

LIFE CYCLE ANALYSIS OF FISCHER-TROPSCH DIESEL PRODUCTION FROM A
THEORETICAL WILLOW FARM

By

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To my parents, friends, family, and influences

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LIST OF ABBREVIATIONS

ASF	Anderson-Schulz-Flory
BBC	British Broadcasting Company
BD	Biodiesel
Btu	British thermal unit
CC	Combined cycle
CIDI	Compression ignition direct injection
CNG	Compressed natural gas
CONV	Conventional
COP	Coefficient of performance
EIA	Energy Information Administration
EtOH	Ethanol
FC	Fuel cell
FP	Fuel processor
ft	Foot
FT	Fischer-Tropsch
FTD	Fischer-Tropsch diesel
FU	Functional unit
g	Gram
G,H ₂	Gaseous hydrogen
Gasol	Gasoline
GH ₂	Gaseous hydrogen
GJ	Gigajoule
REET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H	Enthalpy

ha	Hectare
HE	Herbaceous
HEV	Hybrid electric vehicle
ISO	International Organization for Standardization
J	Joule
K	Kelvin
kg	Kilogram
kJ	Kilojoule
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
L,H ₂	Liquid hydrogen
LCA	Life cycle assessment
LS	Low-sulfur
LSD	Low-sulfur diesel
LNG	Liquid natural gas
MeOH	Methanol
mg	Milligrams
mmBtu	One million British thermal units
Mg	Megagram
MJ	Megajoule
NG	Natural gas
NNA	Non-North American
NREL	National Renewable Energy Laboratory
od	Oven dried

O-D	Origin-to-destination
p	Passenger
PTO	Take off power
PTW	Pump to wheel
RME	Rapeseed methyl ester
SETAC	Society of Environmental Toxicology and Chemistry
SI	Spark ignition
SRC	Short rotation coppice
SRF	Short rotation forestry
SRIC	Short rotation intensive cropping
SRWC	Short rotation woody cropping
Tg	Teragram
TTW	Tank to wheel
ULSD	Ultra low sulfur diesel
US	United States
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
WGS	Water gas shift
WTP	Well to pump
WTT	Well to tank

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The environmental performance of woody biomass harvested from a theoretical 10,000-hectare willow farm to be used as feedstock for a Fischer-Tropsch (FT) diesel production plant is analyzed using life cycle assessment (LCA) methodology. The life cycle includes energy inputs and emissions from fuel production, nursery operations, machinery manufacture and transportation, fertilizer manufacture and transportation, fuel production, farming operations, biomass transportation, gasification, FT synthesis, and FT diesel fuel transportation. Data for field operations are taken from studies done on actual willow farms in the United States. Energies and emissions for all inputs are taken from several outside sources, so as to result in a range of data. Three different harvest yields of 10, 13.5, and 18.7 oven dry tons per hectare are assumed. Over the life of the farm, farming operations produce between 51 and 71 units of biomass energy per unit of fossil energy consumed and release between 5.2 and 6.6 Mg of CO₂ eq. per hectare. Fertilizer utilization and biomass harvesting represent the most energy intensive and environmentally destructive operations.

The FT diesel production plant consists primarily of a gasifier and FT-reactor. Data for six gasifiers and five FT-reactors are used from other studies, and result in 18 possible

configurations Airblown systems are primarily for tri-generation, while oxygen systems are primarily for maximized fuel production. Heat balances are performed on the production plant, to utilize waste streams, which are fed into a gas and steam turbine. Excess waste heat is also used to run an absorption refrigeration cycle to cool the gas turbine inlet air. The resulting production plant produces between 210 and 662 barrels of Fischer-Tropsch diesel per day. The resulting energy balances for FT diesel before transportation, including electricity as a co-product, are between 11.6 and 17. After the fuel is transported, the energy balances are between 7.7 and 11.5. For every megajoule of FT diesel produced, an average of 65 grams of CO₂ eq. gases is released. Results confirm data from other studies, and support the claim that FT diesel from willow biomass is a viable substitute for conventional fuels.

CHAPTER 1 INTRODUCTION

1.1 Fossil Fuels

Fossil fuels are energy-rich hydrocarbons found within the top layers of the Earth. Since the beginning of the Industrial Revolution, fossil fuels have played a major role in supplying and continuing to meet the world's ever-growing demands for energy. Circa 2009, the global consumption of energy is estimated to be around 501 trillion megajoules (475 quadrillion British Thermal Units), and is projected to increase to 733 trillion megajoules (695 quadrillion British Thermal Units) by the year 2030, as seen in Figure 1-1 (EIA 2008). The main types of fuel used for energy are coal, natural gas, petroleum, nuclear, and renewables, of which petroleum is the most highly consumed (EIA 2008). The primary use for petroleum is in transportation fuels, while the other fuels are primarily used for heating and electricity. Virtually all transportation fuels are made from fossil fuels (coal, oil, and natural gas), which provide more than 85% of all energy consumed within the United States, as seen in Figure 1-2 (USDOE 2008). In order to keep powering its economy, it is very likely that the United State's dependence on fossil fuels will continue to increase, along with the deployment of new renewable and nuclear technologies. Also, fossil fuels provide more than 70% of the energy used for electricity generation in the United States, while less than 1% comes from renewable sources (not including hydroelectric power), which is further evidence of the high reliance on fossil fuels (EIA 2007b).

The fact that fossil fuels are a finite and non-renewable resource makes for a serious shortcoming when it comes to their use as a primary fuel. It is believed by many scientists that almost all of the Earth's bountiful supplies of petroleum basins have been located and have been either partially or completely extracted. Consequently, using fossil fuels for energy is not a sustainable practice, since it most likely takes hundreds of thousands of years for fossil fuels to

form. As a result, alternative energy sources should be further researched, particularly those that are renewable and sustainable. An analysis to estimate the year in which the maximum rate of global extraction will take place was conducted by The Energy Information Administration of the U.S. Department of Energy. Using growth rates of 0%, 1%, 2%, and 3%, the projected peak years were estimated to be 2075, 2050, 2037, and 2030, respectively, as illustrated by Figures 1-3 and 1-4 (Wood et al. 2000). These results are further evidence of the importance and need to transition from fossil fuels to alternative energy sources in the near future, so as to start supplementing fossil fuel supplies that will most likely begin to diminish in the near future.

Fossil fuel combustion has a tremendously negative impact on the environment, which is another reason to transition over to renewable energy sources. Combustion engines, whether in power plants or in transportation vehicles, release greenhouse gases, such as carbon dioxide and nitrous oxide, which accumulate in the atmosphere and in turn absorb infrared radiation from the Earth's surface, resulting in a gradual increase in the global climate temperature (USEPA 2009a). It should also be noted that greenhouse gases are also released from naturally occurring events, such as volcanic eruptions and changes in the Earth's orbit, but contributions from these compared to human activities are considered trivial (USEPA 2009c). The significant increase in carbon dioxide in the atmosphere has led some scientists to predict a global warming scenario that could potentially result in a variety of environmental problems, such as disrupted weather patterns and polar ice cap melting, both of which can have disastrous effects on all living creatures that inhabit this planet. A measure of the impact a process has on global warming can be quantified by the amount of carbon dioxide released by the process. Of all the greenhouse gases, carbon dioxide single-handedly accounts for 84% of all greenhouse gas emissions, of which fossil fuel combustion is the most significant contributor, as seen in Figure 1-5 (USEPA

2009c). It should also be noted that global levels of atmospheric carbon dioxide in 2005 were estimated to be 35% more than levels prior to the Industrial Revolution (USEPA 2008a).

Another consequence of fossil fuel combustion is ozone production, through the release of (and subsequent chemical reactions between) nitrogen oxides and volatile organic compounds. Ozone in the upper levels of the atmosphere is beneficial, as it blocks out harmful UV rays. However, emissions from motor vehicles, power plants, gasoline vapors, and chemical solvents raise the concentrations of ground-level ozone, which is the main compound found in smog (USEPA 2009b). High levels of ground-level smog can pose a serious health risk, as it can trigger a variety of health problems, such as chest pain, coughing, and throat irritation. This smog can also damage ecosystems and vegetation (USEPA 2008c). There are already some cities, such as Beijing, where smog levels are so dangerously high that people wear smog masks to prevent inhalation of harmful chemicals (BBC 2008).

Acid rain is another harmful result of the environmental impact of combusting fossil fuels. Acid rain forms when sulfur dioxide and nitrogen oxide emissions react with water vapor, air, and various compounds in the atmosphere, resulting in a precipitation with a pH of 5.5 or less. In the United States, an estimated 67% of sulfur dioxide and an estimated 25% of nitrogen oxides are emissions from electric generation power plants that burn fossil fuels (USEPA 2007b). Acid rain has been responsible for the acidification of lakes and streams, the damage of high elevation trees, and accelerating the rate of decay of building materials, paints, and historic monuments (USEPA 2007a). Since acid rain forms high in the atmosphere, wind can carry the harmful compounds to far distances.

In the United States, both government and non-government organizations have made efforts to control the levels of air pollutants in the atmosphere. The most notable government

attempt was legislation passed under the Clean Air Act of 1970, along with its amendments. The Clean Air Act of 1970 gives the EPA authority to set limits on certain pollutants, including limits on how much can be in the air anywhere in the United States, as a means of ensuring basic health standards and environmental protection from air pollution for all Americans, as well as a means of holding companies accountable for contributing to air pollution (USEPA 2008b). The EPA sets levels for six criteria air pollutants by developing human health-based or environmentally-based criteria for each of the pollutants in question. The six criteria pollutants are particulate matter smaller than 10 microns, ground-level ozone, carbon monoxides, sulfur oxide, nitrogen oxides, and lead (USEPA 2008d). All these criteria pollutants are primarily emissions from fossil fuel combustion, with the exception of lead, which is only released in trace amounts.

A significant shortcoming to the Clean Air Act of 1970 is that the six criteria pollutants do not include the greenhouse gases that are the main contributors to global warming and climate change, including carbon dioxide, methane, nitrous oxide, and fluorinated gases. Nevertheless, legislation has been passed on local, federal, and international levels to regulate emissions of these harmful gases and promote the use of renewable and sustainable energy. Examples of legislation passed on the local level are the Florida Renewable Energy Tax Incentives Program, the Infrastructure Investment Tax Credit Program, and the Florida Renewable Energy Production Tax Credit Program. On the national level, example of grants and programs include the USDA Renewable Energy Systems and the Energy Efficiency Improvement Program. Finally, on the international level, the most widely known initiative has been the Kyoto Protocol. All these legislations demonstrate the push by organizations within the United States and around the world to stabilize and eventually control the concentrations of greenhouse gases in the atmosphere.

The need to convert to a sustainable and renewable energy sector is quite evident and is being recognized throughout the world. Such a conversion will be an immense task, and will require massive changes in every field that effects energy production, including infrastructure, industry, agriculture, economy, research and development, and government. A successful conversion to a sustainable economy would also require change on an individual level as well, one in which people will realize how their lifestyles and rate of energy consumption affects other people throughout the world. As a result, the only way to successfully transition over would be through gradual changes. Such a transition would need to occur in the near future, so as to not be outpaced by the diminishing returns of fossil fuels, which could potentially lead to a global energy crisis that could have disastrous effects, such as worldwide food shortages and the ceasing of transportation.

1.2 Alternative Fuels

Ever since human beings first discovered fire, biomass fuels in solid form, such as wood, have been extensively used throughout the world for heating and cooking, and after leaps in technological advances, for producing electricity and mechanical power. However, since the discovery of fossil fuels, the consumption of biomass fuels have steadily declined, mainly due to the cheap price and abundance of fossil fuel, making most biofuels economically unfeasible. In 2006, biomass contributed to slightly more than 3% of the total energy and about 47% of the total renewable energy consumed within the United States (EIA 2007c). However, as gas prices steadily increase, along with the threat of diminishing fossil fuel returns, fuels from biomass are once again becoming a viable option for energy. The Energy Information Administration (EIA) predicts that 470 million gallons of biodiesel will be made in 2010 and that 630 million galls will be made in 2020 (EIA 2004).

Biomass feedstock for biofuels can come from a variety of sources, including municipal waste, sugars, starch, vegetable oils, non-food crops, and alcohol. Biomass can be converted into biofuels through several methods, including gasification, anaerobic digestion, transesterification, yeast fermentation, and the Fischer-Tropsch process. The two most commonly used methods for biofuels production are yeast fermentation on high-sugar crops, such as corn and sorghum, to produce ethanol, and extracting oils from plants such as palm, soybeans, and algae to make biodiesel. Ethanol is a fuel that plays a potentially significant role in liquid fuel production. Gasoline is currently being sold in the United States with mixtures of up to 10% ethanol. Some of the major concerns with corn ethanol production are that it might have a net negative energy balance and that it can promote monoculture production as in Iowa that can have disastrous effects on topsoil (Pimentel 2003).

It is clear that biofuels have the potential to compete with fossil fuels as the major source for the world's ever-growing energy needs, particularly in the transportation sector. The potential of biofuels is illustrated by an EIA study which shows that, in 2007, 700,000 cars in the United States were powered by either biofuels or non-fossil fuel based technologies (EIA 2007a). Legislation has also been passed, on both state and federal levels in the United States, to promote the use of biofuels for energy. On the federal level, the Energy Act of 2003 has provisions to provide annual grants worth \$50 million for a biomass program. On state levels, the 'Clean and Green' energy bill was passed in Montana to provide tax incentives to a broad base of energy programs including biodiesel plants.

Currently, there are several alternative technologies that are being researched for the possibility of one day replacing fossil fuels. One environmentally safe alternative with high potential is hydrogen, particularly as a fuel for fuel cells. Just recently, the federal government

passed a bill to spend \$2.4 billion dollars to promote the research of hydrogen plug-in hybrid electric vehicles (USDOE 2009). However, the main problem with hydrogen is the immense initial cost to switch over to a hydrogen economy, as significant infrastructure changes would be needed. Some other fuels being looked into for the transportation sector are methanol, compressed natural gas, and propane. Other energy production methods, such as wind and solar power, are suitable for electricity production, but not for liquid fuel production, using current technology. This is the case because wind and solar power are difficult to store, and come from intermittent sources.

1.3 Fischer-Tropsch Diesel

The fuel that will be the focus of this paper is Fischer-Tropsch (FT) diesel, which is a synthetic form of diesel. The technology for FT synthesis was developed in 1925 in Germany, when Dr. Hans Tropsch and Professor Franz Fischer applied for a patent that described a unique process to make liquid hydrocarbons from hydrogen and carbon monoxide gases, utilizing metal as a catalyst (Speight 2008). Soon afterwards, experiments proved the process to be successful, and mass production of FT fuel from coal began, and even went on to take its first serious place in the industrial sector in 1935 (Speight 2008). By the early 1940's, production of liquid hydrocarbons from coal using FT synthesis reached more than 540 million kilograms per year in Germany; four facilities in Japan as well as plants in France and Manchuria were also fully operational (Speight 2008). However, after World War II, fuel production from coal was no longer economically feasible, since it could no longer compete with the cheap prices and abundance of petroleum products made from crude oil. As a result, the FT process remained fairly dormant for generations, with the exception of a few production facilities around the world. There is now a renewed interest in the process because of the increasing prices of petroleum products as well as environmental concerns from the threat of global warming.

There are three main steps required for the successful production of FT fuels. First, the type of feedstock should be chosen and then harvested. This paper will focus on using willow biomass as a feedstock. Second is the gasification process, which extracts energy-rich hydrocarbon gases from the feedstock. The final step is to send the extracted gases, also known as syngas, into a FT-reactor, where FT fuels are produced. These three major steps will be described in greater detail in the following sections.

1.3.1 Willow Biomass

The practice of growing trees on short rotations, as a means of producing biomass feedstock for energy, is known as short rotation coppicing¹ (SRC), and is an old silvicultural practice that was commonly used prior to and early on into the industrial revolution (Andersson et al. 2002). Environmental groups around the world took on a renewed interest in SRC during the 1960s with research focusing on growing crops with high energy content. After the oil crisis of the 1970's, researchers focused on using rapidly growing broadleaved trees, including willow (*Salix* sp.), poplar, Miscanthus, and Sycamore maple, for producing woody biomass (Mitchell et al. 1999).

This study will focus on using willow (genus *Salix*) as a biomass feedstock, since it is currently one of the fastest growing energy crops, and represents an excellent source of renewable and sustainable energy. Willow SRC also benefits the environment by reducing net concentrations of greenhouse gases in the atmosphere, improving water and soil quality, expanding wildlife habitats, increasing land use diversity, and stimulating rural economies (Heller et al. 2003). In addition, willow is also a great choice for SRC because of its ease at propagating vegetatively and its ability to tolerate a wide range of climactic and edaphic (soil)

¹ Other common names for short rotation coppicing include short rotation forestry (SRF), short rotation intensive culture (SRIC), and short rotation woody cropping (SRWC).

conditions; it grows closer to the Arctic Circle than any other woody biomass (Ledin 1996). A study done Borjesson et al. concludes that *Salix* has relatively high yields compared to several other energy crops (Table 1-1).

As of now, Sweden is the only country in the world to produce willow on a large scale. However, the US has a strong potential for the cultivation of willows on extensive agricultural land. While only a few species of *Salix* clones have been tested in small-scale farms, many more promising clones have yet to be tested (Ledin 1996). The Salix Consortium represents a powerful alliance of over 20 organizations with a goal of promoting the commercialization of willow SRC in the northeast Midwest regions of the United States; in 1995, the Salix Consortium was awarded a grant under the Biomass Power for Rural Development Program to develop willow as a dedicated energy feedstock crop (Heller et al. 2003). Over 200 hectares of willow have been established thus far in western and central New York.

1.3.2 Gasification

Gasification is the process used to convert carbonaceous matter into a synthetic or combustible gas. Gasification involves complex reactions of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 700 °C or higher to produce an energy rich syngas. Syngas, in turn, can be used to provide electric power and heat or as a raw feedstock for chemical synthesis, liquid transportation fuels, or gaseous fuels such as hydrogen (Speight 2008). After the feedstock matter has been converted to a syngas, gas-cleaning devices such as cyclone filters and zinc oxide guard beds remove unwanted substances such as sulfur compounds, tar, and ash. Gasifiers operate at substoichiometric conditions in order to only reach partial combustion. The oxygen supplied to the gasifier is controlled such that heat and new gaseous fuel are produced at the same rate as feed material is gasified. Some gasifiers employ the use of indirect heating as a means of avoiding combustion of the feedstock as well as to avoid diluting

the syngas with nitrogen and excess CO₂. When the feedstock material is heated under gasification conditions, the first process it goes through is pyrolysis, during which light volatile hydrocarbons rich in hydrogen, are evolved and tars, phenols, and hydrocarbon gases are released (Rezaiyan et al. 2005). In pyrolysis, the feedstock thermally decomposes in order to yield solid carbon ash and a syngas with higher hydrogen content than the original feedstock. The main options for gasifiers are oxidative material, operating temperature and pressure, and direct or indirect heating. Different types of gasifiers can be seen in Figure 1-6.

There are many reactions that take place during gasification, and all of them can be seen in Figure 1-7. Most of the oxygen sent into the gasifier, either as pure oxygen or air, is consumed from reaction 1 through reaction 3, in order to provide sufficient heat to dry the solid fuel, break up chemical bonds, and raise the reactor temperature to drive gasification reactions 4 through 9 (Rezaiyan et al. 2005). It should also be noted that many factors affect the net chemical composition and heating value of the syngas, including feedstock compositions, particle size, heating rate, feedstock moisture, residence time, and plant configuration (Speight 2008).

Gasification technology has been in use since the 19th century. The first industrial applications took place in 1816, when syngas from gasified coal was used to light the streetlamps of Baltimore. A survey that took place in 2003 indicated the successful operation of 163 commercial gasification projects worldwide consisting of a total of 468 gasifiers (Rezaiyan et al. 2005). Recent commercial projects use refinery waste or products that no longer have any value in the market, such as heavy oils and petroleum coke. Since the feedstock for gasification is most often agricultural, gasification is considered to be a renewable and sustainable technology.

1.3.3 The Fischer-Tropsch Process

Once the syngas from gasification has gone through several cleaning methods, it then goes through the FT-reactor. The gas is cleaned beforehand to avoid the presence of impurities that can potentially deactivate the catalyst within the FT-reactor. The FT process is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms (Speight 2008). Typical catalysts used are cobalt and iron. The main purpose of the FT-reactor is to produce a synthetic substitute fuel for petroleum, as well as other products such as wax and lubrication oil.

The FT process basically functions as a process of building carbon chains, where groups of methylene are attached to the carbon chain. Equation 1 can describe the overall FT chemical reaction. It should be noted that the initial reactants for Equation 1 are also the products of the gasification process.



However, the actual partial reactions that take place in the FT process have been, and remain, a matter of controversy since the 1930's (Speight 2008). The speculated reactions along with the reaction enthalpies are listed in Figure 1-8. The exact behavior of any of these chemical reactions is not known to any degree of certainty. It is known, however, that the partial reactions are highly exothermic; the total heat rejected from the process accounts for almost 25% of the heat of combustion of the syngas, thereby creating a theoretical upper limit on the efficiency of the FT process (Speight 2008).

For industrial FT applications, temperature control and reactor cooling are the most important factors in maximizing fuel production as well as lengthening the lifetime of the

catalyst. Currently, there are four types of FT-reactors that have been designed, and can be seen in Figure 1-9; some are designed for high temperature applications while some for low. The cetane number is defined as the measure of the ignition quality of a diesel fuel. The slurry phase reactor is a commonly used design; diesel produced from it is very paraffinic in nature, and has a cetane number in excess of 70 (Speight 2008). As a result, diesel engines operating on FT fuel can experience significantly less knocking and increased lifetimes. In addition, FT diesel is sulfur-free and nitrogen-free, which further emphasizes the environmental benefits of switching over to FT fuels. It should also be noted that FT fuels could also be used to “sweeten” or upgrade conventional fuels (Speight 2008).

At the moment, only a handful of companies around the world have commercialized the FT technology. The two biggest plants in operation are in Bintulu, Malaysia and in South Africa. The plant in Bintulu is operated by Shell, and uses natural gas as feedstock to produce primarily low sulfur FT diesel and food-grade wax. The plant in South Africa is operated by Sasol, and uses coal and natural gas as a feedstock to produce a variety of synthetic petroleum products. Syntroleum is a US company that has produced more than 400,000 gallons of synthetic diesel and jet fuel from the FT process, using natural gas at its plant in Tulsa, Oklahoma (Zamorano 2006). As a result, the combination of biomass gasification and the FT process represents a very promising means of producing alternative transportation fuels.

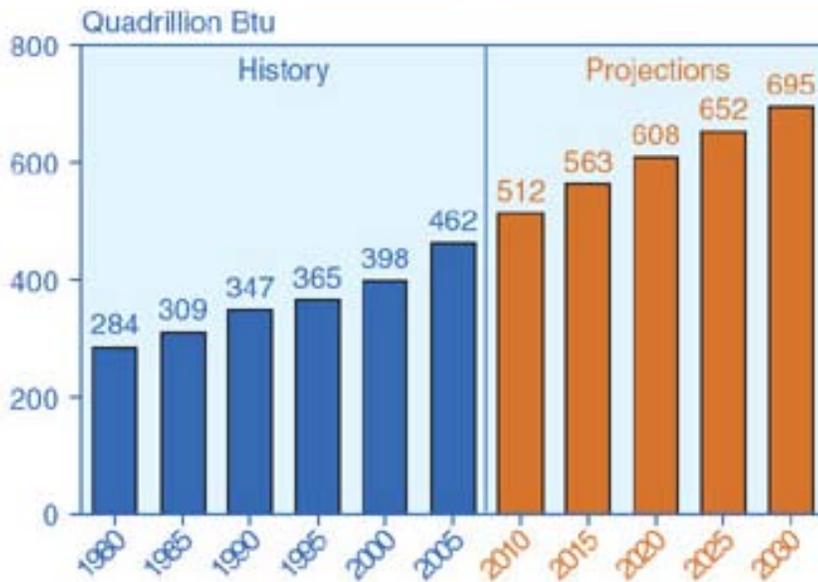


Figure 1-1. World marketed energy consumption, 1980-2030 (EIA 2008)

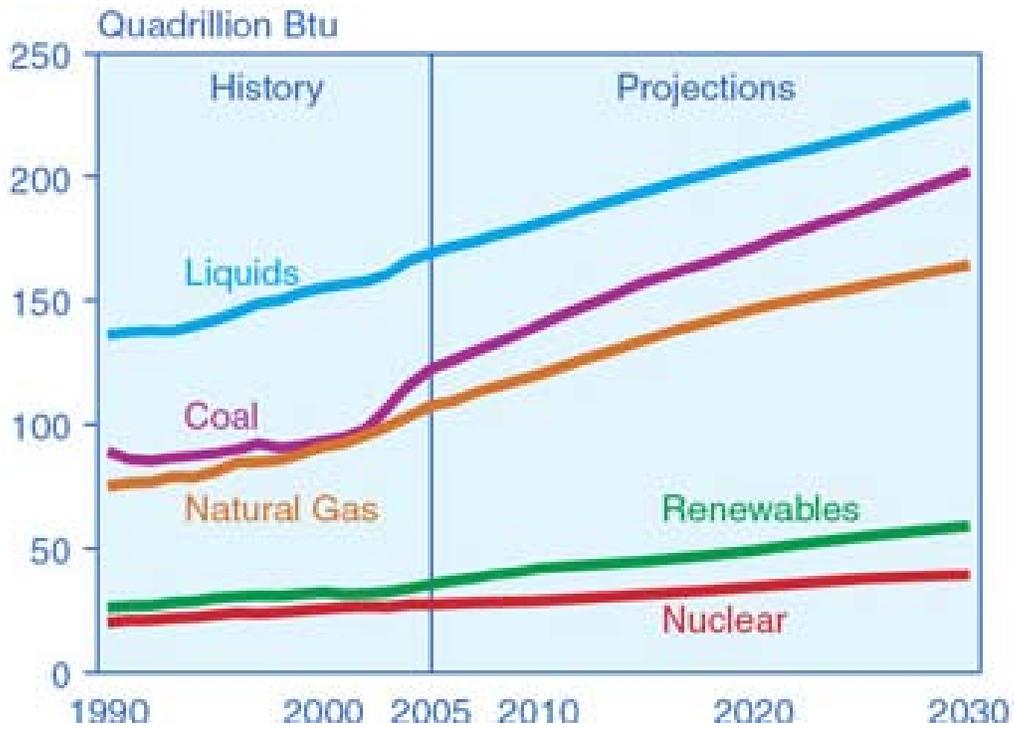


Figure 1-2. World marketed energy use by fuel type, 1990-2030 (USDOE 2008)

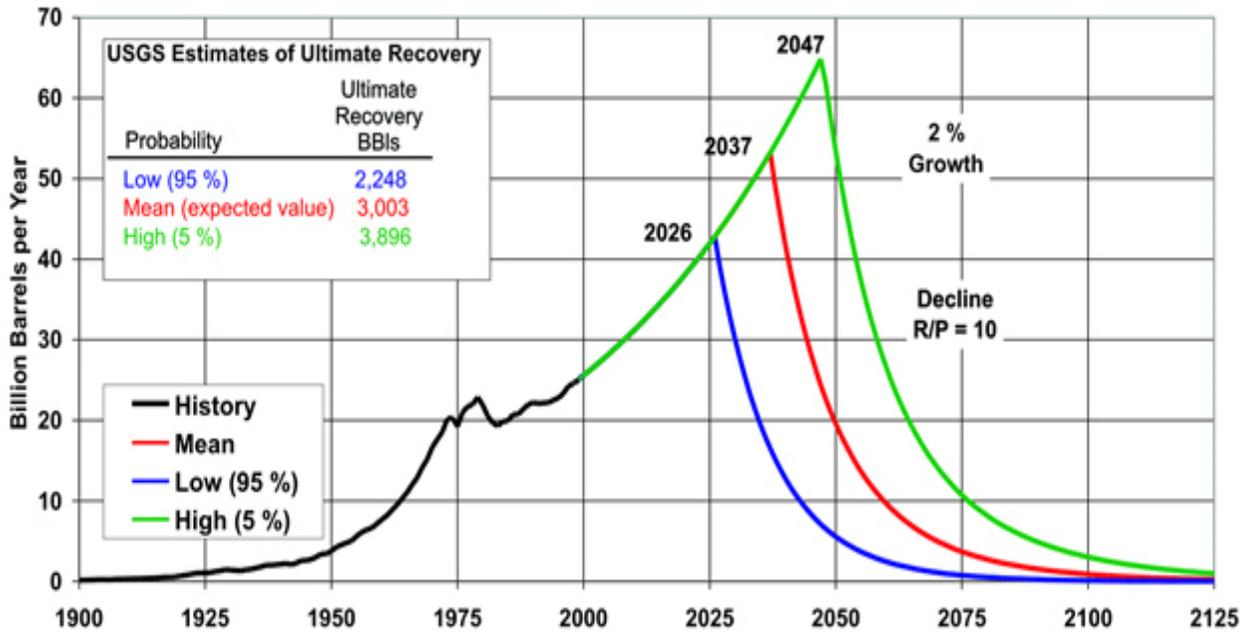


Figure 1-3. Annual production scenarios with 2% growth rates (Wood et al. 2000)

Probability Estimate	Ultimate Recovery BBbls	Annual Demand Growth, %	Peak Year	Peak Rate, MMBbls/yr	Peak Rate, MMBbls/day
Low (95%)	2,248	0.0	2045	24,580	67
	2,248	1.0	2033	34,820	95
	2,248	2.0	2026	42,794	117
	2,248	3.0	2021	48,511	133
Mean (expected value)	3,003	0.0	2075	24,580	67
	3,003	1.0	2050	41,238	113
	3,003	2.0	2037	53,209	146
	3,003	3.0	2030	63,296	173
High (5%)	3,896	0.0	2112	24,580	67
	3,896	1.0	2067	48,838	134
	3,896	2.0	2047	64,862	178
	3,896	3.0	2037	77,846	213

Figure 1-4. World oil production forecast (Wood et al. 2000)

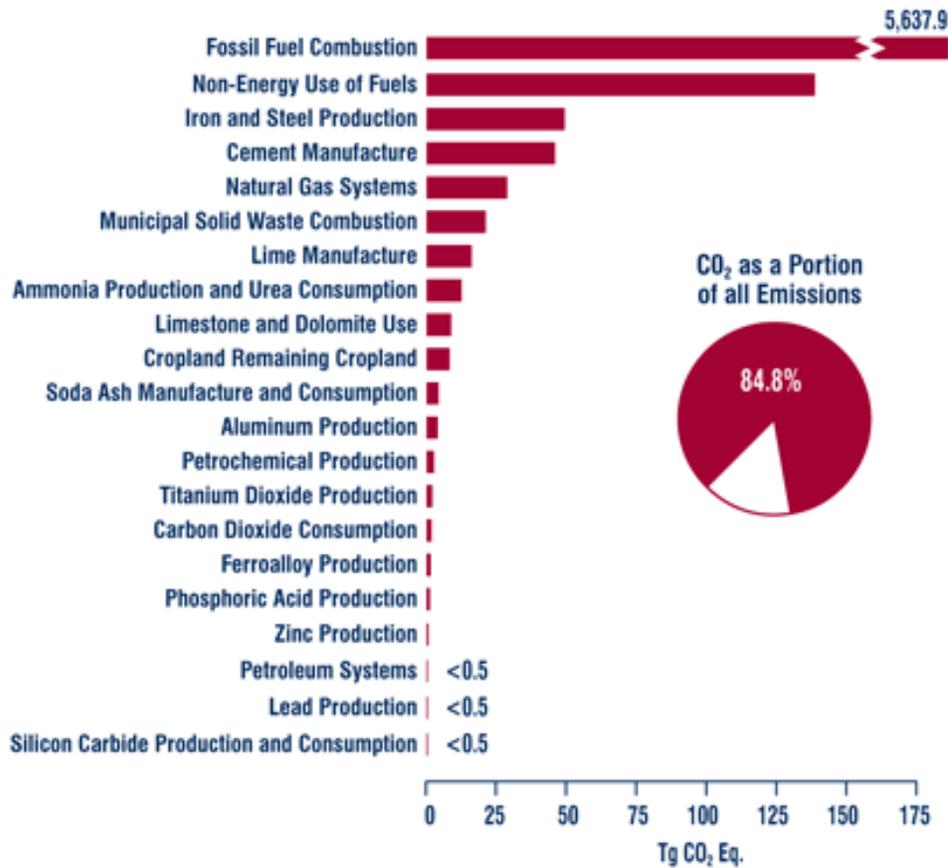


Figure 1-5. 2006 Sources of CO₂ emissions (EPA 2009c)

Table 1-1. Energy content and harvested yields for various energy crops (Borjesson 1996)

Biomass resource	Energy content GJ dry Mg ⁻¹	Dry Mg / ha / year		GJ / ha / year	
		Today	2015	Today	2015
Wheat (grain)	18.5	5.1	7.5	94	140
Rape (seed)	27.8	2.5	3.1	70	86
Potatoes	17.0	7.7	10	130	180
Sugar beet	17.4	11	14	190	240
Clover-grass ley	18.4	7.5	11	140	200
Lucerne	19.0	8.0	14	150	270
Reed canary grass	18.4	6.5	12	120	220
<i>Salix</i>	19.5	9.3	17	180	330
<i>Straw</i>	18.1	2.0	2.0	36	36

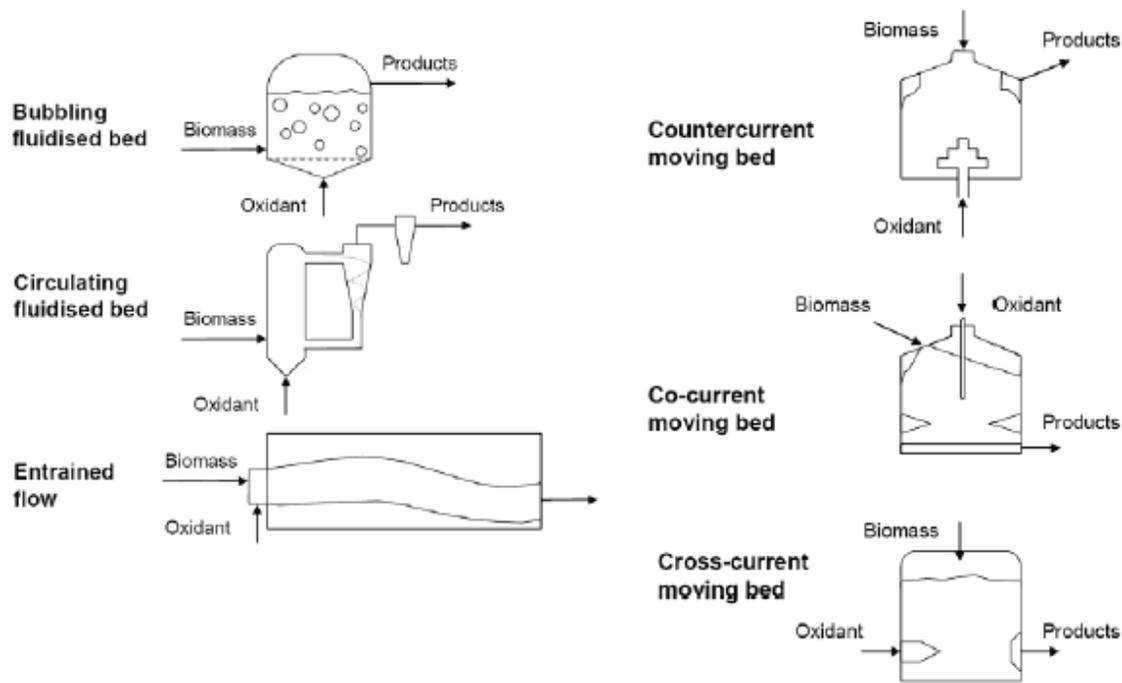
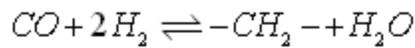


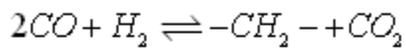
Figure 1-6. Various design configurations for gasifiers
(<http://www.zero.no/transport/bio/gasification4>)

- 1) $C + O_2 \rightleftharpoons CO_2$
- 2) $C + \frac{1}{2}O_2 \rightleftharpoons CO$
- 3) $H_2 + \frac{1}{2}O_2 \rightleftharpoons H_2O$
- 4) $C + H_2O \rightleftharpoons CO + H_2$
- 5) $C + 2H_2O \rightleftharpoons CO_2 + 2H_2$
- 6) $C + CO_2 \rightleftharpoons 2CO$
- 7) $C + 2H_2 \rightleftharpoons CH_4$
- 8) $CO + H_2O \rightleftharpoons H_2 + CO_2$
- 9) $CO + 3H_2 \rightleftharpoons CH_4 + H_2O$
- 10) $C + H_2O \rightleftharpoons \frac{1}{2}CH_4 + \frac{1}{2}CO_2$

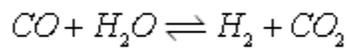
Figure 1-7. Gasification chemical reactions (Rezaiyan et al. 2005)



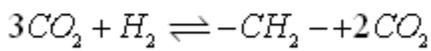
$$\Delta H_{300K} = -165.0 kJ / mol$$



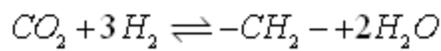
$$\Delta H_{300K} = -204.7 kJ / mol$$



$$\Delta H_{300K} = -39.8 kJ / mol$$



$$\Delta H_{300K} = -165.0 kJ / mol$$



$$\Delta H_{300K} = -165.0 kJ / mol$$

Figure 1-8. Speculated chemical reactions and enthalpies for the Fischer-Tropsch process (Speight 2005)

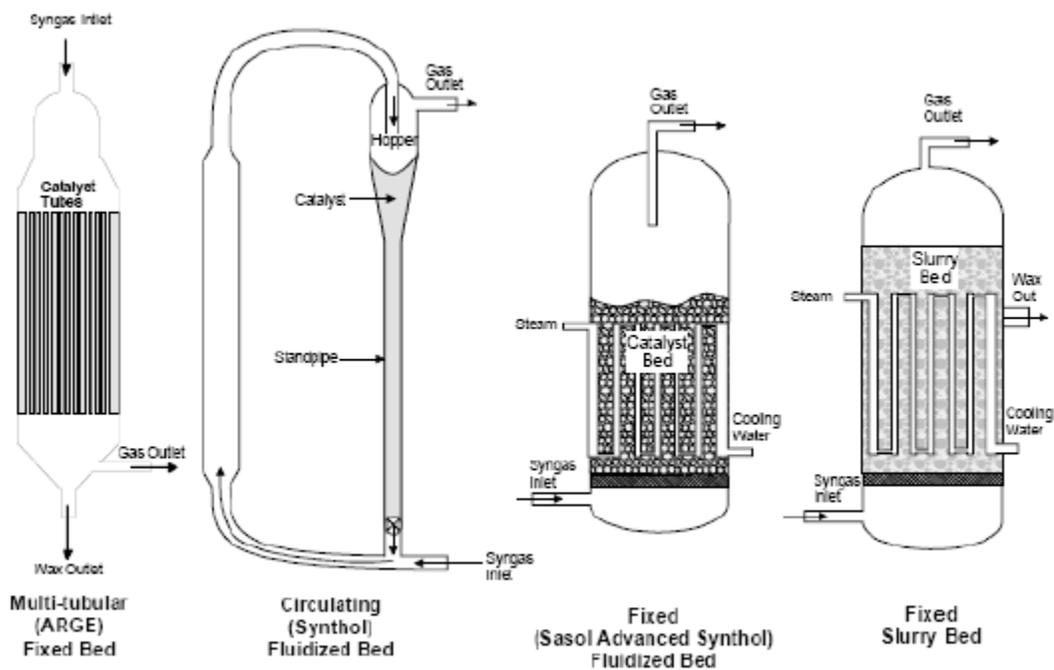


Figure 1-9. Various Fischer-Tropsch reactors design configurations (<http://www.zero.no/transport/bio/ft3.gif>)

CHAPTER 2 METHODOLOGY

2.1 Introduction to Life Cycle Assessments

A life cycle assessment (LCA) is an environmental management tool which allows for the quantification of environmental burdens and the accompanying potential impacts through the entirety of a product's life cycle: from raw material collection through manufacture, use, end-of-life treatment, and disposal (Azapagic 1999). LCAs have a wide variety of useful applications, and assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle, informing decision-makers in industry, governmental and non-governmental organizations, and in proving environmental claims, ecolabelling schemes, and environmental product declarations (SETAC 2009). The International Organization of Standardization (ISO) 14040 family of standards has developed life cycle assessment guidelines and examples.

