Universiteit Utrecht

Modeling the biomass supply chain using a discrete, geospatial explicit approach

Fischer-Tropsch diesel from lignocellulosic biomass

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Summary

Biomass used for the purpose of energy generation (bioenergy), is considered as one of the most promising alternatives to the use of fossil-resources. However, the viability of the large-scale use of biomass as a fuel depends for a large extent on the costs and the greenhouse gas balance of the bioenergy production chain, of which feedstock supply from a field side to the throat of a refinery or conversion plant, is one of the largest contributors.

The main objective of this master thesis was to provide further insight into the costs, energy consumption and GHG emissions of the FT-diesel supply chain from field- to refinery-gate by addressing discrete logistic process details as well as geographic explicit transport details of inter-continental supply chains. To fulfill this objective, a new modeling tool (BLCM-UU) was developed using two existing models on biomass logistics, each with its own strength and weaknesses. These models on biomass logistics, where combined with a biofuel conversion model assuming a Fischer-Tropsch (FT) diesel plant for end conversion of lignocellulosic biomass to biofuel.

The three models used for the development of the integrated FT-diesel supply chain modeling tool are: the Biomass Intermodal Transportation (BIT-UU) Model that uses ESRI's ArcGIS Network Analyst; the Biomass Logistic Model (BLM) developed by the Idaho National Laboratory (INL); and the FT Conversion Model developed by van Vliet et al. (2009).

With the developed BLCM-UU six case studies have been conducted to assess the cost, energy and GHG performance of FT-diesel production from stover, switchgrass and woody biomass with the source of the biomass in the United States and with the FT-diesel conversion plant located in The Netherlands. Before long distance transportation, all raw biomass is assumed to be preprocessed into pellets. Besides the feedstock type, the analyzed chains differed in the scale of the FT-plant (400 and 2000 MWth input). The results, provided as a breakdown of the costs and GHG emissions, are depicted in figure A and figure B. For all six demonstrated cases there were two distinct contributors found to the total costs of the FT-diesel supply chain: first of all the costs for conversion and second the costs for long distance transportation. The costs for densification into pellets (included in the costs for preprocessing) were found to be low compared to the total costs of the supply chains. The most economic supply chain (considering the same scale of the FT-plant) is the supply chain for the production of FT-diesel from woody biomass. The supply of FT-diesel from woody biomass (WoodyPTL2000) was found to be nearly cost effective (current: $108.48 per barrel crude oil, 21 € / GJ diesel) and would become cost effective at a crude oil price of 121$/bbl. Thereby, even when considering supply chains with long distance transportation from terminal to refinery, FT-diesel production in Europe might become cost effective in the future and contribute to the RES 2020 targets of 20% renewable energy in 2020 (Renewable Energy Directive 2009/28/EC).

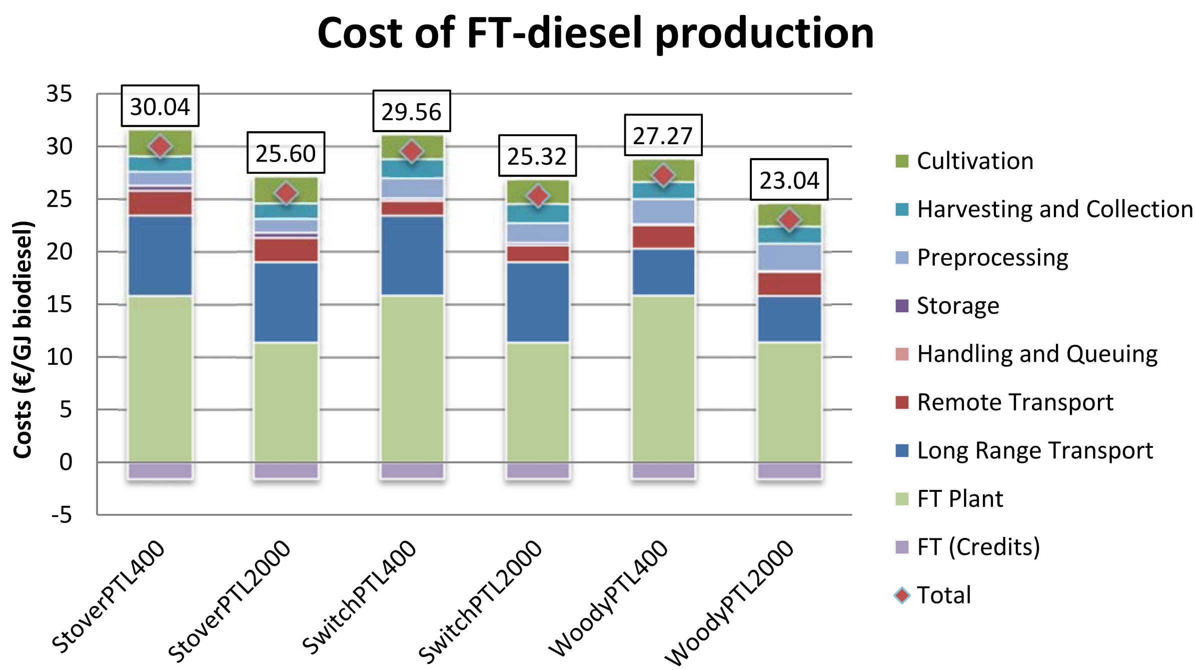

Figure A – Cost of FT-diesel production per component of the FT-diesel supply chain[1]

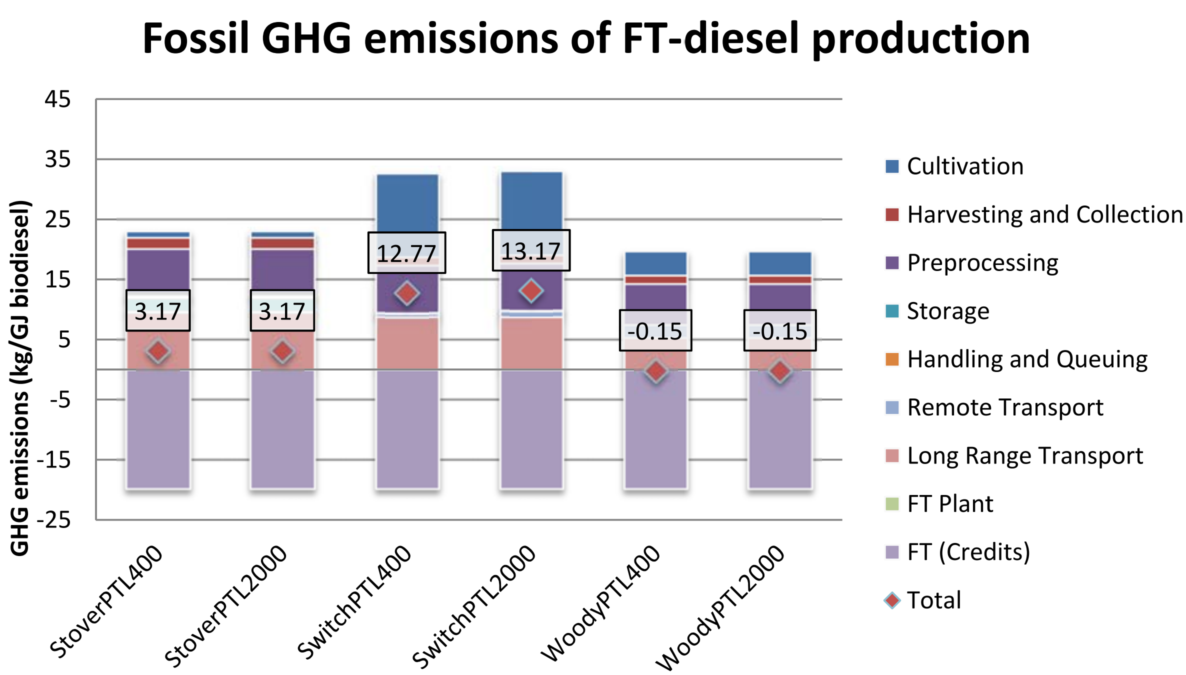

Figure B – Fossil GHG emissions of FT-diesel production per component of the FT-diesel supply chain

[1] Remote Transport consists of the operations to transport the biomass from Field to Depot and from Depot to Terminal. Long Range Transport is the intermodal transportation of the biomass from Terminal to the FT-plant. FT Plant includes all the operations in the FT plant, including: storage, preprocessing, handling & queuing and end-conversion. FT (Credits) are the savings from excess electricity from cogeneration in the FT-plant.

For all six biofuel production chains, a negative fossil energy consumption was found[2]. The lowest negative fossil energy consumption was found for the supply chain from switchgrass. With respect to GHG emissions only negative emissions were found for the supply chains from woody biomass, the chains for stover and switchgrass do emit greenhouse gasses from which the chain for FT-diesel from switchgrass is performing the worst by far. With an overall found range for the GHG emissions of -0.15 - 13.17 g CO2eq / MJ FT-diesel produced, the emissions for the six case studies fall within the ranges found by other studies. Considering a GHG emission factor of 83.8 g $CO2_{eq}$ / MJ for fossil diesel[3] all six cases can be considered as robust GHG emission savers and meet the reduction of 60% with respect to diesel production from fossil sources required by the RES Directive[4] (Renewable Energy Directive 2009/28/EC). For the stover cases the reduction is 96%, for switchgrass 84-85% and for woody biomass 100%. Since in each of the examined supply chains long distance transportation takes place and each chain meets the 60% reduction required by the RES Directive, it can be concluded that long distance transportation does not have to be a barrier for biofuel production chains in Europe with a feedstock supply source at a distant location.

To determine how robust the conclusion is that a large share of the total costs of the FT-diesel supply chain are associated with the long distance transportation of the biomass (terminal to refinery), three sensitivity analyses have been performed targeted on the key uncertain parameters of intermodal transport of biomass: the time charter rates, the fuel prices for IFO380 and the ocean vessel size. This was performed by additionally running the model for respectively the lowest and highest time charter rates in the period 2007-2011; the lowest and highest fuel prices for IFO380; and by running the model with the specifications of two other types of ocean vessels: Supramax and Panamax. The sensitivity analysis found, that from the extremes in the time charter rates and from the extremes in the fuel prices for IFO380 (in the period 2007-2011), the costs of the supply chain for FT-diesel from woody biomass are most sensitive to the time charter rates. Although the time charter rates and fuel costs for IFO380 were found to have an effect on the total costs of the supply chain, even when considering the lowest values in the period 2007-2011, the costs for intermodal long distance transportation remains to be a large share of the total costs of the supply chain.

The in this thesis developed modeling tool provides insight in the cost structure, potential cost reductions (for example due to economies of scale), and transport details (through detailed depiction of intermodal, geographic explicit transport) of the FT-diesel supply chain. Furthermore it provides the opportunity to compare the performance (in terms of costs, energy consumptions and GHG emissions) of multiple alternative supply chains from various feedstock and source and demand regions. Due to its ability to address for both geospatial details and details of logistic processes the developed modeling can be used to study the effects of densification (unprocessed, chips, pellets, torrefaction) and the effects of new technologies on the overall performance of the supply chain.

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[2] Negative costs, energy consumption and GHG emissions are a result of crediting for the benefits of (excess) electricity exported to the grid due to co-generation of electricity in the FT-plant.
[3] The use of the figure 83.8 g $CO2_{eq}$ / MJ for diesel is prescribed by the RES directive; this figure includes the emissions from the production of the fossil diesel (Renewable Energy Directive 2009/28/EC).
[4] Note: The RES Directive uses the emissions from a biomass electricity plant instead of the (in this thesis used) emissions from baseline electricity generation in Western Europe for calculating emission savings.

Preface

This report presents the results of the master thesis project “Modeling the biomass supply chain using a discrete, geospatial explicit approach” which has been conducted in context of a joint project for IEA Bioenergy Trade Task 40 by the Copernicus Institute of Sustainable Development – Utrecht University and the Bioenergy group of the Idaho National Laboratory (INL). The challenge presented to me in this thesis was to develop a method to study the FT-diesel supply in terms of costs, energy consumption and GHG emissions using three existing models (INL BLM, BIT-UU, van Vliet FT Conversion Model).

I would like to thank Ric Hoefnagels for supervising me, correcting my work, sharing his knowledge and guiding me through the process of writing this thesis. The discussions with him in the context of this thesis have been highly motivating. Furthermore I wish to thank Oscar van Vliet and the Bioenergy group of the Idaho National Laboratory for making their models available to me and Dr. Machteld van den Broek and Dr. Martin Junginger for assessing my work.

Thijs Cornelissen,
July, 2013.

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1 Introduction

1.1 Background

Biomass is considered as one of the most promising alternatives to the use of fossil-resources. It has the potential to mitigate climate change and is able to improve energy security of supply. In the last decade, lignocellulosic biomass has moved from a local source of energy to an internationally tradable energy commodity and the traded volume is still expected to grow rapidly (Heinimö et al, 2009). This movement is aided by the processing of woody biomass resources into wood pellets which are energy dense, uniform and homogenous. These characteristics make them an easily tradable commodity (Hess et al., 2009). The international trade volume of wood pellets has more than doubled from 1.5 Mt in 2004 to 3.6 Mt in 2006 and the expected demand for wood pellets is estimated to be 20 Mt in 2020 depending on policies on co-firing, CO_2 emission allowances and support for decentralized heating (Cocchi et al 2011, Lamers et al. 2012). Also, global production of liquid biofuels increased exponentially from 370 PJ in 2000 to over 2100 PJ in 2009 of which 6 % was net traded globally in 2009, with Europe remaining the most important market for biodiesel (Lamers, Hamelinck et al. 2011).

