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UNIVERSITY OF CALIFORNIA  
RIVERSIDE

Life Cycle Analysis of the Production of Aviation Fuels  
Using the CE-CERT Process

A Thesis submitted in partial satisfaction  
of the requirements for the degree of

Master of Science

in

Chemical and Environmental Engineering

by

Sangran Hu

June 2012

Thesis Committee:

Prof. Joseph Norbeck, Chairperson

Prof. Akua Asa-Awuku

Dr. Wayne Miller

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The Thesis of Sangran Hu is approved:

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Committee Chairperson

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## ABSTRACT OF THE THESIS

Life Cycle Analysis of the Production of Aviation Fuels  
Using the CE-CERT Process

by

Sangran Hu

Master of Science, Graduate Program in Chemical and Environmental Engineering  
University of California, Riverside, June 2012  
Prof. Joseph Norbeck, Chairperson

The global concern of the depletion of fossil fuels and the threat of global climate change has spawned efforts in the development of sustainable fuels. The production of aviation fuels need to have a low overall CO<sub>2</sub> life cycle emission profile (a 20% reduction from the petroleum-based fuel baseline), and, most importantly, meet the demanding fuel specifications required for aviation fuels. Synthetic fuels have been produced commercially via the Fischer-Tropsch process for several years using fossil based feedstock (e.g., coal, lignite). The products, as either blended drop-in or totally synthetic fuel, have been tested and shown to have

properties meeting oil specifications when used as an aviation fuel for both civil and military aircraft. The goal for this research was to assess the technical viability of producing drop-in aviation biofuels from co-mingled fossil and carbonaceous feedstock using the CE-CERT process. The CE-CERT process has been shown to have higher efficiency than conventional gasification technologies when used with non-sustainable feedstock. A model of the whole production process has been built using the Aspen Plus process modeling software. Life cycle analyses (LCA) using a modified GREET model were then conducted based on the results of the process modeling.

It is found that using biosolid as the sustainable portion of the feedstock, with additional carbon capture and storage (CCS), the CE-CERT process combined with synthetic aviation fuel production processes results in high fuel conversion efficiencies and very low GHG emissions. Biosolid mass percentage in feedstock should be higher than 17% to meet the GHG reduction goal. To have zero emission in the well-to-tank (WTT) process, biosolid mass percentage should be no higher than 23%. High biosolid mass percentage is not suggested for the process. A feedstock mass ratio of 75%coal/25%biosolid is quite ideal for the process.

**Keywords:** LCA, Fischer-Tropsch, aviation fuel, modeling, GREET, Aspen Plus

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# **1 Introduction**

## **1.1 General background**

### **1.1.1 Aviation fuel history**

The history of kerosene-based aviation fuel began over sixty years ago. The world's first jet using a turbine engine was built and tested by Hans von Ohain in Germany on August 27<sup>th</sup>, 1939<sup>1</sup>.

This event marked the beginning of a new era in aviation history. Gasoline, the fuel used for internal combustion piston engines at that time, was used to power the engine. It was not until two years later that kerosene, once used mainly for lighting, became the fuel for jet engines. Frank Whittle from Britain developed a new turbine engine in 1941, and chose kerosene rather than gasoline as the fuel. This was motivated in large part because the supply of gasoline was short during World War II. Whittle's work turned out to be the forerunner for future jet engine design, and kerosene became the predominant aviation fuel.

The early jet engines were more tolerant to fuel properties compared to gasoline and diesel engines. It was even claimed that these new engines could operate on any fuel from whiskey to peanut (vegetable) oil<sup>2</sup>. The development of new engine technology and the desire for higher engine efficiency sparked the need for improved fuel properties, e.g., lower freezing point. This led to the introduction of various types of fuel, such as "wide cut fuel", which was a mixture of kerosene and naphtha. It became obvious that a standard for fuel quality and fuel properties

was necessary. The first jet fuel specification in the United States, AN-F-32, was published in 1944. It was based on JP-1, a wide cut fuel used by the military. Early US jet fuel specifications focused less on the properties of kerosene when compared with the standards in the UK, and were more likely to be derived directly from regulations of aviation gasoline<sup>1,3</sup> JP-1 was soon surpassed by fuels with improved performance like JP-2 and JP-4. JP-4 soon became the primary aviation fuel used by the US Air Force.

Wide cut jet fuel dominated the market in the early 1950s. Its biggest advantage was the good availability, which was greater than gasoline or kerosene alone. The low freezing point of wide cut fuels also made it possible for planes to reach higher altitudes. The fuel's high volatility, however, inevitably raised concerns about safety. Handling wide cut fuel meant higher risk of fire and explosion. Mass loss of fuel due to evaporation was another big disadvantage<sup>4</sup>.

**Table 1 Some important physical properties of Jet A & Jet A-1. (Taken from BP product handbook 2004)**

	Jet A-1	Jet A
Flash point	42 °C	51.1 °C
Freezing point	-47 °C	-40 °C
Density at 15 °C	.804 kg/L	.820 kg/L
Specific energy	43.15 MJ/kg	43.02 MJ/kg
Energy density	34.7 MJ/L	35.3 MJ/L

Kerosene-based fuel, as a consequence of years-long debate reclaimed the leading position in the field of aviation fuel. USAF started to convert the use of JP-4 to kerosene-based fuels JP-8 and JP-5 (specified by DoD specification MIL-DTL-5624 and 83133), and the process to produce was settled in the 1980s. Kerosene-based

fuel, Jet-A and Jet-A1 (specified in the British Aviation Turbine Fuel Defense Standard 91-91) collectively have the highest market share in the commercial-use aviation fuel market. The specifications of these fuels are given in Table 1.

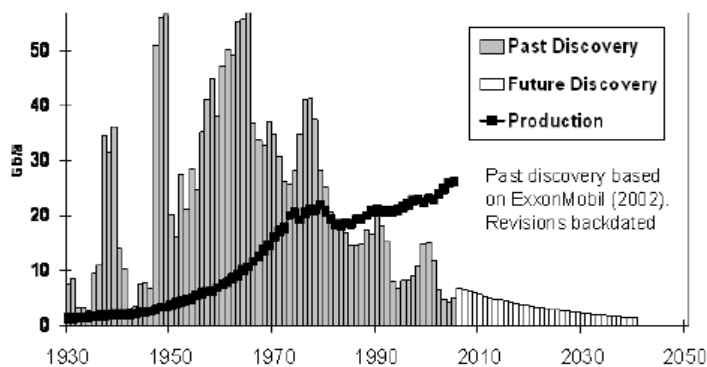
### **1.1.2 Current status and future issues**

Aviation transportation plays an important role in the world's economy. Air transportation industries provided almost 5.5 million jobs globally in 2006 and contributed \$408 billion to the global GDP<sup>5</sup>. The commercial aviation industry is a key contributor to the American economy, providing more than 5 percent of U.S. gross domestic product and nearly 11 million American jobs<sup>6</sup>. Conventional aviation fuel comes mostly from the kerosene fraction of crude oil, which is 8-10% of the crude oil supply<sup>7</sup>. Not all kerosene goes to aviation fuel production. The International Energy Agency (IEA) has estimated that since 2001 aviation fuel production accounted for only 6.0-6.3% of global refinery production<sup>8</sup>.

Global energy demand is projected to increase 1.5% between 2007 and 2030<sup>9</sup>, according to IEA's 2009 World Energy Outlook (WEO). This increasing rate is much lower than the estimation in the previous report in 2008. This was a consequence of the economic crisis. One concern is that the rising energy demand may make it difficult for aviation production and supply to keep pace with the growth in world energy. Previous research, for example, has predicted that an increase in the aviation fuel portion of refinery production (from 6.3% to about 9.3%) will be required in the

2020-2026 time frame. The expected future percentage increase of aviation fuel in another future projection was even higher (19.8%) by 2026<sup>6</sup>.

The depletion of oil reserves may make the problem more complicated. The percentage of oil use in the global energy mix declined from 33% to 28% in 2009,



**Figure 1 The rate of oil discovery and fuel production. From *Alternate Fuels for use in Commercial Aircraft* by David L. Daggett et al.**

although oil is still the largest source of energy followed by coal. Obviously there will be a day when world oil consumption reaches a maximum and then

decreases to depletion. The WEO 2010's New Policies Scenario predicts that oil usage will peak around 2035. World oil prices and the rate of depletion of oil reserves are the two main factors that will affect the exact date of the peak.

Another important issue confronting the aviation transportation industries is the new policies and regulations associated with climate change. Aviation transportation accounts for about 2% of total global greenhouse gas (GHG) emission. Thus, aviation plays a minor role in world GHG emissions compared to ground transportation (ground transportation accounts for 85% of global GHG emission<sup>10</sup>). Nevertheless, it is still expected that aviation transportation systems will be required to reduce the GHG emissions of the whole life cycle of fuel production and engine

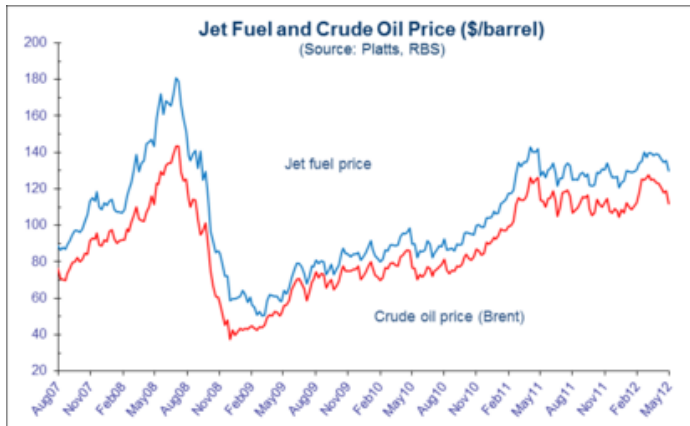
emissions.