As defined by the ISO 14040 family of standards, a life cycle assessment consists of four main stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope definition stage includes defining the system under study, the overall goal of the study, boundary conditions, assumptions, and the appropriate functional unit(s). The functional unit for a study is defined as the amount of final products or services to which the LCA is applied; it is used as a means to compare data with other LCAs done on similar products or services. For example, if the life cycle for corn production was being compared to that of sugar cane, an appropriate functional unit would be bushels harvested per hectare. All inputs and outputs can then be individually considered by their contribution to the total bushels harvested per hectare.

In the inventory analysis phase, data collection is used to gather information on material, energy, and emission flows, so as to quantify the environmental burdens for the life cycle of a product or process. The burdens are defined by resource consumption and emissions to air, water, and solid waste (Azapagic 1999). In addition, great care must be taken to obtain accurate and relevant data, as flawed data can drastically affect the net results of the LCA. For example, being off by one bushel per hectare seems relatively insignificant for a small farm, but for a 10,000 hectare farm this will result in 10,000 bushels not being accounted for.

The third stage in an LCA is the impact assessment stage. In order to successfully go through this stage, the relevant environmental impacts and their accompanying stressors must be identified; examples include global warming, acid rain, and human toxicity potential. The production of these stressors is to be inventoried through all stages within the defined boundaries of the study. The impact analysis stage then uses the data from the stressors to quantify the impacts upon the environment. The impacts can even be further aggregated to a single environmental stressor by attaching weighing factors to the impacts as a means of indicating their relative significance (Azapagic 1999). As a result, a LCA conducted by proper guidelines can yield numerical results that can then be easily analyzed and compared with other resulting impacts of a similar system or process under study.

The last and final stage is interpretation, which is also known as improvement analysis. In this step, the results of the LCA are used to figure out ways in which the product or process under study can be improved. This is done by pinpointing the most damaging and unfavorable stages of the subject life cycle, analyzing the material and energy flows within these stages, and then seeking alternative routes that are more favorable. The improvement analysis stage can also

be used to perform sensitivity analysis, as a means of finding which input streams most significantly affect the output streams.

It should be noted that there are two rules used for streamlining data, the five percent and one percent rules. If a material for an LCA analysis contributed to 5% or less of the total product mass, it can be considered as a trivial input. If an input contributes to 1% or less of the total input mass, it can be considered as a trivial input as well. However, inputs that are considered toxic are exceptions to both of these rules, and must be included in the LCA, regardless of their contributions to the total mass or inputs (USEPA 2006).

LCAs have been used since the 1990's for decision-making in the corporate and public sectors. Some of the more notable recent examples of LCA applications in corporate decision making include the energy, transportation, chemical, nuclear, metal, polymer, paper, forest, textile, leather, water, and electronics sectors, as well as other industries. The uses by industry type can be seen in Figure 2-1. Within the United States, the USEPA is encouraging policy-making through the use of LCAs for various projects, such as the establishment of subsidies or tax credits for alternative fuels and using a life cycle approach for the development of the maximum achievable control technology standard under the 1990 Clean Air Act (Curran 1997).

2.2 Life Cycle Assessments of Liquid Fuel Production Systems

Numerous life cycle assessments have been done on liquid fuel production systems, as well as the accompanying feedstocks, which are usually energy crops. LCAs for fuels have different boundaries when compared to traditional LCAs of non-fuel products, since fuels can be used in a variety of transportation vehicles and combustion engines. The starting point for fuels in LCAs is known as the “well” phase, which is a term used to describe the extraction stage of the fuel, and the ending point is known as the “wheel” phase, where it is combusted in a specific vehicle. In between these two points is the “pump” or “tank” phase, which represents a fueling

station, before the fuel enters the vehicle for combustion. As a result, boundaries for LCAs done on transportation fuels can either be based on well-to-wheel (WTW), well-to-pump (WTP)², or pump-to-wheel (PTW) studies as seen in Figure 2-2.

“Well-to-tank energy use and greenhouse gas emissions of transportation fuels” (NREL 2001a) is an extensive series of LCAs done by the National Laboratory of Renewable Energy (NREL) to compare an array of alternative and conventional fuels. The total energy uses for producing each of the fuels includes energy from renewable and nonrenewable sources. In order to calculate the total energy inputs, various computer models, such as GREET 2.7, were used to trace back to the energy content of the primary energy feedstocks for most of the transportation fuels. Transportation energies for various fuels were averaged with respect to average distances traveled to the final destination within the United States. Also, for each fuel, the life cycle included extraction, production, transportation, processing, conversion, and distribution.

Well-to-tank total energy use results can be seen in Figure 2-3 and Figure 2-4. The units for the fuels listed are the energy required for producing 1055 megajoules (MJ) of the specified fuel. For conventional petroleum fuels, only about 25% of the energy value of the fuel is needed for production; while natural gas based fuels, particularly FT fuels, require about 75% of the energy value. Hydrogen fuels perform very poorly, requiring between 100% and 300% of the energy value of the final product to be made. Well-to-tank energy efficiencies for the same fuels can be seen in Figures 2-5 and 2-6. Conventional petroleum products and compressed natural gas score the highest, with energy efficiencies around 80%, while hydrogen fuels perform the worst, with energy efficiencies between 30% and 60%. Figures 2-7 and 2-8 display the WTT fossil fuel energy input for the same set of fuels. Conventional petroleum and ethanol score the best;

² Well-to-pump is also known as well-to-tank (WTT).

petroleum products scored well because their final combustion value is deducted, since it represents fossil fuel energy. As a result, all alternative fuels scored very poorly, particularly hydrogen-based fuels. Lastly, Figures 2-9 and 2-10 display the greenhouse gas emissions for the same fuels. For every megajoule of energy produced, conventional fuels release about 19 grams of CO₂ equivalent emissions, while natural gas, hydrogen fuel cells, and electricity release about 28 grams, between 94 and 330 grams, and up to 28 grams, respectively.

“Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems” (NREL 2001b) is another highly detailed group of LCAs performed by the NREL. Data from the previous WTT studies were incorporated with TTW data from several major fuel production companies in order to produce data for WTW analysis. Figure 2-11 displays WTW results for conventional fuels and hybrid fuel vehicles running on spark ignition (SI) and compression ignition direct injection (CIDI) engines, along with hybrid electronic vehicles (HEV). Gasoline, diesel, and FT-diesel scored the best, burning about 3.9 MJ per kilometer. Ethanol scored the poorest, burning about 7.2 MJ per kilometer. Figure 2-12 displays the greenhouse gas emissions for the same fuels. For every kilometer traveled, ethanol vehicles release about 93.2 grams of CO₂ equivalent emissions, while gasoline, diesel, FT diesel, and CNG release between 248.5 and 341.7 grams. Figures 2-13 and 2-14 display WTW energy and greenhouse gas emission results for several more fuels. Gasoline, diesel, hydrogen fuel cells, and methanol all score quite well, burning only about 3.3 MJ per kilometer driven, and all release about 300 grams per 1055 MJ of fuel combusted.

A detailed study by Tom Beer et al. considers life cycle emissions of various alternative fuels. The study encompasses steps from extraction to distribution for the full life cycle of fuels. Fuels are compared on the basis of emissions per energy used (g/MJ), as well as the mass of

emissions per ton per kilometer of distance traveled (g/t km). It should be noted that emissions per energy used act as a WTP analysis, while emissions per ton per kilometer of distance traveled act as a WTW analysis, since it also involves data specific to a chosen vehicle.

Figure 2-15 shows the results comparing CO₂ equivalent emissions for WTW and WTP results for low sulfur diesel, ultra low sulfur diesel, FT diesel, and reprocessed ultra low sulfur diesel. For every megajoule of FT diesel produced and burned, slightly less than 100 grams of CO₂ equivalent greenhouse gases are released. Figure 2-16 shows similar results for biodiesel from various energy crops including canola, rape seed, soybean, and waste oil. Low sulfur diesel releases more CO₂ equivalent emissions than biodiesel made from the several energy crops listed. Figure 2-17 compares emissions for low sulfur diesel, diesohol, and ethanol made from various crops, including molasses, wheat starch waste, wheat, wood waste, and ethylene. Ethanol from woodwaste has significantly less emissions than the other fuels listed, releasing only about 10 grams of CO₂ equivalent emissions for every megajoule of fuel burned, and slightly more than 10 grams per ton per kilometer traveled. Lastly, Figure 2-18 compares emissions for compressed natural gas (CNG) and different variations of liquefied natural gas (LNG). The best performing fuel, with regards to emissions, is LNG, releasing slightly more than 60 grams of CO₂ equivalent emissions for every megajoule of fuel burned.

A study by Eric D. Larson reviewed and compared several LCAs done on liquid biofuels systems (Larson 2006). He calculated the avoided emissions from converting to alternative fuels. Almost 1300 kg and 1000 of CO₂ eq. emissions per hectare year are avoided by using ethanol from wheat straw and ethanol from rapeseed oil, respectively. Avoided emissions from WTW analysis are also present in this study.

An extensive number of LCAs have been performed on fuel systems. For simplicity, data has been compiled from numerous studies on WTT and WTW LCAs for transportation liquid fuels, and can be seen in Tables 2-1 and 2-2, respectively. It should be noted that this LCA will be WTT analysis, and a WTW analysis can take place once the viability of using FT-diesel is confirmed. It can be concluded that the large number of LCAs being performed on alternative fuels is a clear indication of the potential that they have to offer as a substitute to conventional petroleum fuels.



Figure 2-1. Various uses in industry for life cycle assessments (Baumann 1996)

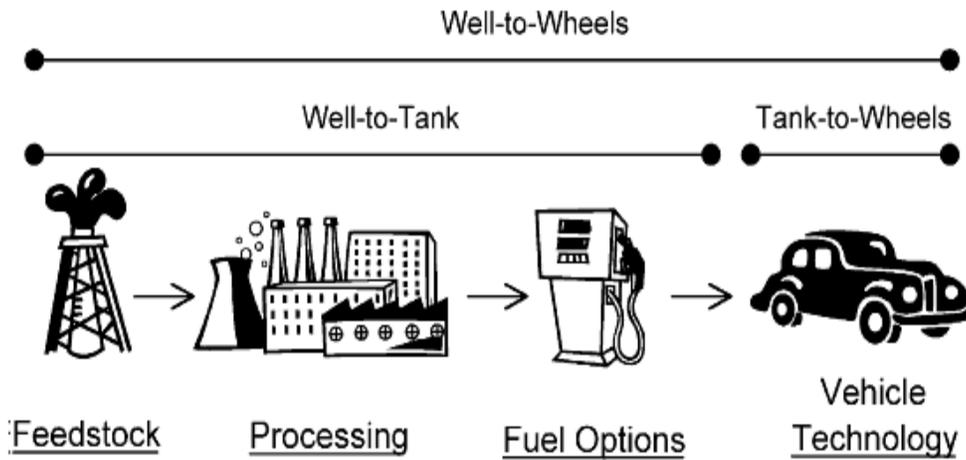


Figure 2-2. Various boundaries for transportation fuel LCAs (Semelsberger 2005)

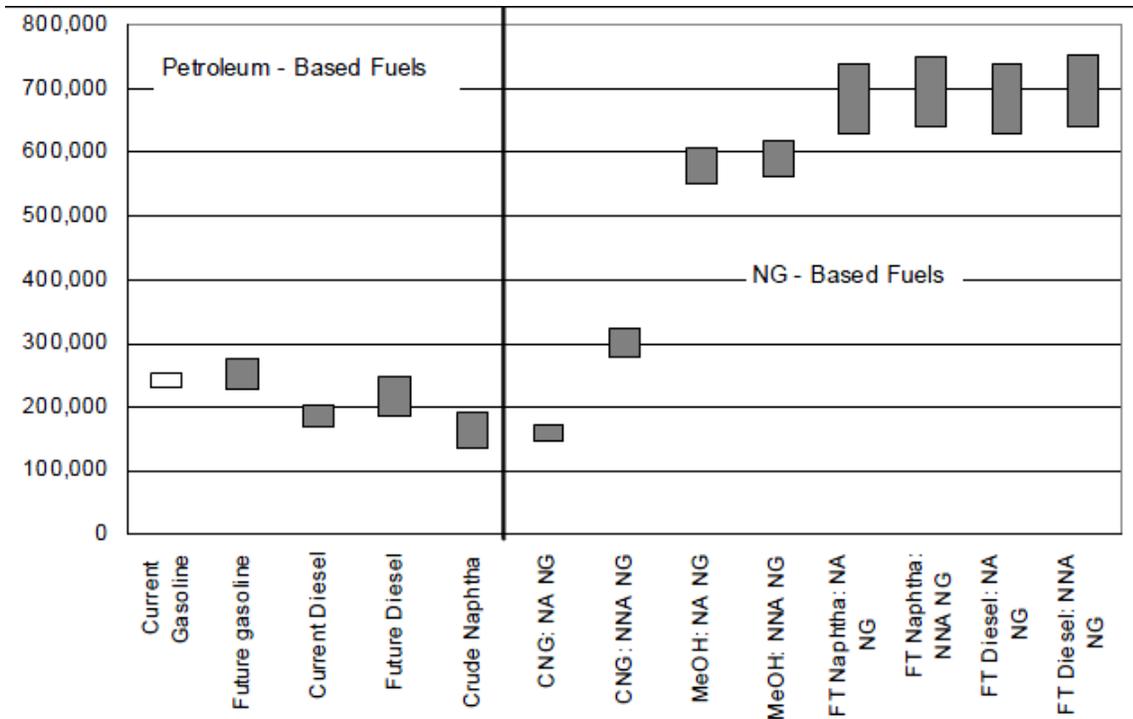


Figure 2-3. Well-to-tank total energy use of various fuels (Btu/mmBtu of fuel delivered to vehicle tanks) (NREL 2001a)

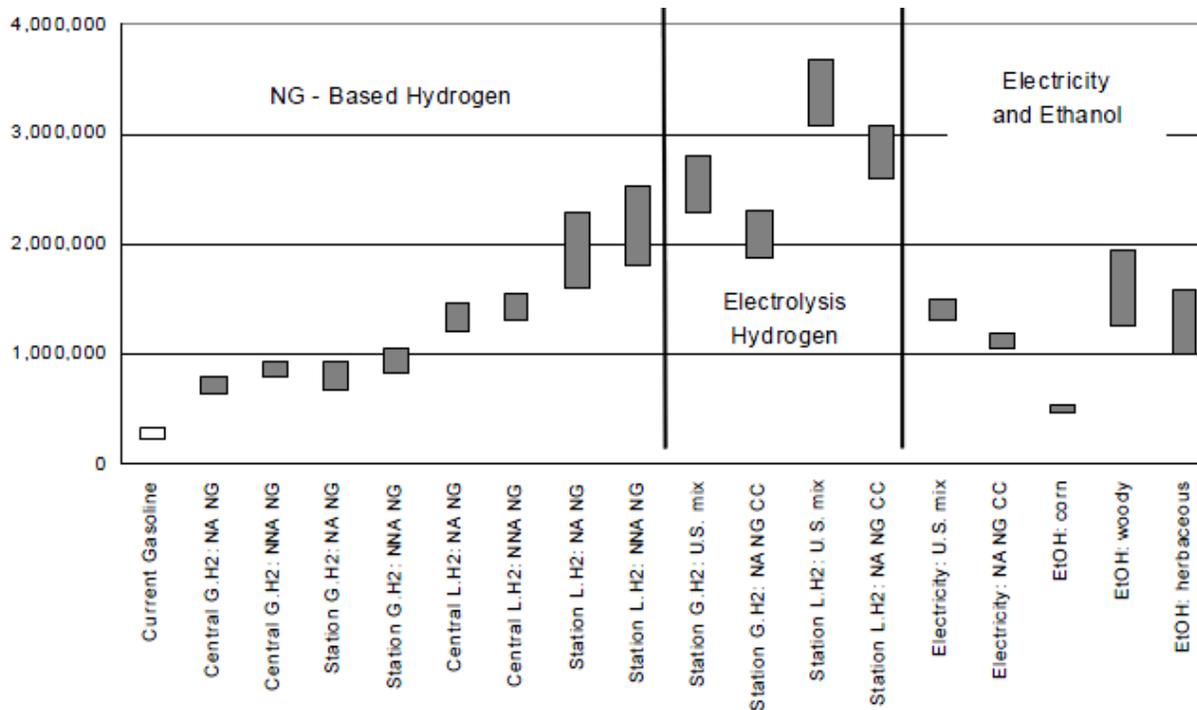


Figure 2-4. Well-to-tank total energy use of various fuels (Btu/mmBtu of fuel delivered to vehicle tanks) (NREL 2001a)

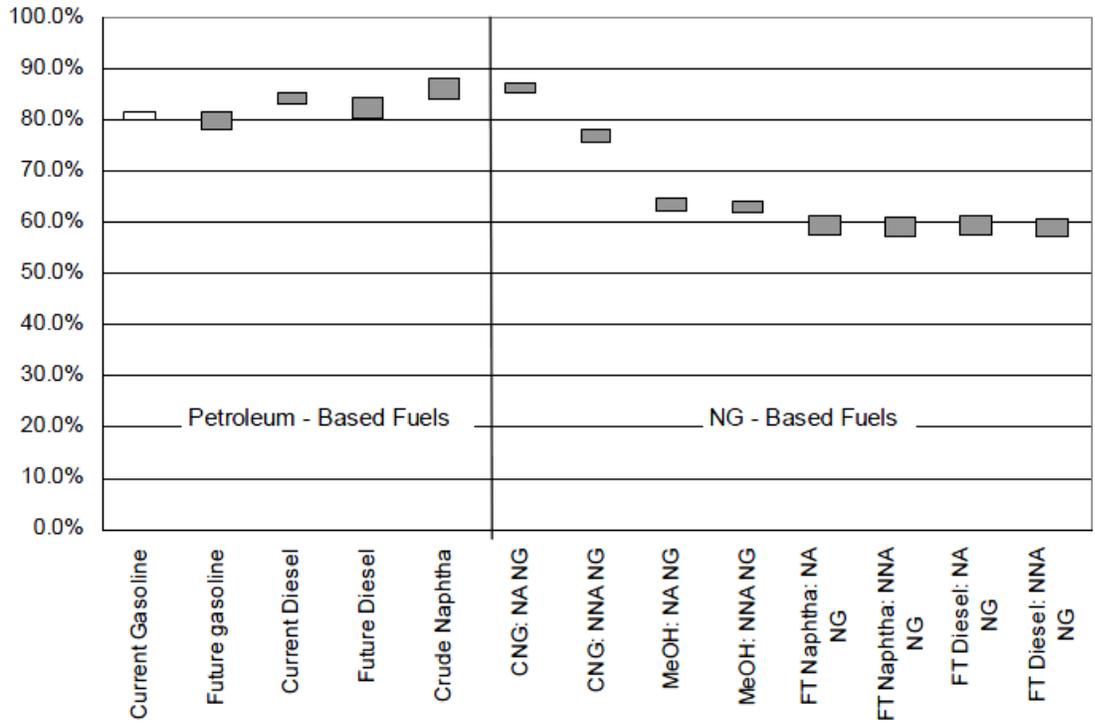


Figure 2-5. Well-to-tank energy efficiencies of various fuels (NREL 2001a)

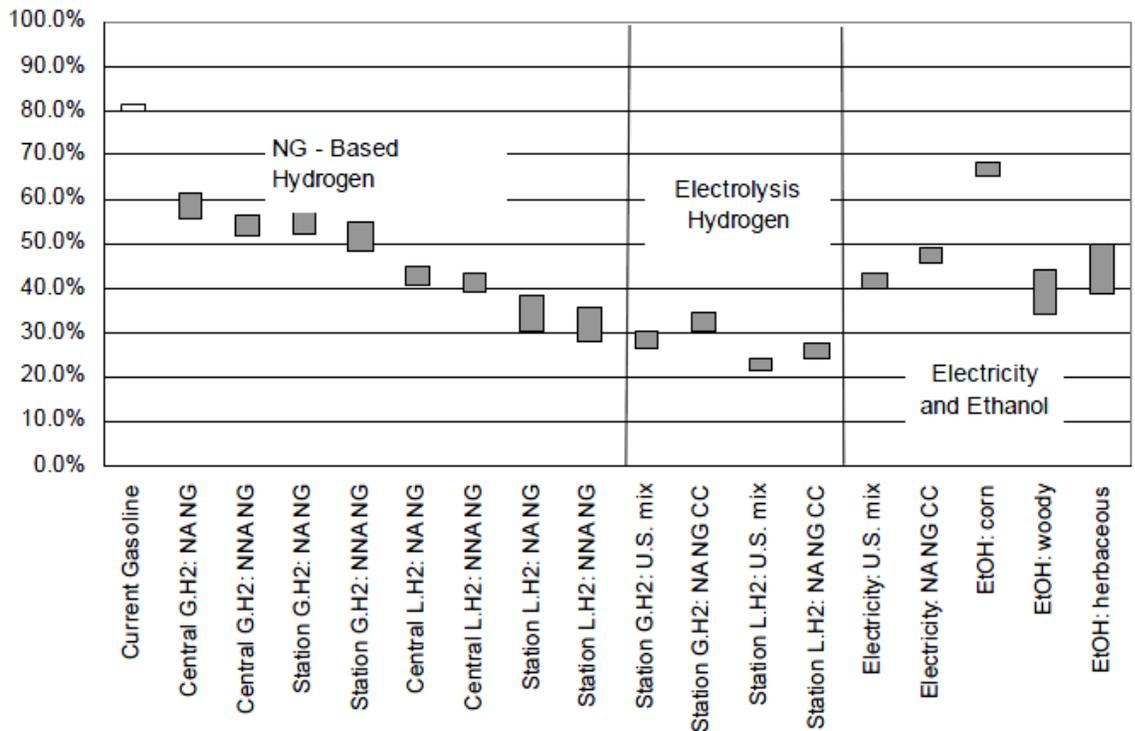


Figure 2-6. Well-to-tank energy efficiencies of various fuels (NREL 2001a)

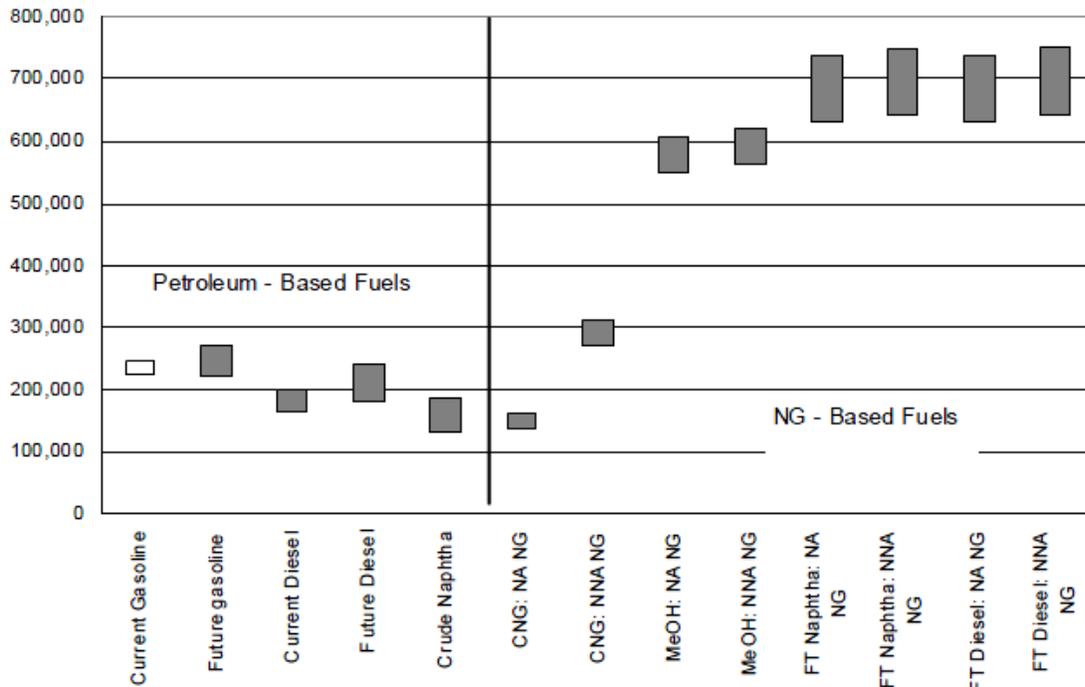


Figure 2-7. Well-to-tank fossil fuel energy use of various fuels (Btu/mmBtu of fuel delivered to vehicle tanks (NREL 2001a))

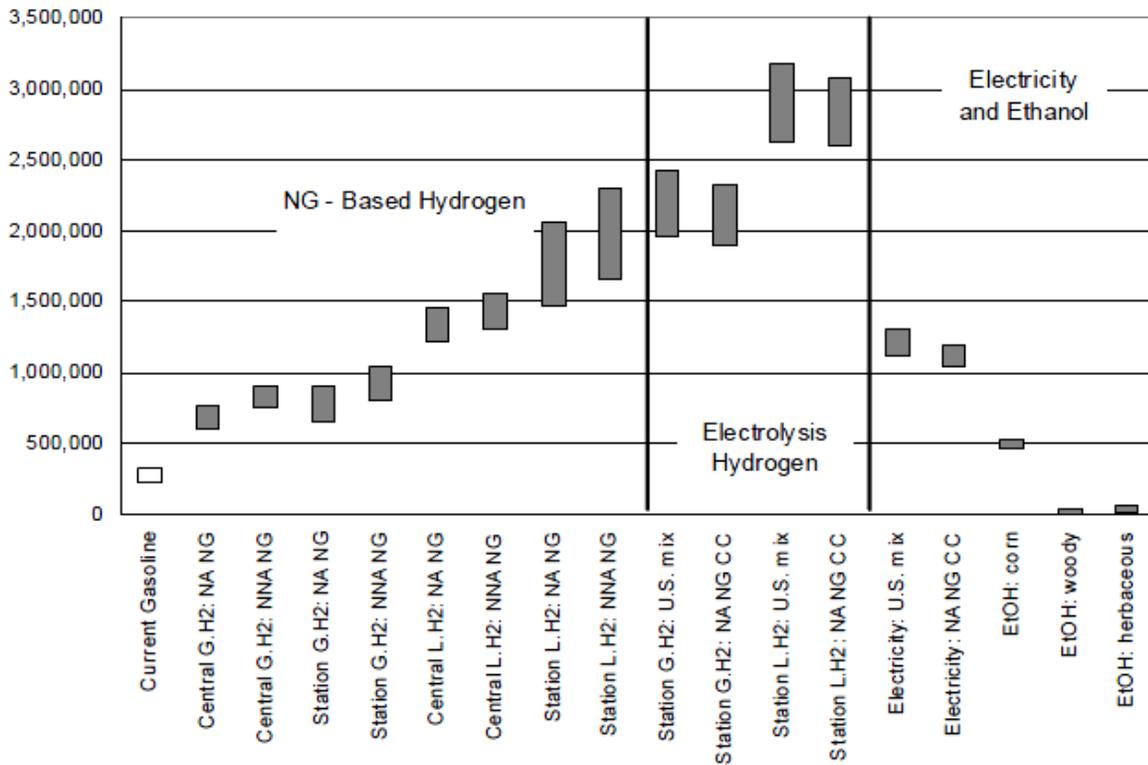


Figure 2-8. Well-to-tank fossil fuel energy use of various fuels (Btu/mmBtu of fuel delivered to vehicle tanks (NREL 2001a))

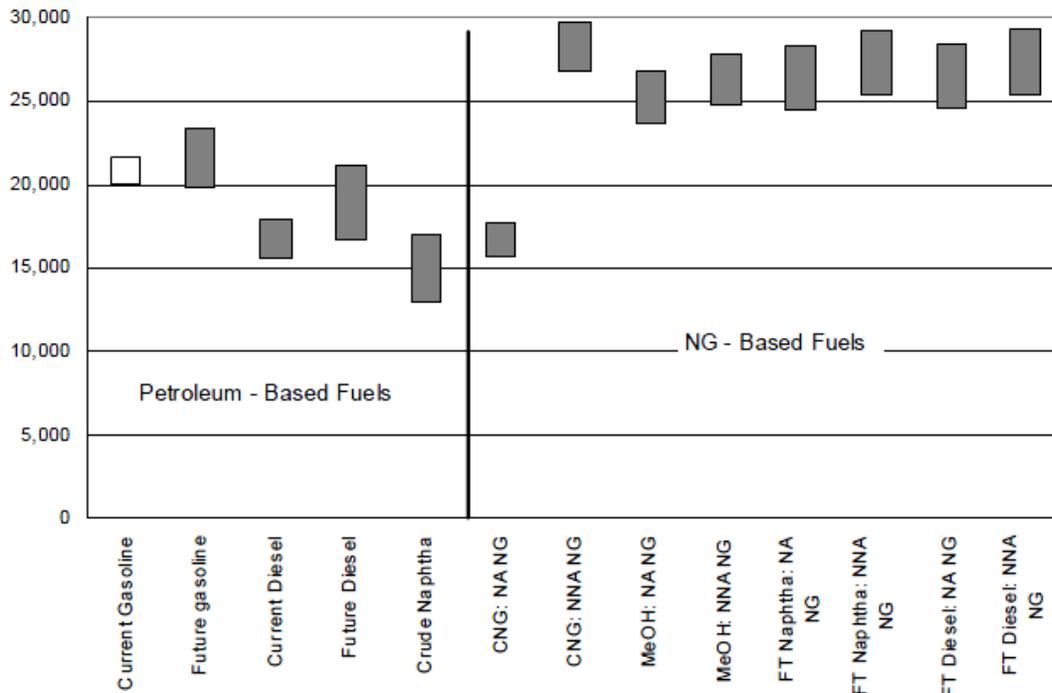


Figure 2-9. Well-to-tank greenhouse gas emissions of various fuels (g/mmBtu of fuel delivered to vehicle tanks) (NREL 2001a)

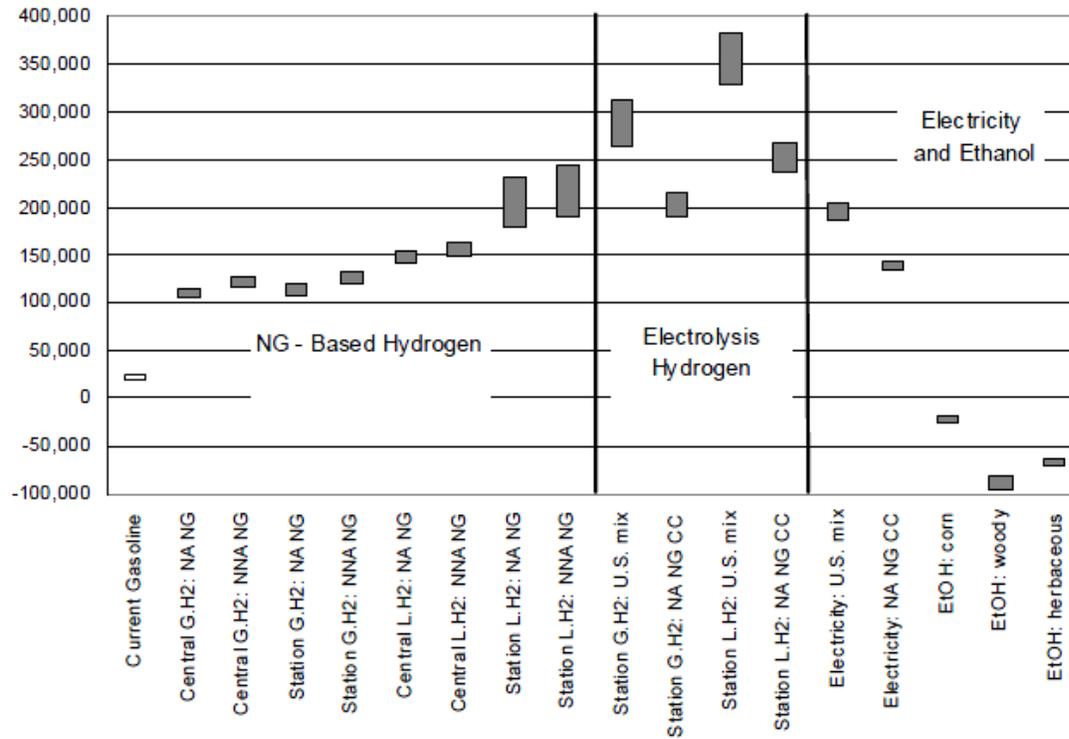


Figure 2-10. Well-to-tank greenhouse gas emissions of various fuels (g/mmBtu of fuel delivered to vehicle tanks) (NREL 2001a)