One of the major issues concerning the costs of the biomass supply chain is that most often biomass supply potentials are not equal to the potential demand in specific regions as regions with high supply potentials are often located remote from regions with high energy demands. This implies that biomass would have to be transported between regions with a surplus on biomass potential to regions of which its biomass demand exceeds their potential. These logistic processes induce costs, energy and GHG emissions. Although this problem also exists for fossil energy commodities, trade of bioenergy commodities is unique in the sense that it is less mature and supply is more heterogeneous and more decentralized in nature compared to, for example, coal. This makes calculating and optimizing for costs and/or GHG emissions more complex. The viability of the large-scale use of biomass as a fuel highly depends on the costs and the greenhouse gas balance (GHG) of the biomass supply chain. Insight in the associated costs, environmental performance, bottlenecks and potential improvements is therefore of great importance.

1.2 Problem definition

Lignocellulosic biomass comes from a variety of sources and preprocessing, densification (such as conversion into wood pellets) and conversion into FT-synfuel can take place at different places in the distribution chain. This makes cost calculation and optimization of the supply chain highly complex (Searcy et al., 2010). The costs of distribution are determined by multiple factors such as the processing of the biomass, fuel and electricity prices, the density of the biomass, distance of transportation and the properties of the transportation network. Several models have been developed in the past to model the total costs of the biomass supply chain. An example of such a model is the model developed by Hamelinck et al. (2005). This and other models do not or limited include the modeling of the geo-spatial features of real world transportation networks and the effects of changing parameters such as fuel costs, processing costs and scale on the least cost optimal routes. Instead, generalized estimates are being used for the transportation distances and the transportation costs of biomass. In addition, these models have often limited flexibility in studying the effects of adding, omitting or substituting steps in the biomass supply chain. Based on a review of existing literature on biomass logistics and biomass feedstock transportation systems, Miao et al. (2012) concluded that there is a lack on performance based evaluation and design of feedstock supply procedures, equipment, facility, transportation regulation and policy. They also identified the need for an integrated framework addressing these challenges.

Some of these issues have been addressed in recently developed models. The first issue, taking into account the properties of real world transportation networks, has been addressed by the BIT-UU geospatial model developed by the Copernicus Institute of Utrecht University (Hoefnagels et al., 2011). This model is geospatial explicit, but is aggregated on logistic processes other than transport. A second developed model is the Biomass Logistic Model (BLM) from the Idaho National Laboratory (INL). This model includes discrete processes on most logistic steps but takes a rather simplistic approach on calculating transportation distances or transport modes without considering real world transportation networks (Searcy et al., 2010).
A modeling tool that has attention for both geospatial details and the details of logistic processes could provide further insight in the associated costs, energy consumption and GHG of the biomass supply chain.

1.3 Objective

The main objective of this master thesis was to provide further insight into the cost, energy consumption and GHG emissions of the FT-diesel supply chain from field- to refinery-gate by addressing discrete logistic process details as well as geographic explicit transport details of inter-continental supply chains, thus complementing existing models and overcoming the knowledge gap currently present due to the limitation of these existing models.
Cultivation of the feedstock is purposely omitted from the scope of this thesis because the operations during the cultivation of the feedstock do not describe or directly constrain the engineering operations or the logistics of the supply system (Searcy, Hess 2010, p.10).

To fulfill the objective, a new modeling tool was developed to overcome the present gap in analysis capabilities caused by the limitations of the existing models. The modeling tool developed in this thesis will be referred to in this document as the Biomass Logistics and Conversion Model (BLCM-UU). To illustrate the insights the BLCM-UU can yield it was applied to six case studies.

The BLCM-UU provides the opportunity to calculate the monetary costs, energy consumption and GHG emissions of the FT-diesel supply chain in detail, while (unlike models currently available) additionally addressing discrete logistic processes and geographic explicit transport details of inter-continental supply chains (such as transportation and geographic locations of supply, demand and trade routes). Since the order of operations in a supply chain can change based on the feedstock type and the type of supply system, the model needed to be developed in such a way that is flexible in the ability to add, omit or substitute steps in the supply chain model, so that it was able to facilitate the analysis of different supply chains.

In this thesis, the BLCM-UU model was used to evaluate six case studies were then conducted to demonstrate that the new model can assess the following three aspects and, by doing that, illustrate that the modeling tool yields new insights in:

- the costs of producing one GJ of FT-diesel when considering the FT-diesel supply chain from field to refinery-gate;

- the specific GHG emissions of producing FT-diesel (kg CO_{2eq} / GJ) when considering the FT-diesel supply chain from field to refinery-gate;
- the specific energy consumption (GJ_p / GJ_f) of producing FT-diesel when considering the FT-diesel supply chain from field to refinery-gate.

1.4 Scope

1.4.1 Supply chains

The focus in the modeling process has been on lignocellulosic biomass feedstock. The biomass supply regions included in the case studies in thesis, using the developed modeling tool, are the Mid-West and South-East of the United States. These are prime locations for herbaceous and woody biomass respectively. The demand region considered was Rotterdam, The Netherlands being one of the major locations for import of biomass from overseas locations (Cocchi et al. 2011, Lamers et al. 2012).

Six supply chains were examined in the case studies in this master thesis. All are FT-diesel supply chains with the refinery[5] assumed to be located in Rotterdam, but they differ in the geographic location of the source of the biomass, the scale of the Fischer-Tropsch plant (400MW/2000MW) and the type of biomass feedstock (stover/switchgrass/woody). A description of the examined supply chains can be found in Table 1.

	StoverPTL400	*StoverPTL2000*	*SwitchPTL400*	*SwitchPTL2000*	*WoodyPTL400*	*WoodyPTL2000*
Source location	Mid-West United States	Mid-West United States	Mid-West United States	Mid-West United States	South-East United States	South-East United States
Source type	Stover	Stover	Switchgrass	Switchgrass	Wood	Wood
Location terminal	Kansas City	Kansas City	Kansas City	Kansas City	Savannah	Savannah
FT plant location	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands
FT plant type	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW

Table 1 - Description supply chains of case studies

[5] Also referred to in this thesis as FT plant.

Note however, that the developed modeling tool is capable of assessing supply chains for all possible supply regions in the United States and demand regions in Europe.

1.4.2 **Biomass and commodity types**

The developed modeling tool is valid for several types of biomass (herbaceous residues, short rotation woody, energy crops, woody residues and algae) and feedstock formats such as pellets and chips using the rich database of the existing BLM Model developed by INL.

The three types of raw biomass resources that were considered in the demonstrated cases are: stover, switchgrass and woody biomass. The pre-processed feedstock format that was considered for long distance transportation in these six cases is pellets.

1.4.3 **Costs, Energy and GHG emissions**

This thesis only includes the 1st and 2nd order energy inputs (both direct and indirect energy inputs for the production of FT-diesel) for the supply chains; the 3rd order energy inputs and GHG emissions (for construction and dismantling of capital goods, for example, the production of a ship) are not considered, consistent with the EU RES directive on liquid biofuels. These 3rd order energy inputs and emissions are very uncertain and contribute in most cases only marginally to the total supply chain (SenterNovem, 2008). The costs of machines and equipment are, however, included in this thesis to be able to account for the effect of economies of scale and because CAPEX (capital expenditures) attribute substantially to the total supply cost.

The functional units that are used in this thesis are Euro/GJ FT-diesel produced [costs]; kgCO_2-eq/GJ FT-diesel produced [GHG emissions]; GJ / GJ FT-diesel produced [energy consumption].

1.5 Outline

The structure of this report is as follows. After the introduction in Section 1, Section 2: Methodology, covers the general approach and details on the linking of three existing models and the development of the new BLCM-UU modeling tool in this thesis. Section 3: Results, describes the details and the results of the six case studies conducted for the demonstration of the BLCM-UU and the new insights it provides. This section also includes the results of three sensitivity analyses that have been performed using the new modeling tool to assess the impact of key uncertainties of model parameters on the results. The benefits and limitations of the developed modeling approach are discussed in section 4. Finally, the conclusions are presented in section 5.

2 Methodology

2.1 Introduction

A biomass to FT-diesel supply chain, which is the subject of this thesis, is a particular set of operations, in a particular order, that biomass goes through from field to refinery-gate with as final output FT-diesel.

In the supply chain for bioenergy, such as the supply chain for FT-diesel, six major components can be distinguished: Harvesting and Collection, Storage, Transportation, Preprocessing, Handling and Queuing, Conversion. Examples of operations in the supply chain associated with the Storage component are operations such as piling chopped material or stacking into large square bales. The order in which operations in a supply chain take place is influenced by many factors such as the choice of biomass/feedstock as input, the type of commodity (such as pellets) and the choice of end-conversion technology. Therefore each supply chain is unique in its structure, represented by a unique flowchart. Two examples of types of supply chains can illustrate the previous (the occurrence of multiple operations from one major component and the differences that can be caused by the choice of feedstock) (Searcy, Hess 2010).

In the conventional supply chain using herbaceous as feedstock, the feedstock is first harvested into a windrow as a first operation in the chain, and collected into bales of biomass (Hess et al 2009). These bales are then transported to the field side for storage, and from there transported to the refinery by truck. After the goods have been received at the refinery, there is a preprocessing step that takes place (generally grinding), after which, as a final step, the conversion operation takes place.

For a conventional woody biomass supply chain, harvesting and collection takes place by felling and piling the trees, after which these are skidded to the landing, where chipping or grinding of the trees (preprocessing) takes place before they are transported to the refinery. After it is stored at the refinery, additional preprocessing takes place (mostly drying and/or hammermilling) (Searcy, Hess 2010).

Advanced supply chains could have multiple preprocessing, storage and handling and queuing operations.

The different operations of the biomass supply system can take place at four sites: Fieldside, Depot, Export Terminal and Refinery. In Table 2 an overview is given of the operations per component and the distinct locations they can take place.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="4">Locations</th></tr>
<tr><th>Fieldside</th><th>Depot</th><th>Terminal</th><th>Refinery</th></tr>
<tr><th rowspan="6">Components of Supply chain</th><td>Harvesting & Collection</td><td>Harvesting
Baling / Bundling
Collection</td><td></td><td></td><td></td></tr>
<tr><td>Storage</td><td>Storage Fieldside</td><td>Storage Depot</td><td>Storage Terminal</td><td>Storage Refinery</td></tr>
<tr><td>Transportation</td><td>Transportation from Field</td><td>Transportation from Depot</td><td>Transportation from Terminal</td><td>Transportation from Refinery[6]</td></tr>
<tr><td>Preprocessing</td><td>Preprocessing Fieldside</td><td>Preprocessing Depot</td><td>Preprocessing Terminal</td><td>Preprocessing Refinery</td></tr>
<tr><td>Handling & Queuing (H&Q)</td><td></td><td>H&Q Depot</td><td>H&Q Terminal</td><td>H&Q Refinery</td></tr>
<tr><td>End-conversion</td><td></td><td></td><td></td><td>End-conversion into FT-diesel</td></tr>
</table>

Table 2 - Operations by component and location

[6] Not modeled in this thesis

2.2 Development of an integrated modeling tool (BLCM-UU)

To fulfill the analysis objective of this thesis a new integrated analysis tool was developed to provide further insight into the cost, energy consumption and GHG emissions of the FT-diesel supply chain from field- to refinery-gate. Integrated, because three distinct models have been unified into a single model called the Biomass Logistics and Conversion Model (BLCM-UU) such that they behave like a unit to external stimuli.

The three models that are included in the BLCM-UU are:

- The Biomass Logistic Model (BLM) developed by INL,
- The Intermodal Transport Network Model (BIT-UU) model developed by the UU[7],
- The Fischer-Tropsch Conversion Model developed by van Vliet et al. (2009).

The BLM INL Model and BIT-UU Model are used to model the biomass logistics in the BLCM-UU (paragraph 2.3); the van Vliet Fischer-Tropsch Conversion Model is used to model the conversion operations (paragraph 2.4) in the BLCM-UU as is depicted in Figure 1.

INL BLM - Biomass Logistic Model

BIT-UU – Intermodal Transport Network Model

Van Vliet – Fischer-Tropsch Conversion Model

Figure 1 – Location/phase of the FT-diesel supply chain where the three included models have their main application

[7] "Development of a tool to model European biomass trade; Report for IEA Bioenergy Task 40" by Hoefnagels et al. (2011).

Central in the development of the integrated supply chain analysis tool was the Biomass Logistic Model (BLM) from the Idaho National Laboratory (INL) (paragraph 2.3.1). A flexible tool with the ability to model multiple types of feedstock and conversion processes and has attention for discrete logistic process details. Subsequently the BIT-UU Model was integrated in the BLCM-UU (paragraph 2.3.3) to address geographic explicit details of inter-continental intermodal transportation of biomass between the terminal and the refinery. To analyze the feedstock supply chain in context of a complete biofuel production system, the FT Conversion Model, developed by van Vliet et al. (paragraph 2.4.1) was included in the developed modeling tool. Figure 1 depicts in which location/phase of the FT-diesel supply chain the three included models have their main application.

The integration of the three individual models has been established by the development of intelligent interfaces between the INL BLM and BIT-UU and between the INL BLM and van Vliet FT Conversion Model. This has been implemented by the addition of two new submodels to the INL BLM Model as is depicted in Figure 2. The included models and their integration in the UU-BLCM are discussed in detail in the next chapters.