There are several ways to reduce GHG emissions. One way is to increase the operational efficiency of aircraft engines. Today aircraft engine are 70% more efficient than 40 years ago. The current fuel rate is approximately 3.5 liters of fuel per passenger per 100 km<sup>11</sup>. Further improvement in fuel rate use is expected. A 20% improvement of aircraft efficiency from 1997 levels is likely by 2015 and possibly 40 to 50% improvement is anticipated by 2050<sup>12</sup>. Improvement in the overall efficiency of aircraft engines is a long-term effort. This only slows down the rate of energy consumption, however, and does not solve the energy supply and GHG emission issues discussed above. Alternative solutions need to be investigated.

Developing renewable replacements that have comparable quality and combustion performance of traditional petroleum-based aviation fuels appear to be a necessity. Firstly, these fuels would ease the concern for the rapid depletion of oil. Secondly, sustainable fuels help to solve the GHG problem as they are renewable. If the carbon content in these fuels comes directly from the CO<sub>2</sub> in the atmosphere, once they are released back to the atmosphere the net CO<sub>2</sub> emission is controlled and the global concentrations are stabilized. In one word, these fuels could be totally carbon neutral and much “greener” than traditional aviation fuel.

An unstable oil price is another reason that we should use alternative aviation fuels instead of petroleum-derived fuel. In 2006, the cost of fuel became the largest element of operating costs for U.S. air carriers for the first time in history<sup>13</sup>. The





**Figure 2 Jet fuel and crude oil price history.**

**From IATA website:**

[http://www.iata.org/whatwedo/economics/fuel\\_monitor/page](http://www.iata.org/whatwedo/economics/fuel_monitor/page)

reached \$130.0/barrel in May 2012, forcing industries to face this problem again (see Fig.2).

It should be noted that another important criterion for prospective new fuels is that they should be compatible with the current commercial aviation infrastructure, including delivery, storage and the aircraft fleet<sup>14</sup>. These are called fungible fuels. They can be “dropped in” the current system and if produced can have an impact on the aviation system in a short period of time<sup>11,12</sup>. This implies that sustainable synthetic hydrocarbon fuel could be the preferred option.

Thus, we can conclude: (1) developing alternative, sustainable hydrocarbon jet fuels could be a quite reasonable and desirable way to solve the problems that come with vast increase of aviation fuel consumption such as fuel supply, fossil fuel depletion and GHG emission; (2) alternative sustainable jet fuels are expected to be environment-friendly, economically sustainable, compatible with aviation infrastructure, and have high quality and good combustion performance,.

price of aviation fuel approached \$180/barrel in 2008 as the price of crude oil increased. After a sharp decrease around 2008 and 2009, aviation fuel price began to rise again and

### **1.1.3 Aviation biofuels**

Biofuels are alternative fuels totally or partly produced from biomass. Biomass could be cultivated, harvested or simply recovered from other processes, and then converted to hydrocarbon fuels through various different pathways.

Regulations of alternative aviation biofuel usage were first established in 2009 as D7566 by the American Society for Testing and Material (ASTM national). In 2011 the standard was revised as D7566-11. According to the statement, “Aviation turbine fuel manufactured, certified and released to all the requirements of this specification meets the requirements of specification D1655 and shall be regarded as specification D1655 turbine fuel.” Thus, fuels that pass D7566-11 can be considered as fully fungible or “drop-in” aviation fuels.

Several experiments and demonstrations were conducted before the standard was released. In 2008, a Boeing 747 of Virgin Airline departing from London to Amsterdam became the first airline to operate a commercial flight with a biofuel blend (20%). This was followed by a similar demonstration by Air New Zealand, in 2009. Continental Airline made the first demonstration biofuel-powered flight in the U.S, in January, 2009. The first commercial flight using biofuels took off in November, 2011.

Biofuel is also a high priority topic for military-related research. The Defense Advanced Research Projects Agency (DARPA), established in 1958, initiated a biofuel program with the aim of developing renewable jet fuel for military aviation

that meets or exceeds JP-8 performance metrics to help reduce the military's dependence on traditional petroleum-derived fuels<sup>15</sup>. The U.S. Air Force plans to convert one-half of the petroleum-based jet fuel that it uses to nonpetroleum-based fuel by the year 2016. The U.S. Navy has announced a goal of supplying 50 percent of its total energy consumption from alternative sources by 2020<sup>5</sup>.

The first generation of biofuels came primarily from cultivated plants. Plants will absorb the CO<sub>2</sub> from the atmosphere when growing and becomes the future carbon content in biofuels. Also, animal fat and vegetable oil could be converted to fuel through a process called hydroprocessing.

Two examples of the first generation biofuel are biodiesel from bio-derived oil processing and bio-ethanol from sugar-containing plant fermentation. Neither one of these fuels can be used as an aviation alternative fuel. Bio-ethanol does not fit the current aviation infrastructure. Biodiesel has high energy content but high freezing point. Another problem with the first generation biofuel is that there is a competition between land usage of food plant and fuel feedstock. Corn and soybean are primary food crops as well As an important feedstock for biofuel. Furthermore, many countries cannot provide enough land for energy crop cultivation<sup>16</sup>.

The second and third generation biofuels have much better potential as aviation fuel compared to the first generation biofuels. New generation of biofuels come from easy-growing non-food crops or plants and other sustainable sources, which avoid the criticism of food crop consumption.

Energy crops are first cultivated then harvested as a feedstock for further treatment. Plants like algae, soybean, camelina and jatropha that have high lipid (oil) content are usually put in an extraction process to collect the oil. The final aviation fuel product (often called bio-oil) is obtained after special hydrotreatment and cleaning steps. Another important type of second generation aviation biofuel is Fischer-Tropsch fuel.

## **1.2 Fischer-Tropsch synthetic jet fuel**

### **1.2.1 Brief history of Fischer-Tropsch process**

The Fischer-Tropsch (F-T) process is a technology that has been shown to produce synthetic fuels with excellent quality. The feedstocks used with the F-T process are first treated to produce a gas mixture of CO and hydrogen (called syngas or synthesis gas). The syngas mixture is then converted by the F-T process. A series of paraffinic hydrocarbons with carbon number ranging from 1 to 70 is produced via the synthesis, which can be upgraded and distilled to produce what is called synthetic F-T liquid fuels. The process to produce syngas usually uses coal or other non-sustainable feedstocks. Recent applications using sustainable feedstock, such as switchgrass and forest residues, have resulted with a sustainable fuel. In these cases, the F-T fuels are regarded to be biofuels.

The F-T process was first introduced by Franz Fischer and Hans Tropsch in the 1920s. The F-T process was commercialized in Germany in 1936 as a method to

solve the German petroleum supply in WWII. Coal was used as the. Nine plants were built by the end of 1938, having a combined capacity of about  $660 \times 10^3$  t per year<sup>17</sup>. F-T fuels accounted for 9% of German war production of fuels and 25% of the automobile fuel<sup>18</sup>.

The German plants closed after WWII but the technology drew the world's attention as the reserve of crude oil was grossly limited because of the war. An F-T plant with a capacity of  $360 \times 10^3$  t per year was built in Brownsville, Texas in 1950 to 1953. The South African Coal and Oil Ltd (Sasol) built its first F-T plant in Sasolburg, South Africa in 1955 with the capacity of 8000 bpd<sup>19</sup>. However, due to the discovery of oil field in Middle East, a sharp decrease in crude oil price occurred in the 1950s. F-T fuels became economically unviable so they didn't have a huge impact.

F-T technology began to attract the attention from the public in the 1970s, as a result of the Middle East oil crisis in 1973. Sasol built two new F-T plants in 1980 and 1982<sup>17</sup>.

Fischer-Tropsch jet fuel is also called synthetic paraffinic kerosene (SPK). The greatest advantage of SPK over petroleum-based jet fuel is that it is highly paraffinic and clean. There are almost no aromatics and low olefin concentration in SPK as a consequence of the details of the F-T process. Olefins and aromatics are the main cause of incomplete fuel combustion. Thus SPK has even better combustion performance compared to other fuels. Also there is no sulfur content in SPK. The

disadvantages of SPK are less fluidity and lower density (all caused by the high paraffin concentration). This can be corrected by using additives. So SPK has great potential as future jet fuel surrogate. It is one of the first biofuels listed in the D7566-11 specification

### 1.2.2 Fischer-Tropsch reaction

The chemical reaction of the Fischer-Tropsch synthesis is described as:



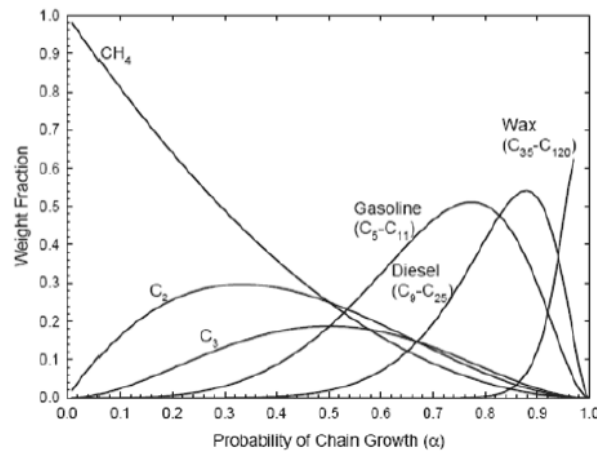
The mechanism is believed to be polymerization of  $\text{CH}_2$  fragments<sup>20</sup>. There are mainly two types of F-T synthesis. One is low-temperature F-T (LTFT). The operation temperature of LTFT ranges from 200 °C to 250 °C. Another option is high-temperature F-T (HTFT). Operation temperature of HTFT is controlled within the range of 300-350 °C<sup>21</sup>.

Catalyst in F-T reaction is important as they provide an attachment surface for intermediates in the reaction<sup>22</sup>. Only cobalt metal and iron carbides catalysts<sup>23</sup> have been commercialized. Ruthenium can be used as catalyst as well but due to its over-activity and high price, it is not recommended for ordinary F-T reactions. Commonly speaking, iron catalyst is applied in HTFT and cobalt in LTFT.