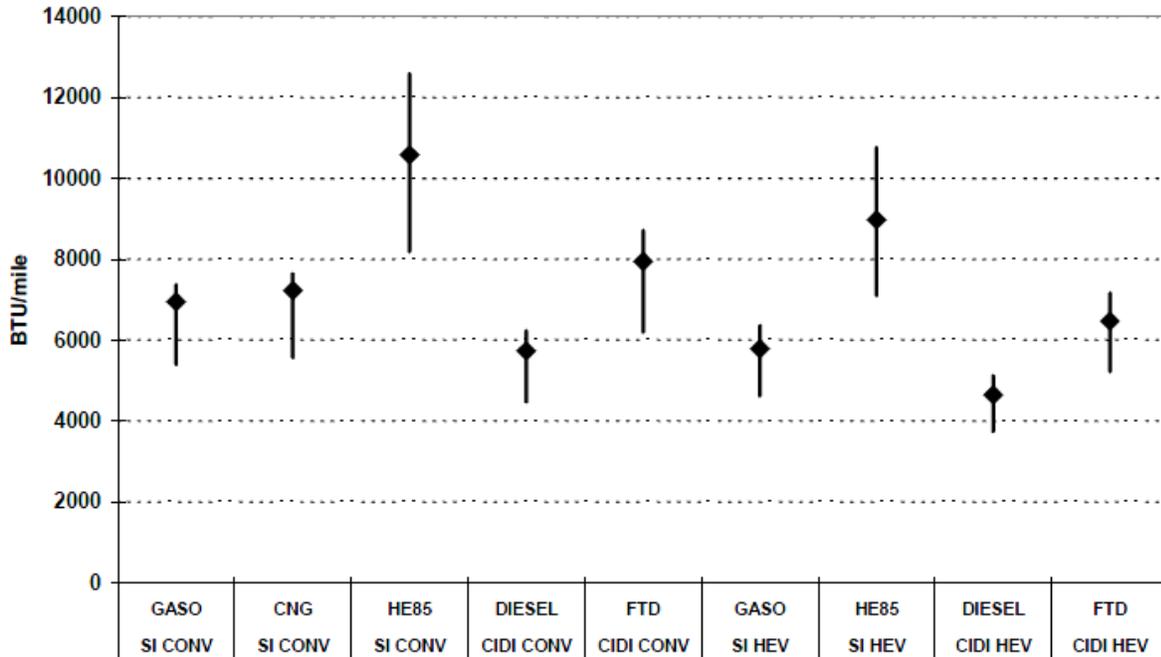


Figure 2-11. Well-to-wheel total energy use for conventional and hybrid fuel/vehicle pathways (NREL 2001b)

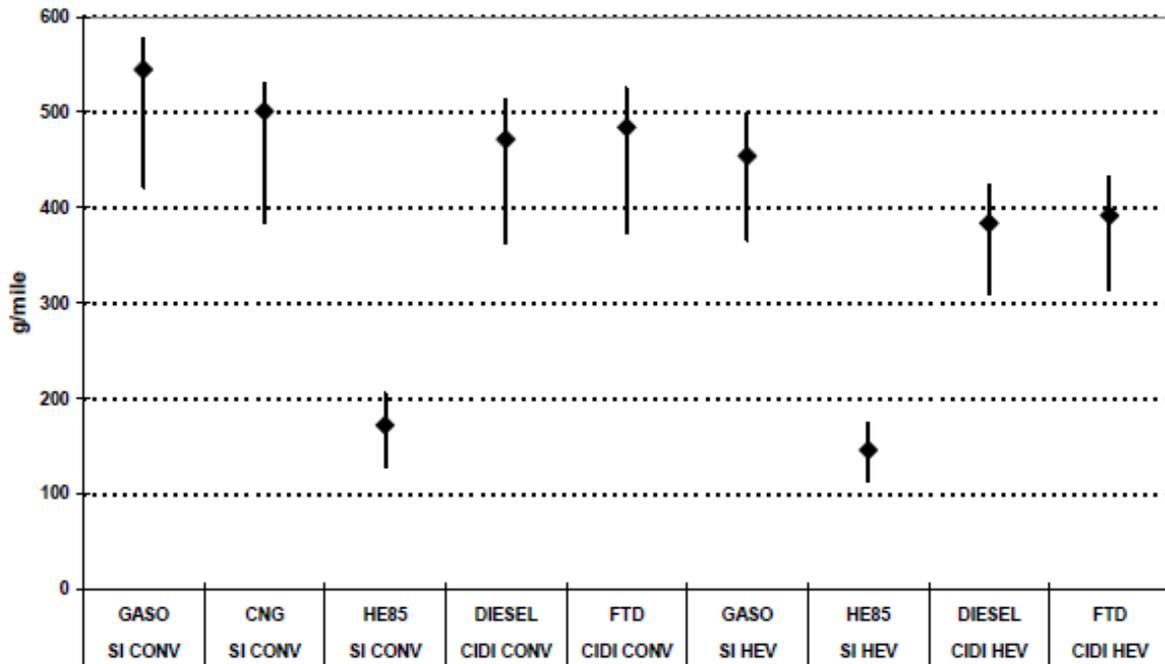


Figure 2-12. Well-to-wheel emissions for conventional and hybrid fuel/vehicle pathways (NREL 2001b)

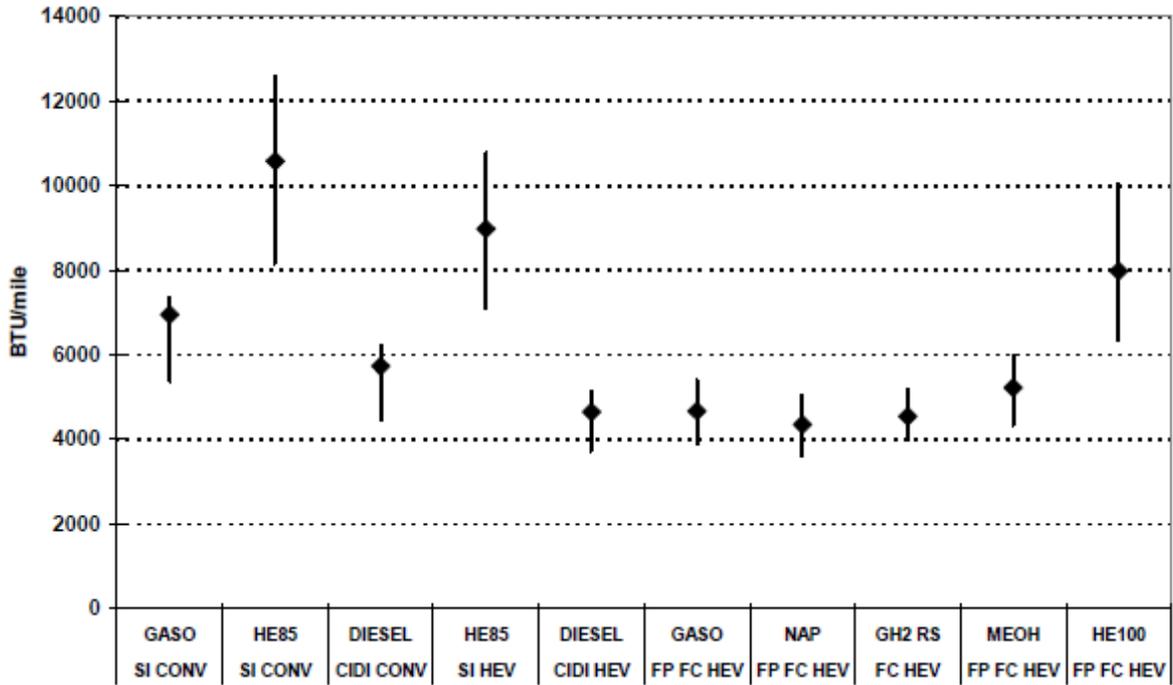


Figure 2-13. Well-to-wheel total energy use for conventional and hybrid fuel/vehicle pathways (NREL 2001b)

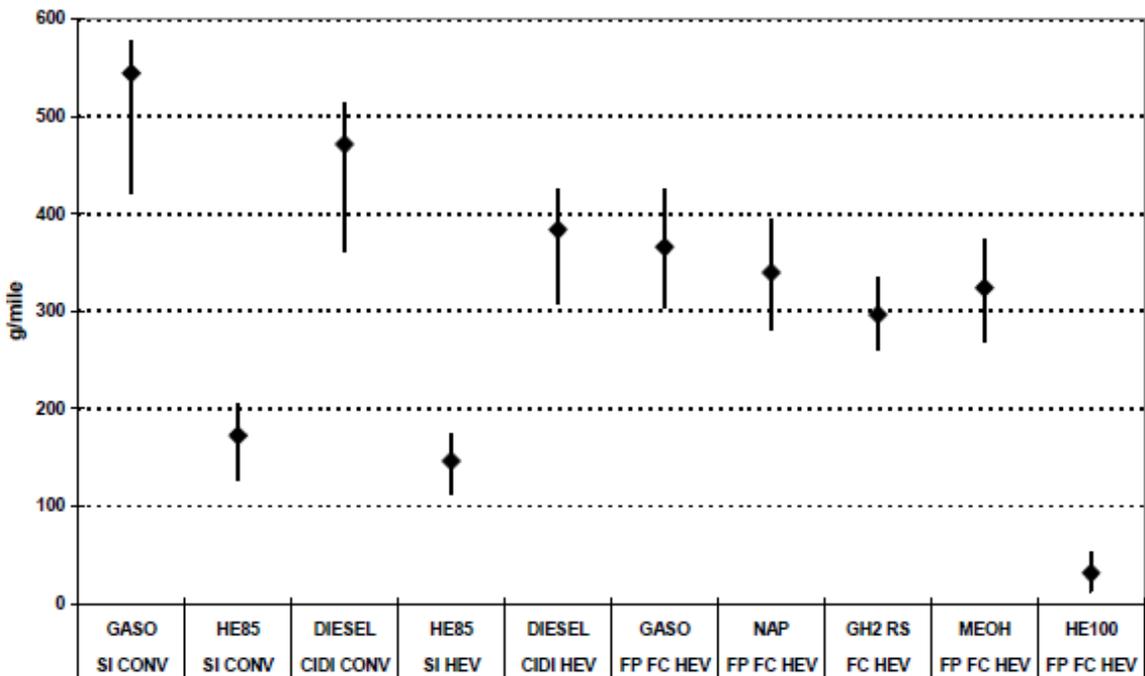


Figure 2-14. Well-to-wheel emissions for conventional and hybrid fuel/vehicle pathways (NREL 2001b)

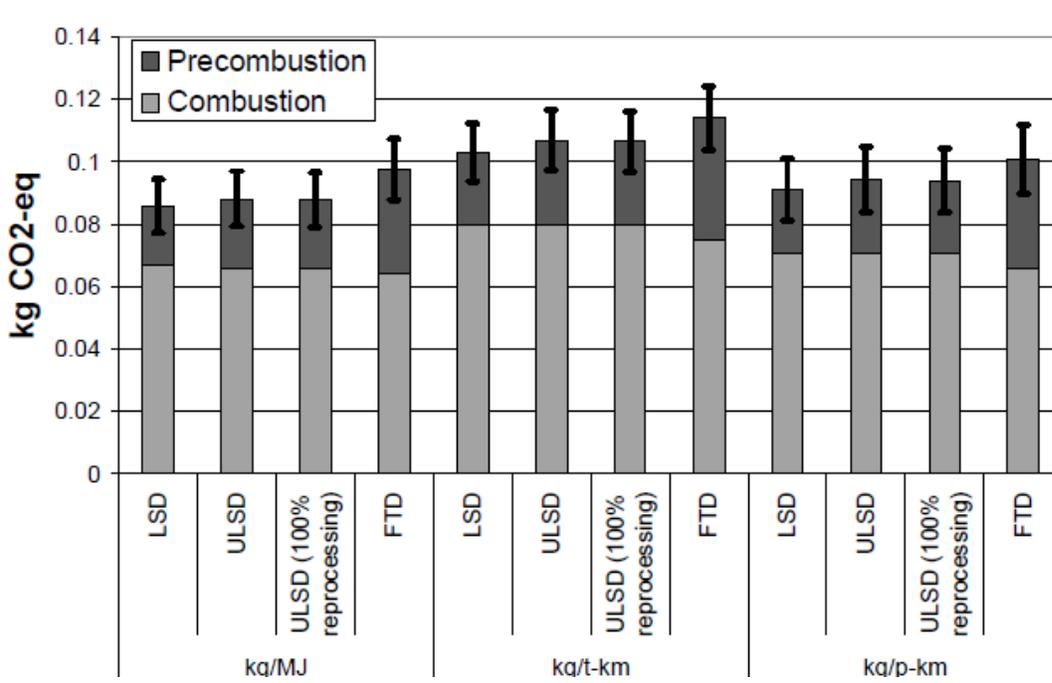


Figure 2-15. Greenhouse gas emissions for several fuels (Beer et al. 2001)

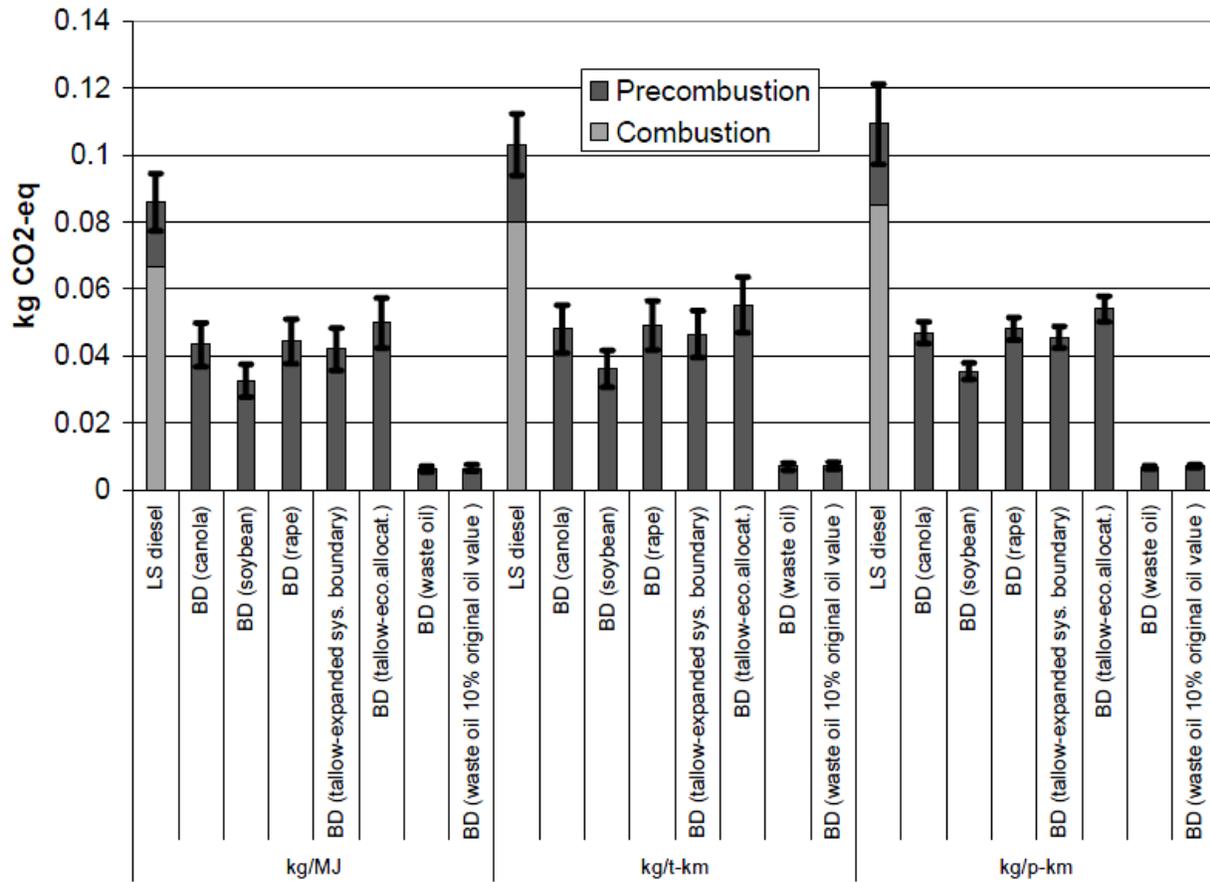


Figure 2-16. Greenhouse gas emissions for various fuels (Beer et al. 2001)

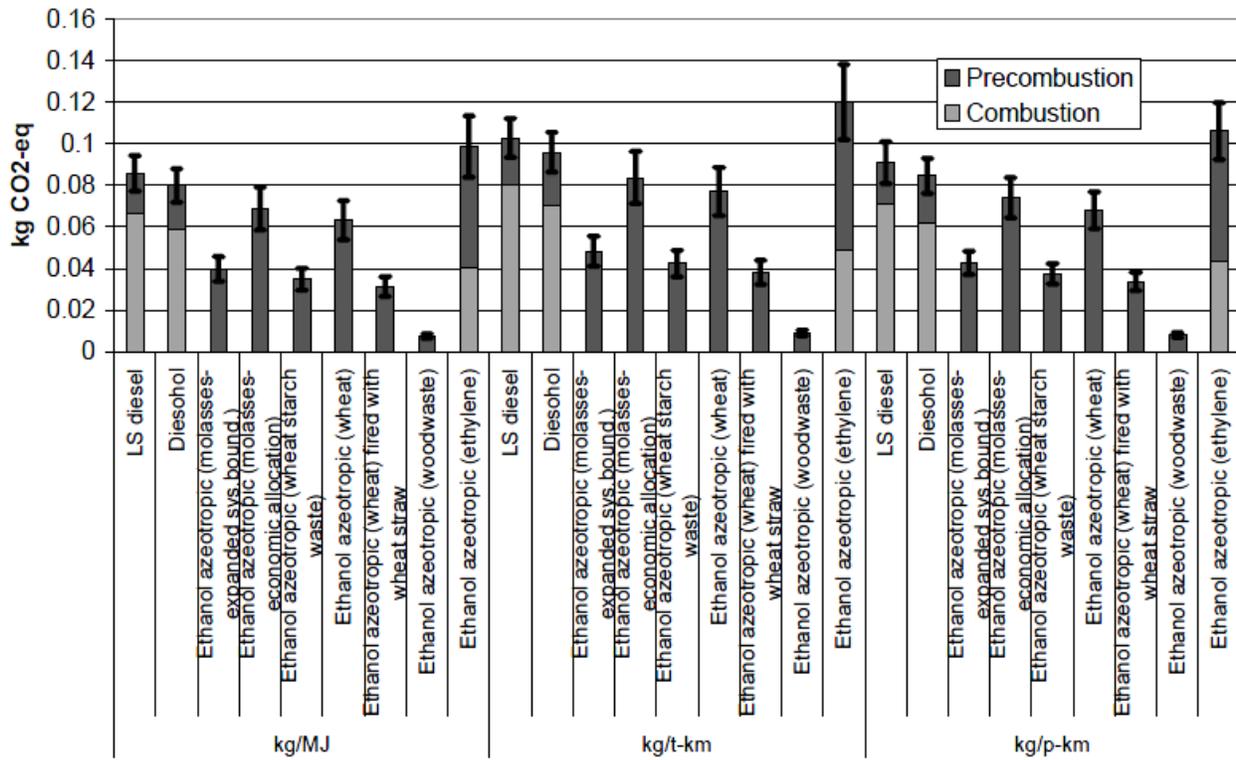


Figure 2-17. Greenhouse gas emissions for various fuels (Beer et al. 2001)

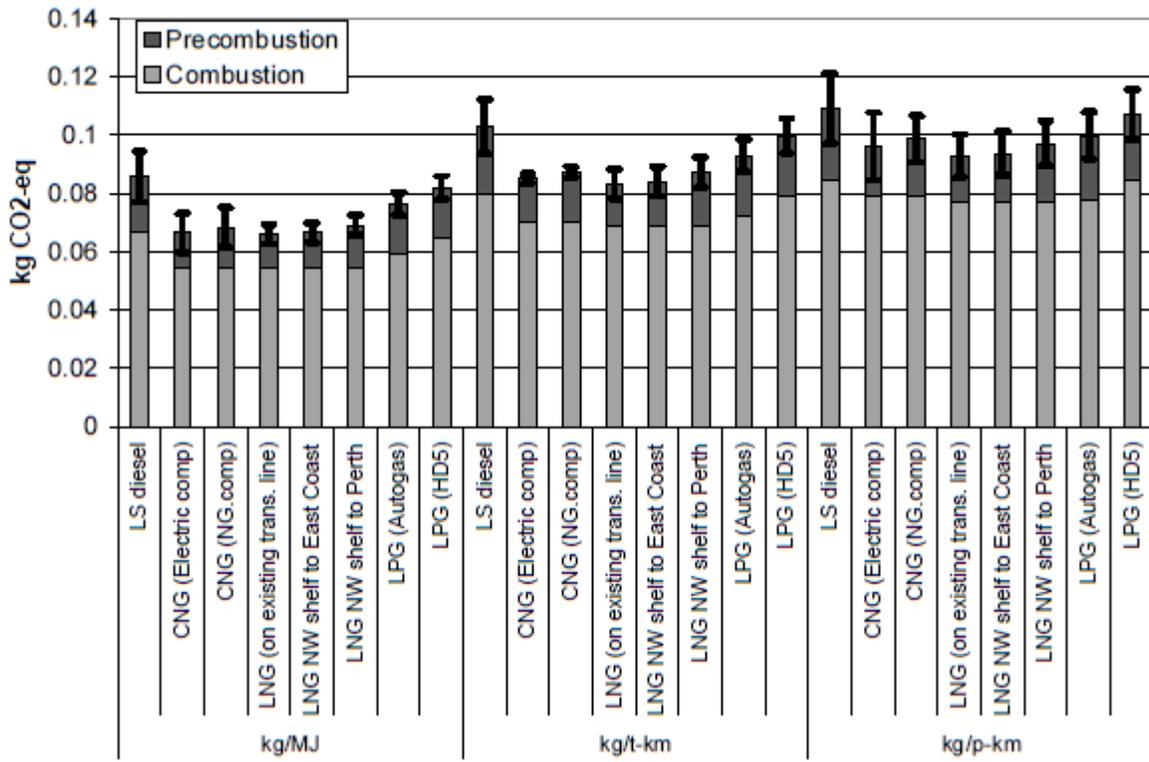


Figure 2-18. Greenhouse gas emissions for various fuels (Beer et al. 2001)

Table 2-1. Emissions from various well-to-tank LCAs on liquid fuel systems

Fuel type	Additional info / feedstock	Reference	CO ₂ eq.	Units
Gasoline	Conventional	Kim et al. 2003	0.09	kg / MJ
	Conventional	Semelsberger 2005	0.12	kg / MJ
Diesel	Low sulfur	Beer et al. 2001	0.09	kg / MJ
	Ultra low sulfur	Beer et al. 2001	0.09	kg / MJ
	Fischer-Tropsch (natural gas)	Beer et al. 2001	0.10	kg / MJ
	Fischer-Tropsch (biomass)	Semelsberger 2005	-0.60	kg / MJ
	Conventional	Kim et al. 2003	0.10	kg / MJ
	Conventional	Semelsberger 2005	0.10	kg / MJ
Biodiesel	Canola	Beer et al. 2001	0.04	kg / MJ
	Soybean	Beer et al. 2001	0.03	kg / MJ
	Rape seed	Beer et al. 2001	0.04	kg / MJ
	Waste oil	Beer et al. 2001	0.01	kg / MJ
Ethanol	Poplar	Semelsberger 2005	-0.25	kg / MJ
	Wheat straw	Beer et al. 2001	0.03	kg / MJ
Hydrogen	Natural gas	NREL 2001a	11.89	kg / kg H
	Photovoltaic cells	Koroneos et al. 2004	0.04	kg / MJ
	Wind power	Koroneos et al. 2004	0.01	kg / MJ
	Biomass	Koroneos et al. 2004	0.02	kg / MJ
	Natural gas	Koroneos et al. 2004	0.08	kg / MJ
LPG	Conventional	Kim et al. 2003	0.08	kg / MJ
Natural gas	Conventional	Kim et al. 2003	0.07	kg / MJ
Fuel oil	Conventional	Kim et al. 2003	0.08	kg / MJ
Naphtha	Conventional	Semelsberger 2005	0.10	kg / MJ

Table 2-2. Emissions from various well-to-wheel LCAs on liquid fuel systems

Fuel type	Additional info / feedstock	Reference	CO ₂ eq.	Units
Gasoline	Conventional	Larson 2006	0.17	kg / km
	Conventional	Baral et al. 2006	0.19	kg / km
	Conventional	Kim et al. 2005	0.23	kg / km
Diesel	Low sulfur	Beer et al. 2001	0.10	kg / t km
	Ultra low sulfur	Beer et al. 2001	0.11	kg / t km
	FT Diesel (natural gas)	Beer et al. 2001	0.12	kg / t km
	FT Diesel (natural gas)	Van Vliet et al. 2009	0.22	kg / km
	FT Diesel (coal)	Van Vliet et al. 2009	0.34	kg / km
	Conventional	Baral et al. 2006	0.28	kg / km
	Conventional	Larson 2006	0.16	kg / km
Biodiesel	Canola	Beer et al. 2001	0.05	kg / t km
	Soybean	Beer et al. 2001	0.04	kg / t km
	Rape seed oil	Beer et al. 2001	0.05	kg / t km
	Waste oil	Beer et al. 2001	0.01	kg / t km
Biodiesel	B20	Baral et al. 2006	0.24	kg / km
	B100	Baral et al. 2006	0.05	kg / km
Ethanol	Wheat straw	Beer et al. 2001	0.04	kg / t km
	Wood	Larson 2006	0.04	kg / km
	Wheat straw	Larson 2006	0.14	kg / km
	E10	Baral et al. 2006	0.18	kg / km
	E10	Kim et al. 2005	0.21	kg / km
	E85	Baral et al. 2006	0.10	kg / km
RME	Conventional	Larson 2006	0.90	kg / km

CHAPTER 3 LIFE CYCLE ASSESSMENT

This section will provide details of the methodology used for the life cycle assessment of a theoretical willow farm integrated with a gasifier and FT-reactor used for Fischer-Tropsch diesel production. The primary task of a researcher performing a LCA is data collection. This section will provide details of sources and references for all the data used in the various parts of the life cycle, including any assumptions that had to be made for the analysis.

3.1 Data Acquisition

Several resources were used to gather the data required for the LCA. The primary source for emissions and energy inputs was GREET 2.7 (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), which is a multidimensional spreadsheet model in Microsoft Excel developed by Argonne National Laboratories. GREET works by allowing researchers and analysts to evaluate various vehicle and fuel combinations on full fuel-cycle/vehicle-cycle bases. The credibility of GREET is noted by the fact that it is sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and it is used by the USDOE, other government organizations, as well as the industry. For a specified fuel and vehicle system, GREET can quantify three major groupings of data: the total consumption of energy, fossil fuels, petroleum, coal, and natural gas; the CO₂ equivalent emissions of greenhouse gases, primarily carbon dioxide, methane, nitrous oxide; and the emissions from the six criteria pollutants. Additionally, GREET has built-in statistical data for average transportation distances of chemicals, fuels, and fertilizers, along with the accompanying emissions.

Data for primary energy inputs and emissions were also obtained from other sources as a means of comparison and validation, including scientific literature sources, such as journals, articles, and books, and well-known credible sources such as the International Panel of Climate

Change (IPCC). For data on farming operations, energy inputs, and emissions, along with information on gasification and FT synthesis, data were primarily obtained from scientific journals on previous life cycle assessments of similar systems. However, if data could not be obtained from scientific journals, miscellaneous resources, such as engineering reference books and manufacturing company websites, were utilized for data collection. As an example, Seimen's company website was utilized to determine the efficiencies for steam turbines and gas turbines.

3.2 Life Cycle Assessment

3.2.1 Goal, Scope, Boundaries, and Functional Unit

The overall goal of this LCA is to determine the environmental impact from using willow feedstock for the production of FT diesel, as well as to see how the energy balance for this fuel compares to that of other liquid transportation fuels. The results could help to prove whether FT diesel is a viable substitute for current conventional fossil fuels. This LCA will only inventory energy and emission inputs, and as a result, economic considerations will be outside of the scope of this study. The stages for the LCA will include fuel extraction, production and transportation, chemical production and transportation, machinery production and transportation, farming operations (nursing, planting, harvesting, etc.), biomass transportation, gasification and FT-synthesis.

Level diagrams were created to visually display the components that are included within the scope of the LCA. A Level 1.0 diagram of the LCA can be seen in Figure 3-1, which describes the main steps including biomass cultivation, gasification, and FT synthesis. It should be noted that the gasification and FT synthesis stages would be coupled together. A Level 2.0 diagram for biomass cultivation can be seen in Figure 3-2; the major steps in biomass cultivation include nursery operations, farm operations, harvesting, and the production and transportation of

fertilizer, machinery, and chemicals. A Level 3.0 diagram for biomass cultivation can be seen in Figure 3-3; the system components represent the farming operations necessary for successful willow growth. A Level 1.0 diagram for gasification can be seen in Figures 3-4, 3-5, and 3-6. The variations in gasification configurations will be discussed later. Lastly, Figure 3-7 displays a Level 1.0 diagram for the FT process; the products of the LCA, in addition to FT diesel, will also include electricity and waste heat.

The inventoried stressors for this LCA were carbon dioxide, nitrous oxides, and sulfur oxides. As a result, this LCA will result in environmental impacts for categories of global warming impact and acid rain potential. A functional unit of kilograms of emission per megajoule of fuel produced was used for the analysis. This functional unit allows for direct comparison of the results with other studies done on FT diesel production systems from woody biomass. Results for the energy balance of FT diesel will be unitless, and are a ratio of useful energy of a product to the fossil fuel energy put into creating that same product.

3.2.2 Willow Farm Characteristics

The theoretical willow farm for this study will have a total area of 10,000 hectares, and will be located within the United States. Circa 2009, there are more than 10.5 million hectares of conservation land with protective status. Through further government legislation, willow can potentially be grown on such land. Since farmers have already successfully grown willow in areas of New York, it will be assumed that the theoretical willow farm will be located there. The location of choice for the farm is provisional, since average transportation distances of fuels and chemicals within the United States will be used.

There are many significant considerations that need to be taken into account for willow cultivation, primarily choosing suitable environmental conditions. Soil properties are critical for the successful and sustainable production of willow crops. Good agricultural soils suit willow the

best, although it can also grow on soils that are questionable for growing traditional food crops (Table 3-1). Optimal yields of willow in primary rotations will result from selecting land with high quality soil. Also, the best willow growth occurs on sites with a large rooting volume and good aeration, water, and nutrient availability (Abrahamson et al. 2002). The pH of the soil should ideally be between 5.5 and 8.0. It is also recommended to use land which is relatively flat, to allow tractors and machinery to move with relative ease around the plantation. In addition, any rocks protruding more than two inches above the surface of the soil should be eliminated, so as to avoid damage to harvesting equipment and expensive saw blades (Abrahamson et al. 2002).

Planting density is also another important consideration for the successful growth of willow. Numerous values of different recommended planting densities, as well as rates of fertilizer application and potential yields can be seen in Table 3-2. It should be noted that data presented in Table 3-2 are from studies done on willow from various parts of the world, mainly Sweden; it is assumed that willow grown in America will behave similarly to that of willow grown in Sweden, although this could possibly lead to certain inaccuracies within the LCA. It will be assumed that double-row spacing will be used, with a planting density of 15,300 plants per hectare.

The theoretical 10,000-hectare willow farm will be shaped circularly, so as to maximize the efficiency of tractor movement within the farm. The fuel production system, consisting of the gasifier, FT-reactor, and several other components will be located in the center of the farm. The 10,000 hectares will be split up into three separate fields of 3,333 hectares, which will each be on separate farming schedules, in order to be more constantly productive as opposed to a single field on a fixed schedule. As recommended by the Salix Consortium, the total lifetime of a willow farm is 24 years; the lifetime includes seven harvests with intervals of 3 years in between each

harvest (Heller et al. 2004, Abrahamson et al. 2002). The remaining three years include two years for initial field preparation and a year for stool elimination. Since the willow farm is split into 3 separate fields, harvesting can then take place each year, for a different field. As a result, the shifting schedules of each field will result in a total lifetime of 26 years for the entire farm, since the field which starts the latest will only start seeing farm operations on the second year. A diagram of the theoretical willow farm can be seen in Figure 3-8.

3.2.3 Willow Farm Materials

The materials included in the LCA analysis are all the materials needed for farming operations. These consist of fuels, chemicals, and materials including diesel, gasoline, LPG, heavy fuel oil, bituminous coal, petroleum coke, naphtha, natural gas, electricity, steel, cast iron, rubber, wood, lubricant, ammonium sulfate, glyphosate, simazine, oxyfluorfen, carbaryl, nitrogen fertilizer, urea fertilizer, granular fertilizer, potash, and limestone. The list of materials was gathered from various sources, which will all be described in greater details later in the analysis.

Certain assumptions for inputs had to be made because of a lack of data from literature sources. It was assumed that the inputs and emissions for steel construction were identical to that of cast iron. It was assumed that inputs and emissions for granular fertilizer are calculated by adding up 15% of energy and emission values for nitrogen, P_2O_5 , and K_2O fertilizer. Data for limestone was taken specifically for agricultural limestone. As recommended by other studies, input energies and emissions for lubricants were taken to be 4% to that of diesel fuel (Matthews 2001). Also, engine oil was considered to be analogous to heavy fuel oil.

3.2.4 Energy Inputs for Fuels, Chemicals, and Materials

After a list of materials needed for the willow farm was compiled, the next step was to find the associated energy inputs and emissions for each of the inputs. GREET 2.7 was used as

the primary source of data for this calculation. GREET 2.7 provides data for all stages of energy inputs, including production, refining, extraction, transportation, and distribution; it lists these values as the percent of the combustion value of the fuel needed for the specific step. The emissions for each of these stages are also included. The data obtained from GREET 2.7 for contributions to total input energies and emissions for fuels can be seen in Tables 3-3 through 3-6. For diesel fuel, it can be seen that the stages of refining, transportation and distribution all take 12.04%, .43%, and .2% of the total value of combustion, which is 42.79 MJ / kg (Table 3-3). The total input energy for diesel is then calculated by dividing the combustion value by one plus the sum of the percentages, which results in a net energy input of 48.21 MJ for the combustion of one kilogram of diesel fuel. Emissions are also inventoried from several steps, including production, transportation, distribution, combustion, and non-combustion. Non-combustion refers to average emissions from leakage that occurs between all the stages. Combustion emissions for each fuel are also based on the type of device the fuel is burned in; industrial boilers were chosen for all fuels except for gasoline, in which case stationary combustion engines were chosen.

A similar set of data was obtained for chemicals and fertilizers, as seen in Tables 7 through 3-10. The steps included for these inputs include energy and emissions associated with production and transportation from plant to bulk center, bulk center to mixer, and mixer to farm. Rather than listing contributions as a percentage of the net combustion value, the contributions are listed in units of megajoules per kilogram, since most of these materials are non-combustible. All data in Tables 3-3 through 3-10 are taken from data embedded in GREET 2.7, except for data associated with glyphosate production, which was taken from a study by M.C. Heller et al. Also, as seen in Table 3-7, certain chemicals such as limestone and glyphosate were assumed to not

need mixing, and thus have no contributions from transportation to a mixing center, as based on data embedded within GREET.

The transportation inputs in the previous tables are based on statistical data for average transportation distances, which are embedded within GREET 2.7. The data on transportation distances and modes can be seen in Tables 3-11 through 3-14. It can be seen that 24% of heavy fuel is imported, while the rest is produced domestically. The imported heavy fuel oil travels an average of 3000 miles on an ocean tanker. Once imported and shipped to a terminal, the heavy fuel oil then travels distances of 340 and 400 miles via a barge and pipeline, respectively, to get to the bulk center, where it then travels an average of 30 miles via a truck to a fueling station. For chemicals and fertilizers, it is assumed that herbicides and pesticides require the same transportation distances and modes. It is also assumed that 100% of limestone is produced domestically, as based on embedded information within GREET 2.7.

The energy intensities for each mode are needed along with the transportation distances and modes; Tables 3-15 and 3-16 display this information for all the fuels and chemicals needed for the willow farm. The energy intensities are based on data embedded in GREET 2.7, which are partially obtained from the NREL LCI Database. The energy intensities include the distance from origin to destination (O-D), as well as backhauling. Certain fuels, like natural gas, do not need backhauling since they are transported mainly via pipeline. It can be seen that conventional diesel has energy intensities of 23, 291, 813, 267, and 743 joules per kilogram per kilometer for modes of ocean tanker, barge, rail, pipeline, and truck, respectively, for origin to destination transportation. It should be noted that energy intensities increase with a smaller mode of transportation, since less can be stored for each trip.

In addition to data obtained from GREET 2.7 software, data for input energies and emissions for all materials needed were obtained from other sources as a means of comparing and validating data from GREET 2.7. It was then realized that several studies had inputs values listed for the same fuel with significantly different values, so a decision was then made to create several pathways for material flows. Such a methodology would result in a range of results, rather than a single data point. The energy inputs and emissions associated with all the pathways can be seen in 3-17 through 3-20. It should also be noted that pathway 1 is considered the main pathway, so all fuels and emissions that are missing from the other pathways use data from pathway 1 as default.