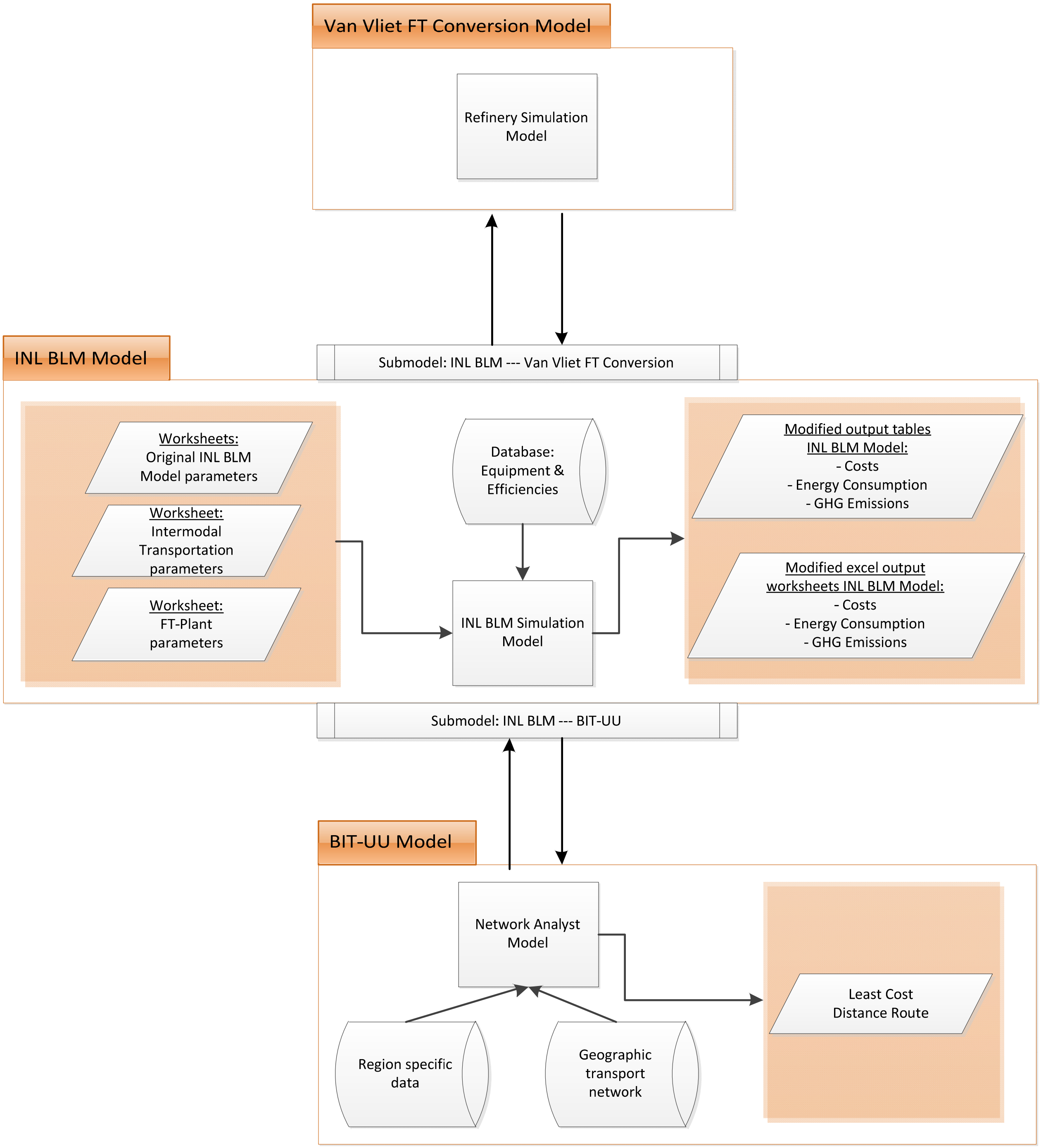
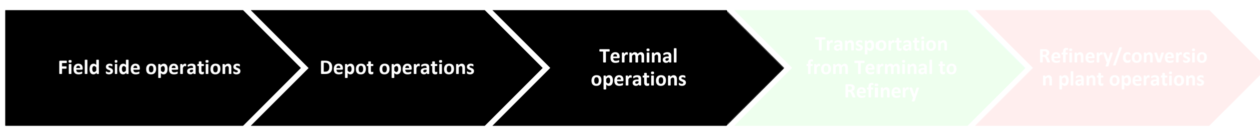


Figure 2 - The Biomass Logistics and Conversion Model (BLCM-UU) integrated model (The data flows between the included models are discussed in detail in the next chapters)

2.3 BLCM-UU: Biomass Logistics

2.3.1 Description of INL BLM Model

In this section the integration of the INL BLM Model in the overall Biomass Logistics and Conversion Model (BLCM-UU) is covered. The INL BLM Model is applicable for the fieldside, depot and terminal operations as depicted in Figure 3.



INL BLM - Biomass Logistic Model

BIT-UU – Intermodal Transport Network Model

Van Vliet – Fischer-Tropsch Conversion Model

Figure 3 – Location/phase of the FT-diesel supply chain where the INL BLM Model has its main application

The INL BLM Model includes the modeling of material flows, equipment, and operations involved with the collection, harvesting, storage, preprocessing, handling and queuing, and transportation of a single concurrent feedstock type for use at a bio refinery. The BLM Model however does not include the end conversion of the biomass into final energy carriers such as Fischer-Tropsch diesel or electricity; it only includes the logistics for getting the biomass to the refinery (Searcy et al., 2010).

Each of the involved operations that make up the supply chain can be specified to take place at the field side, a depot, a terminal or at the refinery (although this might not always be applicable). Table 3 provides an overview of the operations of the supply chain that are included in the original INL BLM Model.

The model works by simulating the flow of biomass through the entire supply chain while keeping track of changes in the properties such as the moisture content and densities of the biomass.

For this the INL BLM structure is comprised of several location sub-models: fieldside, depot, terminal, and refinery. Within the location sub-models, sub-models for the components of the supply chain (Harvesting & Collection, Storage, Transportation, Preprocessing, and Handling and Queuing) build the biomass supply chain. All operations involved in the physical flow and evolution of biomass to bioenergy (field to the throat of the refinery or power plant) are accounted for.

		Locations			
		Fieldside	*Depot*	*Terminal*	*Refinery*
Components of Supply chain	*Harvesting & Collection*	Harvesting Baling / Bundling Collection			
	Storage	Storage Fieldside	Storage Depot	Storage Terminal	Storage Refinery[8]
	Transportation	Transportation from Field	Transportation from Depot	Transportation from Terminal[8]	Transportation from Refinery[9]
	Preprocessing	Preprocessing Fieldside	Preprocessing Depot	Preprocessing Terminal	Preprocessing Refinery[8]
	Handling & Queuing		H&Q Depot	H&Q Terminal	H&Q Refinery[8]
	End-conversion				End-conversion into FT-diesel

Table 3 – Operations of supply chain included in the original INL BLM Model (indicated in blue)

Details about equipment costs and operation efficiencies for a variety of biomass feedstock types and formats have been included in the model by a provided database. The INL BLM Model allows users to identify equipment, material characteristics, and order of operations in the supply chain, along with model inputs through an extensive input controls spreadsheet. In addition several predefined scenarios are provided to the user in this spreadsheet.

The results of the model consists of a table that provides details about the costs involved ($ / dry matter (DM) ton) and the energy used (MBtu / DM ton) by the supply chain (Figure 4). The results are also exported to an output spreadsheet for further analysis.

[8] This operation of the supply-chain will not be modeled by the INL BLM Model in the developed BLCM-UU.
[9] Not modeled in this thesis

Cost Summary ($/ DM ton)						
	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)
Total Grower's Payment					0.00	
Harvesting	4.40	0.65	1.29	0.00	1.94	134.58
Baling/ Bundling	25.03	4.02	7.45	0.00	11.47	25.27
Collection	6.11	0.90	0.98	0.00	1.88	25.42
Total Harvest & Collection	**35.54**	**5.57**	**9.72**	**0.00**	**15.29**	**185.27**
Transportation FROM Field	6.08	1.12	7.36	0.00	8.48	91.80
Transportation FROM Depot	0.00	0.00	0.00	0.00	0.00	0.00
Transportation FROM Terminal	0.00	0.00	0.00	0.00	0.00	0.00
Total Transportation	**6.08**	**1.12**	**7.36**	**0.00**	**8.48**	**91.80**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery	12.90	3.62	9.07	0.00	12.69	221.80
Total Preprocessing	**12.90**	**3.62**	**9.07**	**0.00**	**12.69**	**221.80**
Storage Fieldside	9.64	2.97	0.76	1.00	4.73	10.92
Storage Depot	0.00	0.00	0.00	0.00	0.00	0.00
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery	0.55	0.20	0.83	0.00	1.02	10.92
Total Storage	**10.19**	**3.16**	**1.59**	**1.00**	**5.75**	**21.83**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery	1.18	0.24	1.06	0.00	1.30	15.31
Total Handling & Queuing	**1.18**	**0.24**	**1.06**	**0.00**	**1.30**	**15.31**
Total	**65.90**	**13.71**	**28.80**	**1.00**	**43.51**	**536.00**

Figure 4 – Example of INL BLM output table[10]

The strength of BLM Model is its flexibility and ability to model multiple types of feedstock and conversion processes and its attention for discrete logistic process details. Although it uses in depth details about the key performance parameters of the equipment used to transport the feedstock, the calculation of the transport distances is rather simplistic. It does not include geospatial details and only includes the modeling of a single mode of transport, or unimodal transportation, by truck or rail. The transportation distances are mainly calculated by using the draw/supply radius technique[11] or are totally exogenous and need to be specified as an input to the model. Especially when considering long distance inter-continental supplies chains to

[10] Installed Capital is expressed in $ / short ton dry input capacity installed. Ownership, operating and total cost are expressed in $ / short ton dry produced.
[11] The draw radius technique is a method to calculate transportation distances by assuming an equal distance distribution of acres throughout the draw radius from a central gathering point.

transport the feedstock between a terminal and a bio refinery, the inclusion of intermodal transportation networks to the model can significantly improve the BLM Model. A modeling tool that covers both geospatial details and the details of logistic processes would provide more insight in the associated costs, energy consumption and greenhouse gasses (GHG) of the biomass supply chain. This is the reason the focus in this thesis has been on improving the modeling of the long distance intercontinental transfer between the export terminal and the refinery.

2.3.2 Modifying the INL BLM Model for GHG emissions

In order to analyze the FT-diesel supply chain in terms of GHG emissions, using the developed BLCM-UU tool, every operation of the supply chain has to be modeled with attention for GHG emissions. Numerous operations in the BLCM-UU are modeled using the INL BLM Model but this specific model does not keep track of the GHG emissions emitted; this poses a problem for the development of the BLCM-UU tool. However since the BLM Model does keep track of the machine properties of the supply chain including the fuel consumption per machine type; the number of machines used and the type of fuel used, it is possible to calculate 1st and 2nd order GHG emissions per operation related to fuel use by using fuel specific GHG emission factors.

GHG emissions per machine (ton / DM ton) =
*(Diesel fuel consumption machine (Gallons) * Emissions factor diesel (ton / Gallon)*
+
*Electricity consumption machine (kWh) * Emission factor electricity (ton / kWh))*
/
Annual demand of the bio refinery (DM ton)

The GHG emissions per operation are aggregated per component: Harvesting & Collection, Storage, Transportation, Preprocessing and Handling & Queuing and included in the output tables of the INL BLM Model (Figure 5).

GHG emissions per supply chain component = ∑ GHG emissions per machines of the component

	GHG (ton CO2eq / ton)
Total Grower's Payment	
Harvesting	0.01
Baling/ Bundling	2.20e-3
Collection	2.21e-3
Total Harvest & Collectior	**0.02**
Transportation FROM Fielc	0.01
Transportation FROM Depc	0.02
Transportation FROM Termi	0.00
Total Transportation	**0.03**
Preprocessing Fieldside	0.00
Preprocessing Depot	0.07
Preprocessing Terminal	0.00
Preprocessing Refinery	
Total Preprocessing	**0.07**
Storage Fieldside	9.50e-4
Storage Depot	3.17e-4
Storage Terminal	0.00
Storage Refinery	
Total Storage	**1.27e-3**
Handling At Depot	0.00
Handling at Terminal	0.00
Handling at Refinery	
Total Handling & Queuing	**0.00**
Total FT Plant	4.62
Total	**4.73**

Figure 5 – Extension to output tables of the INL BLM Model (Figure 4) to include details about GHG emissions (per unit of short ton dry)

2.3.3 Integration of BIT-UU Model

In this paragraph the extensions and modifications that were performed on the INL BLM Model to include intermodal transportation in the BLCM-UU are described. For this, the existing single transportation mode modeling steps of transport of the feedstock from terminal to refinery are eliminated from the INL BLM Model and replaced by the multimodal BIT-UU Model (Table 4) which is capable of calculating the most cost efficient route (while reporting costs, energy consumption and GHG emissions) for intermodal transport of the biomass from the terminal to the refinery.

