E.
Discounted cash flow sheets for HDRD production

Tables E-1 and E-2 show the discounted cash flow analyses developed for HDRD plants using canola oil and camelina oil as feedstocks, at their optimum size – 812 million L/year. In these tables, costs are given in 2010 Canadian dollars. Plant construction begins in 2010 with oil production starting in 2013 and ending in 2042 (30 year plant life).

Table E-1: Discounted cash flow analysis for canola-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Capital cost	88228	154399	198512	0	0	0	0	0	0	0
Catalyst operating cost				869	886	904	922	940	959	978
Electricity cost				4403	4910	5009	5109	5211	5315	5421
Natural gas cost				13741	15290	15596	15908	16226	16550	16881
Fuel gas credit				-30	-34	-35	-36	-36	-37	-38
Cooling water cost				3168	3564	3636	3708	3782	3858	3935
Vegetable oil cost				559562	629507	642097	654939	668038	681398	695026
Hexane makeup cost				274518	308832	315009	321309	327735	334290	340976
Hydrogen cost				10988	12362	12609	12861	13119	13381	13649
Labor cost				2699	2753	2808	2864	2922	2980	3040
Vegetable oil trans. cost				27651	31108	31730	32364	33012	33672	34345
Other cost				2206	2250	2295	2341	2388	2435	2484
Heavy ends credit				-183202	-206102	-210224	-214428	-218717	-223091	-227553
Total cost	88228	154399	198512	716572	805326	821433	837861	854618	871711	889145
PV of total cost	110673	172926	198512	639796	642001	584679	532476	484933	441636	402204
HDRD produced (000 L)				649940	731183	731183	731183	731183	731183	731183
HDRD price ($/L)				1.15	1.18	1.20	1.22	1.25	1.27	1.30
HDRD revenue				749309	859832	877029	894569	912461	930710	949324
PV of HDRD revenue				669026	685453	624252	568515	517755	471527	429426
Net revenue	-88228	-154399	-198512	32737	54506	55596	56708	57842	58999	60179

Table E-1 (cont.): Discounted cash flow analysis for canola-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	8	9	10	11	12	13	14	15	16	17
Capital cost	0	0	0	0	0	0	0	0	0	0
Catalyst operating cost	998	1018	1038	1059	1080	1102	1124	1146	1169	1192
Electricity cost	5530	5640	5753	5868	5986	6105	6227	6352	6479	6609
Natural gas cost	17219	17563	17915	18273	18639	19011	19392	19779	20175	20578
Fuel gas credit	-39	-39	-40	-41	-42	-43	-43	-44	-45	-46
Cooling water cost	4014	4094	4176	4260	4345	4432	4520	4611	4703	4797
Vegetable oil cost	708927	723105	737568	752319	767365	782713	798367	814334	830621	847233
Hexane makeup cost	347795	354751	361846	369083	376465	383994	391674	399508	407498	415648
Hydrogen cost	13921	14200	14484	14774	15069	15370	15678	15991	16311	16637
Labor cost	3101	3163	3226	3290	3356	3423	3492	3562	3633	3705
Vegetable oil trans. cost	35032	35733	36448	37176	37920	38678	39452	40241	41046	41867
Other cost	2534	2584	2636	2689	2743	2797	2853	2910	2969	3028
Heavy ends credit	-232104	-236746	-241481	-246311	-251237	-256262	-261387	-266615	-271947	-277386
Total cost	906928	925066	943568	962439	981688	1001322	1021348	1041775	1062611	1083863
PV of total cost	366293	333588	303804	276678	251975	229477	208988	190328	173335	157858
HDRD produced (000 L)	731183	731183	731183	731183	731183	731183	731183	731183	731183	731183
HDRD price ($/L)	1.32	1.35	1.38	1.41	1.43	1.46	1.49	1.52	1.55	1.58
HDRD revenue	968311	987677	1007431	1027579	1048131	1069093	1090475	1112285	1134530	1157221
PV of HDRD revenue	391084	356166	324366	295404	269029	245009	223133	203210	185066	168543
Net revenue	-88228	-154399	-198512	32737	54506	55596	56708	57842	58999	60179