As stated before, most of the data within pathway 1 was obtained from GREET software, version 2.7. Energy inputs are listed in units of megajoules required to produce one kilogram of the specified material. All emissions are listed as kilograms of the specified greenhouse gas released per kilogram of material used or burned, except for natural gas and electricity, where emissions are listed as listed as kilograms per cubic foot and kilowatt-hour (kWh), respectively. Pathway 2 consists of data primarily from a study done by T.O. West et al., entitled “A Synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States” (West et al. 2002). Data obtained from this study include emissions for fuels and chemicals, as well as energy inputs for chemicals and fertilizers. Pathway 2 also uses data for steel and rubber production from studies done by Anderson et al. and Amari et al., respectively. Pathway 3 consists of data primarily from IPCC Guidelines of 1996 which includes emissions for all fuels listed as well as wood, steel, limestone, and ammonium sulfate. Pathway 3 also consists of similar inputs for steel and rubber from pathway 2. It should be noted that data taken from the IPCC Guidelines of 1996 were taken from the energy industry section.

Pathway 4 consists of data from a combination of studies, including one done by Pimentel entitled “Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative” (Pimentel 2003), as well as data from the IPCC Guidelines of 1996 and a study done by Borjesson. In addition to providing a range of inputs, using several pathways also is a way of performing sensitivity analysis, and to see which inputs have the most significant effects on the results.

3.2.5 Nursery Operations

The initial step in biomass cultivation is the production of planting stocks via nursery production. Data for the necessary nursery production was obtained from a study by M.C. Heller et al. The data in the study is from a nursery in Saratoga Springs, New York. All the inputs can be seen in Tables 3-21 through 3-24. Surface water used for irrigation was neglected from the inputs, as data on energy required for irrigation could not be obtained. The inputs listed in Table 3-21 through 3-42 are for the production of 456,437 planting stocks; as a result, all energy inputs and emissions were then normalized for the production of 15,300 planting stocks, which is the assumed planting density. All nursery production inputs were sent through the four pathways. In addition, it is also assumed that the nursery is in the center of the willow farm, and that transportation energy associated with the transporting of planting stocks is considered trivial.

3.2.6 Fertilizer and Herbicide Application

A very important consideration for energy crops is the amount of fertilizer and herbicide used, since they take quite a lot of energy to produce, as seen in Tables 3-25 through 3-28. Although ammonium sulfate requires much less energy per kilogram produced than compared to glyphosate, simazine, and oxyfluorfen, it is used in much higher quantities. For this study, an application 100 kg of nitrogen fertilizer per hectare per year will be used, as studies indicate no benefits are present in excess of this amount (Adegbi et al. 2003). In addition, 2.5 kg of

glyphosate, 2.24 kg of simazine, and 1.12 kg of oxyfluorfen will be applied once per hectare, for weed control and the elimination of vegetation prior to planting (Heller et al. 2004). Although the herbicides require a tremendous amount of energy to be produced, their relatively light use on the farms indicates that the varying recommended uses amongst different studies is relatively insignificant. All fertilizer and herbicide application inputs were sent through the four pathways.

3.2.7 Machinery Manufacture & Transport

The next step in the LCA is to calculate the energy required and the accompanying emissions for manufacturing and transporting tractor equipment and implements to the willow farm. A list of tractors and implements, including their weight, power requirements, and operating rates was obtained from the study done by M.C. Heller et al., and can be seen in Table 3-29. Based on operating rates in Table 3-29, along with recommended lifetimes of 1500-2500 hours and 12,000 hours for various implements and tractors, respectively, the total number of each required for the willow farm was calculated (ASAE 1999). The inputs necessary for the production of one kilogram of tractor and implement were obtained from M.C. Heller's study. For tractor manufacturing, all inputs except for fuel, oil, cast iron, steel, and tire rubber were considered trivial. Tire rubber's assumed composition is 33.3% steel and 66.6% rubber (Amari et al. 1999). The fuel and oil input was estimated as 84% engine oil and 16% heavy fuel oil. For implement manufacturing, iron ore energy inputs were assumed to be similar to cast iron (Andersen et al. 2001). Mineral oil required for implement production was considered trivial, according to the 5% rule. All tractor and implement manufacturing inputs were sent through all four pathways, and can be seen in Tables 3-30 through 3-37.

In addition to manufacturing, the energy inputs and emissions for transporting the farm equipment to the willow farm need to be factored in as well. It is assumed that the average manufacturing plant is within 350 miles of the willow farm, and that 300 miles of this distance is

traveled via rail and the rest via truck (Borjesson 1996). There is no assumed backhauling for the rail. The assumed energy densities for rail and truck are 14 and 743 joules per kilogram per kilometer, respectively, as is based on data from the NREL LCI Database. Inputs energies and emissions for this section were simply added on to each pathway. The input energies and emissions added can be seen in Table 3-38 and 3-39.

3.2.8 Field Operations

The next step in biomass cultivation after nursing operations is field operations. For these operations, the tractors and implements mentioned previously are heavily used, which results in a need to calculate the amount of diesel fuel and oil consumed in the processes. The field operations and their timelines are listed in Table 3-40. It can be seen that mowing, applying contact herbicide, plowing, disking, seed cover cropping, cultipacking, planting, applying pre-emergent herbicide, coppicing, and weed control only take place once for each willow field, while fertilizing and harvesting take place seven times throughout the lifetime of each field. Documenting fuel consumption is not a common practice for a farmer; as a result, this LCA will have to rely on miscellaneous sources, such as engineering data estimates of fuel consumption from the American Society of Agricultural Engineers (ASAE 1999). For most farm operations, Equation 1 can be used to calculate diesel consumption. In Equation 1, Q_{diesel} represents diesel fuel consumption (liters / hour), P_T is the total power required for an operation (kW), and P_{max} is the maximum available take-off power (PTO) from the specified tractor (kW).

$$Q_{diesel} = P_T \left(2.64 \frac{P_T}{P_{max}} + 3.91 - 0.203 \sqrt{738 \frac{P_T}{P_{max}} + 173} \right) \quad (4-1)$$

The maximum take-off power is a property of the tractor, while P_T is a property of the specified operation and implement. Table 3-41 lists assumed power requirements for certain

power intensive operations. For operations omitted in Table 3-41, ASAE recommends using data provided in Table 3-42 in conjunction with Equation 2:

$$P_T = \frac{F_2 W T S}{3.6 E_m E_t} (A + B S + C S^2) \quad (4-2)$$

Hydraulic and electric power consumption rates for the tractor are considered negligible. In Equation 3, A, B, and C are parameters specific to the machine, F_2 is the dimensionless soil texture parameter for medium textured soils, W is the machine width (m), T is the depth of tillage (cm), S is the field velocity (km / h), E_m is the mechanical efficiency of the transmission and power train, and E_t is the net overall tractor efficiency. E_m will be set to 0.96; under the assumption the tractors have gear transmissions (ASAE 1999). Equation 3 was used to calculate oil consumption rates, where Q_{oil} is the rate of oil consumed, in liters per hour. The total diesel and oil consumed from farm operations can be seen in Table 3-43. Inputs for farm operations were then sent through all four pathways.

$$Q_{oil} = 0.00059 P_{max} + 0.02169 \quad (4-3)$$

Harvesters are an important choice for the willow farm, as harvesting is an energy intensive task; in fact, it is the most energy intensive of all the farming operations (Lettens et al. 2003). The most efficient harvesters up to date are the modified Claas Jaguar harvester and the Salix Maskiner Bender harvester, which can both harvest about 1 – 2 acres per hour (Abrahamson et al. 2002). However, the Claas Jaguar has not been used significantly in the United States, so the Salix Maskiner Bender will be chosen as the harvester.

3.2.9 Willow Biomass Harvest Yields

The harvests for a willow farm will vary from year to year. The resulting yields from other LCAs show an average of several harvests, and can be seen in Table 3.2. Successive rotations from the first harvest have additional growth advantage because the willow's root

system is already established (Heller et al. 2004). All over the world, *Salix* production varies between 2.2 – 13.5 odt / ha /year (Mitchell et al. 1999). For this system, three different constant yields will be assumed that represent conservative, realistic, and optimistic yields of willow biomass. A low yield of 10 oven dry tons / ha / year, will be used as the conservative yield. A realistic yield of 13.5 oven dry tons be taken from data of actual willow farms grown in the United States. Based on a study done by Borjesson, yields can be expected to reach up to 18.7 oven dry tons per hectare by the year 2015, which will be used as the optimistic (or futuristic) yield.

In addition, a study by Adegbidi for predicting willow yields from nitrogen fertilizer application rates resulted in the fitting of data by nonlinear regression into an exponential saturation function, represented by Equation 4.

$$Y = I + A(1 - e^{v \cdot \text{fert.rate}}) \quad (3-4)$$

In Equation 4, Y is the overall harvested yield (odt / hectare), I equals 5.876 odt / year, A equals 6.856 odt / year, v equals -0.00916, and r^2 equals 0.63; given the poor correlation, Equation 4 is considered provisional, and will not be used to predict harvest yields based on amounts of fertilizer applied to the willow farm (Adegbidi et al. 2003). More research is needed to accurately predict harvest yields confidently. It should be noted that plugging in a fertilizer application rate of 100 kg / ha into Equation 3-4 results in a yield of 10 odt / ha / year, which, coincidentally, is the conservative yield for this study.

3.2.10 Biomass Transportation

The final phase in biomass cultivation is to transport all the harvested biomass to the center of the farm, where it will be used as feedstock for the production plant. To calculate the average distance traveled by trucks in the willow farm, equations for average hauling distance

will be used (Overend 1982). Equation 6 displays the variables needed to calculate this information.

$$D = \frac{2}{3} R_o \tau \quad (3-5)$$

In Equation 5, R_o is the containing radius of the willow farm and τ is the tortuosity factor, which is defined as the ratio of actual distance traveled to the line of sight. The radius for a 10,000-hectare field is 5.64 kilometers, and a tortuosity factor of 1.8 was chosen, as an average between the tortuosity factors for a rectangular road grip and a broken landscape (Overend 1982). The resulting average hauling distance, D , comes out to 6.77 km. To calculate the fuel consumption and emissions for hauling the biomass, 40-ton capacity heavy trucks with a fuel consumption of 39 liters / kilometer are used (Heller et al. 2004). As a result of having three different scenarios for harvested yields, there will be three scenarios for transporting biomass to the gasifier.

3.2.11 Drying and Storage

Upon successful transportation to the center of the willow farm, the biomass will then be stored until it is used as feedstock. Precaution should be taken in storage, as current systems of storage result in high dry matter losses, heat development with the risk of self-ignition, and health risks caused by the release of high concentrations of allergenic microspores into the air (Jirjis 1995). In addition, a decrease in energy density from storage is primarily a result of bark content reduction (Nurmi 1995).

There are techniques for drying biomass in storage, including continuous ventilation with ambient air, cooling by intermittent low volume ventilation, evaporative cooling by intermittent ventilation, and natural convective cooling (Jirjis 1995). The option for cooling that result in the least amount of dry matter loss is continuous ventilation with ambient air, which results in about

3.5% dry matter losses. The dry matter losses from Jirjis's study will be used as provisional data, as there is a general lack of data on this subject. It is also assumed that harvested willow biomass has moisture content of 50%, and after drying and storage, the resulting moisture content reduced to 30%. Also, dry matter losses will not be included, as it is provisional data.

3.2.12 Carbon Balance from Biomass Cultivation

After biomass transportation takes place, the next step in the LCA is a provisional carbon balance for the system. A carbon balance can be done in this step rather than at the end because all carbon dioxide emissions from FT diesel combustion are recycled back into the willow farm, thereby creating a means of continuously recapturing greenhouse gases. Carbon sequestered in soil is known as soil organic carbon (SOC).

Photosynthesis causes plant growth, which in turn transfers carbon to the soil; a portion of carbon from plant decomposition also adds to the SOC content. Data from limited studies on carbon sequestration for energy crops suggest that there are significant differences in rates of soil carbon sequestration for energy crops as a result of heterogeneous on-site configurations, as well as factors such as soil grade, history of land-use, environment, and harvest yields (Grogan et al. 2002). The main factors in determining the rates of carbon sequestration in willow farm soil are carbon inputs into the system, rates of decomposition for the soil carbon pools, initial soil properties, farming operations, and the depth of soil which is being affected by the energy crop (Grogan et al. 2002). The downside in assessing SOC dynamics is that it requires several decades' worth of data collection to draw any significant conclusions, mainly because SOC changes occur very slowly. As illustrated in Figure 3-9, soil and litter carbon reach a relative steady state after 100 years for forest trees.

Data for carbon sequestration in soil, roots, and belowground biomass were obtained from several studies, and can be seen in Table 3-44. Rates of carbon sequestration in soil and

roots are in Mg of carbon per hectare per year, while rates of total belowground sequestration are in tons of carbon per hectare. Data in Table 3-44 comes from studies done on willow farms with many different configurations. In order to calculate a provisional rate of willow farm carbon sequestration, an average was taken from values found in Table 3-44. Since soil and root sequestration rates were listed per year, these values were multiplied by the lifetime of the farm, after the first harvest, which is 21 years. After normalizing these values, the average values for soil and root sequestration rates were then averaged with the values for total belowground sequestration rates, and the resulting provisional rate of carbon sequestration for the entire lifecycle of the willow farm came out to 12.14 Mg Carbon / ha / year. This provisional value was then subtracted from total CO₂ emissions from biomass cultivation, to see if the willow farm is a potential carbon sink. As a comparison, natural woodlands can sequester up to 13 Mg of Carbon / ha / year (Grogan 2002 et al.).

3.2.13 Nitrogen Balance for Biomass Cultivation

A provisional nitrogen balance for biomass cultivation was calculated similarly to the way the provisional carbon balance was calculated. Nitrogen leaves and enters the willow farm through several mechanisms, including leaching, denitrification, leaf litter, mineralization, and deposition. Leaching occurs when nitrogen passes through the soil and enters groundwater, where it acts as a pollutant. Aside from reaching peak concentrations during the establishment phase, groundwater nitrogen concentrations for willow farms are within a safe range; the peak concentrations are a result of an underdeveloped root system and heavy fertilizer application rates (Aronsson et al. 2000).

Denitrification is a process which takes place in many ecosystems and occurs when oxygen consumption exceeds that of oxygen supplied. High rates of denitrification occur in

warmer climates, while colder climates demonstrate lower rates, mostly as a result of snow acting as an insulation barrier for controlling N₂O fluxes (Maljanen et al. 2003).

Data on nitrogen balances from leaching, denitrification, leaf litter, and deposition were obtained from various studies, and can be seen in Table 3-45. Rates for nitrogen leaching and N deposition from leaf litter are in units of kg N per hectare, while units for nitrogen denitrification and deposition are in kg N per hectare per year. In order to obtain a provisional datum for nitrogen sequestration of a willow farm, all data for nitrogen balancing were averaged. It should be noted that nitrogen deposition is the primary factor in nitrogen balancing, while leaching and leaf litter can be neglected. For the full lifecycle of a willow farm, a provisional value of 300 kg N / hectare of sequestration was calculated. This value will then be subtracted from nitrogen emissions encountered from biomass cultivation, to determine if the willow farm is a potential nitrogen sink. It must be stressed that results for this are strictly provisional.

3.2.14 Production Plant Commissioning and Decommissioning

The production plant of the LCA will include a gasifier, FT-reactor, as well as other units that will be discussed later. As part of this LCA, energy inputs and emissions associated with the commissioning and decommissioning of the production plant, as well as additional operating demands, will be neglected. Similar studies on gasification systems suggest neglecting these inputs, as normalizing them over a wide farm area will make them relatively trivial inputs (Heller et al. 2003, Spath et al. 2001).

3.2.15 Gasification

After biomass cultivation and transportation, the willow biomass is dried to 30% moisture during storage before being sent to a gasifier. Since three different yields were chosen, the inputs to each gasifier configuration will also have three different inputs. The higher heating value of willow after harvesting and natural drying is assumed to be 19.88 MJ / odkg (Heller et

al. 2003). Dry matter losses from transportation will be considered trivial. The inputs for gasification can be seen in Table 3-46, in various units. It is assumed that the gasifiers will run 8,000 hours a year, which averages out to 22 hours of operation per day; the inputs for tons per day are embedded with this daily average.

After settings the inputs, the next step in the LCA is to select appropriate gasifier configurations for the analysis. There are many different types of gasifiers to choose from, but the circulating fluidized bed (CFB) gasifier was identified as the most suitable type, mainly because of its fuel flexibility, robustness, high throughput, operational experience, and its wide use for biomass conversion. In addition, CFBs are suitable for scales ranging from one to several hundred megawatts (Boerrigter et al. 2002).

A total of six gasifiers were chosen, from two studies. The first three gasifiers were taken from a study by Tijmensen, entitled “Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification” (Tijmensen et al. 2002). In this study, the gasifier specs were taken from pilot scale demonstrations, and can be seen from Tables 3-47 through 3-49. It will be assumed that all the specs for a pilot size gasifier can be linearly scaled, although efficiencies would probably be higher in actual practice. The gas compositions of each syngas are listed on a mass basis. The efficiencies listed for each gasifier result from thermal losses and tar production. Each configuration is either oxygen-blown or airblown, and both have accompanying steam inputs as well. Dolomite flow rates are shown as provisional data for tar crackers, which are high temperature devices used to eliminate tar in syngas. It should also be noted that direct airblown gasifiers produce syngas with significant amounts of N₂, compared to the trace amounts found in indirect gasifiers. For FT fuel production, direct gasification is not favorable because nitrogen dilution from air increases the size and cost of downstream

equipment. However, since economics are not considered in this study, direct gasification will be included (Hamelinck et al. 2004).

The other three gasifiers used for this analysis come from a study done by Hamelinck entitled “Production of FT transportation fuels from biomass; technical options, process analysis and optimization, and development potential” (Hamelinck et al. 2004). The gasifiers in his study are theoretical. In his study, several configurations are listed for air, enriched oxygen, and oxygen-blown gasifiers. However, the most efficient configuration for each type of oxidation medium will be used, and the specs for these three gasifiers can be seen in Tables 3-50 through 3-51. It should be noted that syngas compositions of gasifiers one, two and three differ significantly from that of gasifiers four, five and six. This is most likely a result of different kinetic modeling parameters. As with the previous three gasifiers, it will be assumed that the specifications can be linearly scaled. Dolomite flowrates are included for gasifiers five and six as provisional catalysts for tar cracking units.

The additional drying requirements needed by the dryer are achieved by utilizing waste heat streams, which will be discussed later. H_2/CO ratios are an important property of syngas used for FT fuel production, and can be controlled by inputting steam into the gasifier; however, this reduces the overall efficiency of the gasifier. A water gas shift (WGS) reactor can be utilized for the same purpose, sans efficiency reduction. However, there is a lack of data on utilizing WGSs for this specific application, so steam addition will be used as a control mechanism for H_2/CO ratios, which are typically in the range of .8 – 2.1 (Boerrigter et al. 2002).

3.2.16 Gas Cleaning

Before the syngas can enter the FT-reactor for synthesis, it must go through several cleaning processes, so as to avoid damaging the catalyst in the FT-reactor. The most common contaminants in syngas are soot, alkaline, tar, benzene, toluene, xylene, halide compounds,

nitrogen compounds, and sulphur compounds. Gas can either be cleaned through high temperature or low temperature methods, although hot gas cleaning can be up to 2% more efficient (Tijmensen et al. 2002). A list of methods utilized for gas cleaning can be seen in Figure 3-10. Energy inputs and emissions for gas cleaning will not be considered, since very limited data is available on the subject.

3.2.17 The Fischer-Tropsch Process

After going through several cleaning methods, the syngas is now ready to enter the FT-reactor, where it will be synthesized into liquid fuels. Tri-generation configurations, where the products are heat, electricity, and liquid fuel, are favorable for smaller scale operations, while maximum FT production configurations are favorable for large-scale operations (Boerrigter et al. 2002). A slurry bed FT-reactor will be used for this study, as it is considered the most promising type of reactor according to several authors (Tijmensen et al. 2002). In addition, it is assumed that FT-reactors operate at temperatures between 180 and 250 °C, and at pressures between 2 and 4 MPa, to increase liquid fuel yields and avoid condensation of tars and contaminants. All together, a total of five FT-reactors were chosen to couple with the gasifiers previously mentioned. FT-reactor specifications are listed as products per megajoule of syngas input, and can be seen in Tables 53 through 3-56. .

FT synthesis products are basically hydrocarbons of varying lengths, which can be described by Equation 6. In order to maximize long hydrocarbon chains, a high liquid selectivity is needed (Heller et al. 2003). The Anderson-Schulz-Flory (ASF) distribution accurately describes the relation between hydrocarbon yield and the probability of chain growth. In Equation 6, the length of a hydrocarbon chain is described as a carbon number; α represents the probability of chain growth and n represents the length of the hydrocarbon. As a result, $1-\alpha$ is the

chance of the chain growth terminating. Hydrocarbon yields for varying chain growth probabilities can be seen in Figure 3-11. Also, it should be noted that yields of smaller hydrocarbons ($C_1 - C_4$) decrease as C_{5+} hydrocarbon yields increase. Heating value and properties of smaller hydrocarbons will be estimated to be the same as methane, and will be used for electricity generation via a gas turbine. In addition, selectivity is influenced by a number of other factors, including catalyst preparation and age, as well as reactor temperature and pressure (Tijmensen et al. 2002).

$$C_n = \alpha^{n-1}(1 - \alpha) \quad (3-6)$$

A hydrocracker is a device used to maximize FT diesel production by breaking down larger hydrocarbon chains into smaller chains, through the use of hydrogen. Specifically, hydrocracking involves the breaking of double bonds that attach varying hydrocarbon chain lengths. Depending on the cracking conditions, the products are mainly diesel or kerosene (Tijmensen et al. 2002). It will be assumed that the hydrocracking step is 100% efficient, since 98% efficiency has been achieved in test runs. Inputs for hydrocracking are not included, as there is very limited data on this subject.

The configurations for four FT-reactors can be seen in Tables 3-53 through 3-56. The streams for electricity are considered as useful streams for the production of electricity, and the heat streams are considered as waste heat. FT-reactor one is setup for tri-generation without a WGS reactor, coupled with an airblown gasifier. The H_2/CO ratio for FT-reactor one is around 0.89, which is not suitable for maximizing FT production. FT-reactor two is setup for tri-generation with a WGS reactor, coupled with an airblown gasifier. The H_2/CO ratio for FT-reactor two is 2.0, which is more favorable for increasing FT fuel yields. FT-reactor three is setup for tri-generation with a WGS reactor, coupled with oxygen-blown gasifier. It can be seen

that FT production is significantly higher for FT-reactor three when compared to FT-reactor one and two, most likely because N₂ is not diluting the syngas. The modified version of FT-reactor three converts some useful waste heat into useful electricity production energy, and will be called reactor 3mod (Boerrigter 2002).

In addition to the FT-reactors listed, FT specifications from “Exploration of the possibilities for production of Fischer-Tropsche liquids and power via biomass gasification” (Tijmensen et al. 2002) will be used for the last FT-reactor. In his study, various configurations were used with existing pilot-scale gasifiers. All results from this study were for once through concepts, where gases do not recirculate within the production plant. Results from Tijmensen’s study can be seen in Figure 3-57. It should be noted that the Batelle Columbus (BCL), Institute of Gas Technology (IGT), and Termiska Processor (TPS) gasifiers listed in Table 3-30 correspond to gasifiers one, two, and three, respectively. Only data for maximized FT fuel production were taken from Table 3-57.

3.2.18 Gasifier and Fischer-Tropsch Reactor Coupling

In order to calculate the products of the production plant, gasifiers were coupled up with appropriate FT-reactors. Gasifiers one, three, and four are airblown gasifiers that will be coupled with FT-reactors one, two, and four. Gasifiers two, five, and six are oxygen-blown gasifiers that will be coupled with FT-reactors three, three-mod, and four. It should be noted that FT-reactor four is the only one that is being coupled with oxygen and airblown gasification systems, since it is based on a theoretical system rather than a pilot plant.

3.2.19 Thermodynamic Heat Balance on the Production Plant

The last step in the LCA is to perform a thermodynamic heat balance on the production plant, to ensure that the system is self-sufficient, in terms of energy, and does not need any outside electricity or fuel to operate. If outside power were required, it would then be

incorporated as an energy input along with accompanying emissions. The heat balance diagrams for air and oxygen-blown systems are illustrated in Figures 3-12 and 3-13, respectively. From both diagrams, it can be seen that there are various heat and work inputs needed for different components. Heat is required for the dryer, and the inlet streams of air, steam, and oxygen. Work is needed to power several pumps and compressors in the production plant, as well as the compressor which is coupled with the gas turbine. Heat and work will be provided to these inputs via work from the steam turbine, gas turbine, as well as any excess heat from the FT-reactor.

Several assumptions need to be made about the components of the control volume. First, the heat exchanger will have an assumed effectiveness of 0.8. Syngas from the gasifier has to be cooled significantly before gas cleaning, and so a heat exchanger is used. This heat exchanger essentially acts like a boiler to a Rankine cycle, which powers the steam turbine. Next, the compressor work needed for compressors one and two for air and oxygen-blown systems will be considered negligible, as the heating requirements are significant. It is assumed that the FT-reactor, for all configurations, runs at 250 °C and 6 MPa. The smaller hydrocarbon chains that leave the FT-reactor as flue gas will be treated as methane, which will be fed into the gas turbine, which runs as a Brayton cycle. All waste heat will first be used to satisfy heating needs of the production plant, and once that is satisfied, the excess waste heat is run through an absorption chiller, which cools down inlet air for the gas turbine. For inlet cooling, it is assumed that a 10°F drop in inlet air temperature will increase the gas turbine efficiency by 1%. This estimate should be treated as provisional data. Also, for the oxygen systems, additional work is required to produce pure or enriched oxygen. Equations used for the heat balance are listed below.

$$\dot{Q}_{dryer} = \dot{m}_{feedstock} (.3 - x) h_{fg} \quad (4-7)$$

$$\dot{Q}_{syngas} = \dot{m}_{syngas} C_{p,syngas} (T_e - T_i) \quad (4-8)$$

$$0.8 \dot{Q}_{syngas} = \dot{Q}_{rankine} \quad (4-9)$$

$$\dot{Q}_{steam} = \dot{m}_{steam} (h_{steam} - h_{water}) \quad (4-10)$$

$$\dot{Q}_{O_2} = \dot{m}_{O_2} (h_{O_2,2} - h_{O_2,1}) \quad (4-11)$$

$$\dot{Q}_{air} = \dot{m}_{air} (h_{air} - h_{air}) \quad (4-12)$$

$$COP * \dot{Q}_{waste} = \dot{Q}_{cooling} \quad (4-13)$$

$$C_{p,syngas} = \sum_{i=1}^n m_{fi} C_i \quad (4-14)$$

$$\eta_{steam-turbine} = \frac{W_{ideal}}{(h_{enter} - h_{exit})} \quad (4-15)$$

All heat rates, mass flow rates, enthalpies, temperatures, specific heats, and work are in terms of kW, kg / s, kJ / kg, K, kJ / kg K, and kW, respectively. Equation 7 was used to calculate heating requirements for the dryer. In Equation 4-7, $m_{feedstock}$ is the feedstock flowrate, x is the required feedstock moisture percent for the gasifier, and h_{fg} is the heat of vaporization for water, which is 2257 kJ / kg. Equation 8 was used to find out the ideal amount of heat exchanged in the heat exchanger. In Equation 8, m_{syngas} is the syngas flowrate, $C_{p,syngas}$ is the specific heat of the syngas, and T_e and T_i are the temperatures for the syngas leaving and entering the heat exchanger, respectively. The specific heat for each syngas composition was calculated by using Equation 14, where m_{fi} is the mass fraction for the compound in the syngas and C_i is the specific heat for that compound. Equation 9 was used to calculate the heat transferred to the boiler in the Rankine cycle, in which the air temperature was set to a lower limit of 500 °C, which is

acceptable for smaller scale steam turbines. Equation 10 was used to calculate the heat needed for steam production. In Equation 10, m_{steam} is the steam flow rate, h_{steam} is the enthalpy for steam at the specified pressure at temperature for the gasifier, and h_{water} is the enthalpy for water at ambient conditions. Equation 11 was used to calculate the heat needed for the oxygen. In Equation 11, m_{O_2} is the oxygen flow rate, and $h_{\text{O}_2,2}$ is the enthalpy for oxygen at the specified pressure and temperature for the gasifier, and $h_{\text{O}_2,1}$ is the enthalpy for oxygen at ambient conditions. Equation 12 was used to calculate the heat needed for the air. In Equation 12, m_{air} is the air flow rate, $h_{\text{air},2}$ is the enthalpy for air at the specified pressure and temperature for the gasifier, and $h_{\text{air},1}$ is the enthalpy for air at ambient conditions. Equation 13 was used to calculate the total cooling available for the absorption chiller. In Equation 13, COP is the coefficient of performance for the waste heat stream, and was obtained from a study by Shun-Fu Lee et al. As seen in Figure 3-14, using a double-effect lithium bromide chiller with parallel flow would result in a COP of 1.2 for waste heat above 140 °C (Lee et al. 2001).

The work for the Rankine cycle pump is considered negligible because it is pumping liquid water. It is assumed that 350 kWh is required to produce a ton of 99.5% pure oxygen and that 305 kWh is required to produce a ton of 95% enriched oxygen (Tijmensen et al. 2002). In order to calculate steam turbine efficiencies, data from Siemen's website was used; pressures and temperatures were used to calculate the enthalpy entering and exiting the steam turbine, which are h_{enter} and h_{exit} in Equation 15, respectively. Once these were calculated, they were then divided by the ideal work output, W_{ideal} , which was obtained from Seimen's website. Several data points were plotted and linear regression was used to obtain an equation for steam turbine efficiencies. Efficiencies for gas turbines used for electricity production were obtained from Siemen's website as well. Data points were used for linear regression, in the same manner as was

done for the steam turbines. For the gas turbines, it is assumed that the data provided by Seimen's website includes the work necessary to run the compressor, which is significant in a Brayton cycle. The results for the heat balance can be seen in Tables 3-58 through 3-63. All data in these tables are based on gasifier specifications. However, since electricity production from the gas turbines is based on the FT-reactor specifications, they are not included in Tables 3-58 through 3-63, but will be discussed in the results section.

The last step in the heat balance stage was to utilize waste heat streams to improve the performance of the production plant. After the COP and $Q_{cooling}$ were calculated, the next step was to find out by how many points it could increase the efficiency of the gas turbine. The exhaust rates for gas turbines were obtained from Siemen's website, and linear regression was performed to obtain an equation for exhaust rates from energy inputs. The gas turbines were assumed to run on a purely stoichiometric mix, which would be 17.2 kg of air for every kg of fuel. As a result, the mass flow rates of air entering the turbine could then be calculated. The cool inlet air temperature could then be calculated by using the first law of thermodynamics. It was assumed that 80% is the maximum efficiency for a gas turbine, and that after that condensation could pose a problem; this assumption is provisional.

3.2.20 Environmental Impact Assessment

One of the goals of this study was to quantify the environmental impact of producing FT diesel from willow, with respect to global warming and acid rain. As a result, the impact assessment phase of this LCA focused on global warming and acid rain impacts. In order to assess the impact, global warming potentials (GWP) and acid rain potentials (ARP) were used. Potentials are used as a relative scale to compare gases to a reference gas; for global warming potential the reference gas is CO₂. The GWP values obtained for CO₂ and nitrous oxides are 1 and 298, respectively, and ARP values obtained for sulfur oxides are 1 (IPCC 2007). To quantify

the environmental impact, emissions were added from every stage required for FT fuel production, and then multiplied by the appropriate potential factor. The results were then listed in terms of the functional unit, and will be discussed in the next section.

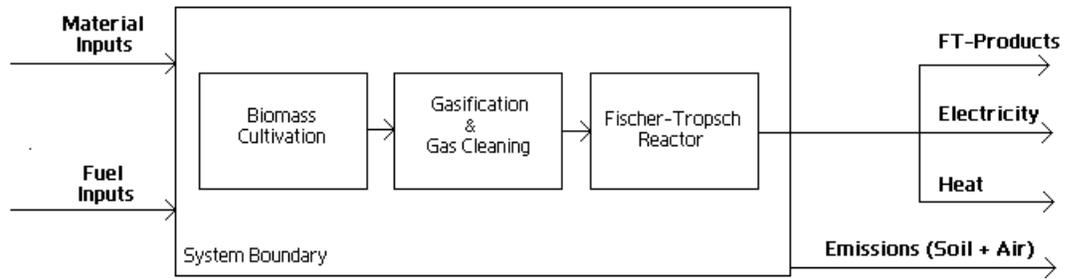


Figure 3-1. Level 1.0 diagram for FT diesel production system

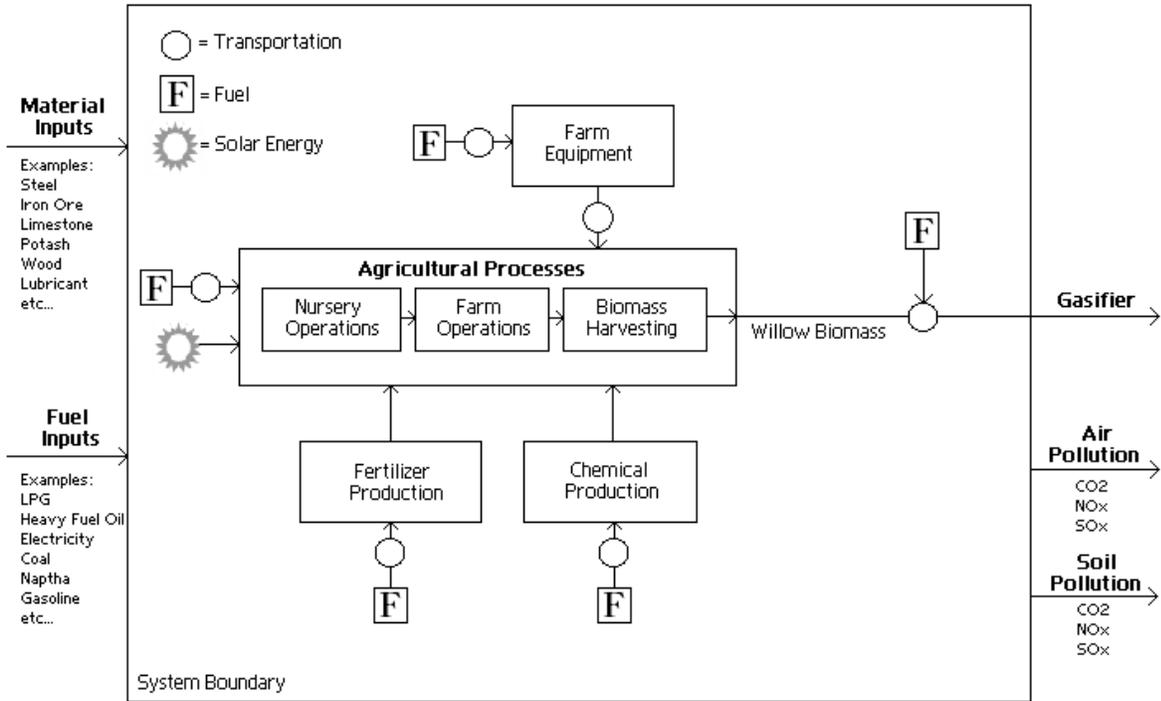


Figure 3-2. Level 2.0 diagram biomass cultivation

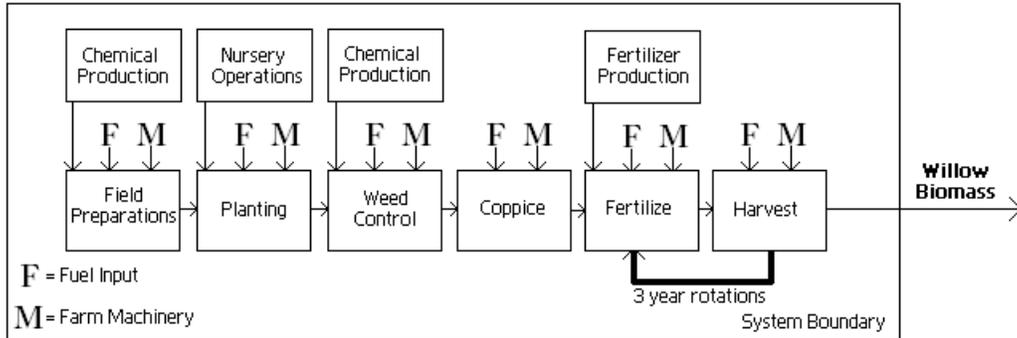


Figure 3-3. Level 3.0 diagram for biomass cultivation (agricultural processes)

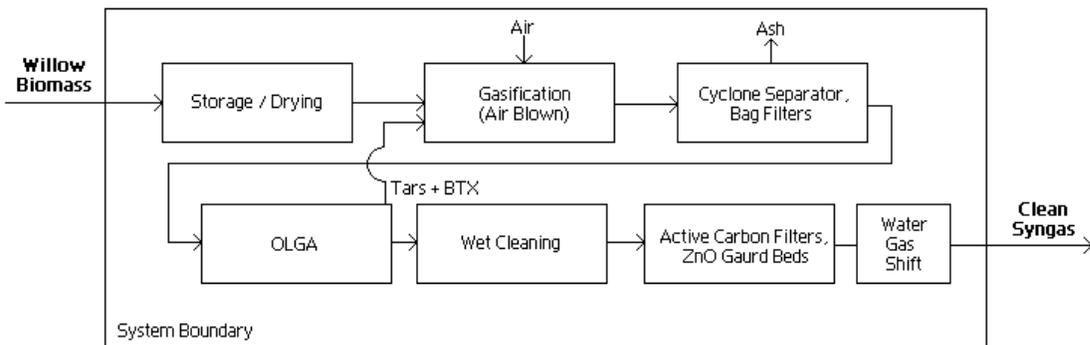


Figure 3-4. Level 1.0 diagram for biomass gasification with a WGS reactor (air-blown)