		Locations			
		Fieldside	*Depot*	*Terminal*	*Refinery*
Components of Supply chain	*Harvesting & Collection*	Harvesting Baling / Bundling Collection			
	Storage	Storage Fieldside	Storage Depot	Storage Terminal	Storage Refinery
	Transportation	Transportation from Field	Transportation from Depot	Transportation from Terminal	Transportation from Refinery[12]
	Preprocessing	Preprocessing Fieldside	Preprocessing Depot	Preprocessing Terminal	Preprocessing Refinery
	Handling & Queuing		H&Q Depot	H&Q Terminal	H&Q Refinery
	End-conversion				End-conversion into FT-diesel

Table 4 - Operations of supply chain modeled using BIT-UU Model (indicated in orange)

The new additions to the BLCM-UU for modeling intermodal transport consist of two major parts: 1) An Intermodal Transport Network Model (BIT-UU) developed in ESRI'S ArcGIS Network Analyst and 2) a new submodel INL BLM – BIT-UU (INL BLM) that provides the link between the intermodal transport network model BIT-UU and the INL BLM Model and takes care of some preliminary calculation steps (

Figure 6). The details of this sub-model are provided in Appendix I. The BLM input controls spreadsheet has been extended with a new worksheet (“Intermodal Transport parameters”, Figure 7) that provides the user with the opportunity to enter details about fuel costs, labor costs, source and destination location, dollar-euro exchange rate, index year and multiple transport mode specific key performance parameters. These parameters are used by the combination of the INL BLM – BIT-UU submodel and BIT-UU Model to determine the most cost efficient route and to calculate the monetary costs, energy consumption and GHG emissions of the transportation of biomass between terminal and refinery. The worksheet has been filled with default values which have been obtained from the article "Development of a tool to model European biomass trade; Report for IEA Bioenergy Task 40" by Hoefnagels et al. (2011) and additional literature research (Appendix III).

[12] Not modeled in this thesis

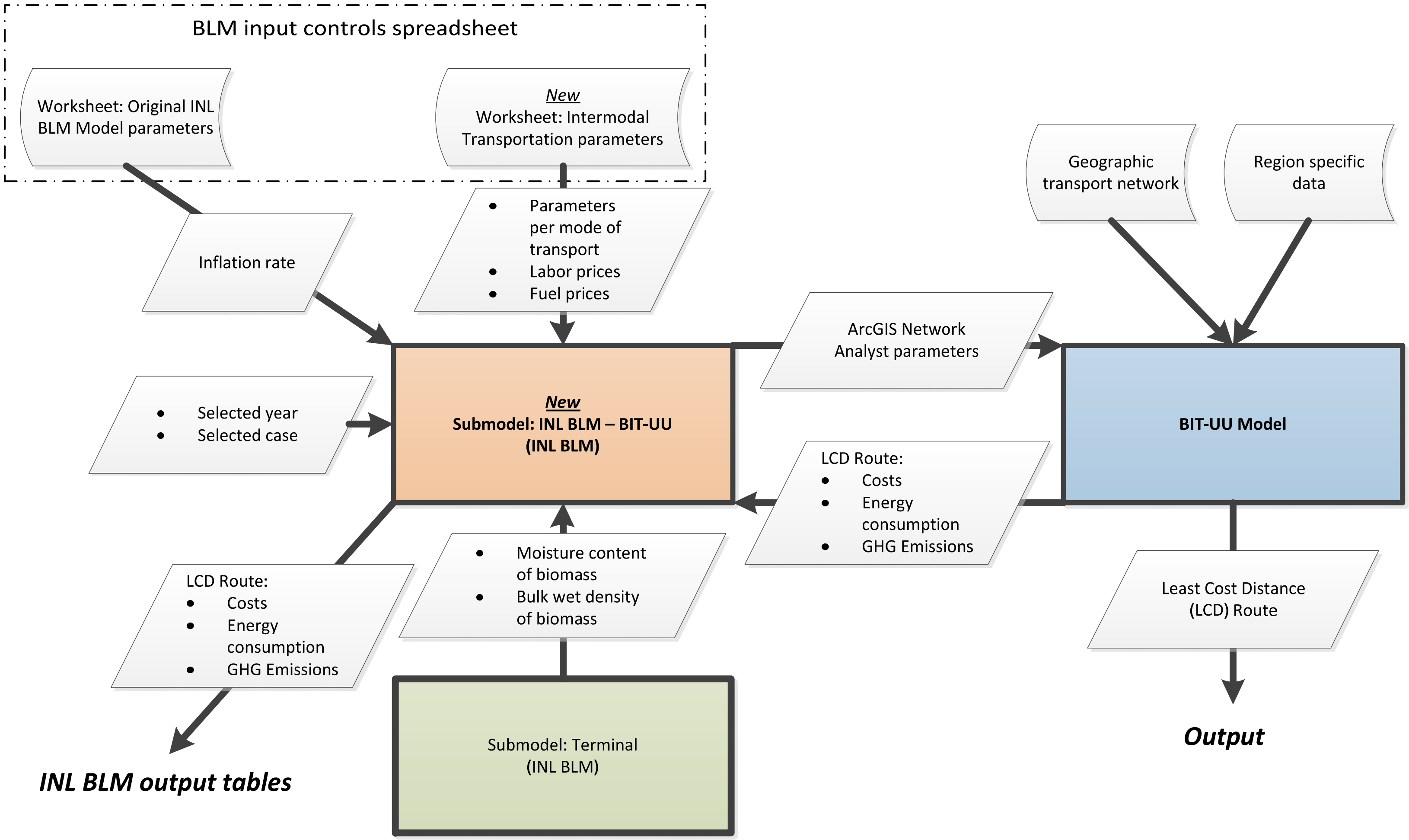


Figure 6 - Inputs/Outputs of submodel: INL BLM – BIT-UU

Transportation ArcGIS		1 Stover, Sq Bale_Transport (bale)to Plant_ Single Grind at Plant	2 Stover, Sq Bale_Transport (bale)to Plant_ Double Grind at Plant	3 Switchgrass, Sq Bale_Transport (bale)to Plant_ Single Grind at Plant	4 Switchgrass, Sq Bale_Transport (bale)to Plant_ Double Grind at Plant	5 Wheatstraw, Sq Bale_Transpo[rt] Single Grind at Plant
Fuel & Labor	**Fuel**					
	Dieselntx	3.50 $/gal	3.50 $/gal	3.50 $/gal	3.50 $/gal	3.50 $/gal
	MDO	1078.96 $/ton	1078.96 $/ton	1078.96 $/ton	1078.96 $/ton	1078.96 $/ton
	IFO380	719.31 $/ton	719.31 $/ton	719.31 $/ton	719.31 $/ton	719.31 $/ton
	Labor					
	Labor cost (NW Europe)	37.00 $/hr	37.00 $/hr	37.00 $/hr	37.00 $/hr	37.00 $/hr
	Labor cost (US Average)	19.30 $/hr	19.30 $/hr	19.30 $/hr	19.30 $/hr	19.30 $/hr
Road	Labour (person/v)	1.00 person/v	1.00 person/v	1.00 person/v	1.00 person/v	1.00 person/v
	Time cost	24.33 $/hr	24.33 $/hr	24.33 $/hr	24.33 $/hr	24.33 $/hr
	Variable cost	0.64 $/mi	0.64 $/mi	0.64 $/mi	0.64 $/mi	0.64 $/mi
	Fuel type (fixed)	Dieselntx	Dieselntx	Dieselntx	Dieselntx	Dieselntx
	Fuel consumption full	21.58 MJ/mi	21.58 MJ/mi	21.58 MJ/mi	21.58 MJ/mi	21.58 MJ/mi
	Fuel consumption empty	13.50 MJ/mi	13.50 MJ/mi	13.50 MJ/mi	13.50 MJ/mi	13.50 MJ/mi
	Maximum load	29.76 tons	29.76 tons	29.76 tons	29.76 tons	29.76 tons
	Maximum load	4237.76 ft3	4237.76 ft3	4237.76 ft3	4237.76 ft3	4237.76 ft3
	Speed (max)	49.71l mi/h	49.71l mi/h	49.71l mi/h	49.71l mi/h	49.71l mi/h
	Load factor (on loaded trips)	100%	100%	100%	100%	100%
	Loaded trips (of total trips)	56%	56%	56%	56%	56%
	Loading Cost	1.19 $/ton	1.19 $/ton	1.19 $/ton	1.19 $/ton	1.19 $/ton
	Unloading Cost	1.19 $/ton	1.19 $/ton	1.19 $/ton	1.19 $/ton	1.19 $/ton
	Loading Fuel	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton
	Unloading Fuel	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton	11.79 MJ/ton
	Loading Time	0.00 h/ton	0.00 h/ton	0.00 h/ton	0.00 h/ton	0.00 h/ton
	Unloading Time	0.00 h/ton	0.00 h/ton	0.00 h/ton	0.00 h/ton	0.00 h/ton
	Loading Labor	0.05 h/ton	0.05 h/ton	0.05 h/ton	0.05 h/ton	0.05 h/ton
	Unloading Labor	0.05 h/ton	0.05 h/ton	0.05 h/ton	0.05 h/ton	0.05 h/ton

Figure 7 – A fragment of the input worksheet for intermodal transport (new addition to the BLM input controls spreadsheet)

The new INL BLM – BIT-UU submodel takes cares of all calculations and unit conversions that are related to the transportation of the feedstock from the (export) terminal to the refinery that are not dependent on geospatial details of the transportation network.

The INL BLM – BIT-UU submodel in turn contains nine submodels that each holds the calculations that are related to a certain mode of transport such as Road, Rail and Ocean. These submodels are referred to as ‘transport mode specific submodels’.
Although the nine transport mode specific submodels are, at the time of writing, identical and therefore might be considered redundant, the explicit design choice was made not to aggregate or generalize the transport mode specific submodels into one generalized submodel. The reason for this is that the current design enables future modification and diversification of the submodels for the different modes of transport and thereby opening up the opportunity to model mode specific details.

2.3.3.1 Transport mode specific submodel design

The input parameters necessary for the calculations in the transport mode specific submodels are a subset of the earlier described input parameters (worksheet: Intermodal Transportation parameters) specific for the mode of transport, the general fuel costs, the labor costs and the density of the feedstock when exiting the terminal. The output of the transport mode specific submodel is a list of ArcGIS Network Analyst parameters which are suitable to be used as an input for the BIT-UU Model.

2.3.3.2 Formulas and calculations

This paragraph covers the calculations that are included in each of the nine transport mode specific submodels. The purpose of these calculations is to transform the parameters from the INL BLM Model (derived from the new worksheet for Intermodal Transportation parameters) into suitable parameters for the BIT-UU Model.

Net payload trip:

The net payload of a trip is defined as the maximum weight that can/will be transported during a single one-way trip. The maximum weight is determined by either the bulk density of the feedstock that may not surpass the maximum weight load capacity of the mode of transport or the maximum bulk volume that the mode of transport can carry.

If (Density feedstock (t / m^3) < Maximum load weight (t) / Maximum load volume (m^3):

*Net payload trip (t) = Maximum load volume (m^3) * Density feedstock (t / m^3)*

Else:

Net payload trip (t) = Maximum load weight (t)

Net payload roundtrip:

The net payload of a roundtrip is defined as the weight ratio between the amount of transported feedstock (by weight) and the maximum mass that could be transported by the specific mode of transport. It is not only determined by the net payload of a single one-way trip, but also by the load factor[13] of loaded trips and the number of loaded trips of total trips[14].

*Net payload roundtrip = (Net payload trip (t) / Maximum load weight (t)) * Load factor of loaded trips * Ratio loaded trips of total trips*

[13] Capacity used during loaded trips.
[14] Based on historical data (NEA, 2004).

Fuel consumption roundtrip:

The fuel consumption of a roundtrip is defined as the fuel consumption for a return trip that does consider the load factor during the entire trip. It is determined by the net payload of the roundtrip and by both the fuel consumption of the mode of transport when it is fully loaded and when it is empty.

*Fuel consumption roundtrip (MJ / km) = Net payload roundtrip * Fuel consumption when full (MJ / km) +*
*(1 - Net payload roundtrip) * Fuel consumption when empty (MJ / km)*

Labor requirement roundtrip:

The labor requirement of a roundtrip is defined as the ratio of labor that is required for the specific roundtrip (considering the net payload) in relation to the ideal situation which is with fully loaded roundtrips where both trips (back and forth) are always fully loaded. It is determined by the net payload of a trip, the maximum mass that can be transported by the mode of transport, the load factor of the loaded trips and the ratio loaded trips of total number trips.

*Labor requirement roundtrip (person / v) = Labor requirement always fully loaded (person / v) * Net payload roundtrip*

Labor cost:

The labor costs are defined as the labor costs of a roundtrip considering the ratio of labor requirement. It is determined by both the labor requirement of a roundtrip and the labor price (wages).

*Labor cost (€ / h) = Labor requirement roundtrip (person / v) * Labor price (€ / h)*

Variable cost roundtrip:

The variable costs of a roundtrip are defined as the general costs (not including costs for labor or fuel) per unit of distance for a roundtrip considering the net payload to transport the feedstock. It is determined by the variable costs per unit of distance when fully loaded and the net payload of a roundtrip.

Variable cost roundtrip (€ / km) = Variable cost per unit of distance (€ / km) / Net payload of a roundtrip

<u>Time cost roundtrip:</u>

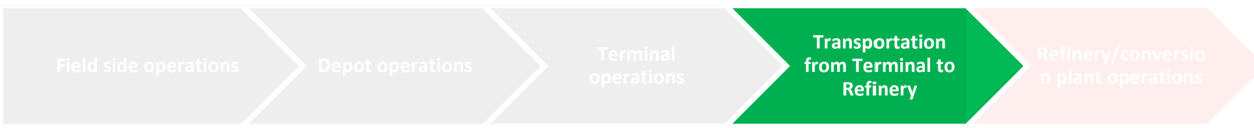
The time costs of a roundtrip are defined as the general costs (not including costs for labor or fuel) per unit of time for a roundtrip considering the net payload to transport the feedstock.
It is determined by the variable costs per unit of time when fully loaded and the net payload of a roundtrip.