Product distribution of F-T synthesis obeys the Anderson-Schulz-Flory distribution:

$$W_n/n = (1-\alpha)^2 \alpha^{n-1}$$

$W_n$  is the total mass ratio of product with the carbon number of  $n$ .  $\alpha$  is chain growth probability, a factor mainly determined by catalyst. The distribution is shown in Fig. 3. In most cases, cobalt catalysts always have a higher  $\alpha$  value than iron catalysts. So this is why LTFT is often applied to produce higher products like diesel or wax, while HTFT is usually designed for higher products like gasoline.



**Figure 3 Weight fraction of F-T synthesis product<sup>a</sup>**

According to Fig.3, for the highest yield of kerosene-range products,  $\alpha$  value should be around 0.8-0.9. So LTFT with cobalt catalyst is more favored for F-T jet fuel production.

### 1.2.3 Feedstock and gasification

Coal, biomass and natural gas are the three most common feedstocks for F-T plants. The process that converts coal, natural gas and biomass to F-T fuel (including

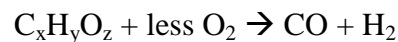
<sup>a</sup> The picture is from the internet:

<http://www.zero.no/transport/biodrivstoff/fischer-tropsch-reactor-fed-by-syngas>

aviation fuel) is called CTL (coal-to-liquid), GTL (gas-to-liquid) and BTL (biomass-to-liquid), respectively. Sometimes coal and biomass are mixed as co-feedstock to add a sustainable portion to the carbon content in feeds. This is called CBTL (coal-biomass-to-liquid).

Syngas needed for the F-T synthesis may be obtained in many different ways including gasification or natural gas reforming. Reforming is for natural gas only so is very limitedly used compared with gasification.

The most traditional way of gasification is partial oxidation (POX), a partial combustion reaction under high temperature. The reaction could be generalized as follows:



Feedstock must be dried before gasified as steam will affect the reaction. A great amount of oxygen or air is required to maintain the oxidizing atmosphere in the reactor. Feedstock could also be gasified in a hydrogen atmosphere. Gasification in a H<sub>2</sub> atmosphere is called hydrogasification, which produce a methane-rich gas mixture. Compared with POX, hydrogasification requires more energy to maintain the operation condition (high temperature, high pressure and H<sub>2</sub> atmosphere). Also direct hydrogasification of a wet feedstock is difficult. Other traditional gasification technologies have similar disadvantages such as high energy consumption and difficulty to treat water content in feedstock<sup>24</sup>.



### 1.3 CE-CERT process

CE-CERT process is a thermo-chemical technology that converts wet carbonaceous materials into F-T synthetic fuels and process heat. It was developed by the Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) from University of California, Riverside.

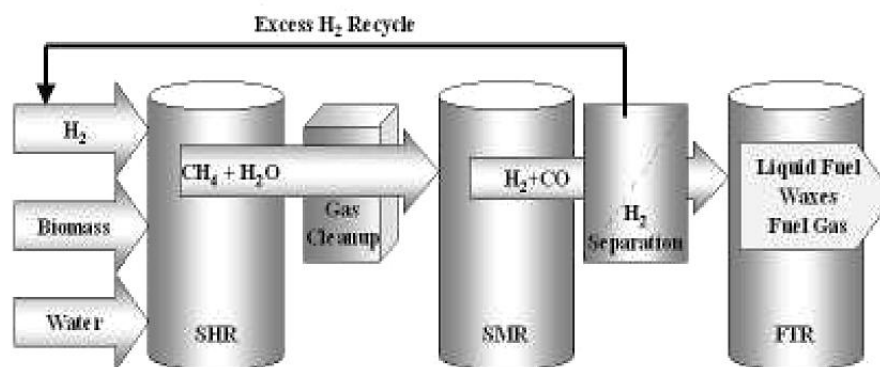


Figure 4 Flowsheet of CE-CERT process

Flow sheet of the whole process is presented in Fig. 4. The most novel part of the CE-CERT process is the steam hydrogasification (SHR) technology that utilizes the water content in the feedstock to enhance the hydrogasification reaction. SHR is also the first step of all the treatment procedures. Feeds in slurry phase could be directly applied in SHR along with extra steam and  $H_2$  streams. A gas mixture (with high methane concentration) is produced. After gas cleaning (to remove the sulphur and phosphorus content), methane produced in the SHR will be reformed in a steam methane reformer (SMR) to yield syngas, which will finally be converted to F-T products in Fischer-Tropsch reactor (FTR). Excess water and hydrogen will be recycled after separated from syngas flow before F-T synthesis.

The great advantage of handling slurry phase feedstocks directly is that it provides the possibility of using biosolid, residue from waste water treatment, as a sustainable biomass feedstock. Compared with traditional biomass feedstocks, biosolid requires no agricultural cultivation input and has feedstock resources all over the country. According to EPA's statistical data, 12,750 publicly owned treatment works generate 5.4 million dry metric tons of sludge annually or 47 pounds of sewage sludge (dry weight basis) for every individual in the United States<sup>25</sup>. 61% of the biosolid residue is applied to land farming, 17% in licensed municipal solid waste landfills, 20% incinerated, and about 1% in surface disposal units. These methods could become huge sources of methane emission. Meanwhile, biosolid land filling is getting more costly and complex<sup>26</sup>. Gasification and combustion to convert biosolid into energy are considered to be better options. Because of the high water content (over 80% mass ratio), biosolids must be dried and pretreated, which is inconvenient and costly for treatment plants. However, other carbonaceous matter can be mixed to increase the carbon content and become a benefit for the biosolid gasification in CE-CERT process.

Previous study at CE-CERT UCR has proved the viability and potentiality of using biosolid as feedstock in CE-CERT process. Water content largely enhanced the conversion. In 2010, DOE/NETL concluded that process has 12 % higher efficiency with 18 % lower capital cost than the most up-to-date conventional mainstream gasification technologies after reviewing the process.

It is also been shown that when biosolid is co-gasified with other feedstocks like coal, the total carbon conversion could be even higher. It is possible that the high metal content of the biosolids feedstock may play a catalytic role during the steam hydrogasification reaction, resulting in increased carbon conversions. Another notable point is that since biosolid usually has a comparatively low carbon content, extra feeds like coal or biomass can help to have a higher fuel yield after F-T synthesis.

Thus although coal is not a sustainable resource of energy, a CBTL process with CE-CERT process combined is expected to be of great potential in Fischer-Tropsch synthetic aviation fuel production. It is expected that due to the high working efficiency and high carbon conversion rate of the SHR, this process could produce less GHG emission and saves more energy in the operation. In one word, we would like to determine the environmental viability of a CE-CERT process as a combined CBTL process producing F-T jet fuel.

#### **1.4. Research Objective**

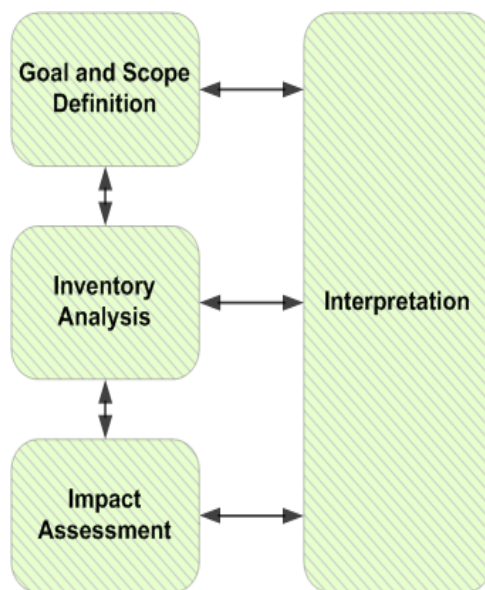
The main objective of this research is to provide an assessment on the environmental impact of synthetic Fischer-Tropsch jet fuel production through the CE-CERT process with coal and biosolids as feedstock.

## 2. Methodology

This section describes the method and models used in this study. A “life cycle analysis” was done to evaluate the overall environmental viability. The GREET software from Argonne National Laboratory is applied as the primary tool for analysis and chemical engineering process modeling software Aspen Plus from AspenTech. Inc is used to provide more engineering details for the assessment.

### 2.1 Life cycle analysis

Life cycle analysis (LCA) is a useful method that evaluates the performance of



**Figure 5** Phase of life cycle analysis. From [http://en.wikipedia.org/wiki/Life-cycle\\_assessment#cite\\_ref-3](http://en.wikipedia.org/wiki/Life-cycle_assessment#cite_ref-3)

a production process.

Through collecting different data concerning each step of the whole manufacture process from its “cradle” (raw material recovery) to “grave” (specified final disposal), an LCA analysis provides a complete flow sheet of both energy and material input/output flows, which would be helpful judging the environmental/economic viability of

the process. In most cases, LCA concerns about two main environmental facts: GHG emission and energy consumption, with the highlight on GHG emission.

A typical LCA analysis is composed by four different parts: definition of goal and scope of this analysis including all assumptions and settings used in the assessment; life cycle inventory (LCI) that contains all the material/energy flows in the system; life cycle impact analysis that files all useful information and final interpretation of the assessment. The interrelationship among the four parts is shown in Fig. 5. These four procedures of LCA analysis are listed as part of ISO 14000 standards (14040:2006 and 14044:2006)<sup>27</sup>. There are also some other specially-modified LCA models such as Economic input–output life cycle assessment (EIO-LCA) and Ecologically-based LCA (Eco-LCA). But they are not as widely used as the traditional LCA.

The different pathways for the jet fuel production process LCA include “Well-to-tank” (WTW, starts with feedstock extraction and ends at fuel storage), “tank-to-wake” (TTW, starts with fuel storage sites and ends at fuel combustion) and “well-to-wake” (WTW, starts with feedstock extraction and ends at fuel combustion).

For aviation fuels, emission in TTW stage accounts for most of the WTW total emission. Yet TTW emission stays constant for one type of fuel if there is no enormous change made on jet engines. Changes could be made during WTT process only. Baseline of WTT total emission set by NETL is 15.10 kg CO<sub>2</sub>e/mmBtu of jet fuel, which equals to 14.31 g CO<sub>2</sub>e/MJ fuel (total WTW emission in the baseline is 88.0 g CO<sub>2</sub>e/MJ)<sup>28</sup>. Reduction goal set by EISA in 2007 is that any new renewable

fuel must have a 20% or less total GHGs emitted during its life cycle compared to this baseline.