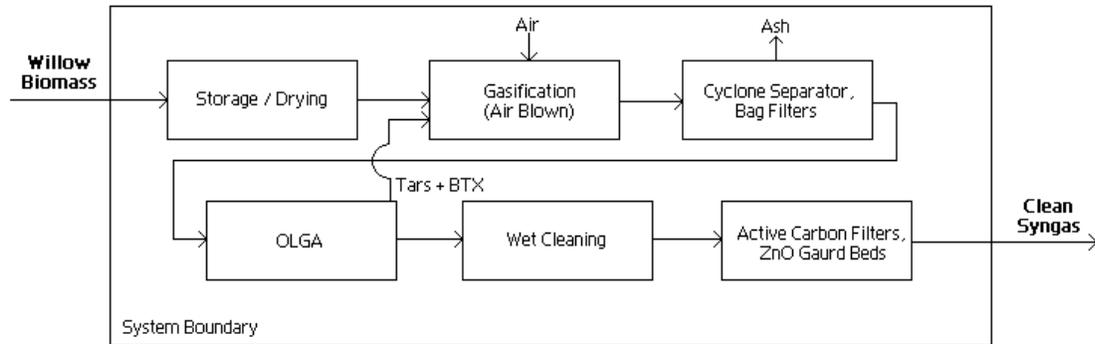


Figure 3-5. Level 1.0 diagram for biomass gasification (air-blown)

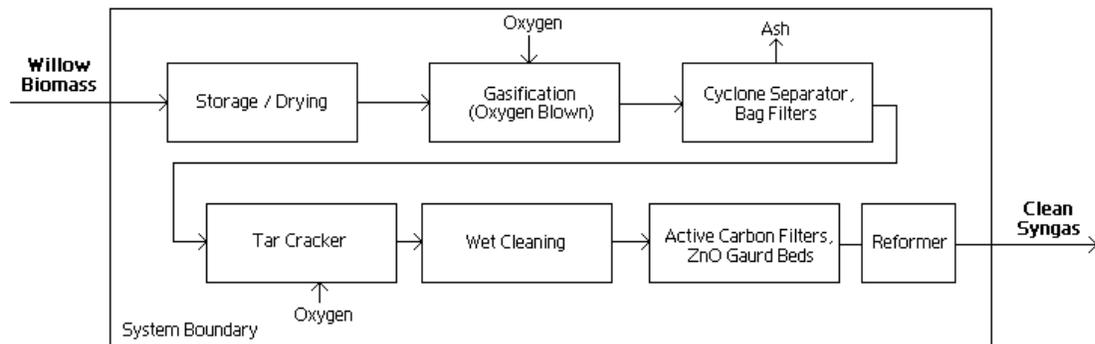


Figure 3-6. Level 1.0 diagram for biomass gasification with a reformer (oxygen-blown)

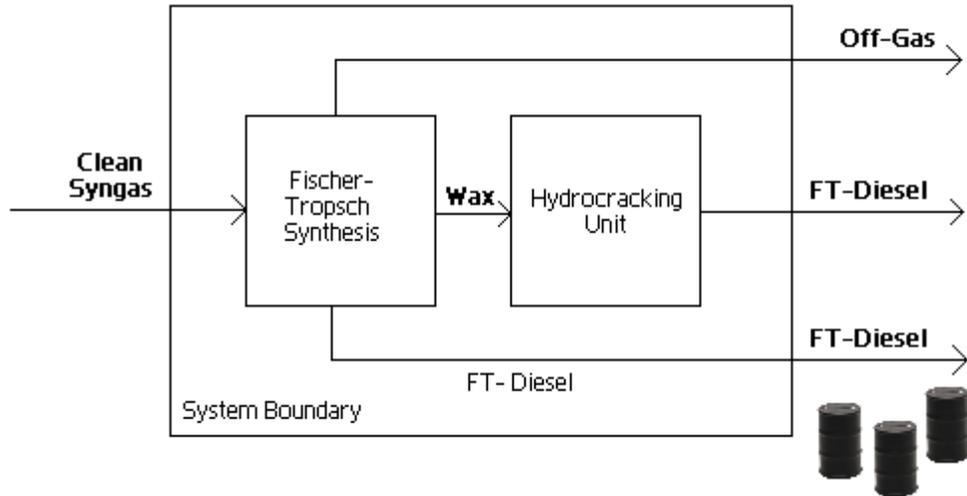


Figure 3-7. Level 1.0 diagram for FT synthesis

Table 3-1. Soil characteristics for willow biomass crops (Abrahamson et al. 2002)

Soil characteristic	Suitable	Unsuitable
Texture	Loams, sandy loams, loamy sands, clay loams and silt loams	Coarse sand, clay soils
Structure	Well developed to single grain structure	Massive or lacking structure
Drainage	Imperfectly to moderately well drained	Excessively well or very poorly drained
pH	5.5 to 8.0	Below 5.5, above 8.0
Depth	18 inches or more	Less than 18 inches

Table 3-2. Recommended inputs and yields from several LCA studies

Planting density (plants / ha)	N fertilizer applied (kg / ha)	Yield odt / ha yr	Study
15300	100	13.1	Heller et al. 2004
-	80	-	Aronsson et al. 2000
-	81	9.9	Borjesson 1996
-	81	11	Borjesson 1996
10000	-	13.5	Mitchell et al. 1999
10000	-	12	Mitchell et al. 1999
18000	-	12	Ledin 1996
10000	70	10	Letkens et al. 2003
36000	-	-	Nurmi 1995
16000	-	-	Larsson 1998
6000	100	12	Abrahamson et al.2002
10000	-	12	Matthews 2001
15200	-	-	Adegbidi et al. 2003
-	75	-	Mortensen et al. 1998
11000	77	-	Zan et al. 2001

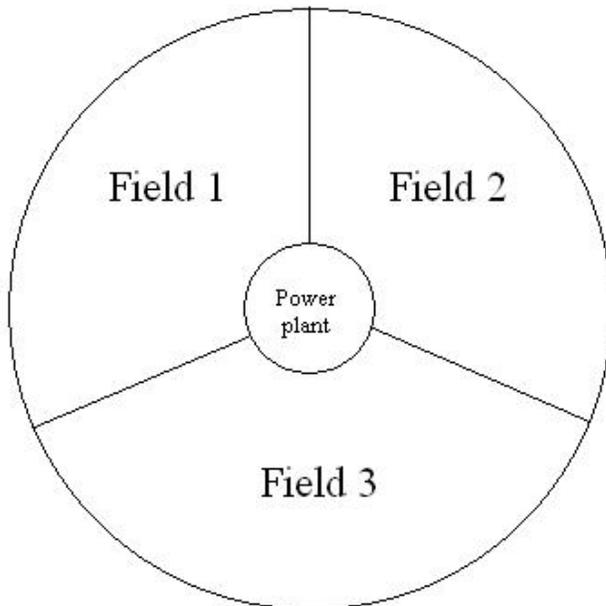


Figure 3-8. Field configuration schematic

Table 3-3. Energy contributions from various stages for fuel production (GREET 2.7)

Fuel	Refining	Transportation	Distribution	Combustion	Total input energy	Units
Conventional diesel	12.04%	0.43%	0.20%	42.79	48.21	MJ / kg
Diesel (tractor)	12.04%	0.43%	0.20%	42.79	48.21	MJ / kg
Conventional gasoline	15.72%	0.41%	0.19%	43.45	50.54	MJ / kg
LPG	6.77%	0.64%	0.23%	46.61	50.17	MJ / kg
Residual fuel oil	6.77%	0.71%	0.00%	39.46	42.41	MJ / kg
Coal	1.10%	187976 btu / ton	0	26.12	26.63	MJ / kg
Petroleum coke	24.54%	30327 btu / ton	0	29.50	36.77	MJ / kg
Crude naphtha	6.77%	0.40%	0.21%	44.94	48.26	MJ / kg
Electricity	40.19%	0	0	3.60	5.00	MJ / kWh
Natural gas	6.31%	0.87%	0	51.57	55.27	MJ / ft ³

Table 3-4. Contributions of CO₂ emissions from various stages for fuel production (GREET 2.7)

Fuel	Production	Transportation	Distribution	Non-combustion	Combustion	Total Emissions	Units
Conventional diesel	0.3270	0.0138	0.0063	0.0375	3.1705	3.5551	kg / kg
Diesel (tractor)	0.3270	0.0138	0.0063	0.0375	3.1397	3.5243	kg / kg
Conventional gasoline	0.4336	0.0135	0.0063	0.0483	3.115	3.6167	kg / kg
LPG	0.2004	0.0259	0	0.0203	3.7573	4.0039	kg / kg
Residual fuel oil	0.1697	0.0219	0	0.0203	3.181	3.3929	kg / kg
Coal	0.0217	0.0187	0	0	2.683	2.7234	kg / kg
Petroleum coke	0.4910	0.0026	0	0	2.928	3.4216	kg / kg
Crude naphtha	0.1933	0.0135	0.0071	0.0203	2.134	2.3682	kg / kg
Electricity	1.0213	0	0	0	0	1.0213	kg / kWh
Natural gas	0.1782	0.0267	0	0.0605	0.0029	0.2683	kg / ft ³

Table 3-5. Contributions of NO_x emissions from various stages for fuel production (GREET 2.7)

Fuel	Production	Transportation	Distribution	Non-combustion	Combustion	Total Emissions	Units
Conventional diesel	0.0004	0.0002	0	0.0001	0.0033	0.0040	kg / kg
Diesel (tractor)	0.0004	0.0002	0	0.0001	0.0278	0.0285	kg / kg
Conventional gasoline	0.0006	0.0002	0	0.0001	0.0197	0.0206	kg / kg
LPG	0.0003	0.0004	0	0.0001	0.0055	0.0062	kg / kg
Residual fuel oil	0.0001	0.0003	0	0.0001	0.0032	0.0037	kg / kg
Coal	0.0001	0.0003	0	0	0.0038	0.0042	kg / kg
Petroleum coke	0.0009	0	0	0	0.0028	0.0037	kg / kg
Crude naphtha	0.0003	0.0002	0	0.0001	0.0069	0.0074	kg / kg
Electricity	0.0023	0	0	0	0	0.0023	kg / kWh
Natural gas	0.0009	0.0002	0	0.0001	0.0028	0.0040	kg / ft ³

Table 3-6. Contributions of SO_x emissions from various stages for fuel production (GREET 2.7)

Fuel	Production	Transportation	Distribution	Non-combustion	Combustion	Total Emissions	Units
Conventional diesel	0.0003	0.0001	0	0.0002	0.0003	0.0009	kg / kg
Diesel (tractor)	0.0003	0.0001	0	0.0002	0.0003	0.0009	kg / kg
Conventional gasoline	0.0003	0.0001	0	0.0002	0.0001	0.0007	kg / kg
LPG	0.0002	0.0002	0	0.0002	0.0090	0.0095	kg / kg
Residual fuel oil	0.0001	0.0001	0	0.0002	0	0.0004	kg / kg
Coal	0	0	0	0.0001	0.0050	0.0051	kg / kg
Petroleum coke	0.0006	0	0	0	0.0056	0.0062	kg / kg
Crude naphtha	0.0002	0.0001	0	0.0002	0.0040	0.0044	kg / kg
Electricity	0.0064	0	0	0	0	0.0064	kg / kWh
Natural gas	0.0009	0	0	0.0005	0	0.0014	kg / ft ³

Table 3-7. Energy contributions from various stages for chemical production (GREET 2.7)

Material	Production	Plant - Bulk center	Bulk center - Mixer	Mixer - Farm	Total input energy	Units
Ammonium Sulfate	45.13	0.51	0.16	0.18	45.98	MJ / kg
Urea	53.39	0.67	0.16	0.18	54.4	MJ / kg
15-15-15 fertilizer	10.73	0.26	0.07	0.08	11.15	MJ / kg
Nitrogen fertilizer	48.54	0.56	0.16	0.18	49.44	MJ / kg
P ₂ O ₅ fertilizer	14.11	0.60	0.16	0.18	15.05	MJ / kg
K ₂ O fertilizer	8.91	0.57	0.16	0.18	9.82	MJ / kg
Limestone	8.15	0	0.16	0	8.31	MJ / kg
Glyphosate	476	0.58	0.16	0	476.7	MJ / kg
Simazine	225.6	0.58	0.16	0.18	226.5	MJ / kg
Oxyfluorfen	267.6	0.58	0.16	0.18	268.5	MJ / kg
Carbaryl	332	0.58	0.16	0.18	333.0	MJ / kg

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Table 3-8. Contributions of CO₂ emissions from various stages for chemical production (GREET 2.7)

Material	Production	Process	Plant - Bulk center	Bulk center - Mixer	Mixer - Farm	Total	Units
Ammonium Sulfate	2.5569	1.2385	0.0396	0.0116	0.0135	3.8601	kg / kg
Urea	1.5146	-0.7341	0.0396	0.0116	0.0135	0.8452	kg / kg
15-15-15 fertilizer	0.6147	0	0.0202	0.0052	0.0061	0.6462	kg / kg
Nitrogen fertilizer	2.4409	0	0.0436	0.0116	0.0135	2.5097	kg / kg
P ₂ O ₅ fertilizer	0.9916	0	0.0465	0.0116	0.0135	1.0632	kg / kg
K ₂ O fertilizer	0.6655	0	0.0448	0.0116	0.0135	0.7354	kg / kg
Limestone	0.6073	0	0	0.0116	0	0.6189	kg / kg
Glyphosate	24.307	0	0.0453	0.0116	0.0135	24.378	kg / kg
Simazine	17.320	0	0.0453	0.0116	0.0135	17.39	kg / kg
Oxyfluorfen	22.193	0	0.0453	0.0116	0.0135	22.263	kg / kg
Carbaryl	24.233	0	0.0453	0.0116	0.0135	24.304	kg / kg

Table 3-9. Contributions of NO_x emissions from various stages for chemical production (GREET 2.7)

Material	Production	Process	Plant - Bulk center	Bulk center - Mixer	Mixer - Farm	Total	Units
Ammonium Sulfate	0.0021	0	0.0008	0.0001	0.0001	0.0031	kg / kg
Urea	0.0051	0	0.0011	0.0001	0.0001	0.0063	kg / kg
15-15-15 fertilizer	0.0019	0.0001	0.0004	0	0	0.0024	kg / kg
Nitrogen fertilizer	0.0034	0	0.0009	0.0001	0.0001	0.0045	kg / kg
P ₂ O ₅ fertilizer	0.0072	0.0004	0.0006	0.0001	0.0001	0.0084	kg / kg
K ₂ O fertilizer	0.0019	0	0.0009	0.0001	0.0001	0.0029	kg / kg
Limestone	0.0009	0	0	0.0001	0	0.0009	kg / kg
Glyphosate	0.0391	0	0.0009	0.0001	0.0001	0.0402	kg / kg
Simazine	0.0273	0	0.0009	0.0001	0.0001	0.0283	kg / kg
Oxyfluorfen	0.0358	0	0.0094	0.0001	0.0001	0.0453	kg / kg
Carbaryl	0.0424	0	0.0009	0.0001	0.0001	0.0435	kg / kg

Table 3-10. Contributions of SO_x emissions from various stages for chemical production (GREET 2.7)

Material	Production	Process	Plant - Bulk center	Bulk center - Mixer	Mixer - Farm	Total	Units
Ammonium Sulfate	0.0013	0	0.0003	0	0	0.0016	kg / kg
Urea	0.0026	0	0.0005	0	0	0.0031	kg / kg
15-15-15 fertilizer	0.0104	0.0011	0.0002	0	0	0.0117	kg / kg
Nitrogen fertilizer	0.0043	0	0.0004	0	0	0.0047	kg / kg
P ₂ O ₅ fertilizer	0.0639	0.0070	0.0004	0	0	0.0713	kg / kg
K ₂ O fertilizer	0.0014	0	0.0004	0	0	0.0018	kg / kg
Limestone	0.0010	0	0	0	0	0.001	kg / kg
Glyphosate	0.0377	0	0.0004	0	0	0.0381	kg / kg
Simazine	0.0261	0	0.0004	0	0	0.0265	kg / kg
Oxyfluorfen	0.0345	0	0.0004	0	0	0.0349	kg / kg
Carbaryl	0.0256	0	0.0004	0	0	0.026	kg / kg

Table 3-11. Modes and average distances traveled by fuels to a terminal (GREET 2.7)

Fuel		Percent	To terminal		
			Ocean Tanker	Pipeline	Rail
Conventional gasoline	Domestic	96%	0	0	0
	Imported	3%	2,600	0	0
	Imported	1%	0	750	800
Conventional diesel	Domestic	96%	0	0	0
	Imported	4%	1300	0	0
LPG	Domestic	80%	0	0	0
	Imported	20%	5200	0	0
Crude naphtha	Domestic	80%	0	0	0
	Imported	20%	1700	0	0
Heavy fuel oil	Domestic	76%	0	0	0
	Imported	24%	3000	0	0
Natural gas	Domestic	100%	0	500	0

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Table 3-12. Modes and average distances traveled domestically by fuels to a bulk terminal and refueling station (GREET 2.7)

Fuel	To bulk terminal			To station		
	Ocean tanker	Barge	Pipeline	Rail	Truck	Truck
Conventional gasoline	1500	520	400	800	0	30
Conventional diesel	1500	520	400	800	0	30
LPG	0	520	400	80	0	30
Crude naphtha	0	520	400	80	30	30
Heavy fuel oil	0	340	400	0	0	30
Natural gas	0	0	0	0	0	0

Table 3-13. Modes and average distances traveled by chemicals to a terminal & bulk terminal (GREET 2.7)

Chemical		Percent	To terminal	To bulk terminal	
			Ocean tanker	Barge	Rail
Ammonium Sulfate	Domestic	40%	0	400	750
	Imported	60%	3000	0	0
Urea	Domestic	40%	0	400	750
	Imported	60%	5200	0	0
N fertilizer	Domestic	40%	0	400	750
	Imported	60%	3700	0	0
P ₂ O ₅ fertilizer	Domestic	40%	0	400	750
	Imported	60%	4200	0	0
K ₂ O fertilizer	Domestic	40%	0	400	750
	Imported	60%	3900	0	0
CaCO ₃	Domestic	100%	0	0	0
	Imported	0%	0	0	0
Herbicides	Domestic	40%	0	400	750
	Imported	60%	4000	0	0
Insecticides	Domestic	40%	0	400	750
	Imported	60%	4000	0	0

Table 3-14. Modes and average distances traveled domestically by chemicals to a mixer and farm (GREET 2.7)

Chemical	To mixer	To farm
	Truck	Truck
Ammonium Sulfate	50	30
Urea	50	30
N fertilizer	50	30
P ₂ O ₅ fertilizer	50	30
K ₂ O fertilizer	50	30
CaCO ₃	0	50
Herbicides	50	30

Table 3-15. Energy intensities for various modes of transport for fuels (GREET 2.7)

Fuel		(btu/ton-mile)				
		Tanker	Barge	Rail	Pipe	Truck
Conventional gasoline	O - D	32	403	253	370	1028
	Backhaul	29	307	0	0	1028
Conventional diesel	O - D	32	403	253	370	1028
	Backhaul	29	307	0	0	1028
LPG	O - D	43	403	253	370	1,285
	Backhaul	38	307	0	0	1,285
Crude naphtha	O - D	32	403	253	370	1,168
	Backhaul	29	307	0	0	1,168
Heavy fuel oil	O - D	38	403	253	370	1,028
	Backhaul	34	307	0	0	1,028
Natural gas	O - D	0	0	0	405	0
Coal	O - D	0	403	370	0	1028
	Backhaul	0	0	0	0	0
Petroleum coke	O - D	0	0	0	0	1028
	Backhaul	0	0	0	0	0

Table 3-16. Energy intensities for various modes of transport for chemicals (GREET 2.7)

		(btu/ton-mile)				
Fuel		Tanker	Barge	Rail	Truck	Truck
Ammonium Sulfate	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
Urea	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
N fertilizer	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
P ₂ O ₅ fertilizer	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
K ₂ O fertilizer	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
CaCO ₃	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
Herbicides	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199
Insecticides	O - D	48	403	370	1,142	2,199
	Backhaul	43	0	0	1,142	2,199

Table 3-17. Energy inputs and emissions for fuels and chemicals for pathway 1

Product	Energy input	Units	Reference	CO ₂	NO _x	SO _x	Units	Reference
Steel	37.73	MJ / kg	GREET 2.7	3.1020	0.0029	0.0029	kg / kg	GREET 2.7
Cast iron	37.73	MJ / kg	-	3.1020	0.0029	0.0029	kg / kg	-
Tractor input energy	4.28	MJ / kg	GREET 2.7	0.0305	0.0004	0.0005	kg / kg	GREET 2.7
Rubber	43.33	MJ / kg	GREET 2.7	2.826	0.0046	0.0039	kg / kg	GREET 2.7
Ammonium Sulfate	45.98	MJ / kg	GREET 2.7	3.8601	0.0031	0.0016	kg / kg	GREET 2.7
Urea fertilizer	54.4	MJ / kg	GREET 2.7	0.8452	0.0063	0.0031	kg / kg	GREET 2.7
15-15-15 fertilizer	11.15	MJ / kg	-	0.6462	0.0024	0.0117	kg / kg	-
N fertilizer	49.44	MJ / kg	GREET 2.7	2.5097	0.0045	0.0047	kg / kg	GREET 2.7
P ₂ O ₅ fertilizer	15.05	MJ / kg	GREET 2.7	1.0632	0.0084	0.0713	kg / kg	GREET 2.7
K ₂ O fertilizer	9.82	MJ / kg	GREET 2.7	0.7354	0.0029	0.0018	kg / kg	GREET 2.7
Limestone	8.31	MJ / kg	GREET 2.7	0.6189	0.0009	0.001	kg / kg	GREET 2.7
Glyphosate	476.7	MJ / kg	Heller et al. 2003	24.378	0.0402	0.0381	kg / kg	Heller et al. 2003
Simazine	226.5	MJ / kg	GREET 2.7	17.390	0.0283	0.0265	kg / kg	GREET 2.7
Oxyfluorfen	268.5	MJ / kg	GREET 2.7	22.263	0.0453	0.0349	kg / kg	GREET 2.7
Carbaryl	333.0	MJ / kg	GREET 2.7	24.304	0.0435	0.026	kg / kg	GREET 2.7
Wood	19.58	MJ / kg	GREET 2.7	1.8950	0.002	0.0001	kg / kg	GREET 2.7
Lubricant	1.93	MJ / kg	-	0.1422	0.0002	0	kg / kg	GREET 2.7
Diesel fuel	48.21	MJ / kg	GREET 2.7	3.5551	0.004	0.0009	kg / kg	GREET 2.7
Diesel fuel (tractor)	48.21	MJ / kg	GREET 2.7	3.5243	0.0285	0.0009	kg / kg	GREET 2.7
Gasoline	50.54	MJ / kg	GREET 2.7	3.6167	0.0206	0.0007	kg / kg	GREET 2.7
LPG	50.17	MJ / kg	GREET 2.7	4.0039	0.0062	0.0095	kg / kg	GREET 2.7
Engine oil	42.41	MJ / kg	-	3.3929	0.0037	0.0004	kg / kg	-
Heavy fuel oil	42.41	MJ / kg	GREET 2.7	3.3929	0.0037	0.0004	kg / kg	GREET 2.7
Bituminous coal	26.63	MJ / kg	GREET 2.7	2.7234	0.0042	0.0051	kg / kg	GREET 2.7
Petroleum coke	36.77	MJ / kg	GREET 2.7	3.4216	0.0037	0.0062	kg / kg	GREET 2.7
Naphtha	48.26	MJ / kg	GREET 2.7	2.3682	0.0074	0.0044	kg / kg	GREET 2.7
Electricity	5.00	MJ / kWh	GREET 2.7	1.0213	0.0023	0.0064	kg / kWh	GREET 2.7
Natural gas	55.27	MJ / ft ³	GREET 2.7	0.2683	0.004	0.0014	kg / ft ³	GREET 2.7

Table 3-18. Energy inputs and emissions for fuels and chemicals for pathway 2

Product	Energy input	Units	Reference	CO ₂	NO _x	SO _x	Units	Reference
Diesel fuel	-	MJ / kg	West	3.1746	-	-	kg / kg	West
Gasoline	-	MJ / kg	West	3.225	-	-	kg / kg	West
LPG	-	MJ / kg	West	3.1746	-	-	kg / kg	West
Heavy fuel oil	-	MJ / kg	West	2.9796	-	-	kg / kg	West
Bituminous coal	-	MJ / kg	West	3.3118	-	-	kg / kg	West
Petroleum coke	-	MJ / kg	West	3.3798	-	-	kg / kg	West
Naphtha	-	MJ / kg	West	3.1632	-	-	kg / kg	West
Natural gas	-	MJ / ft ³	West	0.2226	-	-	kg / ft ³	West
Rubber	-	MJ / kg	West	2.8947	-	-	kg / kg	West
Wood	-	MJ / kg	West	1.4922	-	-	kg / kg	West
Electricity	-	MJ / kWh	West	0.9000	-	-	kg / kWh	West
N fertilizer	57.46	MJ / kg	West	2.571	-	-	kg / kg	West
P ₂ O ₅ fertilizer	7.03	MJ / kg	West	1.4858	-	-	kg / kg	West
K ₂ O fertilizer	6.85	MJ / kg	West	0.7717	-	-	kg / kg	West
Lime	1.71	MJ / kg	West	0.6324	-	-	kg / kg	West
Herbicide	266.5	MJ / kg	West	25.861	-	-	kg / kg	West
Insecticide	284.4	MJ / kg	West	26.793	-	-	kg / kg	West
Ammonium Sulfate	57.46	MJ / kg	West	2.571	-	-	kg / kg	West
Steel	20.24	MJ / kg	Anderson	-	-	-	kg / kg	-
Rubber	57.34	MJ / kg	Amari	-	-	-	kg / kg	-

Table 3-19. Energy inputs and emissions for fuels and chemicals for pathway 3

Product	Energy input	Units	Reference	CO ₂	NO _x	SO _x	Units	Reference
Gasoline	-	MJ / kg	-	3.5024	-	-	kg / kg	IPCC 1996
Diesel fuel	-	MJ / kg	-	3.5724	-	-	kg / kg	IPCC 1996
Heavy fuel oil	-	MJ / kg	-	3.2825	-	-	kg / kg	IPCC 1996
LPG	-	MJ / kg	-	3.1657	-	-	kg / kg	IPCC 1996
Naphtha	-	MJ / kg	-	3.5375	-	-	kg / kg	IPCC 1996
Lubricants	-	MJ / kg	-	0.1415	-	-	kg / kg	IPCC 1996
Petroleum coke	-	MJ / kg	-	3.5851	-	-	kg / kg	IPCC 1996
Bituminous coal	-	MJ / kg	-	2.5191	-	-	kg / kg	IPCC 1996
Natural gas	-	MJ / ft ³	-	0.2549	-	-	kg / ft ³	IPCC 1996
Wood	-	MJ / kg	-	2.1896	-	-	kg / kg	IPCC 1996
Iron	-	MJ / kg	-	1.3500	-	-	kg / kg	IPCC 1996
Steel	-	MJ / kg	-	1.0600	-	-	kg / kg	IPCC 1996
Lime	-	MJ / kg	-	0.7500	-	-	kg / kg	IPCC 1996
Ammonium Sulfate	37.50	MJ / kg	IPCC 1996	2.104	-	-	kg / kg	IPCC 1996
Steel	20.24	MJ / kg	Anderson et al. 2001	-	-	-	kg / kg	-
Rubber	57.34	MJ / kg	Amari et al. 1999	-	-	-	kg / kg	-

Table 3-20. Energy inputs and emissions for fuels and chemicals for pathway 4

Product	Energy input	Units	Reference	CO ₂	NO _x	SO _x	Units	Reference
N fertilizer	78.07	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
P ₂ O ₅ fertilizer	17.44	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
K ₂ O fertilizer	13.77	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
Herbicides	422.0	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
Insecticides	422.0	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
Gasoline	55.96	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
Diesel	50.44	MJ / kg	Pimentel 2003	-	-	-	kg / kg	-
Electricity	10.87	MJ / kWh	Pimentel 2003	-	-	-	kg / kWh	-
Steel	24.00	MJ / kg	Borjesson 1996	-	-	-	kg / kg	-
Gasoline	-	MJ / kg	-	3.5024	-	-	kg / kg	IPCC 1996
Diesel fuel	-	MJ / kg	-	3.5724	-	-	kg / kg	IPCC 1996
Heavy fuel oil	-	MJ / kg	-	3.2825	-	-	kg / kg	IPCC 1996
LPG	-	MJ / kg	-	3.1657	-	-	kg / kg	IPCC 1996
Naphtha	-	MJ / kg	-	3.5375	-	-	kg / kg	IPCC 1996
Lubricants	-	MJ / kg	-	0.1415	-	-	kg / kg	IPCC 1996
Petroleum coke	-	MJ / kg	-	3.5851	-	-	kg / kg	IPCC 1996
Bituminous coal	-	MJ / kg	-	2.5191	-	-	kg / kg	IPCC 1996
Natural gas	-	MJ / ft ³	-	0.2549	-	-	kg / ft ³	IPCC 1996
Wood	-	MJ / kg	-	2.1896	-	-	kg / kg	IPCC 1996
Iron	-	MJ / kg	-	1.3500	-	-	kg / kg	IPCC 1996
Steel	-	MJ / kg	-	1.0600	-	-	kg / kg	IPCC 1996
Lime	-	MJ / kg	-	0.7500	-	-	kg / kg	IPCC 1996
Ammonium Sulfate	-	MJ / kg	-	2.1040	-	-	kg / kg	IPCC 1996

Table 3-21. Nursery production energy inputs and emissions for pathway 1

Input	Energy input	Units	Input amount (kg)	Input energy (MJ)	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Ammonium Sulfate	45.98	MJ / kg	249	11449	961.1	0.7647	0.4106
Urea fertilizer	54.40	MJ / kg	249	13545	210.4	1.5739	0.7769
15-15-15 fertilizer	11.15	MJ / kg	3289	36660	2125	7.7486	38.360
Glyphosate	476.7	MJ / kg	3.63	1730	88.49	0.1458	0.1384
Carbaryl	333.0	MJ / kg	6.53	2174	158.7	0.2838	0.1698
Diesel	48.21	MJ / kg	5.26	253.5	18.69	0.0209	0.0045
Gasoline	50.54	MJ / kg	1.77	89.46	6.401	0.0365	0.0012
LPG	50.17	MJ / kg	30.2	1515	120.9	0.1869	0.2854
Heavy fuel oil	42.41	MJ / kg	2.25	95.43	7.634	0.0082	0.0009
Wood	19.58	MJ / kg	1296	25375	2455	2.5920	0.1296
Electricity	5.00	MJ / kWh	9000	45017	9191	20.70	57.240

Table 3-22. Nursery production energy inputs and emissions for pathway 2

Input	Energy input	Units	Input amount (kg)	Input energy (MJ)	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Ammonium sulfate	45.12	MJ / kg	249	11234	961.15	0.7647	0.4106
Urea fertilizer	53.34	MJ / kg	249	13281	892.6	1.5739	0.7769
15-15-15 fertilizer	10.7	MJ / kg	3289	35195	8285	7.7486	38.367
Glyphosate	266.5	MJ / kg	3.63	967.6	93.87	0.1458	0.1384
Carbaryl	284.4	MJ / kg	6.53	1857	174.9	0.2838	0.1698
Diesel	49.82	MJ / kg	5.26	262.0	16.69	0.0209	0.0045
Gasoline	50.58	MJ / kg	1.77	89.53	5.708	0.0365	0.0012
LPG	50.18	MJ / kg	30.2	1515	95.87	0.1869	0.2854
Heavy fuel oil	42.41	MJ / kg	2.25	95.42	6.704	0.0082	0.0009
Wood	19.55	MJ / kg	1296	25336	1933	2.5920	0.1296
Electricity	5.047	MJ / kWh	9000	45423	8100	20.70	57.249

Table 3-23. Nursery production energy inputs and emissions for pathway 3

Input	Energy input	Units	Input amount (kg)	Input energy (MJ)	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Ammonium Sulfate	37.50	MJ / kg	249	9337	523.8	0.7647	0.4106
Urea fertilizer	53.34	MJ / kg	249	13281	210.4	1.5739	0.7769
15-15-15 fertilizer	11.15	MJ / kg	3289	36660	2125	7.7486	38.367
Glyphosate	476.7	MJ / kg	3.63	1730	88.49	0.1458	0.1384
Carbaryl	333.0	MJ / kg	6.53	2174	158.7	0.2838	0.1698
Diesel	49.82	MJ / kg	5.26	262	18.79	0.0209	0.0045
Gasoline	50.58	MJ / kg	1.77	89.53	6.1992	0.0365	0.0012
LPG	50.18	MJ / kg	30.2	1515	95.6	0.1869	0.2854
Heavy fuel oil	42.41	MJ / kg	2.25	95.42	7.385	0.0082	0.0009
Wood	19.55	MJ / kg	1296	25336	2837	2.592	0.1296
Electricity	5.047	MJ / kWh	9000	45423	9191	20.70	57.249

Table 3-24. Nursery production energy inputs and emissions for pathway 4

Input	Energy input	Units	Input amount (kg)	Input energy (MJ)	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Ammonium Sulfate	45.98	MJ / kg	249	11449	961.1	0.7647	0.4106
Urea fertilizer	53.34	MJ / kg	249	13281	210.4	1.5739	0.7769
15-15-15 fertilizer	11.15	MJ / kg	3289	36660	2125	7.7486	38.367
Glyphosate	422.0	MJ / kg	3.63	1531	88.49	0.1458	0.1384
Carbaryl	422.0	MJ / kg	6.53	2755	158.7	0.2838	0.1698
Diesel	50.44	MJ / kg	5.26	265.3	18.79	0.0209	0.0045
Gasoline	55.96	MJ / kg	1.77	99.05	6.199	0.0365	0.0012
LPG	50.18	MJ / kg	30.2	1515.4	95.6	0.1869	0.2854
Heavy fuel oil	42.41	MJ / kg	2.25	95.42	7.385	0.0082	0.0009
Wood	19.55	MJ / kg	1296	25336	2837	2.592	0.1296
Electricity	10.87	MJ / kWh	9000	97830	9191	20.70	57.249

Table 3-25. Fertilizer production energy inputs and emissions for pathway 1

Chemical	Material	Application	(MJ / hectare)	Emissions (kg / ha)		
	Energy input (MJ / kg)	rate (kg / ha)	Input energy (MJ / ha)	CO ₂	NO _x	SO _x
Glyphosate	476.7	2.50	1191	60.94	0.1004	0.0953
Simazine	226.5	2.24	507.5	38.95	0.0635	0.0594
Oxyfluorfen	268.5	1.12	300.7	24.93	0.0507	0.0391
Ammonium Sulfate (N)	45.98	700	32186	2702	2.1497	1.1543

Table 3-26. Fertilizer production energy inputs and emissions for pathway 2

Chemical	Material	Application	(MJ / hectare)	Emissions (kg / ha)		
	Energy input (MJ / kg)	rate (kg / ha)	Input energy (MJ)	CO ₂	NO _x	SO _x
Glyphosate	266.5	2.5	666.4	64.65	0.1004	0.0953
Simazine	266.5	2.24	597.0	57.92	0.0635	0.0594
Oxyfluorfen	266.5	1.12	298.5	28.96	0.0507	0.0391
Ammonium Sulfate (N)	57.46	700	40222	2702	2.1497	1.1543

Table 3-27. Fertilizer production energy inputs and emissions for pathway 3

Chemical	Material	Application	(MJ / hectare)	Emissions (kg / ha)		
	Energy input (MJ / kg)	rate (kg / ha)	Input energy (MJ)	CO ₂	NO _x	SO _x
Glyphosate	476.7	2.50	1191	60.94	0.1004	0.0953
Simazine	226.5	2.24	507.5	38.95	0.0635	0.0594
Oxyfluorfen	268.5	1.12	300.7	24.93	0.0507	0.0391
Ammonium Sulfate (N)	37.5	700	26250	1472	2.1497	1.1543