Time cost roundtrip (€ / h) = Variable cost per unit of time (€ / h) / Net payload of a roundtrip

2.3.4 **Redesign of BIT-UU model**

In this section the integration of the Intermodal Network Transport Model (BIT-UU Model), using ESRI's ArcGIS Network Analyst, in the overall Biomass Logistics and Conversion Model (BLCM-UU) model is covered (Figure 8).

The Intermodal Network Transport Model (BIT-UU Model) is applicable for the long distance intermodal transportation operations to transport the biomass from terminal to refinery.



INL BLM - Biomass Logistic Model

BIT-UU – Intermodal Transport Network Model

Van Vliet – Fischer-Tropsch Conversion Model

Figure 8 – Location/phase of the FT-diesel supply chain where the BIT-UU Model has its main application

The multimodal BIT-UU Model is capable of calculating the most cost efficient route (while reporting costs, energy consumption and GHG emissions) for intermodal transport of the biomass from terminal to refinery. Although the concept of using the ESRI ArcGIS Network Analyst for modeling the long distance transport component of the chain originates from the BIT-UU Model, the model itself has been entirely redesigned. The redesign of the model was necessary to provide better compatibility with the INL BLM Model, to extend the model for routes outside Europe and to improve the modeling of intermodal transfers. The modes of transport included in the developed model are:

- Road [Europe & U.S][15]
- Rail [Europe & U.S.][15]
- Six classes of Inland Waterways [Europe]
- One class of Inland Waterway [U.S.][15]

[15] The properties of the IWW Class 6 vessels, truck and trains in the United States are assumed to be equal to the properties of these modes of transport in Europe due to the lack of data about the United States.

- Short Sea Shipping [Europe]
- Ocean [Global][16]

The input required for the Network Analyst is a network dataset consisting of several network layers which form the transportation network and the definition of network attributes which keep track of the associated costs in terms of costs, energy consumption and GHG emissions for traveling over the network. In addition, parameters have to be provided for the calculation of the network attributes. These parameters have been calculated in the designed INL BLM – BIT-UU submodel described in Section 2.3.3. In the following paragraphs the remaining parts of the dataset, the network layers and the network attributes and their associated evaluators, will be discussed. Box 1 provides a brief explanation of the solving technique used by the ArcGIS Network Analyst.

[16] One concurrent type of ocean mode: Handysize, Supramax or Panamax size vessel.

Dijkstra algorithm

The ESRI ArcGIS Network Analyst that is used to solve for the route that minimizes the total cost of transporting one tonne of biomass from a terminal to a FT plant uses an algorithm that is based on the Dijkstra algorithm for finding shortest paths.

The Dijkstra algorithm is an algorithm that solves a single-source shortest path problem with nonnegative edge path costs by producing a shortest path tree. The algorithm works by finding most optimal path between two specified vertices in a graph. The steps taken by the algorithm can be described as:

1. *Choose the source vertex.*
2. *Define a set S of vertices, and initialize it to empty set. As the algorithm progresses, the set S will store those vertices to which a shortest path has been found.*
3. *Label the source vertex with 0, and insert it into S.*
4. *Consider each vertex not in S connected by an edge from the newly inserted vertex. Label the vertex not in S with the label of the newly inserted vertex + the length of the edge. But if the vertex not in S was already labeled, its new label will be min(label of newly inserted vertex + length of edge, old label).*
5. *Pick a vertex not in S with the smallest label, and add it to S.*
6. *Repeat from step 4, until the destination vertex is in S or there are no labeled vertices not in S.*

Box 1 - Dijkstra algorithm (Cited from: University of Birmingham, 2004)

2.3.4.1 Network layers

In the case of modeling for intermodal transport, the network layers consist of three types of layers: physical network links, network nodes and fictional intermodal transfer links. The physical network links and network nodes will be discussed first.

2.3.4.1.1 Network links and nodes

The network links are the physical links over which a mode of transport can travel, in the case of water based modes of transport these are the shipment routes. Data for the network links was extracted from several sources, primarily: TRANS-TOOL V2 Model, EC GISCO database, WN Network database, NTAD. The data was converted to match the geographic coordinate system of the network dataset, GCS_WGS_1984. The nodes represent geographical locations at which a mode of transport can exit the network, which can be either an endpoint of the route or a location at which transloading between transport modes can take place. An example for a node for a water based mode of transport is a port. The nodes have been extracted from the same data sources as the network links. An overview of the included network links and nodes and the source they were extracted from can be found in Figure 9.

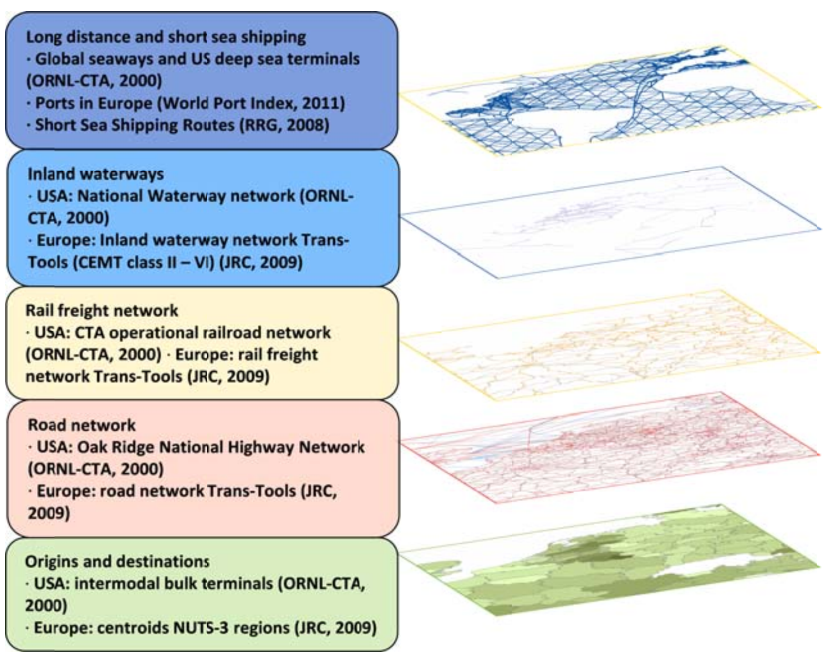


Figure 9 - Network layers included in BIT-UU (Hoefnagels et al., 2011) (updated)

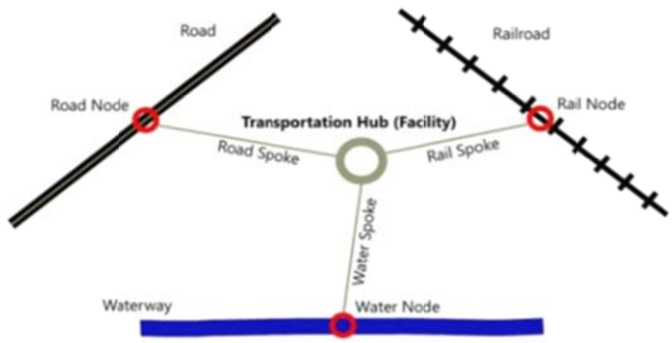
Network links and nodes both have feature attributes assigned, which specify the properties of the node or segment of a network link. These feature attributes are used to calculate the network attributes using the later on described evaluators. An example of a layer attribute for a network segment is the speed at which a mode of transport can travel over a certain link. Other examples of feature attributes that are assigned in this specific network are: diesel excise duty, diesel VAT, labor factor, location in or outside study area, one-way restrictions and toll. The attribute data values were assigned to the network segments by either matching against already assigned attributes or by using the spatial analysis tools provided by ArcGIS.

2.3.4.1.2 Modeling intermodal transfers

To model intermodal transfers, the hub-and-spoke approach was used to link different transportation layers (e.g. road, rail) via intermodal terminals (hubs) using terminal connectors/links (spokes) (the theoretical concepts are explained in Box 2). This approach has been applied to model the intermodal transfers using two different methods for the transfers in Europe and the transfers in the U.S.

Hub-and-spoke approach

The hub-and-spoke is an approach to form a connection between different modal networks that is necessary for ESRI's Network Analyst extension to calculate a Least Cost Distance route for, in this case, intermodal distribution of biomass. It consists of three elements: network segments, network spokes and hubs. Network segments are the corridors for biomass traffic such as roads, railroads and on-water shipping lanes. The network spokes are artificial connections to connect the different modal networks. These spokes connect through intermodal transfer facilities which are the hubs of the hub-and-spoke connection model. It is important to note that the spokes don't necessarily follow physical connections such as roads. Using the hub-and-spoke approach model, it is possible to connect different modes of transport through intermodal transfer utilities and in addition transfer penalties can be applied which can represents cost, energy and GHG emissions associated with intermodal transfers.



Box 2 – Hub-and-Spoke approach E.U. (Winebrake et al., 2008)

For Europe, no data was available for the actual geographical locations of the transfer facilities. Therefore, the locations of transfer facilities were assumed to be represented by the geographical centers of NUTS-3 regions. In addition, it was assumed that when a node of a transport mode was present in a certain NUTS-3 region intermodal transfers from and to the transport mode can occur.

For the U.S. the geographical locations of intermodal transfer facilities are known and a more accurate modeling of the intermodal transfers was possible. For the U.S. the separate network nodes on the links are not connected to a single node representing a transfer facility. Instead they are connected to separate ‘sub-terminal nodes’ (one per mode of transport per terminal) and when transloading between modes is possible, two sub-terminal nodes are connected. This method is schematically depicted in Figure 10.

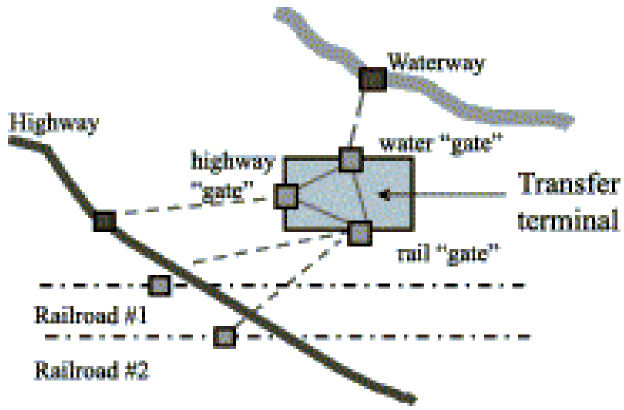


Figure 10 - Hub-and-Spoke approach U.S. (Southworth et al., 2000)

2.3.4.2 Network attributes

2.3.4.2.1 Overview of network attributes

The network attributes in the Network Analyst are the properties of the network that control navigation. Most attributes in the designed network dataset are intermediate attributes and are not directly being optimized for or are being restrictive. These attributes are added for three reasons. The first reason is to overcome the limitation of ESRI’s Network Analyst to use attribute fields of a feature class directly in a script evaluator. The second reason is to make sure that certain calculations which are necessary for multiple evaluators happen only once. Calculations in the network analyst are time consuming, especially the script evaluators. The third and final reason is the improved readability of the model. The only two attributes that directly control navigation (influence the outcome of the optimal route) are the *TotalCost* and *OneWay* attributes. Table 5 provides an overview of all network attributes in the dataset and their unit of measurement. The next paragraphs will discuss the evaluators associated with each of these attributes.

Name	*Units*
DieselExciseDuty	€ / MJ
DieselTx	%
Distance	km
FuelConsumption	MJ / t
FuelCost	€ / t
GHG_emissions	g / t
kmCost	€ / t
LaborCost	€ / h
LaborFactor	%
LoadCapacity	t
OneWay	Yes / No
Speed	km / h
TimeCost	€ / t
TotalCost	€ / t
TransloadingCost	€ / t

Table 5 – Network attributes and their unit of measurement

2.3.4.2.2 Network attribute evaluators

Evaluators related to distance costs

Distance

The evaluators that are assigned to the attribute *Distance* are directly related to the distance traveled over a specific network segment expressed in kilometers and therefore the length of a network segment. The length of the links was most often already available as a feature attribute in the feature class; otherwise the length was calculated using the field calculator. However not all lengths were specified in the same unit of measurement. For example the unit of measurement for the length of the links in the United States is specified in miles, where the unit of measurement for Europe is in kilometers or meters. The following formulas were used to calculate the attribute *Distance*.

U.S. Links:
Distance (km) = Distance (mi) [Feature attribute] / 1.609344

E.U. Links:
Distance (km) = Distance (km) [Feature attribute]

or
Distance (km) = Distance (m) [Feature attribute] / 1000

The connectors and terminal connectors are artificial links, their length (or the distance traveled over these links) has no meaning and therefore the value for distance for these types of links has been set to zero.

Evaluators related to fuel consumption costs

There are four attributes related to the calculation of fuel consumption costs: *FuelConsumption*, *DieselExciseDuty*, *DieselTx* and *FuelCost*.

FuelConsumption

FuelConsumption is an intermittent supporting attribute for the calculation of the *FuelCost*. It is added as an attribute to the network dataset to make the calculation of the *FuelCost* easier to understand. Its value is calculated per unit of feedstock (in this case one metric tonne) by multiplying the distance traveled over the link with the fuel consumption in MJ per kilometer of the mode of transport and dividing the product by the load capacity. The parameter value for the fuel consumption per kilometer has been calculated in the transport mode specific submodels part of the INL BLM – BIT-UU submodel (paragraph 2.3.1). The connectors, which represent intermodal transfers, have fixed but separate fuel consumptions for loading and unloading, which is unique per mode of transport. When feedstock travels over a connector in the from-to direction (terminal node to link node) it is loaded and therefore loading fuel consumption is assigned in this direction, in the to-from direction unloading fuel consumption is assigned to this attribute.