Here we use a typical LCA analysis with the focus on GHG emission and energy consumption to investigate the environmental viability of applying CE-CERT process to traditional F-T jet fuel production. The GHG emission analysis result will be compared with the baseline to draw the conclusions from the study.

## **2.2 GREET model**

GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is a LCA analyzing model designed by Argonne National Laboratory. It is designed “to fully evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels”<sup>29</sup>. Over 100 pathways of fuel production is included in the model. In the latest version (GREET 1\_2011), the production pathway of synthetic jet fuel is introduced for the first time. We use the default model of CBTL F-T jet fuel as the main frame for the analyses contained in this study. Details of the modeling will be modified according to Aspen Plus simulation result.

## **2.3 Aspen Plus Simulation**

Aspen Plus® is a chemical engineering process simulating software developed by Aspen Technology, Inc. Since data about CE-CERT process is not included in

GREET default modeling, Aspen Plus can provide necessary information for LCA such as total GHG emission and energy consumption in fuel processing procedure through process simulation. A gasification-synthesis-combined system based on CE-CERT process is constructed in Aspen Plus modeling to establish the database.

### **3. LCA Results**

The data from the Life Cycle Inventory (LCI) will be listed and the results from the LCA analysis will be presented in this section. A discussion of the results will be given to clarify how different parts of the CE-CERT-technology-applied process affect the environment.

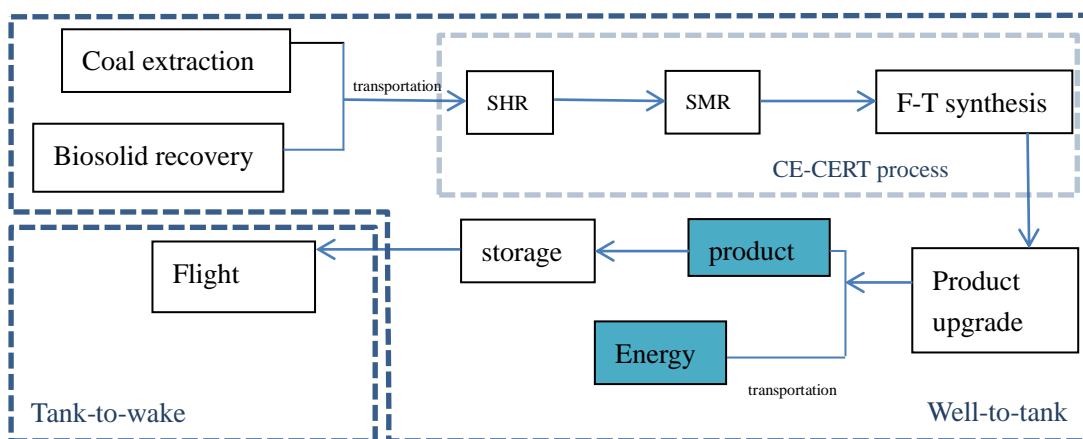
#### **3.1 Goal and scope definition:**

The main goal of LCA analysis is to determine the viability of applying the CE-CERT process to the CBTL F-T fuel production. A total GHG emission assessment will be carried out based on WTT and WTW results and energy consumption assessment of the WTT result.

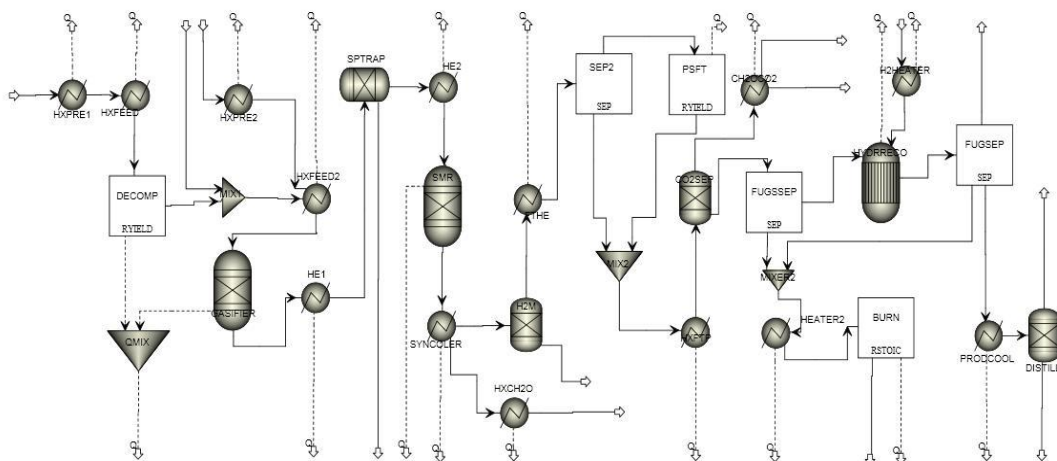
The total pathway of the process is shown in Fig.6. Feedstock is extracted and transported to the plant, cleaned and gasified using the CE-CERT process. Char produced from the SHR is burned to provide energy to keep the SHR temperature stable. A methane-rich gas mix leaves the SHR and goes to the SMR where is is reformed to syngas to be used in the F-T synthesis. Fischer-Tropsch product is upgraded to yield the final product. Finally, F-T fuel is transported, distributed and

used as aviation fuel.

All GHG emission and energy consumption calculations are based on the revised GREET 1\_2011 jet fuel LCA model. The model is modified according to assumptions and Aspen Plus modeling results. The entire process in Aspen Plus is shown in Fig.7.



**Figure 6 Total scope of F-T fuel production combined with CE-CERT process**



**Figure 7 Flow sheet of CE-CERT process simulation in Aspen Plus**

Feedstock with four different mass ratio of coal and biomass (92% coal and 8% biosolid; 75% coal and 25% biosolid; 60% coal and 40% biosolid; 50% coal and 50% biosolid) was used to evaluate the impact of different biosolids/coal mass



mixtures on the final results.

### 3.1.1 Feedstock extraction and transportation

Belt packed cake (BPC) and Utah sub-bituminous coal were used as the two potential feedstocks. The heating value, density and carbon mass ratio of coal was obtained from the GREET 1\_2011. Heating value of biosolid is cited from previous research reports<sup>30</sup>. Detailed biosolid and coal composition analysis was made at CE-CERT UCR<sup>31</sup>. These data are given in Tables 2-4.

**Table 2 Coal and biosolid physical properties**

Liquid Fuels:	Heating value (Btu/gal)	C ratio (% mass)
Coal	22,460,600 (Btu/short ton)	68.9%
Biosolid	17,058,000 (Btu/dry ton)	36.68%

**Table 3 Feedstock elemental analysis**

	Coal (Utah coal)	Biosolid (BPC) <sup>32</sup>
C	68.85	36.68
H	4.74	5.39
N	1.04	5.79
Cl	2.25	0
S	1.18	1.56
O	11.39	20.83

**Table 4 Feedstock proximate analysis**

	Coal (Utah coal)	Biosolid (BPC)
MOI <sup>b</sup>	0.00	0.00
FC	49.45	10.00
VM	40.00	60.25
ASH	10.55	29.75

---

<sup>b</sup> Since moisture content in feedstock will be gasified along with the input water, MOI value in the simulation is assumed to be 0

Coal is first recovered through mining then is transported to the F-T plant. Data used for the energy consumption and GHG emission for coal mining and transportation is from GREET 1\_2011 database. These data are listed in Table 5 and Table 6, respectively

Biosolids is collected from a nearby sludge waste treatment plant. Before it is transported to F-T plant, biosolid is first dewatered at the waste water treatment plant. Total water content in feedstock decreases from 80% to 15%. The transportation is assumed to be a 30 mile one-way distance, using 5 MPG heavy duty diesel trucks<sup>33</sup>. Following the heavy duty diesel truck model in GREET database, the total emission and consumption in transportation (dewatering included) is listed in Tab. 7:

**Table 5 Energy consumption for coal mining and transportation**

	Total energy (Btu/mmBtu coal)	Fossil fuel (Btu/mmBtu coal)	Coal (Btu/mmBtu coal)	Natural gas (Btu/mmBtu coal)	Petroleum (Btu/mmBtu coal)
Mining and cleaning	10,502	9,847	3,094	1,721	5,064
Transportation	1,094	1,083	42	145	897

**Table 6 GHG emission for coal mining and transportation**

	Total GHG (gCO <sub>2</sub> e/mmBtu coal)	CO <sub>2</sub> emission (g/mmBtu coal)	CH <sub>4</sub> emission (g/mmBtu coal)	N <sub>2</sub> O emission (g/mmBtu coal)
Mining and cleaning	4527.799	846.454	147.117 <sup>c</sup>	0.013
Transportation	89.884	84.963	0.173	0.002

<sup>c</sup> Including non-combustion emission of 145.552g/mmBtu coal

**Table 7 Energy consumption and GHG emission for biosolid transportation**

	Total energy consumption (Btu/dry ton of biosolid)	Total GHG (gCO <sub>2</sub> e /dry ton of biosolid)
Biosolid transportation	3.85E+06	303.47

### **3.1.2 Steam hydro-gasification (SHR)**

Biosolid and coal are gasified in the same reactor with extra hydrogen and steam. The mole ratio of hydrogen per total carbon content in feedstock is set to be 1:1. The mass ratio of steam per total mass of feedstock is set to be 2:1. The feedstock will be preheated to 500 °C and cleaned before entering the reactor. The gasifier is operated at 750°C, under the pressure of 400 psi. H<sub>2</sub>S and char will be removed from the gasifier and char will be burned to provide heat and energy for the whole system. Here char is assumed as pure carbon. The combustion heat of char is 30 MJ/kg char.