Table 3-28. Fertilizer production energy inputs and emissions for pathway 4

Chemical	Material	Application	(MJ / hectare)	Emissions (kg / ha)		
	Energy input (MJ / kg)	rate (kg / ha)	Input energy (MJ)	CO ₂	NO _x	SO _x
Glyphosate	422	2.50	1055	60.94	0.1004	0.0953
Simazine	422	2.24	945.3	54.60	0.0635	0.0594
Oxyfluorfen	422	1.12	472.6	24.93	0.0507	0.0391
Ammonium Sulfate (N)	78.07	700	54649	2702	2.1497	1.1543

Table 3-29. Specifications for tractors and implements used for willow farm (Heller et al. 2003)

Operation	Implement	Implement weight (kg)	Tractor power (kW)	Tractor weight (kg)	Operating rate (h / ha)
Mow	1.8 m brushhog	470	54	3240	1.5
Contact herbicide	7.6 m boom sprayer	670	37	2572	0.5
Plow	1.45 moldboard plow	1226	60	3683	1.7
Disk	3.4 tandem harrow disk	1053	54	3240	1.4
Cultipack	3.0 m cultipacker	635	37	3240	0.71
Seed covercrop	12.2 m broadcaster	100	78	2572	0.1
Planting	Salix Maskiner Step	1400	37	5670	2.5
Pre-emergent herbicide	7.6 boom sprayer	670	54	2572	0.46
1st year coppice	2.1 sicklebar mower	270	37	3240	1.5
Weed control	Modified row cultivator	500	54	2572	0.61
Weed control	Badalini rototiller	400	54	3240	1.6
Weed control	7.6 m boom sprayer	670	37	2572	0.46
Fertilize	7.6 m spreader	180	75	4192	0.21
Harvest	Salix Maskiner Bender	1250	78	5670	3

Table 3-30. Tractor manufacturing energy inputs and emissions for pathway 1

Tractor manufacturing	Material energy input	Units	unit / kg tractor	(MJ / kg tractor)	Emissions		
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Aluminum	-	-	0.0033	0	0	0	0
Copper	-	-	0.00083	0	0	0	0
Fuel and oil	47.28	MJ / kg	0.042	1.99	0.1482	0.0002	0
Glass	-	-	0.002	0	0	0	0
Cast iron	37.73	MJ / kg	0.670	25.28	2.0783	0.0019	0.0019
Plastic	-	-	0.0085	0	0	0	0
Steel	37.73	MJ / kg	0.110	4.15	0.3412	0.0003	0.0003
Tire rubber	41.48	MJ / kg	0.160	6.64	0.4669	0.0006	0.0006
Electricity	5	MJ / kWh	5.102	25.52	5.2107	0.0117	0.0325
Process energy	4.28	MJ / kg	-	4.28	0.0305	0.0004	0.0005

Table 3-31. Implement manufacturing energy inputs and emissions for pathway 1

Implement manufacturing	Material energy input	Units	unit / kg implement	(MJ / kg implement)	Emissions		
				Input Energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Iron ore	37.73	MJ / kg	1.44	54.33	4.4669	0.0042	0.0042
Limestone	8.31	MJ / kg	0.32	2.66	0.1981	0.0003	0.0003
Mineral oil	1.93	MJ / kg	0.026	0.05	0.0037	0	0
Diesel	48.21	MJ / kg	0.243	11.72	0.8639	0.001	0.0002
Electricity	5.00	MJ / kWh	3.30	16.51	3.3703	0.0076	0.021

Table 3-32. Tractor manufacturing energy inputs and emissions for pathway 2

Tractor manufacturing	Material energy input	Units	unit / kg tractor	(MJ / kg tractor) Emissions			
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Aluminum	-	-	0.0033	0	0	0	0
Copper	-	-	0.00083	0	0	0	0
Fuel and oil	47.28	MJ / kg	0.042	1.99	0.1320	0.0002	0
Glass	-	-	0.002	0	0	0	0
Cast iron	20.24	MJ / kg	0.67	13.56	2.0783	0.0019	0.0019
Plastic	-	-	0.0085	0	0	0	0
Steel	20.24	MJ / kg	0.11	2.23	0.3412	0.0003	0.0003
Tire rubber	44.99	MJ / kg	0.16	7.2	0.4669	0.0006	0.0006
Electricity	5.00	MJ / kWh	5.102	25.51	4.5918	0.0117	0.0325
Process energy	4.28	MJ / kg	-	4.28	0.0305	0.0004	0.0005

Table 3-33. Implement manufacturing energy inputs and emissions for pathway 2

Implement manufacturing	Material energy input	Units	unit / kg implement	(MJ / kg implement) Emissions			
				Input Energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Iron ore	20.24	MJ / kg	1.44	29.15	4.4669	0.0042	0.0042
Limestone	1.71	MJ / kg	0.32	0.55	0.2024	0.0003	0.0003
Mineral oil	1.93	MJ / kg	0.026	0.05	0.0037	0	0
Diesel	48.21	MJ / kg	0.243	11.72	0.7714	0.001	0.0002
Electricity	5.00	MJ / kWh	3.3	16.51	2.9700	0.0076	0.0210

Table 3-34. Tractor manufacturing energy inputs and emissions for pathway 3

Tractor manufacturing	Material energy input	Units	unit / kg tractor	(MJ / kg tractor)	Emissions		
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Aluminum	-	-	0.0033	0	0	0	0
Copper	-	-	0.00083	0	0	0	0
Fuel and oil	47.28	MJ / kg	0.042	1.99	0.1481	0.0002	0
Glass	-	-	0.002	0	0	0	0
Cast Iron	20.24	MJ / kg	0.67	13.56	2.0783	0.0019	0.0019
Plastic	-	-	0.0085	0	0	0	0
Steel	20.24	MJ / kg	0.11	2.23	0.3412	0.0003	0.0003
Tire rubber	44.99	MJ / kg	0.16	7.2	0.4669	0.0006	0.0006
Electricity	5.00	MJ / kWh	5.102	25.52	5.2107	0.0117	0.0325
Process energy	4.28	MJ / kg	-	4.28	0.0305	0.0004	0.0005

Table 3-35. Implement manufacturing energy inputs and emissions for pathway 3

Implement manufacturing	Material energy input	Units	unit / kg implement	(MJ / kg implement)	Emissions		
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Iron ore	20.24	MJ / kg	1.44	29.15	4.4669	0.0042	0.0042
Limestone	8.31	MJ / kg	0.32	2.66	0.1981	0.0003	0.0003
Mineral oil	1.93	MJ / kg	0.026	0.05	0.0037	0	0
Diesel	48.21	MJ / kg	0.243	11.72	0.8681	0.001	0.0002
Electricity	5	MJ / kWh	3.30	16.51	3.3703	0.0076	0.0210

Table 3-36. Tractor manufacturing energy inputs and emissions for pathway 4

Tractor manufacturing	Material energy input	Units	unit / kg tractor	(MJ / kg tractor)	Emissions		
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Aluminum	-	-	0.0033	0	0	0	0
Copper	-	-	0.00083	0	0	0	0
Fuel and oil	49.16	MJ / kg	0.042	2.06	0.1481	0.0002	0
Glass	-	-	0.002	0	0	0	0
Cast iron	24	MJ / kg	0.67	16.08	2.0783	0.0019	0.0019
Plastic	-	-	0.0085	0	0	0	0
Steel	24	MJ / kg	0.11	2.64	0.3412	0.0003	0.0003
Tire rubber	36.9	MJ / kg	0.16	5.90	0.4669	0.0006	0.0006
Electricity	10.87	MJ / kWh	5.102	55.46	5.2107	0.0117	0.0325
Process energy	4.28	MJ / kg	-	4.28	0.0305	0.0004	0.0005

Table 3-37. Implement manufacturing energy inputs and emissions for pathway 4

Implement manufacturing	Material energy input	Units	unit / kg implement	(MJ / kg implement)	Emissions		
				Input energy	CO ₂ (kg)	NO _x (kg)	SO _x (kg)
Iron ore	24	MJ / kg	1.44	34.56	4.4669	0.0042	0.0042
Limestone	8.31	MJ / kg	0.32	2.66	0.1981	0.0003	0.0003
Mineral oil	1.93	MJ / kg	0.026	0.05	0.0037	0	0
Diesel	50.44	MJ / kg	0.243	12.26	0.8681	0.001	0.0002
Electricity	10.87	MJ / kWh	3.30	35.87	3.3703	0.0076	0.0210

Table 3-38. Energy intensities for various modes of tractor transportation (GREET 2.7)

Weight (kg)		(btu/ton-mile)		Rail	Truck	(kg)	(kg)	(kg)
		Rail	Truck	Total energy (MJ)	Total energy (MJ)	CO ₂ emissions	NO _x emissions	SO _x emissions
2572 (13)	O - D	200	1028	2334	1999	82.79	1.2557	0.025
	Backhaul	0	1028	0	1999	12.57	0.067	0.0035
3240 (22)	O - D	200	1028	4975	4262	176.5	2.677	0.0532
	Backhaul	0	1028	0	4262	26.79	0.1428	0.0074
4192 (2)	O - D	200	1028	293	501	11.96	0.1658	0.0036
	Backhaul	0	1028	0	501	3.15	0.0168	0.0009
5670 (24)	O - D	200	1028	9497	8136	336.9	5.1106	0.1016
	Backhaul	0	1028	0	8136	51.15	0.2726	0.0142

Table 3-39. Energy intensities for various modes of implement transportation (GREET 2.7)

Weight (kg)		#	(btu/ton-mile)		Rail	Truck	(kg)	(kg)	(kg)
			Rail	Truck	Total energy (MJ)	Total energy (MJ)	CO ₂ emissions	NO _x emissions	SO _x emissions
100	O - D	2	200	1028	14	12	0.5	0.0075	0.0001
100	Backhaul	2	0	1028	0	12	0.08	0.0004	0
180	O - D	16	200	1028	201	172	7.13	0.1082	0.0022
180	Backhaul	16	0	1028	0	172	1.08	0.0058	0.0003
270	O - D	12	200	1028	226	194	8.02	0.1217	0.0024
270	Backhaul	12	0	1028	0	194	1.22	0.0065	0.0003
400	O - D	12	200	1028	335	287	11.89	0.1803	0.0036
400	Backhaul	12	0	1028	0	287	1.8	0.0096	0.0005
470	O - D	12	200	1028	394	337	13.97	0.2118	0.0042
470	Backhaul	12	0	1028	0	337	2.12	0.0113	0.0006
500	O - D	6	200	1028	209	179	7.43	0.1127	0.0022
500	Backhaul	6	0	1028	0	179	1.13	0.006	0.0003
635	O - D	9	200	1028	399	342	14.15	0.2146	0.0043
635	Backhaul	9	0	1028	0	342	2.15	0.0114	0.0006
670	O - D	12	200	1028	561	481	19.91	0.3019	0.006
670	Backhaul	12	0	1028	0	481	3.02	0.0161	0.0008
1053	O - D	18	200	1028	1323	1133	46.93	0.7118	0.0142
1053	Backhaul	18	0	1028	0	1133	7.12	0.038	0.002
1226	O - D	14	200	1028	1198	1026	42.5	0.6446	0.0128
1226	Backhaul	14	0	1028	0	1026	6.45	0.0344	0.0018
1250	O - D	96	200	1028	8375	7174	297.1	4.5067	0.0896
1250	Backhaul	96	0	1028	0	7174	45.1	0.2404	0.0125
1400	O - D	20	200	1028	1954	1674	69.33	1.0516	0.0209
1400	Backhaul	20	0	1028	0	1674	10.52	0.0561	0.0029

Table 3-40. Breakdown of farm activities by year and season (Heller et al. 2003)

Year	Season	Activities
0	Fall	Mow, contact herbicide, plow, disk, seed covercrop, cultipack
1	Spring	Disk, cultipack, plant, herbicide, weed control
1	Winter	1st year coppice
2	Spring	Fertilize
4	Winter	1st harvest
5	Spring	Fertilize
7	Winter	2nd harvest
{8-22}	Winter	Repeat harvest, every 3 years

Table 3-41. Recommended power consumption for farming operations (Heller et al. 2003)

Operation	Max PTO (kW)	Total power (kW)
Mow	54	37
Spray herbicide	37	18.5
Spread fertilizer	75	45
Coppicing	54	37
Rototilling	54	48
Planting	78	52
Harvesting	75	78

Table 3-42. Data for fuel consumption equations (ASAE 1999)

Operation	A	B	C	E_t	S	W	T	F_2
Moldboard plow	113	0	2.3	0.72	5.6	1.45	20.3	0.7
Fall disk	53	4.6	0	0.67	6.4	3.4	10.2	0.88
Spring disk	37	3.2	0	0.72	6.4	3.4	10.2	0.88
Cultipack	180	0	0	0.67	4.8	3	6.4	1

Table 3-43. Diesel and fuel oil consumption for all farm operations

Operation	Implement used	Total # of implements	Operation (hours)	Diesel (L)	Engine oil (L)
Mow vegetation	1.8 m brushhog	12	15000	238921	653
Contact herbicide	7.6 m boom sprayer	4	5000	46618	268
Plow	1.45 moldboard plow	14	17000	388219	910
Disk	3.4 tandem harrow disk	18	28000	518513	1499
Cultipack	3.0 m cultipacker	9	14200	252449	618
Seed covercrop	12.2 m broadcaster	2	1000	9646	68
Plant	4 row Salix Maskiner step	20	25000	565654	1088
Pre-emergent herbicide	7.6 m boom sprayer	4	4600	42889	246
1 st year coppice	2.1 sicklebar mower	12	15000	238921	653
Mechanical weed control	Modified row cultivator	6	6100	75484	327
Mechanical weed control	Badalini rototiller	12	16000	316276	696
Chemical weed control	7.6 boom sprayer	4	4600	42889	303
Fertilize	7.6 m spreader	16	14700	301968	995
Harvest	Salix Maskiner Bender	96	210000	6927042	4555

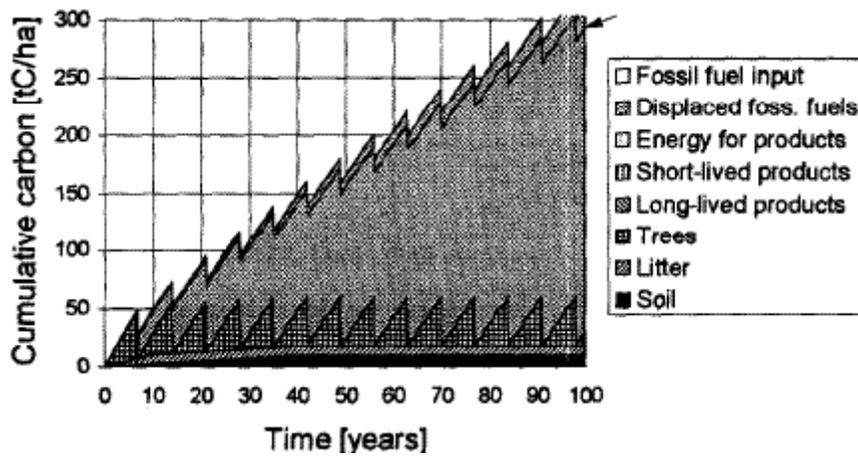


Figure 3-9. Net cumulative carbon sequestration for short-rotation forestry (Schlamadinger et al. 1996)

Table 3-44. Carbon sequestration results from various studies

Soil sequestration	Reference
.900 Mg C / ha yr	Lemus et al. 2005
.040 Mg C / ha yr	Zan et al. 2001
.372 Mg C / ha yr	Grogan et al. 2002
.889 Mg C / ha yr	Smith et al. 2004
.337 Mg C / ha yr	West et al. 2002
Root sequestration	
1.25 Mg C / ha yr	Zan et al. 2001
Belowground sequestration	
8.50 t C / ha	Matthews 2001
12.0 t C / ha	Grogan et al. 2002
18.0 t C / ha	Schlamadinger et al. 1996
15.5 t C / ha	Heller et al. 2004

Table 3-45. Nitrogen sequestration results from various studies

Leaching	Reference
1.6 kg N / ha	Aronsson et al. 2000
7.5 kg N / ha	Mortensen et al. 1998
Denitrification	
1 kg N / ha yr	Aronsson et al. 2000
1.25 kg N / ha yr	IPCC 1996
Leaf litter	
1.35 kg N / ha	Aronsson et al. 2000
Deposition	
16 kg N / ha yr	Heller et al. 2004

Table 3-46. Input rates for gasification in various units

Conservative	10.0	odt / ha / yr
Ideal	13.1	odt / ha / yr
Optimistic	18.7	odt / ha / yr
Conservative	65.75	MW _{th}
Ideal	86.14	MW _{th}
Optimistic	122.96	MW _{th}
Conservative	3.32	kg / s
Ideal	4.35	kg / s
Optimistic	6.21	kg / s
Conservative	11.96	ton / hour
Ideal	15.66	ton / hour
Optimistic	22.36	ton / hour
Conservative	263.0	ton / day
Ideal	344.5	ton / day
Optimistic	491.8	ton / day

Table 3-47. Gasifier 1 specifications

Type	Indirect / airblown	Units
Pressure	2	Bars
Temperature	1136	Kelvin
Feedstock moisture	10	%
Feedstock input	200	dry tons / day
Dolomite Flowrate	0	kg / kg wood
Air flowrate	1.46	kg / kg wood
Oxygen flowrate	0	kg / kg wood
Steam flowrate	0.19	kg / kg wood
Gasifier efficiency	86.8%	unitless
Gas composition	-	-
H ₂ O	18.93	mass %
H ₂	15.89	mass %
CO	35.3	mass %
CO ₂	8.47	mass %
CH ₄	11.99	mass %
C ₂₊	4.57	mass %
C ₂ H ₄	4	mass %
C ₂ H ₆	0.57	mass %
N ₂ + Ar	0	mass %
Other	0.29	mass %
Total	100	mass %

Table 3-48. Gasifier 2 specifications

Type	Direct / O ₂ blown	-
Pressure	34	Bars
Temperature	1255	Kelvin
Feedstock moisture	15	%
Feedstock input	100	dry tons / day
Dolomite flowrate	0.0268	kg / kg wood
Air flowrate	0	kg / kg wood
Oxygen flowrate	0.3	kg / kg wood
Steam flowrate	0.34	kg / kg wood
Gasifier efficiency	80.70%	unitless
Gas composition	-	-
H ₂ O	31.58	mass %
H ₂	20.66	mass %
CO	14.9	mass %
CO ₂	23.73	mass %
CH ₄	8.14	mass %
C ₂₊	0.3	mass %
C ₂ H ₄	0	mass %
C ₂ H ₆	0	mass %
N ₂ + Ar	0.4	mass %
Other	0.3	mass %
Total	100	mass %

Table 3-49. Gasifier 3 specifications

Type	Direct / airblown	-
Pressure	1.3	Bars
Temperature	1173	Kelvins
Feedstock moisture	15	%
Feedstock input	270	dry tons / day
Dolomite Flowrate	0.0268	kg / kg wood
Air flowrate	1.4	kg / kg wood
Oxygen flowrate	0	kg / kg wood
Steam flowrate	0.34	kg / kg wood
Gasifier efficiency	80%	unitless
Gas composition	-	-
H ₂ O	13.49	mass %
H ₂	13.19	mass %
CO	17.14	mass %
CO ₂	12.16	mass %
CH ₄	2.81	mass %
C ₂₊	0.96	mass %
C ₂ H ₄	0.94	mass %
C ₂ H ₆	0.02	mass %
N ₂ + Ar	39.01	mass %
Other	0.3	mass %
Total	100	mass %

Table 3-50. Gasifier 4 specifications

Type	Direct / airblown	-
Pressure	1.3	Bars
Temperature	1123	Kelvin
Feedstock moisture	15	%
Feedstock input	2099	dry tons / day
Dolomite Flowrate	0	kg / kg wood
Air flowrate	0.95	kg / kg wood
Oxygen flowrate	0	kg / kg wood
Steam flowrate	0	kg / kg wood
Gasifier efficiency	84%	unitless
Gas composition	-	-
H ₂ O	9.01	mass %
H ₂	1.12	mass %
CO	18.12	mass %
CO ₂	22.52	mass %
CH ₄	2.98	mass %
C ₂₊	0.93	mass %
C ₂ H ₄	0.56	mass %
C ₂ H ₆	0.62	mass %
N ₂ + Ar	42.84	mass %
Other	1.3	mass %
Total	100	mass %

Table 3-51. Gasifier 5 specifications

Type	Direct / enriched O ₂	-
Pressure	25	Bars
Temperature	1123	Kelvin
Feedstock moisture	15	%
Feedstock input	2098	dry tons / day
Dolomite flowrate	0.0268	kg / kg wood
Air flowrate	0	kg / kg wood
Oxygen flowrate	0.27	kg / kg wood
Steam flowrate	0.43	kg / kg wood
Gasifier efficiency	84%	unitless
Gas composition	-	-
H ₂ O	32.03	mass %
H ₂	1.18	mass %
CO	9.96	mass %
CO ₂	41.75	mass %
CH ₄	7.56	mass %
C ₂₊	1.22	mass %
C ₂ H ₄	0.6	mass %
C ₂ H ₆	0.67	mass %
N ₂ + Ar	3.34	mass %
Other	1.69	mass %
Total	100	mass %

Table 3-52. Gasifier 6 specifications

Type	Direct / O ₂ blown	-
Pressure	25	Bars
Temperature	1123	Kelvin
Feedstock moisture	15	%
Feedstock input	2098	dry tons / day
Dolomite flowrate	0.0268	kg / kg wood
Air flowrate	0	kg / kg wood
Oxygen flowrate	0.213	kg / kg wood
Steam flowrate	0.32	kg / kg wood
Gasifier efficiency	84%	unitless
Gas composition	-	-
H ₂ O	28.26	mass %
H ₂	1.28	mass %
CO	12.9	mass %
CO ₂	43.98	mass %
CH ₄	8.45	mass %
C ₂₊	1.35	mass %
C ₂ H ₄	0.59	mass %
C ₂ H ₆	0.66	mass %
N ₂ + Ar	0.64	mass %
Other	1.88	mass %
Total	100	mass %

Contaminant	Gas phase specification	Treatment method and remarks	
		Existing technologies	Dry gas cleaning
Soot (dust, char, ash)	–	Cyclones, metal filters, moving beds, candle filters, bag filters, special soot scrubber	
Alkaline (halide) metals	0 ppb – <10 ppb	Specifications are met Active coal bed meets specification ^c	Sorbents Under development
Tar	Below dew point at FT pressure Catalyst poisoning compounds <1 ppmV	All tar and BTX: Thermal tar cracker Oil scrubber Specifications are met	All tar and BTX: Catalytic tar cracker Other catalytic operations Under development
BTX	Below dew point at FT pressure		
Halide compounds: HCl (HBr, HF)	<10 ppb	Removed by aqueous scrubber Active coal bed meets specification Absorbed by dolomite in tar cracker (if applicable)	In-bed sorbents or in-stream sorbents <1 ppm Guard beds necessary
<i>Nitrogen compounds</i>	Total nitrogen <1 ppmV <20 ppb Total N		All nitrogen: Catalytic decomposition Combined removal of NH ₃ /H ₂ S
NH ₃		Removed by aqueous scrubber Removed to specification	Selective oxidation Under development
HCN		Active coal bed Possibly preceded by hydrolysis to NH ₃ Specifications are met	
<i>Sulphur compounds</i>	Total sulphur <1 ppmV <10 ppb Total S		All sulphur: In-bed calcium sorbents Metal oxide sorbents <20 ppm
H ₂ S		ZnO guard bed In case of high sulphur loads, a special removal step, e.g. Claus unit	
COS		Active coal bed Possibly preceded by hydrolysis to H ₂ S Specifications are met	

Figure 3-10. Contaminants and gas cleaning methods for FT production (Tijmensen 2002)

Table 3-53. Fischer-Tropsch reactor 1 specifications for once-through, tri-generation without a WGS reactor (airblown systems) (Boerrigter 2002)

In	Type	Out	Type
1	MJ syngas	0.217	MJ FT products
		0.361	MJ electricity
		0.422	MJ waste heat
	Total	1	

Table 3-54. Fischer-Tropsch reactor 2 specifications for once-through, tri-generation with a WGS reactor (airblown systems) (Boerrigter 2002)

In	Type	Out	Type
1	MJ syngas	0.307	MJ FT products
		0.296	MJ electricity
		0.397	MJ waste heat
	Total	1	

Table 3-55. Fischer-Tropsch reactor 3 specifications for once-through, tri-generation without a WGS reactor (oxygen-blown systems) (Boerrigter 2002)

In	Type	Out	Type
1	MJ syngas	0.581	MJ FT products
		0.054	MJ electricity
		0.365	MJ waste heat
	Total	1	

Table 3-56. Fischer-Tropsch reactor 3mod specifications for once-through, tri-generation without a WGS reactor (oxygen-blown systems) (Boerrigter 2002)

In	Type	Out	Type
1	MJ syngas	0.581	MJ FT products
		0.094	MJ electricity
		0.325	MJ waste heat
	Total	1	

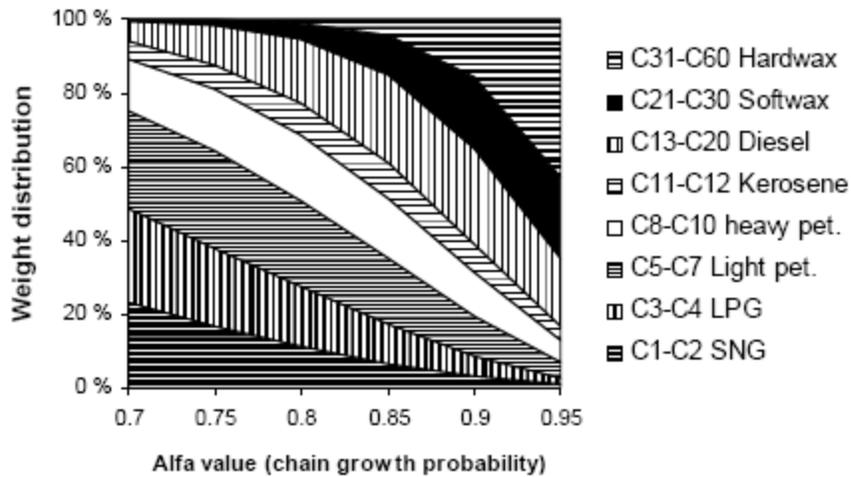


Figure 3-11. Anderson-Schulz-Flory chain growth probability distribution (<http://www.zero.no/transport/bio/ft14.gif>)

Table 3-57. Products for various once-through production plant configurations (Tijmensen 2002)

Concept	BCL	IGT	TPS
$\alpha = .80$	37.7	46.4	36.5
FT liquids (MW_{th})	66.6	78.6	92.4
Power (MW_e)	71.9	91.5	41.5
$\alpha = .85$	38.9	47.8	38.2
FT liquids (MW_{th})	75.4	89.1	104.6
Power (MW_e)	67.4	86.3	35.6
$\alpha = .85$	40.4	49	39.7
FT liquids (MW_{th})	82.9	98	115.1
Power (MW_e)	65.3	81.9	30.5

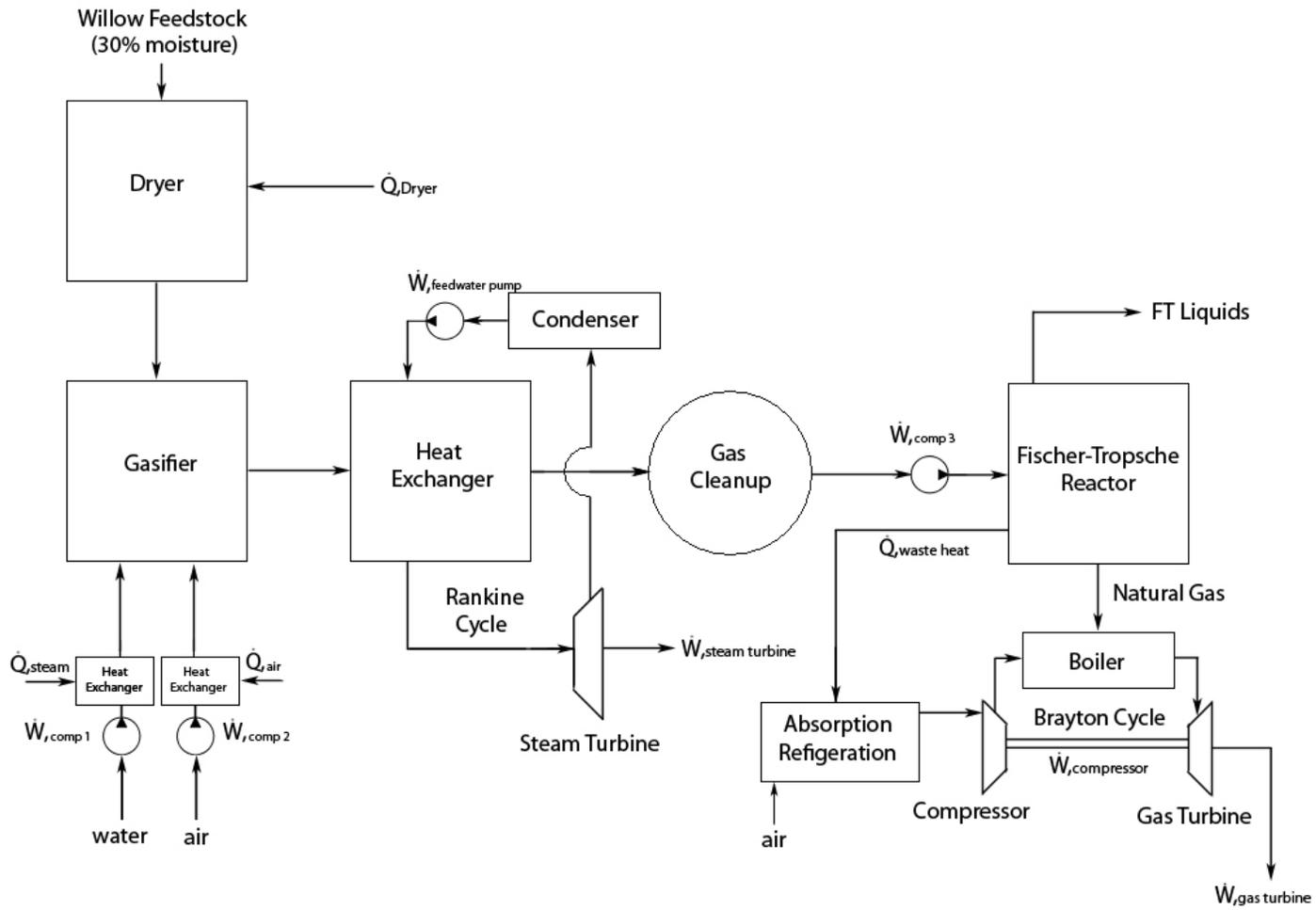


Figure 3-12. Control volume for an airblown system

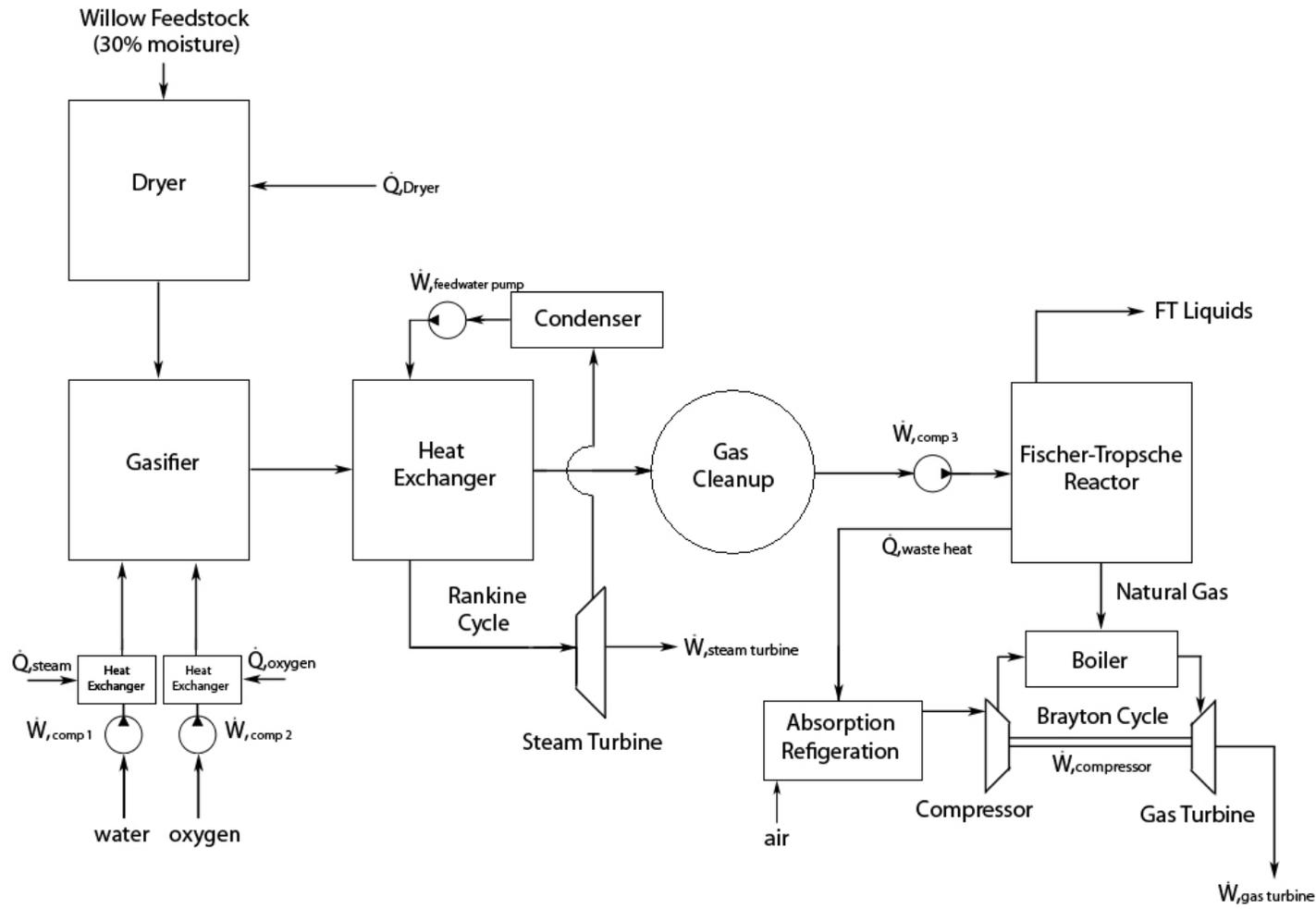


Figure 3-13. Control volume for an oxygen-blown system

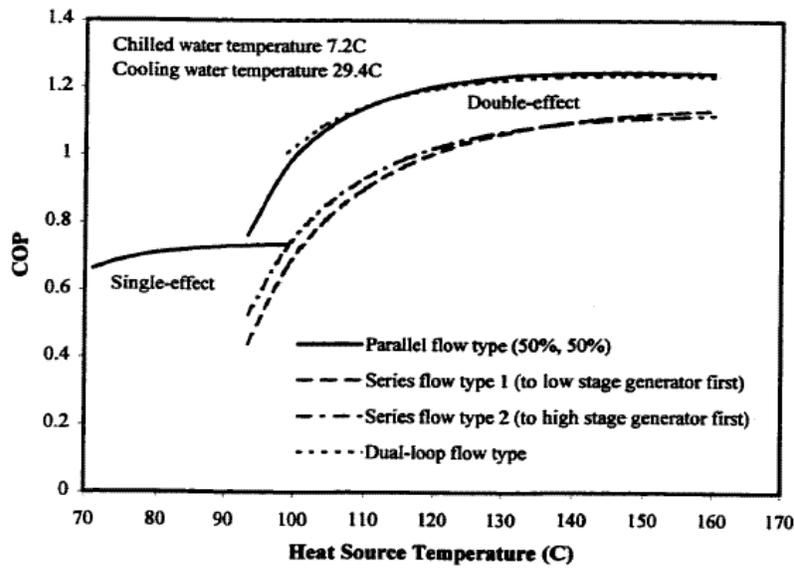


Figure 3-14. COP vs. heat source temperature for various chillers (Lee et al. 2001)

Table 3-58. Gasifier 1 heat balance

Conservative		
Q_{dyrer}	1.498	MW
Q_{air}	1.148	MW
Q_{steam}	2.081	MW
$W_{comp, 3}$	1.156	MW
$W_{steam turbine}$	2.560	MW
Realistic		
Q_{dyrer}	1.963	MW
Q_{air}	1.505	MW
Q_{steam}	2.726	MW
$W_{comp, 3}$	1.515	MW
$W_{steam turbine}$	3.490	MW
Optimistic		
Q_{dyrer}	2.803	MW
Q_{air}	2.148	MW
Q_{steam}	3.892	MW
$W_{comp, 3}$	2.163	MW
$W_{steam turbine}$	5.940	MW

Table 3-59. Gasifier 2 heat balance

Conservative	
Q_{dryer}	1.123 MW
Q_{steam}	3.723 MW
Q_{O_2}	0.453 MW
$W_{\text{oxygen production}}$	1.255 MW
$W_{\text{pump,4}}$	0.177 MW
$W_{\text{steam turbine}}$	3.510 MW
Realistic	
Q_{dryer}	1.472 MW
Q_{steam}	4.879 MW
Q_{O_2}	0.593 MW
$W_{\text{oxygen production}}$	1.694 MW
$W_{\text{pump,4}}$	0.803 MW
$W_{\text{steam turbine}}$	5.030 MW
Optimistic	
Q_{dryer}	2.102 MW
Q_{steam}	6.965 MW
Q_{O_2}	0.847 MW
$W_{\text{oxygen production}}$	2.347 MW
$W_{\text{pump,4}}$	1.146 MW
$W_{\text{steam turbine}}$	7.830 MW

Table 3-60. Gasifier 3 heat balance

Conservative	
Q_{dryer}	1.123 MW
Q_{air}	1.105 MW
Q_{steam}	3.724 MW
$W_{\text{comp, 3}}$	1.113 MW
$W_{\text{steam turbine}}$	2.080 MW
Realistic	
Q_{dryer}	1.472 MW
Q_{air}	1.446 MW
Q_{steam}	4.879 MW
$W_{\text{comp, 3}}$	1.458 MW
$W_{\text{steam turbine}}$	3.290 MW
Optimistic	
Q_{dryer}	2.102 MW
Q_{air}	2.064 MW
Q_{steam}	6.966 MW
$W_{\text{comp, 3}}$	2.081 MW
$W_{\text{steam turbine}}$	4.550 MW

Table 3-61. Gasifier 4 heat balance

Conservative		
Q _{dryer}	1.123	MW
Q _{air}	0.743	MW
Q _{steam}	2.081	MW
W _{comp, 3}	1.113	MW
W _{steam turbine}	2.290	MW
Realistic		
Q _{dryer}	1.472	MW
Q _{air}	0.976	MW
Q _{steam}	2.726	MW
W _{comp, 3}	1.458	MW
W _{steam turbine}	3.290	MW
Optimistic		
Q _{dryer}	2.102	MW
Q _{air}	1.39	MW
Q _{steam}	3.892	MW
W _{comp, 3}	2.081	MW
W _{steam turbine}	4.90	MW

Table 3-62. Gasifier 5 heat balance

Conservative		
Q _{dryer}	1.123	MW
Q _{steam}	4.819	MW
Q _{O₂}	0.453	MW
W _{oxygen production}	3.436	MW
W _{comp, 3}	0.613	MW
W _{steam turbine}	2.810	MW
Realistic		
Q _{dryer}	1.472	MW
Q _{steam}	6.314	MW
Q _{O₂}	0.593	MW
W _{oxygen production}	4.504	MW
W _{comp, 3}	0.803	MW
W _{steam turbine}	4.050	MW
Optimistic		
Q _{dryer}	2.102	MW
Q _{steam}	9.014	MW
Q _{O₂}	0.847	MW
W _{oxygen production}	6.427	MW
W _{comp, 3}	1.146	MW
W _{steam turbine}	6.230	MW

Table 3-63. Gasifier 6 heat balance

Conservative	
Q _{dryer}	1.123 MW
Q _{steam}	3.504 MW
Q _{O₂}	0.453 MW
W _{oxygen production}	3.945 MW
W _{comp, 3}	0.613 MW
W _{steam turbine}	3.030 MW

Realistic	
Q _{dryer}	1.472 MW
Q _{steam}	4.592 MW
Q _{O₂}	0.593 MW
W _{oxygen production}	5.168 MW
W _{comp, 3}	0.803 MW
W _{steam turbine}	4.040 MW

Optimistic	
Q _{dryer}	2.102 MW
Q _{steam}	6.556 MW
Q _{O₂}	0.847 MW
W _{oxygen production}	7.379 MW
W _{comp, 3}	1.146 MW
W _{steam turbine}	6.310 MW

CHAPTER 4 RESULTS

4.1 Life Cycle Assessment

The first results obtained from the LCA were for farming operations needed to grow and harvest willow. It should be noted that all energy balances are a ratio of the useful energy of the product to the fossil fuel energy put into the product. In addition, solar energy was not included in any of the data. The results for the farming operations can be seen in Figures 4-1 through 4-4. All four pathways had equivalent emissions of NO_x and SO_x , since all the pathways used emissions data for these gases from pathway one. The energy inputs are listed in units of megajoules per hectare, and emissions are listed as kilograms per hectare; both correspond to one hectare over the full life cycle of a willow farm. In addition, the units are not yet in terms of the function unit, since fuel has not been produced as yet. The results indicate that fertilizer utilization (including manufacturing and application) and biomass harvesting represent the most energy intensive tasks and result in the highest CO_2 emissions. Biomass harvesting is the only farming operation that releases significant NO_x emissions, while planting, fertilizer utilization, and machine manufacturing release the most SO_x emissions of all the farm operations. The farming operation that varies the most between pathways, with respect to energy input, is fertilizer utilization. The least energy intensive farm operations take place in pathway 3, consuming about 72 GJ per hectare. Pathway 4 is the most energy intensive of the pathways, consuming about 105 GJ per hectare. The most energy-intensive, pathway-specific farm operation is fertilizer utilization in Pathway 4, consuming almost 55 GJ per hectare. The least energy intensive of all farming operations is first year coppicing.