Links:
*FuelConsumption (MJ / t) = (Distance (km) [Network attribute] * Fuel consumption mode of transport per km (MJ / km) [Parameter]) / Load capacity (t) [Network attribute]*

Connectors:
FuelConsumption F-T (MJ / t) = Mode of transport specific loading fuel consumption
FuelConsumption T-F (MJ / t) = Mode of transport specific unloading fuel consumption

DieselExciseDuty and DieselTx

In addition to the bare price of diesel, the fuel costs per MJ for a mode of transport, using diesel as a fuel, also consist of a value added tax (VAT) and excise duty component. Both the tax as the excise duty are country, or in case of the US, state specific. As described during the design of the network layers, additional feature attributes were added to the feature classes that represent links and connectors that hold the value for the diesel tax and excise duty. This does imply that all fuel is bought in the country or state that the fuel is consumed; this might not always be the case. For example, a truck might refuel in the country where it is most economic. Separate network attributes for the diesel excise duty and tax are created to overcome the limitation of the network analyst to use feature attributes directly in a script evaluator. This way the value of feature attributes for tax and excise can indirectly be accessed in the script evaluator for *FuelCost* using the accessible network attributes.

E.U. Links, Connectors for fuel type Dieselntx:
DieselExciseDuty (€ / MJ) = Diesel excise duty (€ / MJ) [Feature attribute]
DieselTx (%) = Diesel tax in percent of Dieselntx price [Feature attribute]

U.S. Links, Connectors for fuel type Dieselntx:
DieselExciseDuty ($ / MJ) = Diesel excise duty ($ / MJ) [Feature attribute]
DieselTx (%) = Diesel tax in percent of Dieselntx price [Feature attribute]

FuelCost

The fuel cost is an important network attribute in the calculation of the total costs of transporting the feedstock from a terminal to a refinery and thereby highly influences the outcome of the most cost efficient route. It is calculated by multiplying the assigned network attribute *FuelConsumption* (in MJ) with the cost of the specific fuel for the mode of transport in Euro or Dollar per MJ fuel. The calculation is the same for both the links as the connectors of the network dataset. In case the fuel consumption for the mode of transport is Dieselntx (diesel excluding VAT and excise duty), country specific tax and excise duty are added to the fuel cost.

Links, Connectors for fuel type MDO or IFO380:
*FuelCost (€ / t) = Fuel consumption (MJ / t) [Network attribute] * Fuel cost (€ / MJ) [Parameter]*

E.U. Links, Connectors for fuel type Dieselntx:
*FuelCost (€ / t) = Fuel consumption (MJ / t) [Network attribute] * ((Fuel cost (€ / MJ) [Parameter] + Diesel excise duty (€ / MJ) [Network attribute]) * Diesel tax (%) [Network attribute])*

U.S. Links, Connectors for fuel type Dieselntx:
*FuelCost (€ / t) = Fuel consumption (MJ / t) [Network attribute] * ((Fuel cost (€ / MJ) [Parameter] + (Diesel excise duty ($ / MJ) [Network attribute] / Exchange rate Dollar-Euro [Parameter])) * Diesel tax [Network attribute])*

Evaluators related to GHG Emissions

GHG_emissions

The network attribute *GHG_emissions* is used to keep track of the GHG emissions from transporting one tonne feedstock from terminal to refinery while optimizing for total transportation costs. By explicitly setting this network attribute as the target attribute for the route solving problem, it would be possible to optimize the route for GHG emissions instead of costs. Optimizing for other than total costs is outside the scope of this thesis and could result in unrealistic routes with very high cost because the model is designed to optimize for economic variables. If required, such a scenario could be better assessed with the BLCM-UU model assuming a carbon tax on fossil fuel consumption. The GHG emissions are calculated by multiplying the previous calculated network attribute for fuel consumption by the emission factor of the mode specific fuel type.

Links, Connectors:
*GHG_emissions (g) = Fuel consumption (MJ) [Network attribute] * Emission factor fuel for Dieselntx, IFO380, MDO (g / MJ) [Parameter]*

Evaluators related to Labor Costs

The calculation of the labor costs is dependent on multiple parameters, network attributes and feature attributes. The first two network attributes that are related to the calculation of *Labor Costs* that will be discussed in this section are the *LaborFactor* and *LaborCost*. This will result in a labor cost factor expressed in Euro per hour. The final calculation of the total labor costs will be performed as part of the *TimeCost* attribute because of its dependence on time.

LaborFactor

Hourly wages are not the same in every country or state. This is this reason a labor factor was introduced into the model, to adjust the labor costs based on the geographical location where the labor is required. This does however assume that the person who delivers the labor is originating from the state or country where the labor is performed, this might not always be the case. However, with the supply chains assessed in this thesis this is not relevant as no mode of transportation crosses international borders apart from bulk ocean shipping. For international ocean shipping, labor cost are implicitly addressed in international time charter rates and do not change per country. The labor factors have been assigned to the link and connector layers as feature attributes during the construction of the geodatabase by performing a spatial analysis. The values for the labor factors were calculated by dividing the local wages by the labor wages in North-West Europe.

Links, Connectors:
LaborFactor = Ratio local labor costs with respect to NW Europe [Feature attribute]

LaborCost

The *LaborCost* network attribute represents the labor costs of a mode of transport per unit of time expressed in Euro per hour. It depends on both the mode specific full time equivalent labor requirement per hour, labor costs and the previously calculated location specific labor factor to correct for country specific labor cost. The *LaborCost* will subsequently be used in the calculation of the time costs.

Links, Connectors:
*LaborCost (€ / h) = Labor factor [Network attribute] * Mode specific labor costs NW Europe [Parameter]*

Evaluators related to Transloading Costs

TransloadingCost

Strictly speaking, transloading costs are the costs associated with both unloading the feedstock from one mode of transport and loading the feedstock into another of the same or different type. However the transloading costs as specified in this network attribute do also include the loading from the terminal into the first mode of transport and the unloading of the feedstock at the end of the transport chain. Since loading and unloading is represented by the connectors in de network dataset, these are the only feature classes that get an evaluator assigned for this network attribute. The transloading costs are calculated by multiplying the previous calculated *LaborCost* network attribute by the loading or unloading labor for a specific mode of transport. In addition, a fixed cost for loading or unloading a tonne of feedstock, which includes all other cost than labor, is added to the costs. Note: Just like the *FuelConsumption* network attribute, loading costs are assigned in the from-to direction and unloading costs in the to-from direction.

Connectors:
*TransloadingCost F-T (€ / t) = Labor costs (€ / h) [Network attribute] * Mode specific loading labor (h / t) [Parameter] + Mode specific additional loading costs (€ / t) [Parameter]*
*TransloadingCost T-F (€ / t) = Labor costs (€ / h) [Network attribute]) * Mode specific unloading labor (h / t) [Parameter] + Mode specific additional unloading costs (€ / t) [Parameter]*

Evaluators related to TimeCost

The *TimeCost* attribute is the sum of multiple time related costs which are calculated in its evaluators. The attribute itself is again part of the *TotalCost* network attribute for which the optimum routing problem is solved. The evaluators for *TimeCost* depend on several parameters and a number of network attributes namely*: LaborCost, TravelTime, LoadCapacity*. The first of these network attributes has already been discussed; the latter two will be discussed in this paragraph before discussion the *TotalCost* attribute itself. The *TravelTime* in turn is dependent on the Speed attribute, which will be discussed first.

Speed
The *Speed* attribute specifies the maximum speed that is allowed by authorities to travel by over a network segment. This speed has been assigned as a feature attribute of the network segment when designing the network link layers by joining available data based on either their link ID or by link type (for example type Highway). When data about maximum speeds was unavailable, the segment is assumed to have no speed restriction and was assigned an artificially maximum speed of 999 km/h that is beyond the maximum speed of the transport modes used. The maximum speeds for network segments in the U.S. are specified in Mile/Hour and had to be converted to Kilometer/Hour.

E.U. Links:
Speed (km / h) = Speed (km / h) [Feature attribute]

U.S. Links:
*Speed (km / h) = Speed (mi / h) [Feature attribute] * 1.609344*

TraveTime

The *TravelTime* attribute specifies the time in hours needed to travel over a network segment (link) or to load/unload feedstock. The travel time for the links is calculated by dividing the network attribute *Distance* by the network attribute *Speed*. In addition, a constraint has been specified to ensure that the speed by which is traveled cannot exceed the maximum speed of a mode of transport. A special case exists for the E.U. road and rail links, the travel time is increased by any ferry sailing time and ferry waiting time that may occur during travel.

Links:
If (Speed (km / h) [Network attribute] < Maximum speed of transport mode (km / h)):
TravelTime (h) = Distance (km) [Network attribute] / Speed (km /h) [Network attribute] + Ferry sailing time (h) [Feature attribute] + Ferry waiting time (h) [Feature attribute]
Else:
TravelTime (h) = Distance (km) [Network attribute] / Max. speed of transport mode (km /h) [Parameter] + Ferry sailing time (h) [Feature attribute] + Ferry waiting time (h) [Feature attribute]

Connectors:
TravelTime F-T (h) = Mode of transport specific loading time (h)
TravelTime T-F (h) = Mode of transport specific unloading time (h)

LoadCapacity

The *LoadCapacity* network attribute specifies the load capacity of a mode of transport in metric tonnes; it has already been calculated in the transport mode specific BLCM-UU submodels.

Links, Connectors:
LoadCapacity (t) = Mode of transport specific load capacity (t) [Parameter]

TimeCost

The *TimeCost* network attribute is calculated by first taking the sum of the mode specific time costs (that does not include labor costs) and the *LaborCost* attribute. The sum is multiplied by the *TravelTime* attribute and, finally, the product is divided by the *LoadCapacity* attribute. The result is the time cost of transporting one metric tonne of feedstock.

Links, Connectors:
*TimeCost (€ / t) = ((Mode of transport specific time costs (€ / h) [Parameter] + LaborCost (€ / h) [Network attribute]) * TravelTime (h) [Network attribute]) / LoadCapacity (t) [Network attribute]*

Evaluators related to Kilometer Costs

kmCost
The *kmCost* is the sum of the two separate distance related costs namely the earlier calculated FuelCost and the mode specific distance costs (that does not include fuel costs). The mode specific distance cost is first calculated by multiplying the variable distance cost by the *Distance* network attribute and dividing the product by the *LoadCapacity* attribute. Although the connectors (the artificial intermodal links) technically speaking have no distance costs, the fuel costs (associated with loading/unloading) are assigned as distance costs in this attribute to simply the calculation of the *TotalCost* attribute.

Links:
*kmCost (€ / t) = ((Distance (km) [Network attribute] * Mode of transport specific distance costs (€ / km) [Parameter]) / LoadCapacity (t) [Network attribute] + FuelCost (€ / t) [Network attribute]*
Connectors:
kmCost (€ / t) = FuelCost (€ / t) [Network attribute]

Evaluators related to Total Costs

As mentioned earlier the *TotalCost* attribute is the network attribute that will be minimized in the route solving process by the network analyst. Its evaluators consist of the sum of the three elements that contribute to the transport costs: the distance costs (*kmCost* attribute), the time costs (*TimeCost* attribute) and the transloading costs (*TransloadingCost* attribute). For the links (network segments) the transloading costs are non-existent and therefore there costs can be omitted in the evaluator for the *TotalCost* attribute.

Links:
TotalCost (€ / t) = kmCost (€ / t) [Network attribute] + TimeCost (€ / t) [Network attribute]
Connectors:
TotalCost (€ / t) = kmCost (€ / t) [Network attribute] + TimeCost (€ / t) [Network attribute] + TransloadingCost (€ / t) [Network attribute]

2.3.4.3 Restrictions and connectivity

2.3.4.3.1 Restrictions

The *OneWay* network attribute is besides the *TotalCosts* attribute the only attribute that directly controls navigation when solving the routing problem using the network analyst. Unlike the *TotalCosts* attribute the *OneWay* attribute is not minimized for but acts as a restriction.

The evaluators of the *OneWay* attribute are used to restrict travel over the network links or elements meeting one of the following conditions:

- The direction of travel over a link is restricted by authorities.
- The network segment is located outside the study area.
- When the purpose of a connector is to provide a path to unload feedstock to an intermodal transfer facility, loading should be restricted over the specific connector and vice versa.

2.3.4.3.2 Connectivity

In an ESRI ArcGIS network dataset, connectivity is a property that defines how lines (links, connectors or terminal connectors) and point features (nodes, centroids) connect to each other. A primary condition for connectivity is that a point feature and a line feature, two line features or two point features spatially coincident. For the network dataset in this thesis, endpoint connectivity is enforced, which means that switching between line features to another line feature or to a point feature is only allowed at an endpoint. This insures that when two network segments are crossing, switching from one mode to another is not possible (for example at a railway crossing). In addition connectivity groups (Figure 11) have been created that specify where and between which network segments switching is allowed to occur.