Table E-1 (cont.): Discounted cash flow analysis for canola-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	18	19	20	21	22	23	24	25	26	27
Capital cost	0	0	0	0	0	0	0	0	0	0
Catalyst operating cost	1216	1241	1265	1291	1316	1343	1370	1397	1425	1453
Electricity cost	6741	6876	7013	7153	7296	7442	7591	7743	7898	8056
Natural gas cost	20990	21410	21838	22275	22720	23175	23638	24111	24593	25085
Fuel gas credit	-47	-48	-49	-50	-51	-52	-53	-54	-55	-56
Cooling water cost	4893	4991	5091	5192	5296	5402	5510	5620	5733	5847
Vegetable oil cost	864178	881462	899091	917073	935414	954122	973205	992669	1012522	1032773
Hexane makeup cost	423961	432440	441089	449910	458909	468087	477448	486997	496737	506672
Hydrogen cost	16970	17310	17656	18009	18369	18736	19111	19493	19883	20281
Labor cost	3779	3855	3932	4011	4091	4173	4256	4341	4428	4517
Vegetable oil trans. cost	42704	43558	44429	45318	46224	47149	48092	49054	50035	51035
Other cost	3089	3150	3213	3278	3343	3410	3478	3548	3619	3691
Heavy ends credit	-282934	-288592	-294364	-300252	-306257	-312382	-318629	-325002	-331502	-338132
Total cost	1105540	1127651	1150204	1173208	1196672	1220606	1245018	1269918	1295316	1321223
PV of total cost	143764	130928	119238	108592	98896	90066	82024	74701	68031	61957
HDRD produced (000 L)	731183	731183	731183	731183	731183	731183	731183	731183	731183	731183
HDRD price ($/L)	1.61	1.65	1.68	1.71	1.75	1.78	1.82	1.85	1.89	1.93
HDRD revenue	1180365	1203973	1228052	1252613	1277666	1303219	1329283	1355869	1382986	1410646
PV of HDRD revenue	153494	139789	127308	115941	105589	96162	87576	79757	72636	66150
Net revenue	74825	76322	77848	79405	80993	82613	84266	85951	87670	89423

Table E-1 (cont.): Discounted cash flow analysis for canola-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	28	29	30
Capital cost	0	0	0
Catalyst operating cost	1483	1512	1542
Electricity cost	8217	8381	8549
Natural gas cost	25587	26098	26620
Fuel gas credit	-57	-58	-60
Cooling water cost	5964	6084	6205
Vegetable oil cost	1053428	1074497	1095987
Hexane makeup cost	516806	527142	537685
Hydrogen cost	20687	21100	21522
Labor cost	4607	4699	4793
Vegetable oil trans. cost	52056	53097	54159
Other cost	3765	3840	48031
Heavy ends credit	-344895	-351793	-358828
Total cost	1347647	1374600	1446206
PV of total cost	56425	51387	48271
HDRD produced (000 L)	731183	731183	731183
HDRD price ($/L)	1.97	2.01	2.05
HDRD revenue	1438859	1467636	1496989
PV of HDRD revenue	60244	54865	49966
Net revenue	91212	93036	50783

Table E-2: Discounted cash flow analysis for camelina-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	-2	-1	0	1	2	3	4	5	6	7
Capital cost	89281	156241	200881	0	0	0	0	0	0	0
Catalyst operating cost				897	914	933	951	970	990	1010
Electricity cost				4540	5064	5165	5268	5374	5481	5591
Natural gas cost				14201	15802	16118	16440	16769	17104	17446
Fuel gas credit				-32	-36	-37	-37	-38	-39	-40
Cooling water cost				3248	3654	3727	3802	3878	3956	4035
Vegetable oil cost				292461	329019	335600	342312	349158	356141	363264
Hexane makeup cost				288922	325037	331538	338168	344932	351830	358867
Hydrogen cost				11342	12759	13014	13275	13540	13811	14087
Labor cost				2743	2798	2854	2911	2969	3028	3089
Vegetable oil trans. cost				27651	31107	31730	32364	33011	33672	34345
Other cost				2232	2277	2322	2369	2416	2464	2514
Heavy ends credit				-100403	-112953	-115212	-117517	-119867	-122264	-124710
Total cost	89281	156241	200881	547802	615442	627751	640306	653112	666174	679498
PV of total cost	111993	174990	200881	489109	490627	446821	406926	370593	337505	307370
HDRD produced (000 L)				649940	731183	731183	731183	731183	731183	731183
HDRD price ($/L)				0.90	0.92	0.94	0.95	0.97	0.99	1.01
HDRD revenue				584103	670259	683664	697337	711284	725509	740020
PV of HDRD revenue				521521	534326	486618	443170	403602	367566	334747
Net revenue	-89281	-156241	-200881	36302	54817	55913	57031	58172	59335	60522