Figure 4-5 illustrates the energy inputs for the major activities in farming operations for all four pathways. Energy from diesel and fertilizer utilization represents the most intense

activities. Energy from diesel consumption represents the highest energy input for pathways one and three, while fertilizer utilization represents the highest energy input for pathways two and four. Figures 4-6 and 4-7 illustrate the net energy balances of all the pathways, before and after biomass transportation, respectively. Results for realistic energy balances for modern day willow farms are between 50 and 70, before transportation, and between 30 and 36, after biomass transportation.

The final step in the agricultural phase was to calculate provisional greenhouse gas balances for carbon and nitrogen resulting from sequestration. The provisional data for carbon can be seen in Table 4-1. Results from this provisional analysis indicate that all four pathways result in a net carbon sink, thus capturing more carbon than is released into the atmosphere. A similar procedure was followed for nitrogen sequestration. All four pathways released about 33.2 kg of nitrogen per hectare. The provisional amount of nitrogen captured in the soil is 27 kg, per hectare. As a result, the system is not a nitrogen sink.

The second and final set of results will be for the entire FT diesel production process, including biomass cultivation, gasification, and FT synthesis. Tables 4-2 through 4-7 display the products for each production plant configuration. FT products are initially displayed in units of barrels per day produced, while electricity and waste heat are in units of megawatts. Steam turbine outputs are listed in terms of megawatts. Results displayed under the ‘after routing’ column refer to the products after accounting for the heat balance across the production plant. Results displayed under the “after inlet cooling” column refer to the products after the efficiency in the gas turbine is increased as a result of using the absorption refrigeration unit to cool turbine inlet air. Results displayed under the ‘after transportation’ column refer to products after taking into account the energy required transporting the fuel. It is assumed that the fuel travels 100

kilometers from the power plant, has a density of 3.017 kilograms per gallon, and a high heating value of 45.47 MJ per kilogram. Energy consumption and emissions for fuel transportation were calculated in the similar fashion to that was used for biomass transportation.

Figure 4-8 illustrates the energy balance for every production plant configuration used in this study. Energy balances listed in ‘after gasification’ include losses from biomass cultivation, transportation, and gasification. Energy balances listed in ‘after FT synthesis’ refer to losses for the entire life cycle up to the finished products, and include the energy from excess electricity produced. Energy balances listed in ‘after transportation’ include the losses from transporting the FT diesel to a pumping station. It can be seen that fuel transportation has a negligible effect on overall energy balances for airblown concepts, such as gasifier one, since only minimal amount of FT diesel were produced. However, for cases where maximum FT fuel production was sought, such as gasifier six, energy balances were significantly affected by fuel transportation. Gasifier six experiences a net reduction of about 10 units in the energy balance as a result of fuel transportation. Also, it should be noted that waste heat was not included in calculating energy balances.

Figure 4-9 illustrates the results of the impact assessment phase for global warming for all production plant configurations. The units for emissions are listed in terms of the functional unit. Figures 4-10 illustrates the results of the impact assessment phase for acid rain for all production plant configurations. The data for Figures 4-9 and 4-10 were taken from the average of conservative, realistic, and optimistic pathways. The maximum value for CO₂ equivalent emissions in Figure 4-9 is for gasifier one paired with FT-reactor four, releasing more than 90 grams per MJ of fuel produced. The minimum value for CO₂ equivalent emissions in Figure 4-9 is for gasifier six paired with FT-reactor four, releasing less than 50 grams per MJ of fuel

produced. The maximum value for SO_x emissions in Figure 4-10 is for gasifier one paired with FT-reactor for, releasing less than 70 mg per MJ of fuel produced. Gasifier six paired with FT-reactor four releases about 35 mg per MJ of fuel produced, which is represents the least SO_x emissions of all production plant configurations.

Next, Figure 4-11 displays the output rates of FT diesel, electricity, and waste heat for all airblown configurations. The airblown configuration with the highest rate of FT diesel production is FT-reactor four coupled with gasifier one, producing about 14 MW of FT diesel. The configuration with the most electricity produced is FT-reactor one coupled with gasifier one, producing about 23 MW_{elec} . Also, the configuration releasing the highest rate of waste heat is FT-reactor one coupled with gasifier four, releasing about 27 MW_{th} of waste heat. Figure 4-12 displays similar output rates, but for oxygen-blown configurations. It can be seen that FT production dominates all the streams, as expected. The highest rates of FT diesel production are reached by several configurations, resulting in almost 35 MW of fuel production. If maximum FT diesel production is sought, FT-reactor three is the best choice.

Figure 4-13 illustrates the production rates of FT diesel for all production plant configurations. As expected, oxygen-blown concepts produce significantly higher rates of FT diesel than airblown concepts.

Lastly, Tables 4-8, 4-9, and 4-10 display the average, maximum, and minimum energy balance results for each of the three predicted harvested yields, at three different phases of the fuel life cycle. The data displayed is only for realistic pathways, and does not necessarily correspond to Figure 4-8, which is based on averages from conservative, realistic, and optimistic pathways. The average realistic energy balances following gasification, FT synthesis, and transportation are 26.6, 14.2, and 9.5, respectively. The maximum realistic energy balances for

the same phases are 31.2, 13.4, and 12.1, respectively, while the minimum realistic energy balances are 23.9, 8.1, and 7.1, respectively.

4.2 Comparison of Results with Other LCAs

Results from this LCA were compared to results from other LCAs done on similar systems, as a means for checking the validity and general accuracy of the results. The farming operations results were the first set of data to be compared. From this study, the average realistic emissions from all four pathways was 1.18 grams CO₂ released per MJ of biomass harvested, along with an average realistic energy balance of 62, before biomass transportation takes place. A study by Heller resulted in 0.68 grams of CO₂ released per MJ of harvested biomass, and an accompanying energy balance of 55 (Heller et al. 2003). The emissions are lower most likely since Heller's study did not include energy required for machine transportation and diesel fuel production, as well as the fact that study was based on a relatively small, 200 hectare field. A study by R.W. Matthews resulted in between 1.2 and 1.4 grams of CO₂ being released per MJ of harvested biomass, and an accompanying energy balance of 27 (Matthews 2001). The emissions results are very similar to that of this study; however, the energy balances vary significantly. This is most likely as a result of Matthew's study including energy required for posting fences, drying, and storage. A study by Roman resulted in 1 gram of CO₂ released per MJ of biomass, with an accompanying energy balance of 33 (Roman et al. 1997). The emission results are similar to that of this study, and the energy balance is significantly lower, most likely since data from the 1980's was used for Roman's study. Lastly, a study by Cannell resulted in CO₂ emissions between 0.5 and 2.0 grams, per MJ of biomass produced (Cannell 2003). Results from Cannell's study agree with that of this study.

Lastly, results for the full LCA of FT diesel from this study will be compared to results from similar studies. It should be noted that there are relatively few studies done for the life cycle of FT diesel made from willow biomass. A study by Semelsberger results in sequestration of 600 grams of CO₂ per MJ of FT diesel produced (Semelsberger 2005). This result cannot be compared accurately because data on carbon sequestration was considered to be provisional. A study by Beer et al. on FT diesel produced from natural gas resulted in 100 grams of CO₂ emissions per MJ of FT diesel produced, which is slightly higher than the average emissions from this study (Beer et al. 2001). Lastly, a study by S. Alhgren et al. for the full life cycle of FT diesel from woody biomass resulted in an energy balance of 9.6, which falls into the energy balance range of this study (Alhgren et al. 2008). It can be concluded that results from this study are comparable to the results of other published studies.

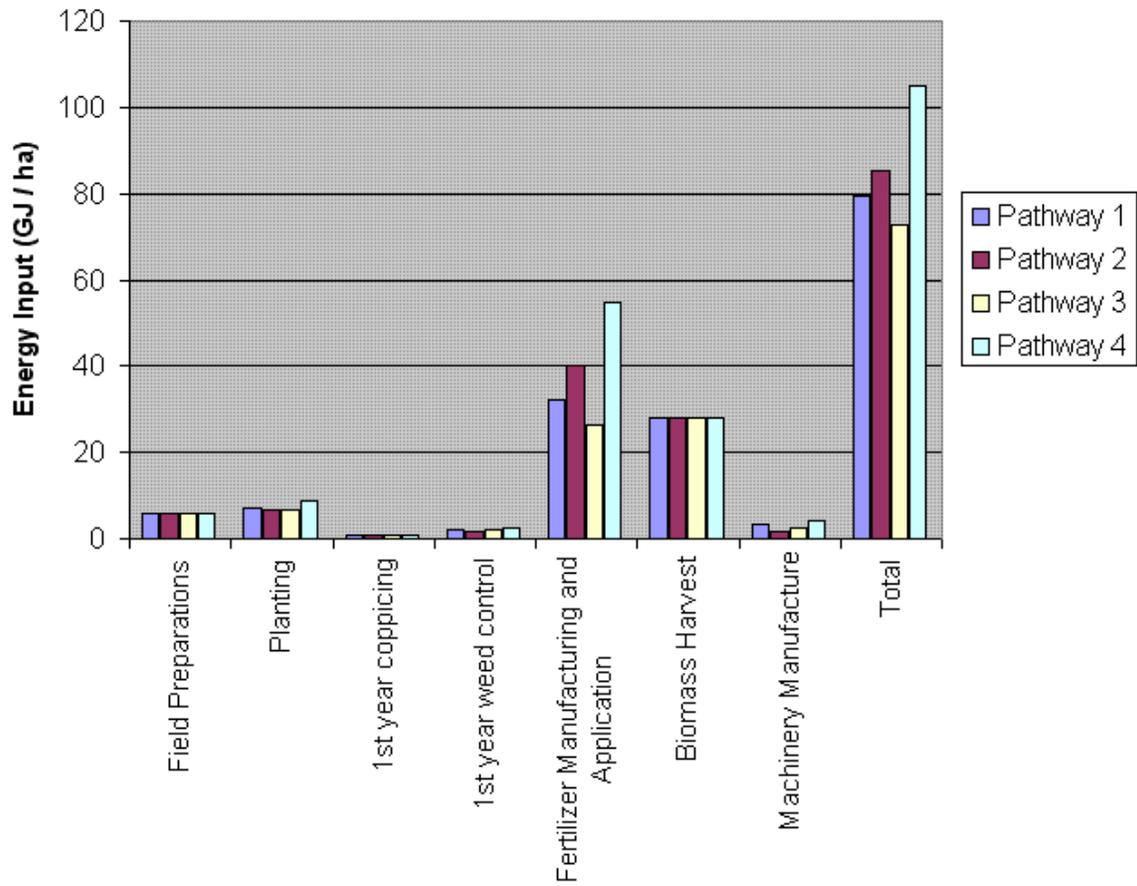


Figure 4-1. Energy inputs from farming operations for all pathways

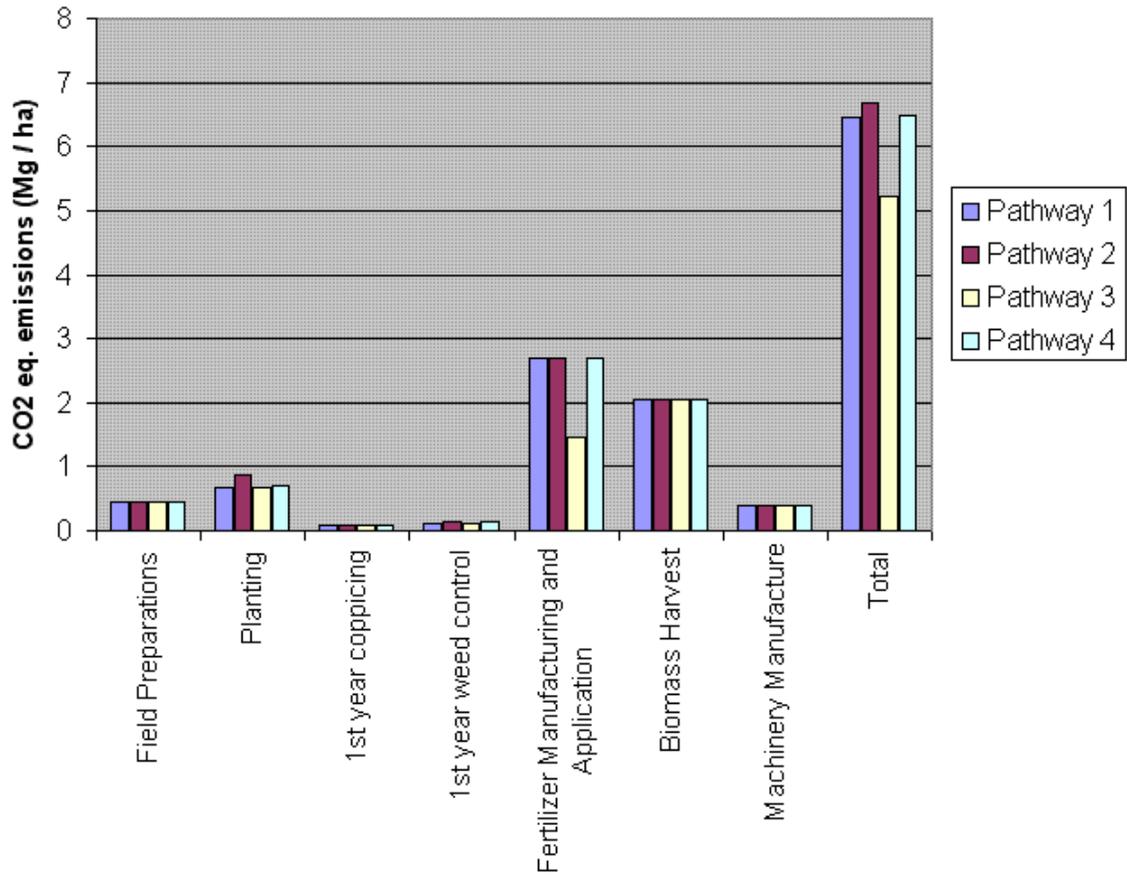


Figure 4-2. CO₂ emission from farming operations for all pathways

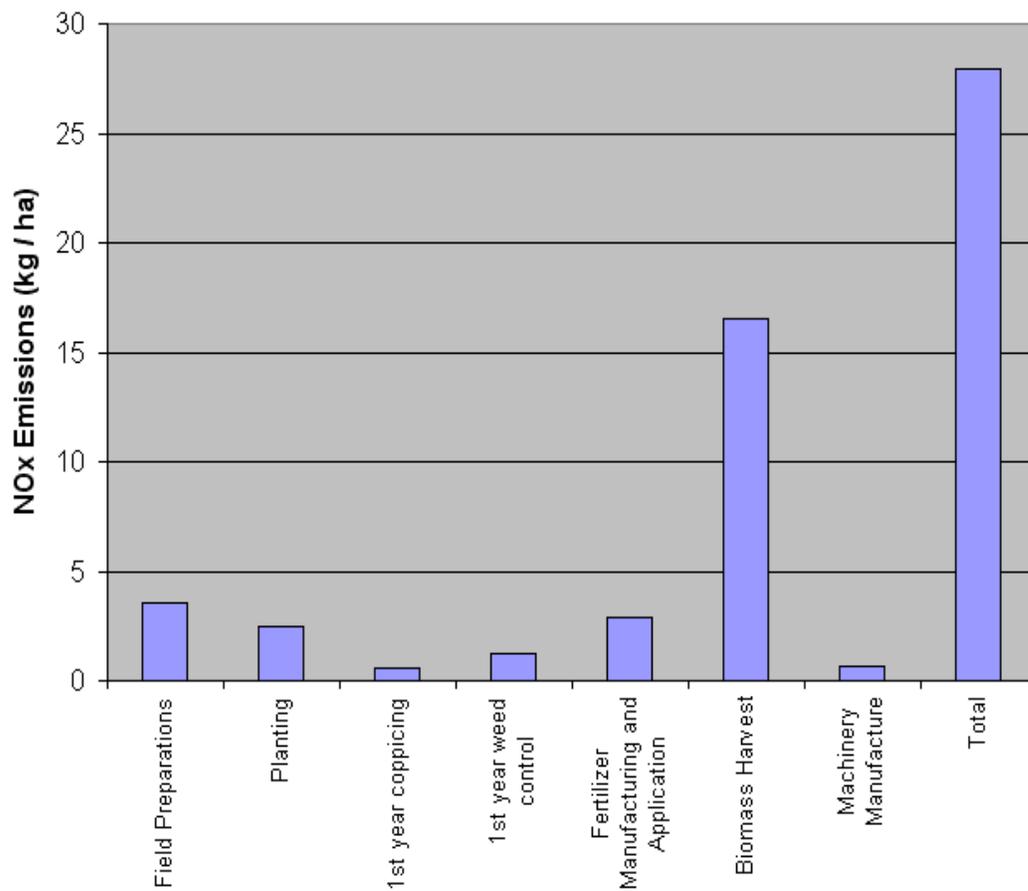


Figure 4-3. NO_x emissions from farming operations for all pathways

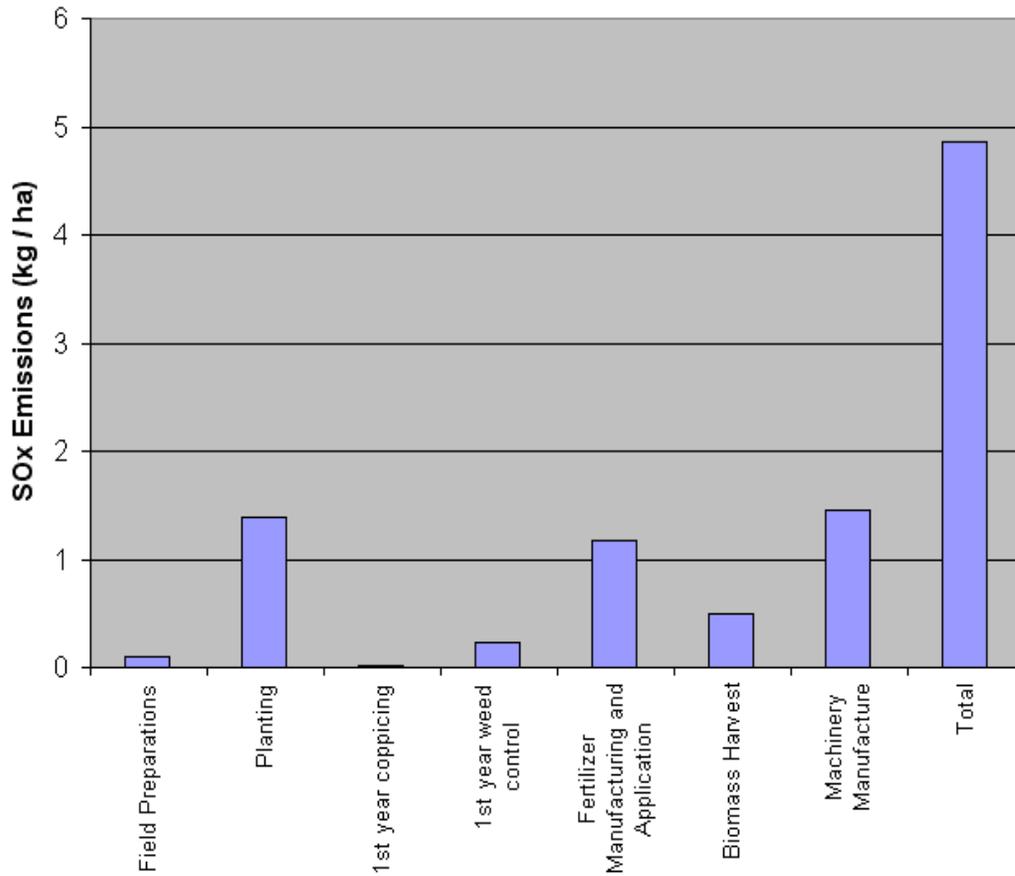


Figure 4-4. SO_x emissions from farming operations for all pathways

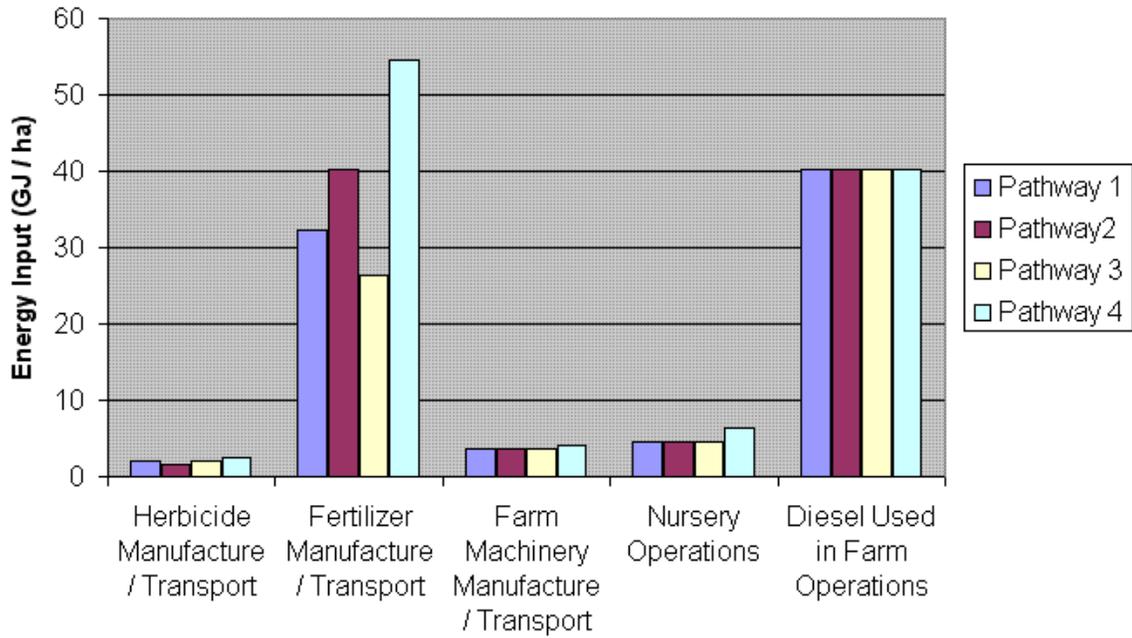


Figure 4-5. Breakdown of major energy activities for all pathways

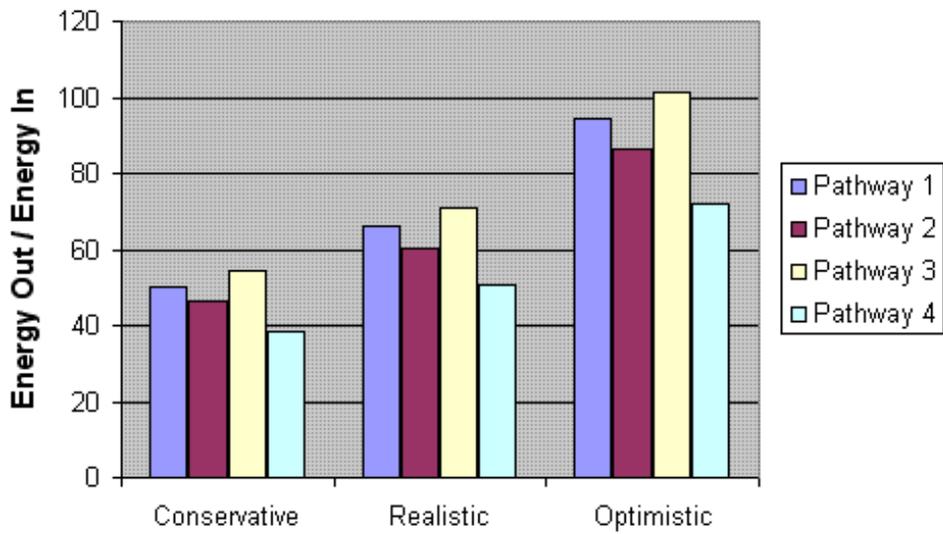


Figure 4-6. Energy balance for all pathways, prior to biomass transportation

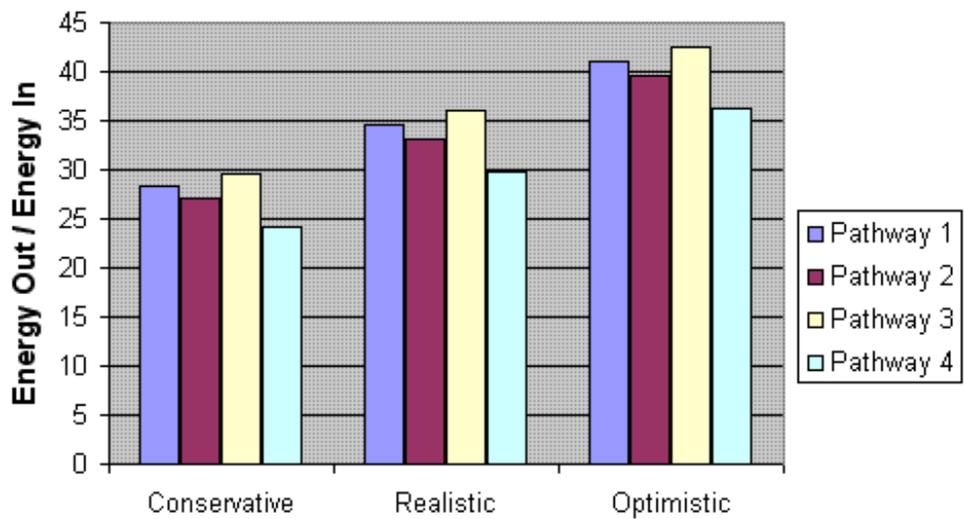


Figure 4-7. Energy balance for all pathways, after biomass transportation

Table 4-1. Provisional carbon sequestration calculations

Pathway	Total C released Mg C / ha	Total C sequestered Mg C / ha	Balance Mg C / ha
1	11.18	12.14	-0.96
2	11.38	12.14	-0.76
3	9.95	12.14	-2.19
4	11.21	12.14	-0.93

Table 4-2. Gasifier 1 + FT-reactor configurations and outputs

Gasifier 1 - FT-reactor 1						
FT-reactor output	Output	Units	After routing	After inlet cooling	After transportation	Units
Conservative	195	Barrels / day	12.36	12.36	10.18	MW _{th}
Steam turbine output	6.50	MW electricity	7.91	17.85	17.85	MW _{elec}
2.56 MW	21.63	MW heat	16.90	10.14	10.14	MW _{th}
Realistic	256	Barrels / day	16.19	16.19	13.33	MW _{th}
Steam turbine output	8.72	MW electricity	8.72	23.52	23.52	MW _{elec}
3.49 MW	28.33	MW heat	22.14	13.96	13.96	MW _{th}
Optimistic	365	Barrels / day	23.11	23.11	19.04	MW _{th}
Steam turbine output	12.82	MW electricity	16.60	34.53	34.53	MW _{elec}
5.94 MW	40.44	MW heat	31.60	21.47	21.47	MW _{th}

Gasifier 1 - FT-reactor 2						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	276	Barrels / day	17.48	17.48	14.41	MW _{th}
Steam turbine output	5.24	MW electricity	6.65	14.89	14.89	MW _{elec}
2.56 MW	20.35	MW heat	15.62	9.86	9.86	MW _{th}
Realistic	362	Barrels / day	22.90	22.90	18.87	MW _{th}
Steam turbine output	7.03	MW electricity	9.00	19.64	19.64	MW _{elec}
3.49 MW	26.65	MW heat	20.46	13.61	13.61	MW _{th}
Optimistic	516	Barrels / day	32.69	32.69	26.94	MW _{th}
Steam turbine output	10.34	MW electricity	14.12	28.99	28.99	MW _{elec}
5.94 MW	38.05	MW heat	29.20	20.34	20.34	MW _{th}

Gasifier 1 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	203	Barrels / day	12.86	12.86	10.60	MW _{th}
Steam turbine output	10.13	MW electricity	11.54	11.96	11.96	MW _{elec}
2.56 MW	6.11	MW heat	1.38	0.00	0.00	MW _{th}
Realistic	266	Barrels / day	16.85	16.85	13.89	MW _{th}
Steam turbine output	13.27	MW electricity	15.25	15.81	15.81	MW _{elec}
3.49 MW	8.00	MW heat	1.81	0.00	0.00	MW _{th}
Optimistic	380	Barrels / day	24.05	24.05	19.82	MW _{th}
Steam turbine output	18.95	MW electricity	22.72	23.52	23.52	MW _{elec}
5.94 MW	11.43	MW heat	2.58	0.00	0.00	MW _{th}

Table 4-3. Gasifier 2 + FT-reactor configurations and outputs

Gasifier 2 - FT-reactor 3						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	487	Barrels / day	30.83	30.83	25.40	MW _{th}
Steam turbine output	0.75	MW electricity	2.83	5.16	5.16	MW _{elec}
3.51 MW	17.43	MW heat	12.13	9.08	9.08	MW _{th}
Realistic	637	Barrels / day	40.39	40.39	33.29	MW _{th}
Steam turbine output	1.01	MW electricity	3.55	5.54	5.54	MW _{elec}
5.03 MW	22.83	MW heat	15.89	12.73	12.73	MW _{th}
Optimistic	910	Barrels / day	57.65	57.65	47.51	MW _{th}
Steam turbine output	1.50	MW electricity	5.84	8.62	8.62	MW _{elec}
7.83 MW	32.60	MW heat	22.68	19.64	19.64	MW _{th}
Gasifier 2 - FT-reactor 3mod						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	487	Barrels / day	30.83	30.83	25.40	MW _{th}
Steam turbine output	1.39	MW electricity	3.46	6.07	6.07	MW _{elec}
3.51 MW	15.52	MW heat	10.22	7.73	7.73	MW _{th}
Realistic	637	Barrels / day	40.39	40.39	33.29	MW _{th}
Steam turbine output	1.86	MW electricity	4.40	7.76	7.76	MW _{elec}
5.03 MW	20.33	MW heat	13.39	10.17	10.17	MW _{th}
Optimistic	910	Barrels / day	57.65	57.65	47.51	MW _{th}
Steam turbine output	2.75	MW electricity	7.09	11.80	11.80	MW _{elec}
7.83 MW	29.02	MW heat	19.11	14.59	14.59	MW _{th}
Gasifier 2 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	224	Barrels / day	14.17	14.17	11.67	MW _{th}
Steam turbine output	11.84	MW electricity	13.92	13.81	13.81	MW _{elec}
3.51 MW	5.19	MW heat	-0.11	0.00	0.00	MW _{th}
Realistic	293	Barrels / day	18.56	18.56	15.30	MW _{th}
Steam turbine output	15.51	MW electricity	18.05	17.90	17.90	MW _{elec}
5.03 MW	6.80	MW heat	-0.14	0.00	0.00	MW _{th}
Optimistic	418	Barrels / day	26.50	26.50	21.84	MW _{th}
Steam turbine output	22.14	MW electricity	26.48	26.27	26.27	MW _{elec}
7.83 MW	9.71	MW heat	-0.21	0.00	0.00	MW _{th}

Table 4-4. Gasifier 3 + FT-reactor configurations and outputs

Gasifier 3 - FT-reactor 1						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	181	Barrels / day	11.41	11.41	9.40	MW _{th}
Steam turbine output	5.97	MW electricity	6.93	16.16	16.16	MW _{elec}
2.08 MW	19.98	MW heat	14.03	7.60	7.60	MW _{th}
Realistic	236	Barrels / day	14.95	14.95	12.32	MW _{th}
Steam turbine output	8.00	MW electricity	9.83	21.73	21.73	MW _{elec}
3.29 MW	26.17	MW heat	18.37	10.61	10.61	MW _{th}
Optimistic	337	Barrels / day	21.35	21.35	17.59	MW _{th}
Steam turbine output	11.77	MW electricity	14.24	30.88	30.88	MW _{elec}
4.55 MW	37.36	MW heat	26.23	16.73	16.73	MW _{th}