### **3.1.3 Steam methane reforming (SMR)**

The SMR converts the methane yielded from SHR into a syngas mixture. Gas that flows out from SHR is heated up to 850 °C, which is the temperature set for SMR. The SMR is operated under the same pressure of 400psi. Excess hydrogen and water will be cooled down after SMR and recycled throughout the process.

### **3.1.4 Low temperature Fischer-Tropsch synthesis (LTFT)**

LTFT and product upgrade simulation follows the kerosene model of Shell

Middle Distillate Synthesis (Shell SMDS). The operation temperature of the F-T reactor is set at 220 °C, using a cobalt catalyst with the probability factor  $\alpha$  of 0.9<sup>34</sup>.

For modeling purposes it was assumed that the ratio of paraffin/olefin mole ratio of all hydrocarbons produced in the FT reactions is 0.7/0.3<sup>35</sup>.

Fuel gas, water and CO<sub>2</sub> will be cooled down and released after the synthesis. Fuel gas (products with the carbon number less than 5) from the F-T reactor will be burned to provide energy for the system. Heavier products including paraffin with carbon number higher than 20 and wax will be put into upgrade.

### **3.1.5 Product upgrade**

Hydrocarbons from F-T reactor will be hydrotreated to get the final product. Following the Shell SMDS design, the reactor is operated under the temperature of 350 °C and the pressure of 507.633 psi (35 bar) in a hydrogen atmosphere. H<sub>2</sub> feed is 20kg/day (converted to fit the 1 dry ton feedstock/day assumption). First olefins in the hydrocarbon mix react with hydrogen and form paraffin. The conversion rate of olefin to paraffin is assumed to be 100%. A sensitivity analysis was performed and it was determined that this assumption had less than a 1% impact on the reactor carbon footprint<sup>36</sup>.

Then paraffin products are cracked and converted to hydrocarbons in the kerosene range. Hydrocarbon conversion process is assumed to be self-supported thus no extra heat is needed and no GHG is released in this step<sup>31</sup>.

According to SMDS kerosene mode designs, kerosene fraction accounts for 50% mass ratio of all liquid products after hydrotreating. Little fuel gas is generated in the upgrade procedure so only fuel gas from F-T synthesis is considered for combustion<sup>37</sup>.

The effect of additives added in the jet fuel final product on both GHG emission and energy consumption could be neglected<sup>35</sup>.

### 3.1.6 Carbon dioxide capture and storage (CCS)

CCS technology captures the CO<sub>2</sub> that is released after the whole process. Energy required for CO<sub>2</sub> capture is 265.1 kWh/g of carbon. The CO<sub>2</sub> capture rate for the CBTL F-T plant is assumed to be 89.10%. Both the two assumptions are from GREET 1\_2011 default CCS model.

### 3.1.7 Jet fuel properties and conversion efficiency

Fuel properties are not measured in the simulation. As F-T SPK from different sources share similar properties, we use the data in GREET database to analyze the GHG emission and energy consumption per MJ of fuel.

**Table 8 F-T jet fuel properties in GREET 1\_2011 database**

Liquid Fuels:	Heating value (Btu/gal)	Density (g/gal)	C ratio (% mass)
SPK (FT Jet Fuel/HRJ)	119,777	2,866	84.7%

As for the conversion efficiency of jet fuel, Stratton et al<sup>38</sup> once defined the efficiency of fuel processing as:

$$\text{Process efficiency} = \frac{1 \text{ MJ fuel}}{1 \text{ MJ feedstock} + \text{process energy}} \quad (\text{Equation 1})$$

It also defines the process efficiency in GREET jet fuel LCA analysis. So here this equation is used for conversion efficiency assessments.

### 3.1.8 Jet fuel transportation and distribution

Energy consumption and GHG emission for jet fuel transportation and distribution are listed in Tab 9 and 10. All data is from GREET 1\_2011 database:

**Table 9 Energy consumption for F-T jet fuel transportation and distribution**

	Total energy (Btu/mmBtu fuel)	Fossil energy (Btu/mmBtu fuel)	Coal (Btu/mmBtu fuel)	Natural gas (Btu/mmBtu fuel)	Petroleum (Btu/mmBtu fuel)
F-T jet fuel transportation	7,621	7,481	736	2,161	4,584
F-T jet fuel distribution	1,970	1,964	23	199	1,742

**Table 10 GHG emission for F-T jet fuel transportation and distribution**

	Total emission (gCO <sub>2</sub> e/mmBtu fuel)	CO <sub>2</sub> emission (g/mmBtu fuel)	CH <sub>4</sub> emission (g/mmBtu fuel)	N <sub>2</sub> O emission (g/mmBtu fuel)
F-T jet fuel transportation	649.50	607	1.56	0.01
F-T jet fuel distribution	160.95	155	0.21	0.004

### 3.1.9 Jet fuel tank-to-wake (TTW) emission

The total GHG emission for aircraft using 100% F-T jet fuel is assumed to be 70.4 g CO<sub>2</sub>e/MJ jet fuel, which is from GREET 1\_2011 F-T fuel TTW model.

### 3.1.10 Sustainable portion of feedstock

Sustainable portion of feedstock is defined as the CO<sub>2</sub> stored/captured in the

feedstock. This is shown as a negative value in total life cycle GHG emission as the CO<sub>2</sub> is captured from the atmosphere. Calculation of sustainable portion of feedstock follows the rule set in GREET model. It is based on the biosolid carbon mass ratio (36.68%). It is assumed that the carbon content in feedstock is 100% converted from CO<sub>2</sub> in the atmosphere thus the sustainable portion of feedstock is 0.493 ton CO<sub>2</sub>/1 dry ton of biosolid.

### 3.2 LCA inventory

Life cycle inventory (LCI) includes all material or energy flows flowing in and out the whole system. Here only GHG and energy is considered. Since the Aspen Plus simulation is based on the assumption of 1 dry ton feedstock per day with different mass ratio of coal/biosolid (92/8, 75/25, 60/40, 50/50), calculations of recovery and transportation are all based on the assumption of total feedstock weight of 1 dry ton. All calculation results here will be shown using the unit of joule (J), megajoule (MJ), kilogram (kg) and gram (g).

#### 3.2.1 Feedstock energy input

Based on the energy content of both coal and biosolid, the total energy input for the four groups of feedstock is listed as:

**Table 11 Total energy input of feedstocks**

	92% coal	75% coal	60% coal	50% coal
Feedstock energy content (MJ)	2.53E+04	2.40E+04	2.28E+04	2.20E+04

Total feedstock energy content decreases with the coal mass ratio as coal accounts for most of the energy content in feedstock.

### 3.2.2 Feedstock recovery and transportation

Total GHG emission and energy consumption when feedstock is recovered, dewatered and transported to the F-T plant is shown in Table 12. Emission increase as the biosolid mass ratio increases. This is because that the GHG emission of transportation per dry ton of biosolid is much higher than that of coal.

**Table 12 Total GHG emission in feedstock transportation and recovery**

	92% coal	75% coal	60% coal	50% coal
Recovery (kg CO <sub>2</sub> e)	103.16	84.10	67.28	56.07
Transportation (kg CO <sub>2</sub> e)	26.33	77.54	122.72	152.85
Total emission (kg CO <sub>2</sub> e)	129.49	161.64	190.00	208.92

Total energy consumption in feedstock transportation is shown in Tab.13. It also increases with the rising biosolid mass ratio.

**Table 13 Total energy consumption in feedstock transportation and recovery**

	92% coal	75% coal	60% coal	50% coal
Recovery (MJ)	251.22	204.80	163.84	136.54
Transportation (MJ)	585.40	1224.89	1789.15	2165.32
Total consumption (MJ)	836.62	1429.69	1952.99	2301.85

### 3.2.3 CE-CERT process and product upgrade

The overall CO<sub>2</sub> emission from the CE-CERT process is low. Part of the emission comes from char and fuel gas combustion. Over 89% of the GHG emission from the whole CE-CERT process is captured and stored if CCS is installed. Tab.14



is a detailed list of GHG emission of each step in CE-CERT process and the total emission with/without CCS, which shows a sharp decrease in total emission when CCS is applied.

**Table 14 GHG emission for CE-CERT process and product upgrade**

	92% coal	75% coal	60% coal	50% coal
Char combustion (kg CO <sub>2</sub> e)	434.87	399.10	367.43	346.32
CE-CERT main parts (kg CO <sub>2</sub> e)	545.21	537.04	528.72	522.47
Fuel gas combustion (kg CO <sub>2</sub> e)	392.02	348.73	310.91	285.91
Product upgrade (kg CO <sub>2</sub> e)	0	0	0	0
Total GHG mission (without CCS) (kg CO <sub>2</sub> e)	1372.10	1284.87	1207.06	1154.70
Total GHG mission (after CCS) (kg CO <sub>2</sub> e)	149.56	140.05	131.57	125.86

As for the energy consumption, heat produced throughout the whole CE-CERT process could provide excess energy for the system and could be converted to electricity. So CE-CERT process here could be regarded as self-sufficient thus energy consumption is assumed to be 0, which is the same as what GREET has suggested for energy consumption in F-T fuel production step. Only energy consumed in CCS operation is considered. Net energy consumption for all four groups of analysis is listed in Tab.15:

**Table 15 Energy flow in CE-CERT process with 1 ton feedstock per day**

	92% coal	75% coal	60% coal	50% coal
Feedstock pretreatment and heating (MJ)	10749.99	10652.44	10566.30	10508.96
SHR energy output (MJ)	1045.44	870.93	724.64	631.97
SMR energy output (MJ)	-5218.56	-4622.46	-4101.97	-3758.40
F-T energy output (MJ)	4273.83	3756.84	3362.55	3101.62
Fuel gas combustion (MJ)	5498.96	4886.36	4351.27	3997.79
Char combustion (MJ)	3559.24	3265.37	3006.24	2833.49
Total heat released from cooling output(MJ)	9114.41	9133.37	9143.23	9150.81
H <sub>2</sub> heating (MJ)	94.61	94.61	94.61	94.61
CO <sub>2</sub> capture and storage (MJ)	318.20	297.97	279.93	267.79
Net energy consumption (MJ)	-7110.52	-6245.40	-5545.13	-5085.93

### 3.2.4 Synthetic jet fuel yield

According to the result of Aspen Plus simulation and upgrade, final product yields of all four groups of simulations listed in Tab.16:

**Table 16 SPK final yield after CE-CERT process and upgrading**

	92% coal	75% coal	60% coal	50% coal
Yield after CE-CERT process (kg)	122.64	109.50	98.01	90.40
Yield after upgrading (kg)	178.36	165.08	153.51	145.87
Total energy content (MJ)	7827.76	7245.16	6737.20	6402.02

### 3.2.5 Synthetic jet fuel (SPK) transportation and distribution

Analysis of SPK transportation and distribution follows the default model of GREET 1\_2011. As the heating value and density of SPK applied in this analysis is the same as that in GREET database, there is no need to make any modification but unit conversion in the default fuel transportation and distribution model.