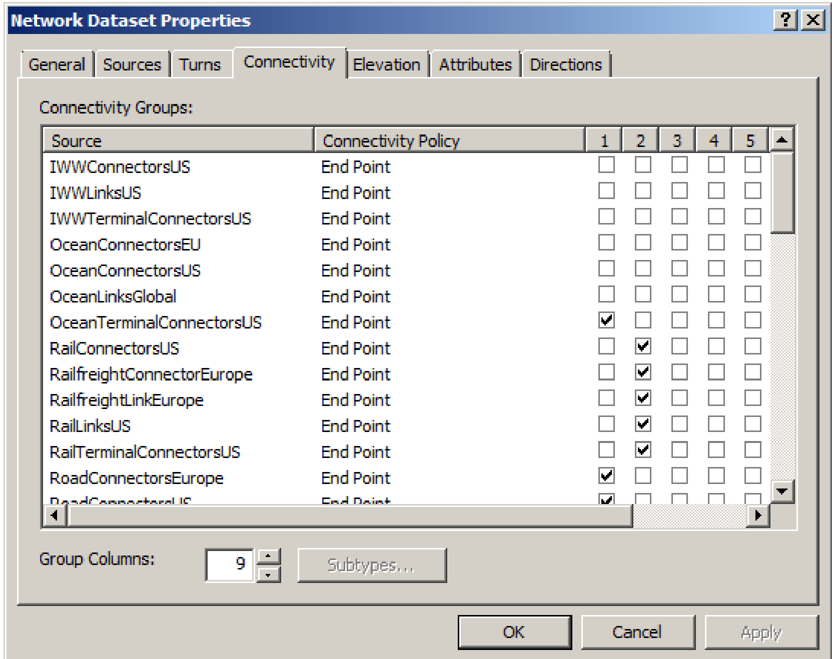
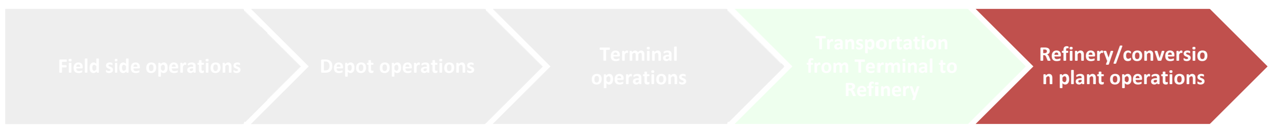


Figure 11 - Connectivity in the ESRI ArcGIS Network Analyst interface for the BLCM-UU Network Dataset

2.4 BLCM-UU: Fischer-Tropsch Conversion

In this section the integration of the Fischer-Tropsch Conversion Model in the overall Biomass Logistics and Conversion Model (BLCM-UU) is covered (Figure 12).

The FT Conversion Model is applicable for the operations associated with the conversion of the biomass into FT-diesel including preprocessing, storage and handling & queuing at the refinery.



INL BLM - Biomass Logistic Model

BIT-UU – Intermodal Transport Network Model

Van Vliet – Fischer-Tropsch Conversion Model

Figure 12 – Location/phase of the FT-diesel supply chain where the Fischer-Tropsch Conversion Model (van Vliet) has its main application

The Fischer-Tropsch Conversion Model is part of a larger Well-To-Wheel model that was developed by van Vliet to calculate the well-to-wheel cost and environmental performance of FT synfuel supply chain. The model developed by van Vliet et al. is a techno-economic spreadsheet model with component specific details that allows system analysis of FT-synfuel production for different plant sizes, feedstock types and feedstock sizes (van Vliet et al., 2009).

For the developed BLCM-UU integrated model, only the FT Conversion Model has been used (Figure 13) from the Well-To-Wheel model module. The reason for this is that the Harvesting and Collection, Preprocessing, Storage, Handling & Queuing and Transport components of the FT-diesel supply chain have already been modeled in more details using the Biomass Logistic part of the BLCM-UU.

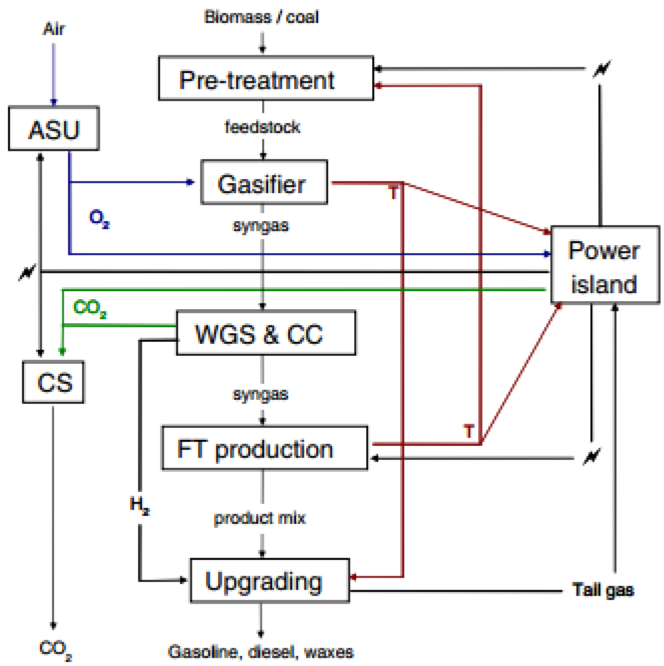


Figure 13 - General layout of an FT plant as modeled by the van Vliet FT Conversion Model (ASU = air separation unit, WGS = water gas shift, CC = CO2 capture, CS = CO2 storage; CS is not included in this thesis) (van Vliet et al., 2009)

2.4.1 Integration of the FT Conversion Model

The Fischer-Tropsch Conversion Model developed by van Vliet has been integrated into the BLCM-UU by creating a new INL BLM – van Vliet FT Conversion submodel. Refinery operations (handling & queuing refinery, preprocessing refinery, storage refinery) are also no longer modeled using the INL BLM Model but by using the van Vliet FT Conversion model (Table 6). The BLM input controls spreadsheet has been extended with a new worksheet ("Conversion Parameters", Figure 14) that provides the opportunity to select a specific type and scale of FT plant and specify the cost base year for cost indexation of the FT plant costs. Additional details, such as the moisture content of the biomass entering the FT plant, are derived from other parts of the INL BLM Model (such as the INL BLM Terminal submodel). An overview of the newly developed submodel for the integration of the FT Conversion Model is depicted in Figure 14, the calculation steps are provided in Appendix II.

		Locations			
		Fieldside	*Depot*	*Terminal*	*Refinery*
Components of Supply chain	*Harvesting & Collection*	Harvesting Baling / Bundling Collection			
	Storage	Storage Fieldside	Storage Depot	Storage Terminal	Storage Refinery
	Transportation	Transportation from Field	Transportation from Depot	Transportation from Terminal	Transportation from Refinery[17]
	Preprocessing	Preprocessing Fieldside	Preprocessing Depot	Preprocessing Terminal	Preprocessing Refinery
	Handling & Queuing		H&Q Depot	H&Q Terminal	H&Q Refinery
	End-conversion				End-conversion into FT-diesel

Table 6 - Operations of supply chain modeled using van Vliet's FT Conversion Model (indicated in green)

[17] Not modeled in this thesis

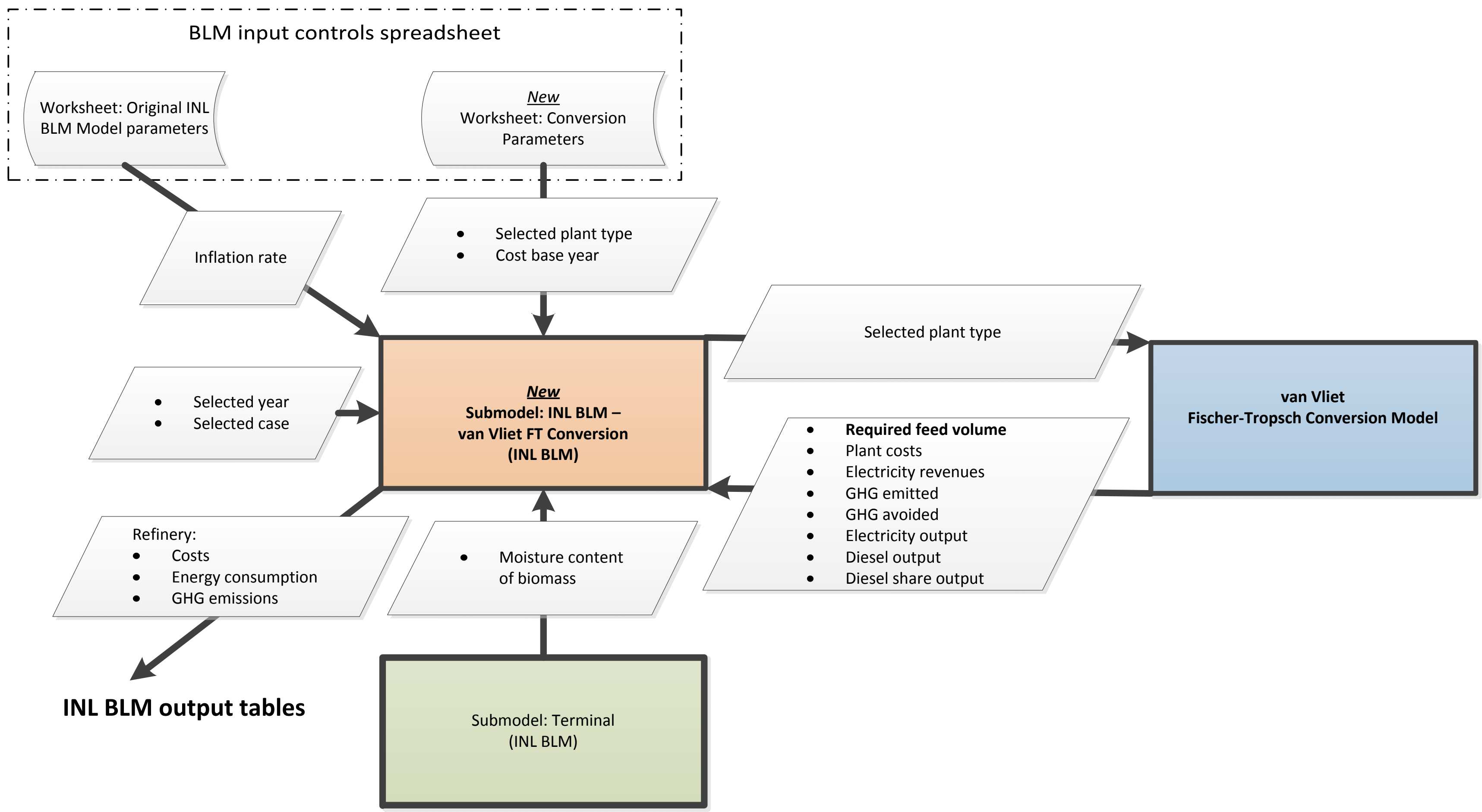


Figure 14 - Inputs/Outputs: INL BLM – van Vliet FT Conversion (New Submodel)

Based on previous described parameters the developed INL BLM – van Vliet FT Conversion submodel retrieves the relevant properties of the selected pre-modeled FT plant from the van Vliet FT Conversion Model to model the FT plant in the BLCM-UU Model. The first output of the submodel is the annual primary biomass demand of the FT-plant in DM tonne (based on the required feed volume of the FT plant). The primary biomass demand is used by the Biomass Logistics part of the BLCM-UU Model to calculate the annual demand of the entire chain and by such the number of acres harvested, the amount and scale of equipment used, etc. The second output is the plant performance data (costs, energy consumption and GHG emissions). Important to note is that the FT- plant in the developed modeling tool can have multiple outputs: petrol, diesel, electricity. Since electricity is not a synthetic fuel-output, the monetary benefits of exporting excess electricity produced and exported to the grid and the related avoided GHG emissions are credited for when calculating the total costs, energy consumption and GHG emissions of the FT-plant using the system expansion approach. Because no fossil fuels are being used in the conversion of biomass into synthetic fuels in the FT-plant, the net result of the FT-plant for energy consumption and GHG emissions will be negative. The last two outputs are the annual diesel production and diesel share of the FT product on an energy basis. These will be used in a subsequent modeling step to allocate the costs, energy consumption and GHG emissions of the entire field- to refinery-gate supply chain to the FT-diesel output per GJ (Box 3).

Unit conversion and allocation

The original output tables of the INL BLM Model are used (after the inclusion of the outputs of the INL BLM – UU BITS and the INL BLM – van Vliet FT Conversion submodels) to present the detailed outputs (per operation of the FT supply-chain) of the BLCM-UU. In the output table of BLM Model the results are however expressed per DM ton of feedstock. To be more specific in: $ / DM ton for costs, MBtu / DM ton for energy consumption and ton CO2eq / DM ton for GHG emissions (Figure 15). All the results have already been credited for the benefits of electricity co-production in the FT-diesel plant; however the output of the supply-chain still consists of two types of synthetic fuels diesel and petrol.

	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	4.45	0.65	1.29	0.00	1.95	134.58	0.01
Baling/ Bundling	24.89	4.01	7.45	0.00	11.46	25.27	2.20e-3
Collection	6.04	0.89	0.98	0.00	1.87	25.42	2.21e-3
Total Harvest & Collection	**35.39**	**5.55**	**9.72**	**0.00**	**15.27**	**185.27**	**0.02**
Transportation FROM Field	7.17	1.34	9.01	0.00	10.35	124.18	0.01
Transportation FROM Depot	9.87	1.77	12.47	0.00	14.24	201.91	0.02
Transportation FROM Termina			0.00	0.00	0.00	0.00	0.00
Total Transportation	**17.04**	**3.11**	**21.48**	**0.00**	**24.59**	**326.09**	**0.03**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	12.35	3.08	10.69	0.00	13.77	304.28	0.07
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**12.35**	**3.08**	**10.69**	**0.00**	**13.77**	**304.28**	**0.07**
Storage Fieldside	9.78	2.96	0.76	1.00	4.73	10.92	9.50e-4
Storage Depot	0.21	0.07	0.25	0.00	0.32	3.64	3.17e-4
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**9.99**	**3.03**	**1.02**	**1.00**	**5.05**	**14.55**	**1.27e-3**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**149.26**		**149.26**	**1,064.99**	4.62
Total	**74.77**	**14.77**	**192.17**	**1.00**	**207.94**	**1,895.18**	**4.73**

Figure 15 – Modified output tables INL BLM (including outputs of new submodels)

To be able to fulfill the research objective of this thesis, the results are, in the developed BLCM-UU, first allocated to FT-diesel and the units converted to € / GJ for costs, GJ / GJ for energy consumption and kg CO2eq / GJ for GHG emissions. The allocation of the costs, energy consumption and GHG emissions to diesel has been performed based on the energy share of the FT-diesel produced as part of the total energy output of the FT-plant with respect to synthetic fuels. The results for the case studies, as will be discussed in the next chapter, will be expressed in these units of measurement.