Gasifier 3 - FT-reactor 2						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	255	Barrels / day	16.15	16.15	13.31	MW _{th}
Steam turbine output	4.81	MW electricity	5.78	13.42	13.42	MW _{elec}
2.08 MW	18.79	MW heat	12.84	7.52	7.52	MW _{th}
Realistic	334	Barrels / day	21.16	21.16	17.43	MW _{th}
Steam turbine output	6.45	MW electricity	8.28	18.15	18.15	MW _{elec}
3.29 MW	24.62	MW heat	16.82	10.13	10.13	MW _{th}
Optimistic	477	Barrels / day	30.20	30.20	24.88	MW _{th}
Steam turbine output	9.49	MW electricity	11.96	25.76	25.76	MW _{elec}
4.55 MW	35.15	MW heat	24.01	15.57	15.57	MW _{th}

Gasifier 3 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	261	Barrels / day	16.50	16.50	13.59	MW _{th}
Steam turbine output	4.37	MW electricity	5.34	10.96	10.96	MW _{elec}
2.08 MW	20.87	MW heat	14.92	10.45	10.45	MW _{th}
Realistic	341	Barrels / day	21.61	21.61	17.81	MW _{th}
Steam turbine output	5.73	MW electricity	7.56	14.92	14.92	MW _{elec}
3.29 MW	27.34	MW heat	19.54	13.84	13.84	MW _{th}
Optimistic	487	Barrels / day	30.85	30.85	25.42	MW _{th}
Steam turbine output	8.17	MW electricity	10.64	21.15	21.15	MW _{elec}
4.55 MW	39.03	MW heat	27.89	20.51	20.51	MW _{th}

Table 4-5. Gasifier 4 + FT-reactor configurations and outputs

Gasifier 4 - FT-reactor 1						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	190	Barrels / day	11.99	11.99	9.87	MW _{th}
Steam turbine output	6.29	MW electricity	7.47	17.13	17.13	MW _{elec}
2.29 MW	20.98	MW heat	17.03	10.48	10.48	MW _{th}
Realistic	248	Barrels / day	15.70	15.70	12.94	MW _{th}
Steam turbine output	8.44	MW electricity	10.27	22.73	22.73	MW _{elec}
3.29 MW	27.48	MW heat	22.31	14.29	14.29	MW _{th}
Optimistic	354	Barrels / day	22.41	22.41	18.47	MW _{th}
Steam turbine output	12.40	MW electricity	15.22	32.65	32.65	MW _{elec}
4.90 MW	39.23	MW heat	31.84	22.10	22.10	MW _{th}

Gasifier 4 - FT-reactor 2						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	268	Barrels / day	16.96	16.96	13.97	MW _{th}
Steam turbine output	5.07	MW electricity	6.25	14.26	14.26	MW _{elec}
2.29 MW	19.73	MW heat	15.79	10.32	10.32	MW _{th}
Realistic	351	Barrels / day	22.21	22.21	18.30	MW _{th}
Steam turbine output	6.80	MW electricity	8.63	18.97	18.97	MW _{elec}
3.29 MW	25.85	MW heat	20.68	13.74	13.74	MW _{th}
Optimistic	501	Barrels / day	31.71	31.71	26.13	MW _{th}
Steam turbine output	10.01	MW electricity	12.82	27.28	27.28	MW _{elec}
4.90 MW	36.90	MW heat	29.52	20.86	20.86	MW _{th}

Gasifier 4 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	233	Barrels / day	14.75	14.75	12.15	MW _{th}
Steam turbine output	12.33	MW electricity	13.50	13.63	13.63	MW _{elec}
2.29 MW	5.40	MW heat	1.46	0.00	0.00	MW _{th}
Realistic	305	Barrels / day	19.32	19.32	15.92	MW _{th}
Steam turbine output	16.15	MW electricity	17.98	18.13	18.13	MW _{elec}
3.29 MW	7.08	MW heat	1.90	0.00	0.00	MW _{th}
Optimistic	435	Barrels / day	27.58	27.58	22.73	MW _{th}
Steam turbine output	23.05	MW electricity	25.87	26.72	26.72	MW _{elec}
4.90 MW	10.10	MW heat	2.72	0.00	0.00	MW _{th}

Table 4-6. Gasifier 5 + FT-reactor configurations and outputs

Gasifier 5 - FT-reactor 3						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	507	Barrels / day	32.09	32.09	26.44	MW _{th}
Steam turbine output	0.79	MW electricity	-0.45	1.15	1.15	MW _{elec}
2.81 MW	18.14	MW heat	11.75	9.63	9.63	MW _{th}
Realistic	663	Barrels / day	42.04	42.04	34.65	MW _{th}
Steam turbine output	1.06	MW electricity	-0.20	1.87	1.87	MW _{elec}
4.05 MW	23.77	MW heat	15.39	12.64	12.64	MW _{th}
Optimistic	947	Barrels / day	60.01	60.01	49.46	MW _{th}
Steam turbine output	1.57	MW electricity	-0.08	3.12	3.12	MW _{elec}
6.23 MW	33.93	MW heat	21.97	18.09	18.09	MW _{th}
Gasifier 5 - FT-reactor 3mod						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	507	Barrels / day	32.09	32.09	26.44	MW _{th}
Steam turbine output	1.45	MW electricity	0.21	2.91	2.91	MW _{elec}
2.81 MW	16.16	MW heat	9.76	6.40	6.40	MW _{th}
Realistic	663	Barrels / day	42.04	42.04	34.65	MW _{th}
Steam turbine output	1.95	MW electricity	0.69	4.18	4.18	MW _{elec}
4.05 MW	21.16	MW heat	12.78	8.44	8.44	MW _{th}
Optimistic	947	Barrels / day	60.01	60.01	49.46	MW _{th}
Steam turbine output	2.87	MW electricity	1.53	6.42	6.42	MW _{elec}
6.23 MW	30.21	MW heat	18.25	12.11	12.11	MW _{th}
Gasifier 5 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	175	Barrels / day	11.06	11.06	9.11	MW _{th}
Steam turbine output	14.10	MW electricity	12.86	14.98	14.98	MW _{elec}
2.81 MW	30.20	MW heat	23.80	20.96	20.96	MW _{th}
Realistic	229	Barrels / day	14.49	14.49	11.94	MW _{th}
Steam turbine output	18.47	MW electricity	17.22	19.99	19.99	MW _{elec}
4.05 MW	39.56	MW heat	31.18	28.21	28.21	MW _{th}
Optimistic	327	Barrels / day	20.69	20.69	17.04	MW _{th}
Steam turbine output	26.37	MW electricity	25.03	28.98	28.98	MW _{elec}
6.23 MW	56.47	MW heat	44.50	40.26	40.26	MW _{th}

Table 4-7. Gasifier 6 + FT-reactor configurations and outputs

Gasifier 6 - FT-reactor 3						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	507	Barrels / day	32.09	32.09	26.44	MW _{th}
Steam turbine output	0.79	MW electricity	-0.74	0.86	0.86	MW _{elec}
3.03 MW	18.14	MW heat	13.06	11.39	11.39	MW _{th}
Realistic	663	Barrels / day	42.04	42.04	34.65	MW _{th}
Steam turbine output	1.06	MW electricity	-0.87	1.19	1.19	MW _{elec}
4.04 MW	23.77	MW heat	17.11	14.94	14.94	MW _{th}
Optimistic	947	Barrels / day	60.01	60.01	49.46	MW _{th}
Steam turbine output	1.57	MW electricity	-0.65	2.25	2.25	MW _{elec}
6.31 MW	33.93	MW heat	24.42	21.37	21.37	MW _{th}

Gasifier 6 - FT-reactor 3mod						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	507	Barrels / day	32.09	32.09	26.44	MW _{th}
Steam turbine output	1.45	MW electricity	-0.08	2.63	2.63	MW _{elec}
3.03 MW	16.16	MW heat	11.08	8.54	8.54	MW _{th}
Realistic	663	Barrels / day	42.04	42.04	34.65	MW _{th}
Steam turbine output	1.95	MW electricity	1.43	3.51	3.51	MW _{elec}
4.04 MW	21.16	MW heat	14.51	12.41	12.41	MW _{th}
Optimistic	947	Barrels / day	60.01	60.01	49.46	MW _{th}
Steam turbine output	2.87	MW electricity	0.66	5.55	5.55	MW _{elec}
6.31 MW	30.21	MW heat	20.71	16.09	16.09	MW _{th}

Gasifier 6 - FT-reactor 4						
FT-reactor output	Output		After routing	After inlet cooling	After transportation	Units
Conservative	401	Barrels / day	25.39	25.39	20.92	MW _{th}
Steam turbine output	2.29	MW electricity	0.76	1.10	1.10	MW _{elec}
3.03 MW	27.68	MW heat	22.60	21.16	21.16	MW _{th}
Realistic	525	Barrels / day	33.26	33.26	27.41	MW _{th}
Steam turbine output	3.00	MW electricity	1.07	1.52	1.52	MW _{elec}
4.04 MW	36.26	MW heat	29.60	27.65	27.65	MW _{th}
Optimistic	749	Barrels / day	47.48	47.48	39.13	MW _{th}
Steam turbine output	4.28	MW electricity	2.06	2.70	2.70	MW _{elec}
6.31 MW	51.76	MW heat	42.25	39.03	39.03	MW _{th}

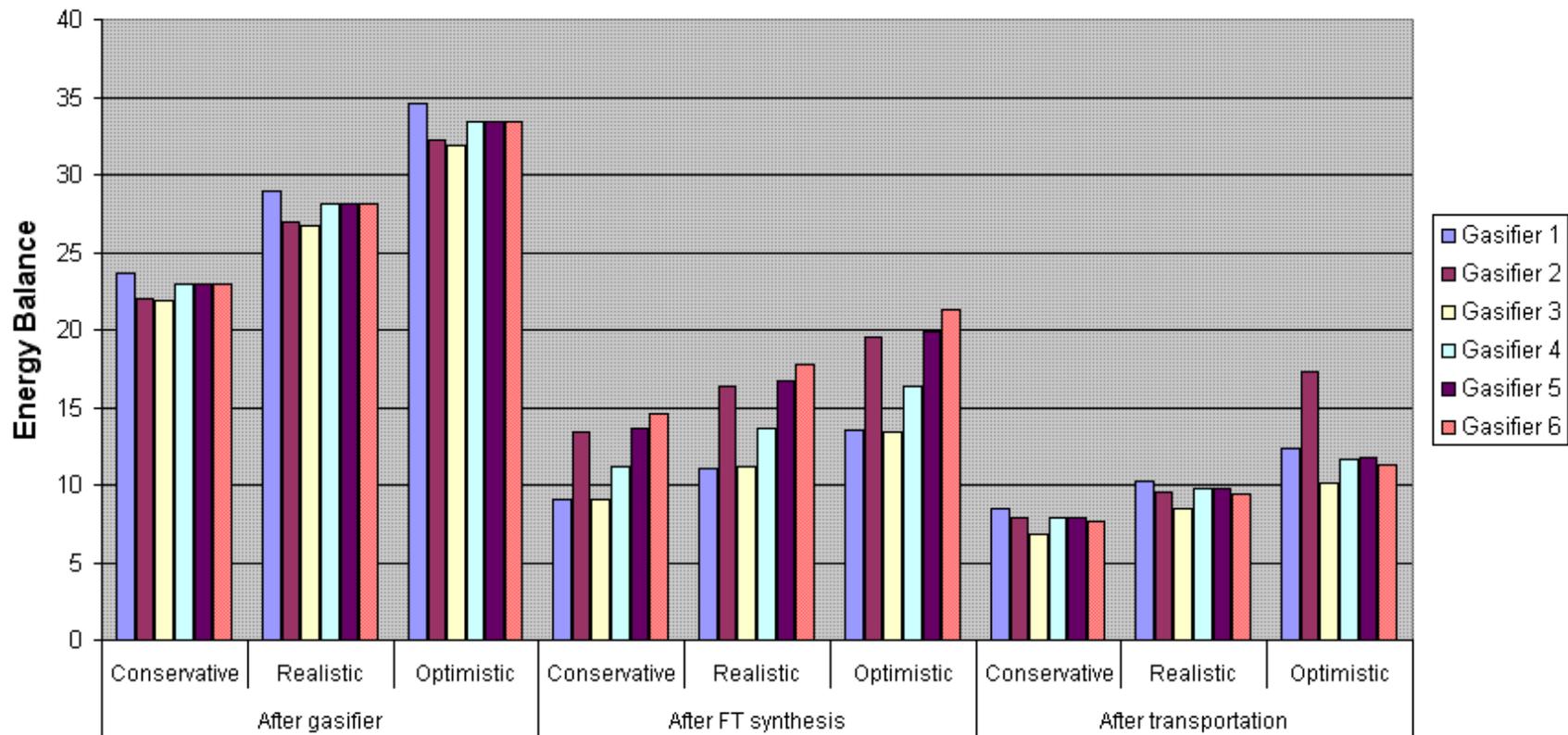


Figure 4-8. Averaged energy balances for all gasifiers, in various stages of FT diesel production

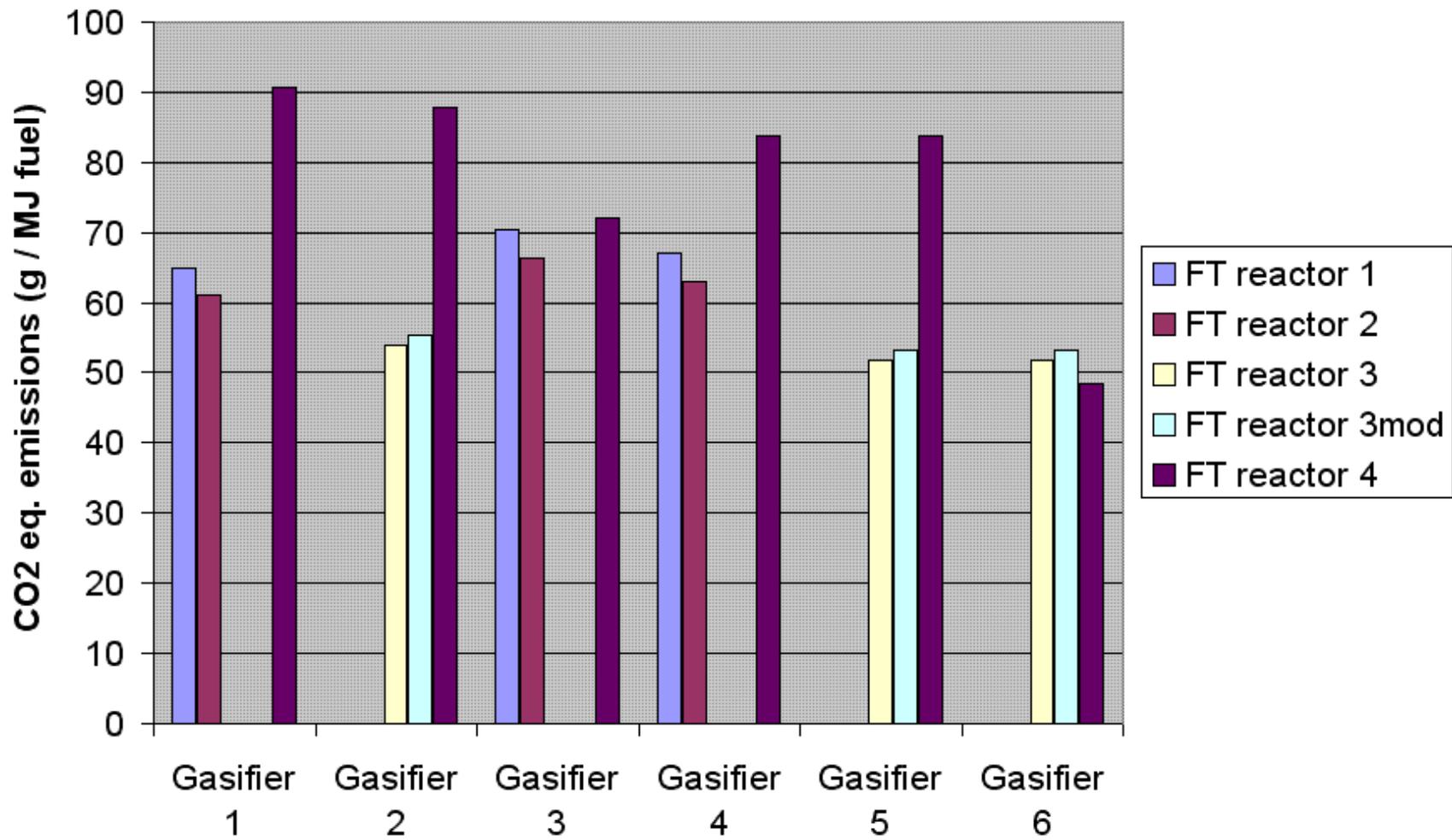


Figure 4-9. Global warming potential for all production plant configurations

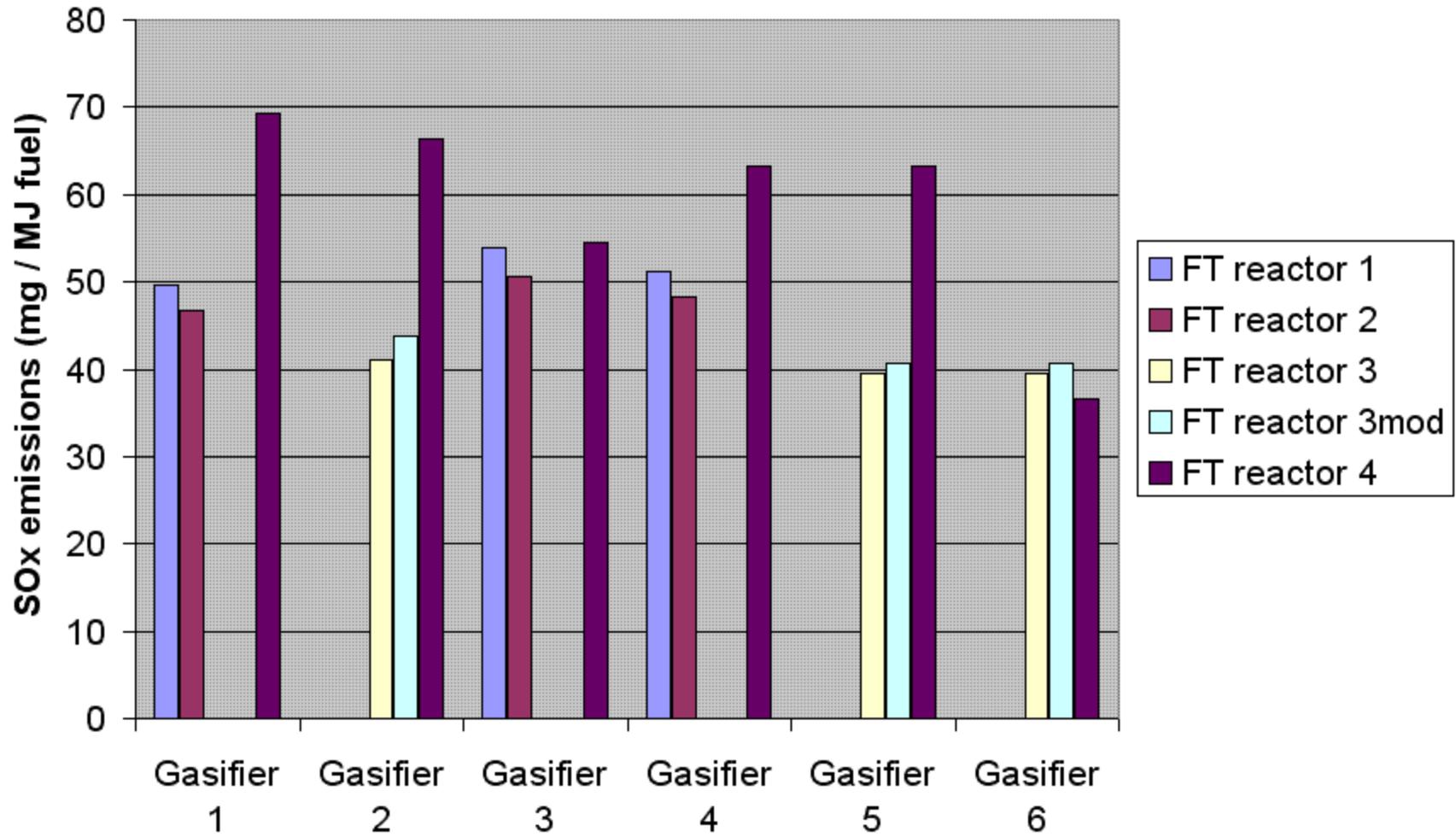


Figure 4-10. Acid rain potential for all production plant configurations

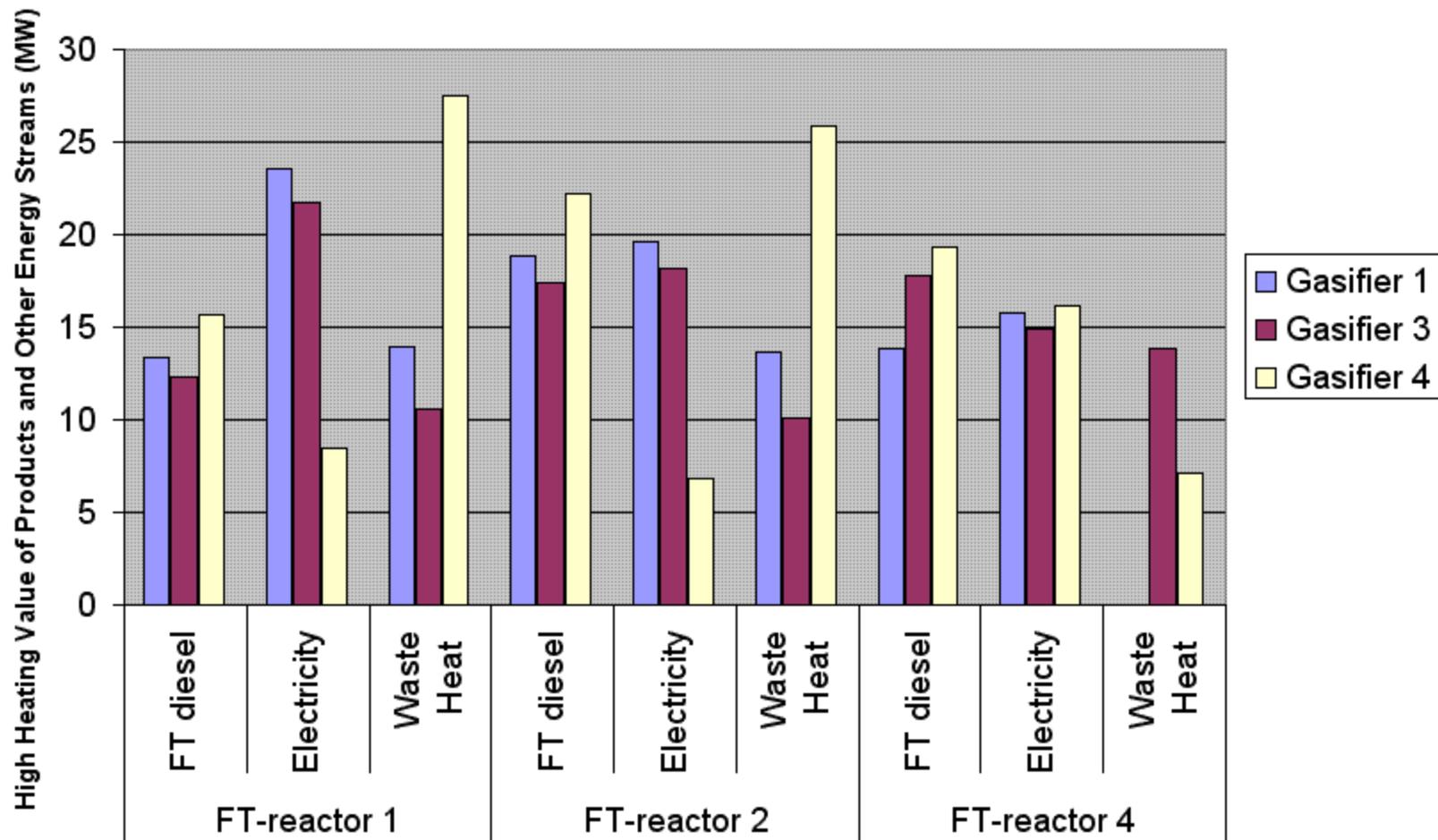


Figure 4-11. FT products for airblown configurations

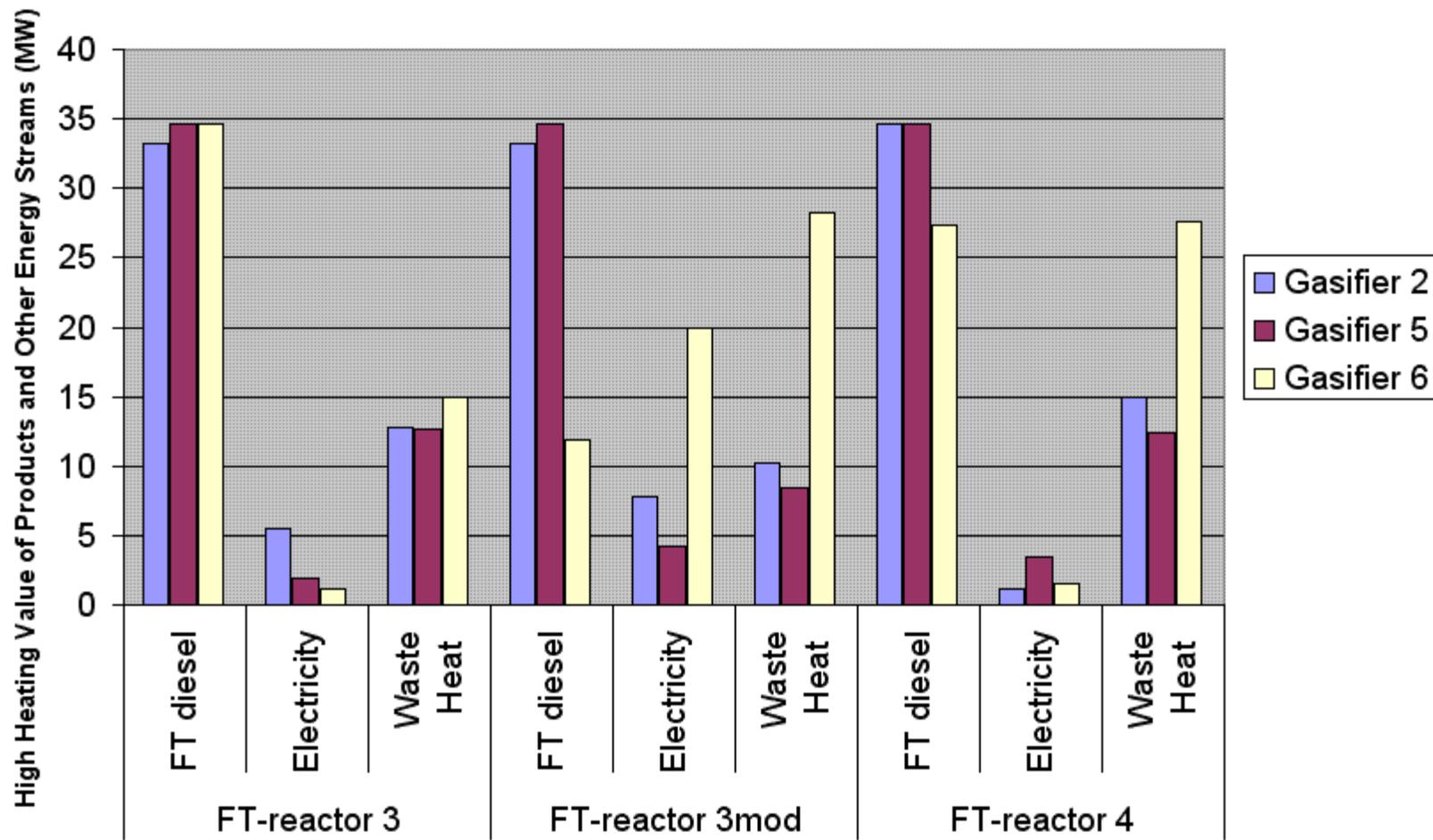


Figure 4-12. FT products for all oxygen-blown configurations

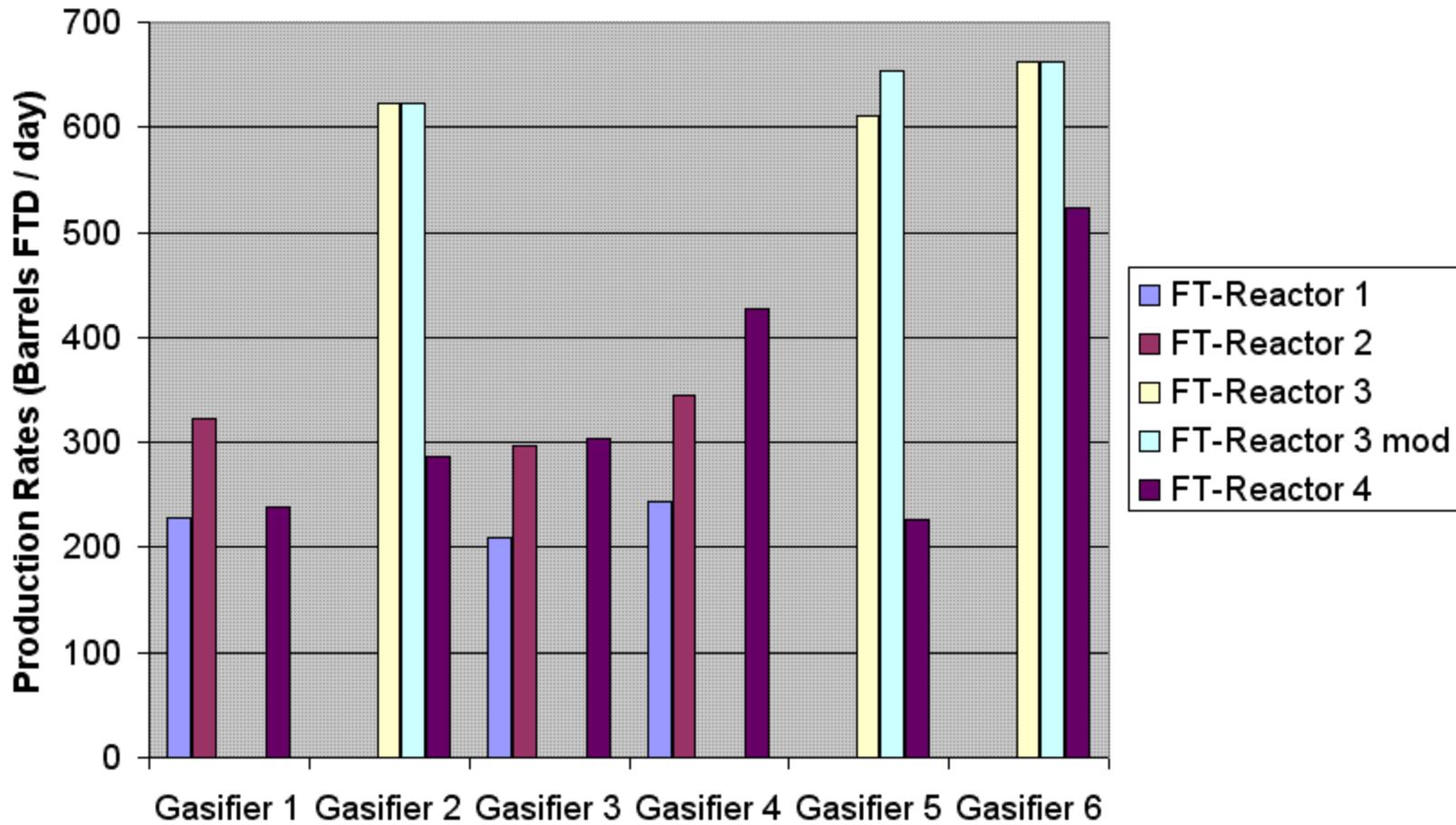


Figure 4-13. FT diesel production for all production plant configurations

Table 4-8. Average energy balance values at various stages of life cycle

	After gasification	After FT-reactor	After transportation
Conservative	21.8	11.6	7.7
Realistic	26.6	14.2	9.5
Optimistic	31.8	17.0	11.5

Table 4-9. Maximum energy balance values at various stages of life cycle

	After gasification	After FT-reactor	After transportation
Conservative	25.6	11.1	9.9
Realistic	31.2	13.4	12.1
Optimistic	36.8	16.2	14.5

Table 4-10. Minimum energy balance values at various stages of life cycle

	After gasification	After FT-reactor	After transportation
Conservative	19.4	6.5	5.7
Realistic	23.9	8.1	7.1
Optimistic	29.0	9.8	8.7

CHAPTER 5 DISCUSSION AND CONCLUSIONS

This study examined and quantified the overall energy balances and environmental impacts associated with the production of FT diesel from willow biomass feedstock grown on a theoretical 10,000-hectare farm. Several different pathways and production plant configurations were examined, so as to provide a range of results that are applicable to a variety of situations. A life cycle assessment was the tool used to implement the analysis, and was limited to the scope of well-to-pump analysis.

The results from the life cycle assessment indicate that FT diesel from willow biomass is favorable as a fossil fuel substitute with respects to environmental impact and energy balance, since conventional gasoline and diesel both have energy balances near 0.8 and CO₂ equivalent emissions near the upper limits to that of FT diesel (Sheehan 2004). The resulting high energy balances values indicate that FT diesel production from willow has the potential to be a sustainable practice, as small amounts of fossil fuel energy are needed to produce FT fuels with high energy content. When compared to other conventional and alternative fuels (Table 2-1), FT diesel has a lower global warming potential than conventional gasoline, diesel, natural gas, and LPG. Its potential for carbon sequestration further helps to reduce and minimize the effects of global warming. On a socioeconomic basis, FT diesel production also has the potential to increase jobs and enliven local economies, since many employees would be needed to work farm operations and the accompanying production plant.

Since employing the operation of a willow farm for fuel production has the potential for reducing the environmental impacts of global warming as well as acid rain, further research and development should be conducted. The results can be used to validate the feasibility of using a willow farm for FT diesel production. There are several recommendations that are advised for

future studies on similar systems. One idea that has potential is to replace nitrogen fertilizer with municipal sewage waste, thereby substituting one of the most energy-intensive tasks with a waste stream. Another idea for future study is to consider no-tillage or reduced-tillage farming, which has the potential to further increase carbon sequestration rates. Studies on similar systems could also include energy and emissions associated with production plant decommissioning, as well as considering human capital involved. Such factors could easily be integrated into an “energy” analysis rather than a life cycle assessment. Also, it would be important for future studies to include the monetary costs associated with FT diesel production, as businesses will only invest in the technology if it is economically feasible and profitable.

The results of this study also reveal the steps in the life cycle of FT diesel production which could be improved on to increase the overall efficiency of the life cycle and help reduce environmental impact. The most energy intensive and environmentally destructive steps were fertilizer production and biomass harvesting. For fertilizer production, research could be done to improve the efficiency of fertilizer production. In addition, further research could be done on the genetic engineering of willow trees, so as to reduce the amount of fertilizer needed by increasing the overall photosynthetic efficiency. For harvesting, research could be done on ways to improve the overall fuel consumption rates of tractors or even on different harvesting techniques. If the highest energy intensive tasks can be successfully reduced, it would further help to make FT diesel a desirable fossil fuel substitute. Using FT diesel synthesized at the power plant for the most energy intensive tasks is one natural solution to reducing environmental impact.

In addition, this study further demonstrates the benefits and robustness of using the LCA guidelines to evaluate liquid fuel transportation fuels. For example, the energy consumed in farming operations was mainly determined by diesel fuel consumption and fertilizer production.

If the inputs were out of the scope of the full life cycle of FT fuel production, the net overall emissions would be drastically lower, as well as the accompanying net energy balances.

In conclusion, the results of this study indicate that FT diesel production is a viable substitute for conventional fuels, as well as several alternative fuels. FT diesel production has the potential to help meet the energy demands of the transportation sector in the United States while simultaneously helping to reduce greenhouse gas emissions. In addition, willow farms can help to create fertile land in areas once considered barren or unfit for crop production. Thus, it is of the utmost importance for research and development to continue for FT diesel, as well as other environmentally friendly fuels, so as to ensure minimal destruction to the environment. In closing, all actions of inhabitants of this planet affect others, including decisions based on energy consumption. In addition to alternative fuels, general awareness and understanding of the current situation is also needed. In the words of environmentalist David Brower: “There is no business to be done on a dead planet”.

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BIOGRAPHICAL SKETCH

Sameer Matta was born and raised in Bombay, India. At the age of 6, he moved with his family to the United States. He is the son of Deepak Matta and Manju Matta. He received his Bachelor of Science degree in Mechanical Engineering from The University of Florida in 2006. Sameer began his graduate studies in the Department of Mechanical and Aerospace Engineering at UF in the fall of 2007. Upon graduation, he plans to pursue a career in the government sector, where he can help to reduce damage to the environment. Outside of engineering, Sameer is also a musician, and enjoys learning about philosophy, political science, and the culinary arts.