The energy consumption and GHG emission is listed in Table 17 and Table 18.

**Table 17 Energy consumption in SPK transportation**

Fuel transportation (J/MJ)	Fuel distribution (J/MJ)	Feed loss (J/MJ)	Total energy consumption (J/MJ)
7,621	1,970	45	9,636

**Table 18 GHG emission in SPK transportation and distribution**

	CO <sub>2</sub> emission	CH <sub>4</sub> emission	N <sub>2</sub> O emission	Total emission
Fuel transportation (g/MJ)	0.58	1.48E-03	1.23E-05	0.62
Fuel distribution (g/MJ)	0.15	2.02E-04	3.79E-06	0.15

### 3.3 Life cycle impact analysis

In this section all the LCA-related data will be summarized and the final result (with the unit converted to g CO<sub>2</sub>e/MJ fuel and J/MJ fuel) will be shown. Here we focus on three aspects: WTT GHG emission, WTW GHG emission, WTT energy consumption and total fuel conversion efficiency. GHG emission results will be compared with baseline and standards or even calculation result from GREET default to evaluate the viability of this process.

#### 3.3.1 WTT GHG emission

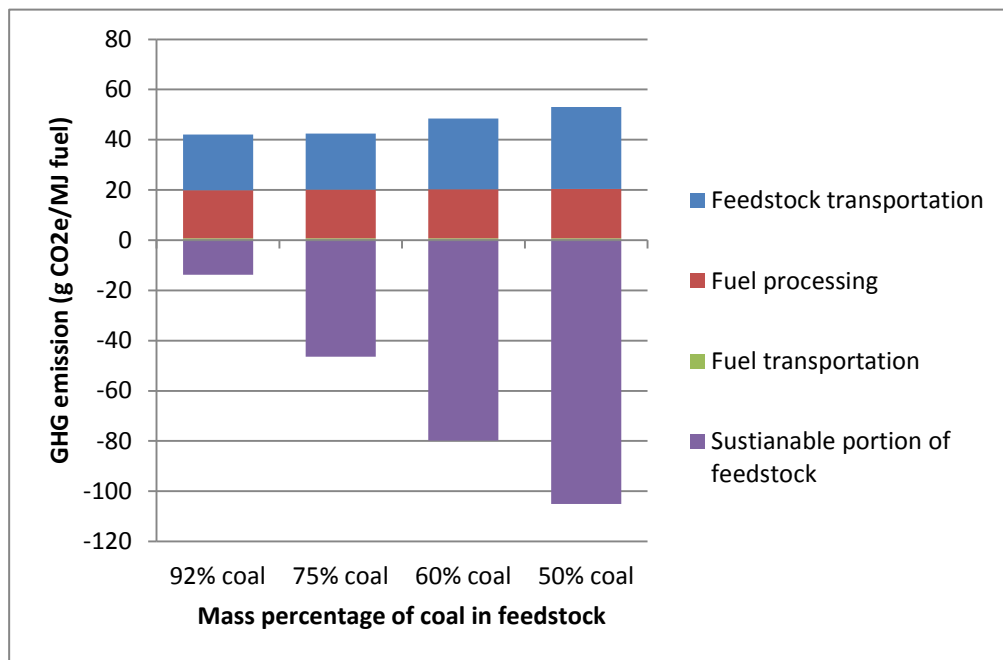
Table 19 summarizes the previous data concerning GHG emission in each procedure in WTT process:

**Table 19 Summary of WTT GHG emission analysis**

	92% coal	75% coal	60% coal	50% coal
<b>GHG emission for each step of WTT process (g CO<sub>2</sub>e/MJ fuel)</b>				
Feedstock transportation	16.54	22.31	28.20	32.63
Fuel processing with CCS	19.11	19.33	19.53	19.66
Fuel processing without CCS	175.29	177.34	179.16	180.36
SPK transportation	0.77	0.77	0.77	0.77
Sustainable portion of biosolid	-13.74	-46.41	-79.85	-105.04
<b>GHG emission for whole WTT process (g CO<sub>2</sub>e/MJ fuel)</b>				
WTT emission (with CCS)	28.29	-3.94	-31.35	-51.98
WTT emission (without CCS)	184.46	154.07	128.28	108.73

Apparently, without CCS the WTT GHG emission would be high so CCS is a must for this process. Only data with CCS installed will be considered in later discussions.

Fig. 8 is lists the GHG emission in each stage of WTT analyses. Emission from fuel processing and fuel transportation almost stays constant while the emission in feedstock transportation increases gradually.



**Figure 8 GHG emission in each stage of WTT process**

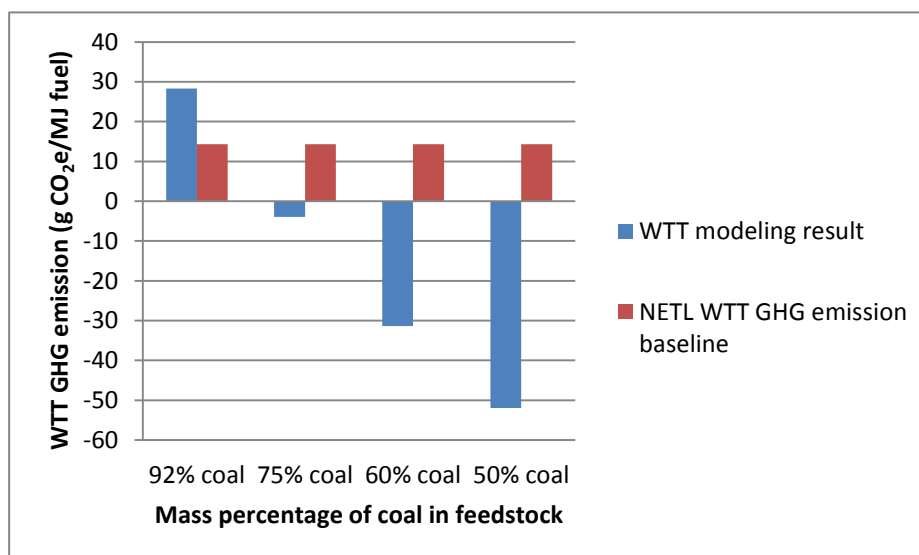
Sustainable portion of feedstock plays the greatest role in GHG emission reduction. As shown in Figure 8, the absorbed CO<sub>2</sub> in feedstock will increase with biosolid mass ratio and it totally covers the emissions from transportation and fuel processing except for the first modeling starts with 92% coal mass ratio.

At the same time, feedstock transportation is the largest source of GHG emission. GHG released from fuel processing per MJ fuel almost stays constant and comparatively low.

In Table 20 the WTT results for all four groups of feedstock are compared with NETL's WTT emission baseline. Fig. 7 shows the difference.

**Table 20 WTT modeling result compared with NETL baseline (14.31 g CO<sub>2</sub>e/MJ fuel)**

	92% coal	75% coal	60% coal	50% coal
WTT modeling result (g CO <sub>2</sub> e/MJ fuel)	28.28	-3.94	-31.35	-51.98
Emission change from baseline	+97.6%	-127.5%	-319.1%	-463.2%



**Figure 9 Modeling and NETL baseline of WTT GHG emission**

From Table 20 and Figure 9 we can see 92% coal and 8% biosolid cannot meet the goal of 20% reduction from the baseline. But 75% coal, 60% coal and 50% coal all met the goal as all of them have negative net emission values. The lowest viable biosolid mass percentage in the feed for this process is yet unknown. A trendline was used to evaluate the approximate biosolid mass percentage (see Figure.10). According to the fitted equation, when the WTT GHG emission equals to 11.37 g CO<sub>2</sub>e/MJ (80% of NETL baseline), the biosolid mass percentage is about 17% of feedstock.

Also if the total WTT GHG emission equals zero, the biosolid mass percentage is about 23%.