Table E-2 (cont.): Discounted cash flow analysis for camelina-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	8	9	10	11	12	13	14	15	16	17
Capital cost	0	0	0	0	0	0	0	0	0	0
Catalyst operating cost	1030	1050	1071	1093	1115	1137	1160	1183	1207	1231
Electricity cost	5702	5816	5933	6051	6173	6296	6422	6550	6681	6815
Natural gas cost	17795	18151	18514	18885	19262	19647	20040	20441	20850	21267
Fuel gas credit	-40	-41	-42	-43	-44	-45	-46	-47	-47	-48
Cooling water cost	4115	4198	4282	4367	4455	4544	4635	4727	4822	4918
Vegetable oil cost	370529	377940	385498	393208	401073	409094	417276	425621	434134	442816
Hexane makeup cost	366044	373365	380832	388449	396218	404142	412225	420470	428879	437457
Hydrogen cost	14369	14656	14950	15249	15554	15865	16182	16506	16836	17172
Labor cost	3151	3214	3278	3344	3411	3479	3548	3619	3692	3766
Vegetable oil trans. cost	35032	35733	36447	37176	37920	38678	39452	40241	41045	41866
Other cost	2564	2615	2667	2721	2775	2831	2887	2945	3004	3064
Heavy ends credit	-127204	-129748	-132343	-134990	-137689	-140443	-143252	-146117	-149039	-152020
Total cost	693088	706949	721088	735510	750220	765225	780529	796140	812063	828304
PV of total cost	279926	254933	232171	211442	192563	175370	159712	145452	132465	120638
HDRD produced (000 L)	731183	731183	731183	731183	731183	731183	731183	731183	731183	731183
HDRD price ($/L)	1.03	1.05	1.07	1.10	1.12	1.14	1.16	1.19	1.21	1.23
HDRD revenue	754820	769916	785315	801021	817042	833382	850050	867051	884392	902080
PV of HDRD revenue	304859	277640	252850	230274	209714	190990	173937	158407	144263	131383
Net revenue	61732	62967	64226	65511	66821	68158	69521	70911	72329	73776

Table E-2 (cont.): Discounted cash flow analysis for camelina-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	18	19	20	21	22	23	24	25	26	27
Capital cost	0	0	0	0	0	0	0	0	0	0
Catalyst operating cost	1255	1280	1306	1332	1359	1386	1414	1442	1471	1500
Electricity cost	6951	7090	7232	7377	7524	7675	7828	7985	8144	8307
Natural gas cost	21692	22126	22569	23020	23481	23950	24429	24918	25416	25924
Fuel gas credit	-49	-50	-51	-52	-53	-55	-56	-57	-58	-59
Cooling water cost	5017	5117	5219	5324	5430	5539	5649	5762	5878	5995
Vegetable oil cost	451673	460706	469920	479319	488905	498683	508657	518830	529207	539791
Hexane makeup cost	446206	455130	464233	473517	482988	492647	502500	512550	522801	533257
Hydrogen cost	17516	17866	18223	18588	18960	19339	19726	20120	20523	20933
Labor cost	3841	3918	3996	4076	4157	4241	4325	4412	4500	4590
Vegetable oil trans. cost	42704	43558	44429	45318	46224	47148	48091	49053	50034	51035
Other cost	3125	3188	3252	3317	3383	3451	3520	3590	3662	3735
Heavy ends credit	-155061	-158162	-161325	-164552	-167843	-171199	-174623	-178116	-181678	-185312
Total cost	844870	861767	879003	896583	914514	932805	951461	970490	989900	1009698
PV of total cost	109867	100057	91123	82987	75578	68830	62684	57087	51990	47348
HDRD produced (000 L)	731183	731183	731183	731183	731183	731183	731183	731183	731183	731183
HDRD price ($/L)	1.26	1.28	1.31	1.34	1.36	1.39	1.42	1.45	1.47	1.50
HDRD revenue	920121	938524	957294	976440	995969	1015888	1036206	1056930	1078069	1099630
PV of HDRD revenue	119652	108969	99240	90379	82309	74960	68267	62172	56621	51566
Net revenue	75251	76756	78292	79857	81455	83084	84745	86440	88169	89932

Table E-2 (cont.): Discounted cash flow analysis for camelina-HDRD plant at optimum plant size (812 million L/year)

Cost items ($000)/year	28	29	30
Capital cost	0	0	0
Catalyst operating cost	1530	1561	1592
Electricity cost	8474	8643	8816
Natural gas cost	26443	26972	27511
Fuel gas credit	-60	-61	-63
Cooling water cost	6115	6237	6362
Vegetable oil cost	550587	561598	572830
Hexane makeup cost	543922	554801	565897
Hydrogen cost	21352	21779	22214
Labor cost	4682	4776	4871
Vegetable oil trans. cost	52056	53097	54159
Other cost	3810	3886	48604
Heavy ends credit	-189018	-192798	-196654
Total cost	1029892	1050490	1116140
PV of total cost	43121	39271	37254
HDRD produced (000 L)	731183	731183	731183
HDRD price ($/L)	1.53	1.56	1.60
HDRD revenue	1121623	1144055	1166936
PV of HDRD revenue	46962	42769	38950
Net revenue	91731	93566	50797