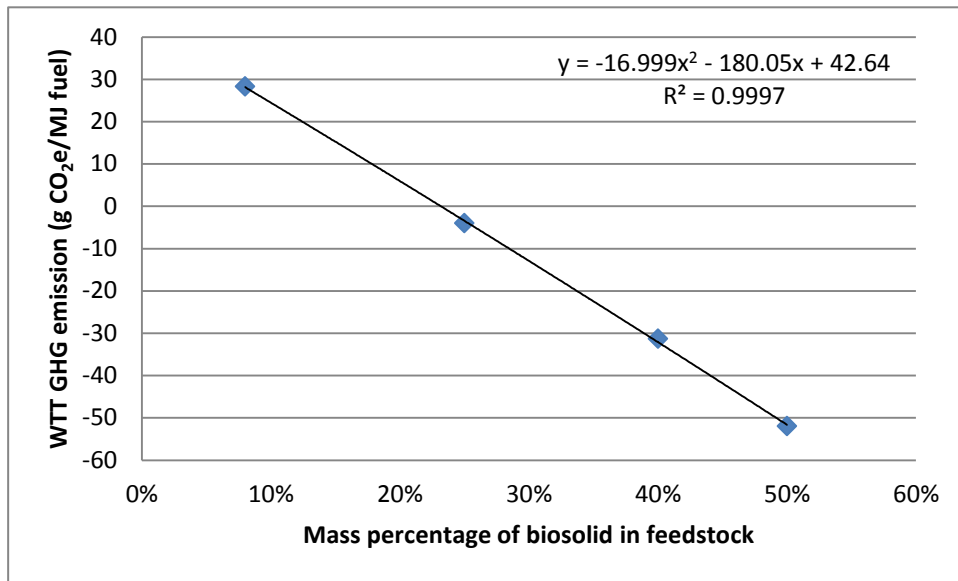


Figure 10 Fitted curve of WTT GHG emission

### 3.3.2 WTW total GHG emission

The TTW total emission in this analysis follows that data in GREET database (70.4 g/MJ fuel). In Table 21 the total GHG emission in the whole WTW process and the emission reduction from the NETL baseline is listed:

Table 21 Total WTW modeling result compared with NETL baseline (88.0 g CO<sub>2</sub>e/MJ fuel)

	92% coal	75% coal	60% coal	50% coal
WTW modeling result (g CO <sub>2</sub> e/MJ fuel)	98.68	66.46	39.05	18.42
Emission change from baseline	+12.13%	-24.5%	-55.6%	-79.1%

The WTW result for 92% coal mass ratio is even higher than the WTW emission baseline of petroleum-based fuel thus is not environmental-friendly as expected. All the other three modeling results shows an obvious reduction in total GHG emission especially with feedstock composed of 60% coal/40% biosolid and 50% coal/50% biosolid.

The modeling results are compared with default modeling result from GREET 2011, too. Table 22 lists the modeling result with other four WTW emission calculation results from GREET default model using four typical biomass in GREET database, which are farmed tree, herbaceous, corn stover and forest residue, mixed with coal at the same mass ratio as feedstock. Figure 11 shows the comparison between the five groups of emission rate.

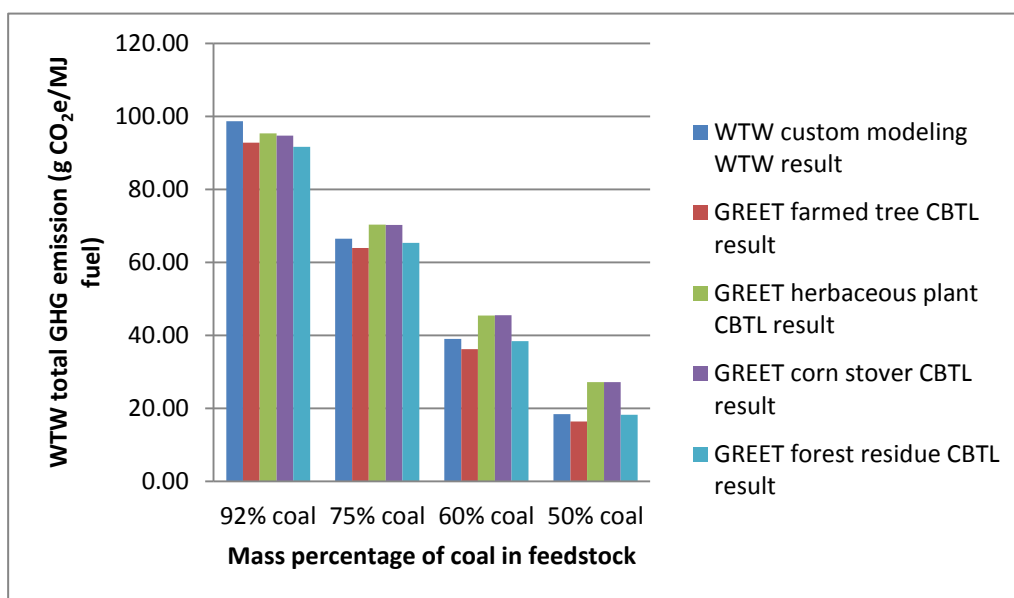
**Table 22 Total WTW modeling result and GREET default modeling results**

	92% coal	75% coal	60% coal	50% coal
Our WTW result (g CO <sub>2</sub> e/MJ fuel)	28.28	66.46	39.05	18.42
GREET result (g CO <sub>2</sub> e/MJ fuel) (farmed tree)	22.36	63.93	36.21	16.40
GREET result (g CO <sub>2</sub> e/MJ fuel) (herbaceous)	24.96	70.33	45.46	27.17
GREET result (g CO <sub>2</sub> e/MJ fuel) (corn stover)	24.33	70.22	45.56	27.24
GREET result (g CO <sub>2</sub> e/MJ fuel) (forest residue)	21.20	65.30	38.45	18.24

For all WTW result except the one with 92% coal mass ratio, the custom modeling result is lower than GREET default result when herbaceous plant or corn stover is used as feedstock. But if farmed tree or forest residue is applied to the GREET default model, the total emission from custom modeling would be higher compared with the GREET modeling result.

According to previous discussions, CO<sub>2</sub> stored in feedstock plays an important part in GHG emission reduction. Farmed tree and forest residue both have a carbon mass ratio of 51.7%, which is in GREET database, while biosolid in this analyses only have 36.8%. So the lower emission rate of farmed tree and forest residue may largely due to the higher mass percentage of carbon in farmed tree and forest residue. With extra CO<sub>2</sub> captured in soil, the net GHG emission from farmed tree processing

is even lower than forest residue. However, farmed tree has the problem of land usage competition so may not be quite ideal for synthetic fuel production.



**Figure 11 WTW modeling result compared with GREET default modeling results**

Comparing the custom modeling result with the GREET result using forest residue can prove the efficiency of CE-CERT process in GHG emission reduction. Forest residue shares some facts in common with biosolids as both of them require no agricultural input when used as sustainable feedstock of F-T synthesis. So the emission of using biosolid as feedstock nearly equals to the emission of using forest residue, which is only less than 1 g/MJ higher. However, GHG emission of using biosolid as feedstock in this CE-CERT-process-combined system should be much lower if biosolid has the same carbon mass ratio as forest residue does, which means a much higher CO<sub>2</sub> amount stored in the feedstock.

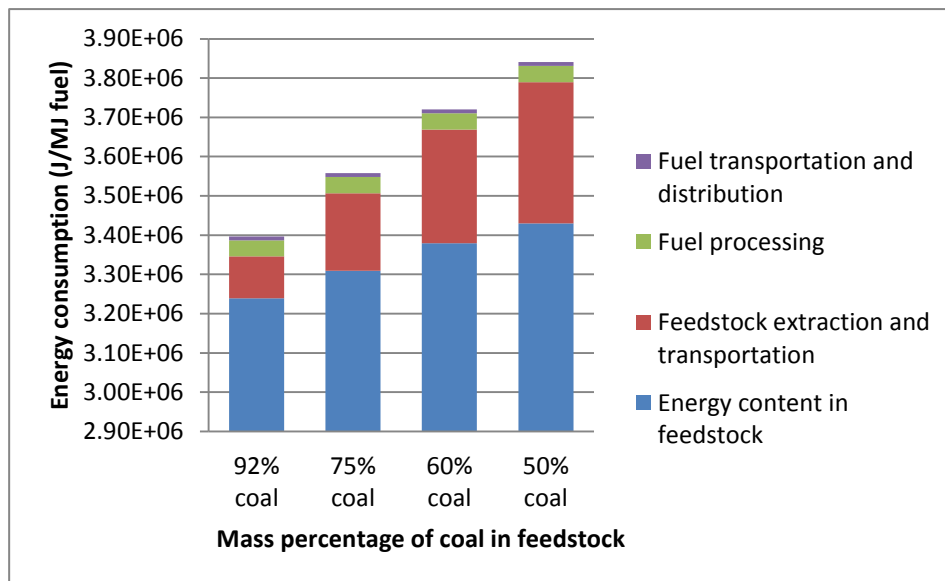


### 3.3.3 WTT energy consumption

Table 23 and Figure 12 summarize all energy consumption in every procedure of WTT analysis. Energy content in feedstock accounts for most of the energy input as coal has high energy content and carbon mass ratio.

**Table 23 WTT total energy consumption**

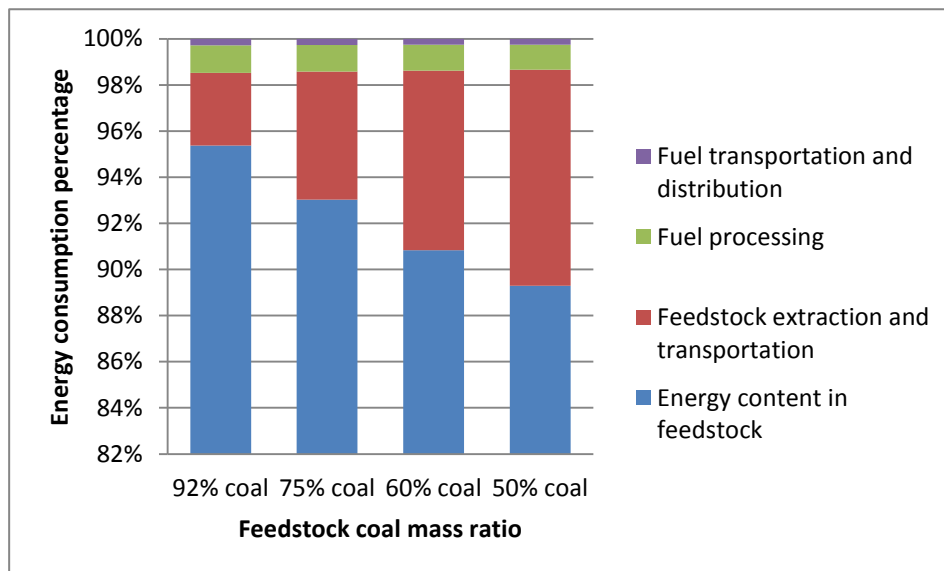
	92% coal	75% coal	60% coal	50% coal
<b>Energy consumption in each step of WTT process (J/MJ fuel)</b>				
Energy content in feedstock	3.24E+06	3.31E+06	3.38E+06	3.43E+06
Feedstock extraction and transportation	1.07E+05	1.97E+05	2.90E+05	3.60E+05
Fuel processing	4.07E+04	4.11E+04	4.15E+04	4.18E+04
Fuel transportation and distribution	9.59E+03	9.59E+03	9.59E+03	9.59E+03
<b>Total WTT energy consumption (J/MJ fuel)</b>				
Total WTT energy consumption	3.40E+06	3.56E+06	3.72E+06	3.84E+06



**Figure 12 Energy consumption for total and each step of WTT process**

To have a better view of how the minor parts of energy input affect the total consumption, Figure 13 is made to show detailed percentage of energy input in every step. According to the graph, energy input from the feedstock per MJ of fuel accounts for no less than 88% of the consumption in WTT process. This is due to the

high energy content of coal. The value of input increases with the mass ratio of biosolid but the percentage in total consumption decreases, which is a result of decreasing fuel yield after all fuel processing steps. Fuel processing only claims a small part of all energy consumption.



**Figure 13 Percentage of energy consumption of each step in total WTT consumption**

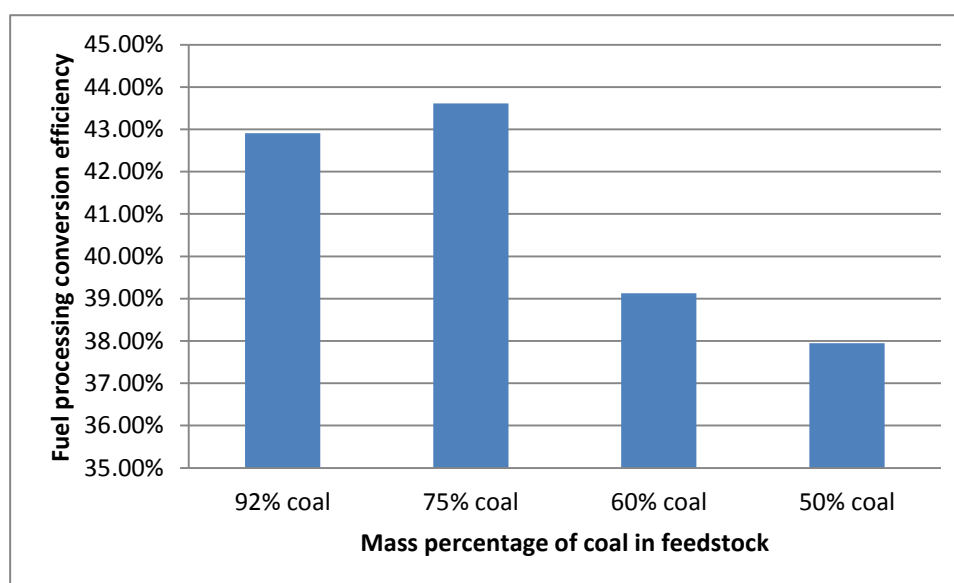
Thus high biosolid percentage causes lower product yield and more energy consumed on biosolid transportation per MJ of fuel produced. Total WTT energy consumed per MJ of fuel produced also increases.

### 3.3.4 Fuel conversion efficiency

The calculation result of conversion efficiency in this process is listed in Table 24 and Figure 14.

**Table 24 Summary of fuel consumption in fuel processing and final fuel conversion efficiency**

	92% coal	75% coal	60% coal	50% coal
<b>Energy input in feedstock and fuel processing (CE-CERT process and upgrading) (MJ)</b>				
Energy content in feedstock	2.54E+04	2.40E+04	2.28E+04	2.20E+04
Net energy consumption in fuel processing	-7110.52	-6245.40	-5545.13	-5085.93
Fuel energy content	7827.76	7245.16	6737.20	6402.02
<b>Total fuel conversion efficiency (%)</b>				
Fuel conversion efficiency	42.91%	43.61%	39.12%	37.95%



**Figure 14 Fuel conversion efficiency in fuel processing**

The total efficiency peaked at 43.61% when coal mass percentage is 75% and it goes down as percentage of coal decreases. For feedstock with 60% and 50% coal, the total efficiency is fairly low compared with common CBTL plants, which usually has a processing efficiency that ranges from 40% to 50%.

Both the numerator and denominator in Equation that determines the working efficiency are functions of coal mass percentage. As coal mass percentage decreases, total carbon mass percentage also gets lower so less fuel is yielded. The energy content in feedstock decreases as well. Feedstock composed by 75% coal and 25%

biosolid could be quite ideal for this process.

Also we can conclude that even providing higher amount of sustainable GHG stored in feedstock, high biosolid mass percentage in feedstock is not suggested as it will cause low fuel conversion efficiency.

#### **4. Summary and future work**

In this Section, previous conclusions and interpretations are summarized. Suggestions about future study on this research are given here as well.

##### **4.1 Summary of interpretations**

Proved by this assessment, CE-CERT process effectively reduces the total WTW emission. CCS is required to be installed. Among the four simulations with coal/biomass feedstock mass ratio of 92%/8%, 75%/25%, 60%/40% and 50%/50%, 92% coal and 8% biosolid cannot meet the goal of 20% GHG emission reduction. All the other three show very good reduction reduction. The lowest viable biosolid mass percentage in feedstock is shown to be around 17% to meet the emission reduction goal. To have zero emission in WTT process, biosolid mass percentage should be higher than 23%. Compared with other traditional CBTL processes, CE-CERT process is also more effective in emission reduction.

Biosolid mass percentage in feedstock significantly affects total GHG emission, fuel yield and conversion. Sustainable portion of biosolid is the most important

factor in total GHG emission, followed by biosolid transportation as the second.

High biosolid percentage in feedstock can greatly reduce total GHG emission because of high amount of GHG stored in feedstock. However, it may cause low fuel yield, more energy consumed per MJ of fuel and low fuel conversion efficiency.

Finally, it is suggested that 75% coal/25% biosolid is a very worth-considering feedstock composition for the process.

## **4.2 Future work**

To have a more detailed and specific study of the whole process, some points are left for further discussion and future study. To build up future experiments and modeling, these factors should be considered:

### **4.2.1 Biosolid percentage in feedstock**

Further investigation on an ideal biosolid mass percentage in feedstock is of critical importance. This requires both experiment and modeling. LCA modeling of this process could be more detailed. For example, more transportation methods of biosolid transportation such as pipeline could be taken into account. Experiments can provide more reliable references for simulations.

### **4.2.2 Process improvement**

Possible process improvement includes more sophisticated simulation model

building and targeted experimental studies for modeling.

More sophisticated simulation model requires for more details of the process. For example, transportation method in this analysis is ground transport only. Pipeline transport is another option for slurry transportation. Another block that needs to be further improved is product upgrade. Treatment process like hydro-isomerization and distillation could be added in the simulation flow sheet to have more realistic information about possible yield of a real manufacturing site<sup>39</sup>.

Targeted experimental studies can provide more reliable references for process modeling. Future experiments may focus on better catalysts for F-T synthesis and product upgrade. Specially designed F-T catalyst can largely increase the selectivity on certain product (gasoline, jet fuel, diesel, wax, etc.) in F-T synthesis. So this is an effective way to increase the total fuel conversion efficiency in the process. Catalysts used for product upgrading have the same function of narrowing the range of different product produced in the chain of cracking reactions. Future simulations or experiments could take these factors into consideration.

Examples of F-T catalysts that have already been applied to similar processes include zeolite (ZSM-5, HZSM-5, ZSM-48, HZSM-48 particularly)<sup>40</sup>, noble metal/oxides/carbon promoted cobalt catalyst<sup>41</sup>. Examples of hydrocracking catalysts are zeolite (ZSM-5, HZSM-57, ZSM-22, etc.), amorphous silica-alumina and solid phosphoric acid<sup>42</sup>.

### **4.2.3 Economic analysis**

Economic analysis is a must for commercialized F-T plants. Economic viability is of critical significance for commercialized manufacturing process. First the scale of the F-T plant should be designed. This is the prerequisite for capital and operation cost estimation. Price of feedstock and crude oil is also important. CE-CERT process can largely reduce the cost on feedstock cultivation. How big the impact that CE-CERT process has on CBTL aviation fuel production process needs further assessments.

## **5. Conclusion**

CE-CERT process using coal and biosolid as feedstock to produce CBTL Fischer-Tropsch aviation fuel is shown to be environmental viable by this assessment. To meet the 20% emission reduction standard, feedstock with biosolid mass ratio higher than 17% is suggested. Compared with traditional CBTL processes, CE-CERT process is more effective in GHG emission reduction. Biosolid plays an important role in emission reduction, process energy consumption, fuel yield and fuel conversion rate. High biosolid percentage in feedstock is not recommended. 75% coal +25% biosolid is a suggested feedstock composition. Investigation on an ideal biosolid percentage is a must for future study. System improvement is also required for further experiments and modeling. Finally, an economic assessment should be carried out to verify the viability of commercializing this process.

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## **Appendix:**

### **Abbreviations**

DoD: United States Department of Defense

IEA: International Energy Agency

WEO: World Energy Outlook

EISA: Energy Independence and Security Act

DOE-NETL: United States Department of Energy, National Energy Technology  
Laboratory

GHG: greenhouse gas

F-T: Fischer-Tropsch synthesis

HTFT: high temperature Fischer-Tropsch synthesis

LTFT: low temperature Fischer-Tropsch synthesis

SPK: synthetic paraffinic kerosene/ Fischer-Tropsch jet fuel

CTL: coal to liquid

BTL: biomass to liquid

GTL: gas to liquid

CBTL: coal-biosolid to liquid

POX: partial oxidation

CE-CERT: Center for Environmental Research and Technology, from Bourns

College of Engineering, University of California, Riverside

SHR: steam-hydrogasification reaction/reactor

SMR: steam methane reformer

FTR: Fischer-Tropsch reactor

LCA: life cycle analysis

LCI: life cycle inventory

WTT: well-to-tank

TTW: tank-to-wake

WTW: well-to-wake

BPC: belt packed cake

SMDS: Shell Middle Distillate Synthesis

CCS: carbon dioxide capture and storage