3 Results

3.1 Six case studies

With the developed FT-diesel supply chain modeling tool in this study, a number of case studies have been conducted to assess the potential cost, energy and GHG performance of FT-diesel production and to demonstrate the model tool. The selected case studies differ on the geographical locations of the source of the biomass in the U.S., the type of feedstock and scale of end conversion plant. The location of the conversion plant is similar for all cases (Rotterdam, the Netherlands). The case studies for biomass supply are based on existing cases taken from the INL BLM Model supplemented with additional properties for long distance intermodal transportation and end-conversion. The case details for the six performed case studies are depicted in Table 7. The names of the cases include the source of biomass fiber (stover, switchgrass, woody biomass), the chain (Pellets to Liquids: PTL) and the size of the FT plant (400 or 2000 $MW_{th\ input}$).

	1	*2*	*3*	*4*	*5*	*6*
	StoverPTL400	StoverPTL2000	SwitchPTL400	SwitchPTL2000	WoodyPTL400	WoodyPTL2000
Source location	Mid-West United States	Mid-West United States	Mid-West United States	Mid-West United States	South-East United States	South-East United States
Source type	Stover	Stover	Switchgrass	Switchgrass	Wood	Wood
Transport to depot	Square bales by truck	Square bales by truck	Square bales by truck	Square bales by truck	Wood chips by truck	Wood chips by truck
Depot	Pelletization	Pelletization	Pelletization	Pelletization	Pelletization	Pelletization
Transport to terminal	Pellets by truck	Pellets by truck	Pellets by truck	Pellets by truck	Pellets by truck	Pellets by truck
Location terminal	Kansas City	Kansas City	Kansas City	Kansas City	Savannah	Savannah
Long distance transport	Pellets, multiple modes of transport	Pellets, multiple modes of transport	Pellets, multiple modes of transport	Pellets, multiple modes of transport	Pellets, multiple modes of transport	Pellets, multiple modes of transport
FT plant location	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands	Rotterdam, The Netherlands
FT plant type	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW	PTL400, Adv. FT, 400MW	PTL2000, Adv. FT, 2000MW
FT energy output	13.4% Petrol, 75.3% Diesel, 11.3% Electricity	13.4% Petrol, 75.3% Diesel, 11.3% Electricity	13.4% Petrol, 75.3% Diesel, 11.3% Electricity	13.4% Petrol, 75.3% Diesel, 11.3% Electricity	13.4% Petrol, 75.3% Diesel, 11.3% Electricity	13.4% Petrol, 75.3% Diesel, 11.3% Electricity
Number of Depots	Calculated by BLM Model	Calculated by BLM Model	8	8	8	8
Year	2012	2012	2012	2012	2012	2012
Average inflation rate	2.2%	2.2%	2.2%	2.2%	2.2%	2.2%

Table 7 – Supply chain details per case

Electricity-specific emission factor for grid electricity	0.56 kg CO2eq / kWh
Baseline electrical efficiency grid electricity	40 %
Electricity price grid electricity	0.044 € / kWh[18]

Table 8- Assumptions grid electricity (The Netherlands) (van Vliet et al., 2009)

Case 1 to 4 in this study focuses on the FT-diesel supply chain from field- to refinery gate for herbaceous feedstock (corn stover and switchgrass). The supply region of the feedstock in these cases is the Mid-West of the United States since it is the prime location of herbaceous feedstock according to the Updated Billion Ton Study (US DoE 2011) (Figure 16). Case 5 to 6 assume woody biomass, produced in the southeast of the U.S. to be the main location for woody biomass supply for energy purposes (Cocchi et al. 2011). A large city in this region, Savannah (GA), has been selected as the location for the terminal for long distance inter-continental transport (Figure 17). The demand location, the location of the FT-plant, is Rotterdam in the Netherlands. End-conversion takes place in a 400MW$_{th\ input}$ or 2000MW$_{th\ input}$ Advanced FT conversion plant. The costs were indexed for inflation for the year 2012 using an average yearly inflation rate of 2.2%. The transport modes specific parameters, as are present in the input controls worksheet, were not modified and left at their default values (Appendix III). The assumptions used for the crediting for electricity production in the FT-plant can be found in Table 8.

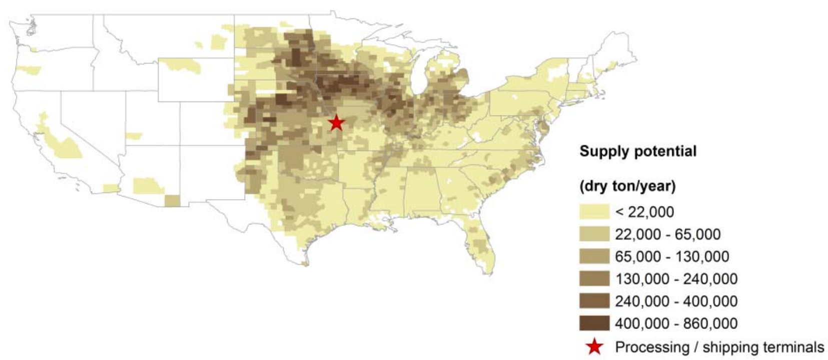


Figure 16 - Supply potential for herbaceous biomass U.S. (Hoefnagels, 2013)

[18] Indexed from 0.038 €(2005) / kWh using an inflation rate of 2.2% (van Vliet et al., 2009)

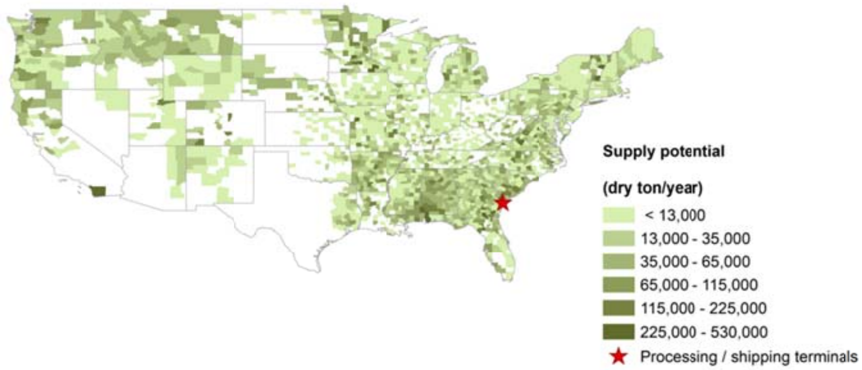


Figure 17 - Supply potential for woody biomass U.S. (Hoefnagels, 2013)

3.2 Case results

The BLCM-UU results comprise of three distinct outputs. The first output covers the long distance transport of pelletized biomass from the export terminal, near the cultivation site to the refinery plant, to the end user (FT-plant), including the actual cost optimized route taken by the included modes of transport. The second output is the table found in Appendix IV this table communicates the results of model run in terms of costs, energy consumption and GHG emissions per dry matter ton of feedstock. The table originates from the INL BLM Model and is supplemented in the developed modeling tool with the data resulting from the GIS transportation and refinery analysis. Due to the fact that these results are expressed per DM ton, the results are not allocated based on the energy content of the outputs of the chain (Diesel, Petrol, Electricity) yet. The third and final output of the model is the set of tables found in Figure 20 to Figure 22. These tables summarize the costs, energy consumption and GHG emissions per component of the FT-diesel supply chain expressed per GJ of final output of FT-diesel. The tables also show the costs, energy and GHG emission savings from excess electricity from cogeneration (system expansion approach). In order to compare the performance of the chains in terms of costs, energy consumption and GHG emissions with other studies, the chains have been supplemented with data for the cultivation of the biomass feedstock to cover the complete supply chain of FT-diesel to refinery gate. The data was derived from the JRC WELL-TO-TANK study (JRC, 2011) and the Updated Billion Ton Study (US DoE 2011).

The results for the case studies, as presented next, were obtained by running the modeling tool six times: once for each unique combination of the three included feedstock types (stover, switchgrass and woody biomass) and the two types of conversion plants (PTL400, PTL2000) using the inputs specified in paragraph 3.1.

The first output of the model, the cost optimal route between export terminal and refinery, can be found in Figure 18 for the herbaceous cases and in Figure 19 for the cases for woody biomass.

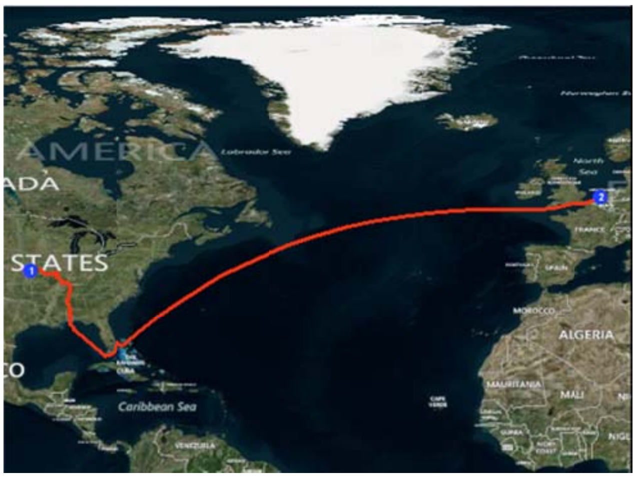


Figure 18 - Solved route: StoverPTL400, StoverPTL2000, SwitchPTL400, SwitchPTL2000

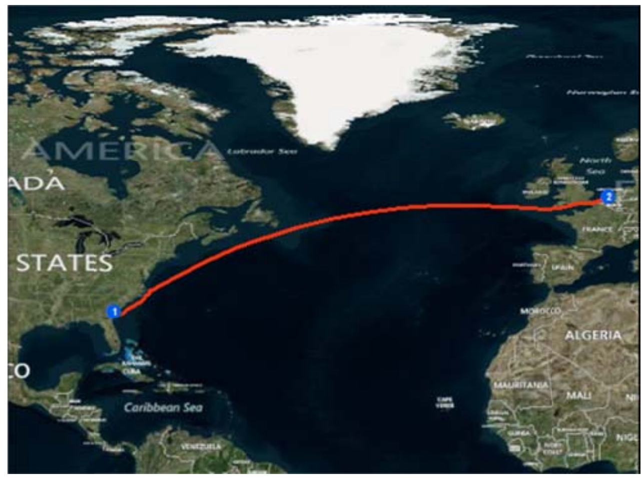


Figure 19 – Solved route: WoodyPTL400, WoodyPTL2000

Because the export terminal locations, the FT-plant locations, the transport modes specific parameters and the bulk density of the pellets leaving the terminal are identical between the four herbaceous cases and are identical between the two woody biomass cases the optimal routes found by the Network Analyst are the same. Note however that the logistic processes before the export terminal (from field to depot and from depot to export terminal, calculated using the INL BLM Model) are different between the cases for stover and switchgrass resulting in different costs, energy requirements and GHG emissions for remote transportation.

The distances traveled per mode of transport are summarized in Table 9. Since the export terminal for the pelletized feedstock for the stover and switchgrass cases is located inland in Kansas City the pellets first have to be transported to an ocean port. The most cost efficient route found by the Network Analyst integrated in the developed modeling tool is by inland waterway. For Case 1-4 the pelletized feedstock is first loaded onto an inland waterway class 6 ship (push barges) and transported by inland waterway over 2023 km. Then, after transloading from barges to an ocean bulk carrier, it is transported by ocean over another 8933 km to the port of Rotterdam, there again after transloading onto a train it is further transported over 14 km to the FT-plant where it is finally unloaded. For Case 5-6 the pelletized feedstock (from woody biomass) is directly loaded onboard an ocean carrier and transported over 7255 km to the port of Rotterdam, the logistic chain from thereon is the same as for Case 1-4.

	Road	*Rail*	*IWW Class 1-6*	*Ocean Handysize*
Stover, Switchgrass	0 km	14 km	2023 km	8933 km
Woody	0 km	14 km	0 km	7255 km

Table 9 - Distances traveled per mode of transport

Table 10 provides an overview of the costs, energy consumption and GHG emissions of the entire supply chain for FT-diesel from well-, till refinery-gate. The negative values are net benefits after crediting for the co-production of electricity in the FT-plant. Figure 20, Figure 21 and Figure 22 provide a breakdown of the results of the FT-diesel supply chain analysis per component of the supply chain. The next paragraphs will discuss the results in more details.

	Stover PTL400	*Stover PTL2000*	*Switch PTL400*	*Switch PTL2000*	*Woody PTL400*	*Woody PTL2000*
Costs (€ /GJ FT-diesel)	30.04	25.60	29.56	25.32	27.27	23.04
Energy consumption (GJ / GJ FT-diesel)[19]	-0.13	-0.13	-0.10	-0.09	-0.16	-0.16
GHG Emissions (kg CO2eq / GJ FT-diesel)[19]	3.17	3.17	12.77	13.17	-0.15	-0.15
GHG Reduction (compared to fossil diesel [20])	96%	96%	85%	84%	100%	100%

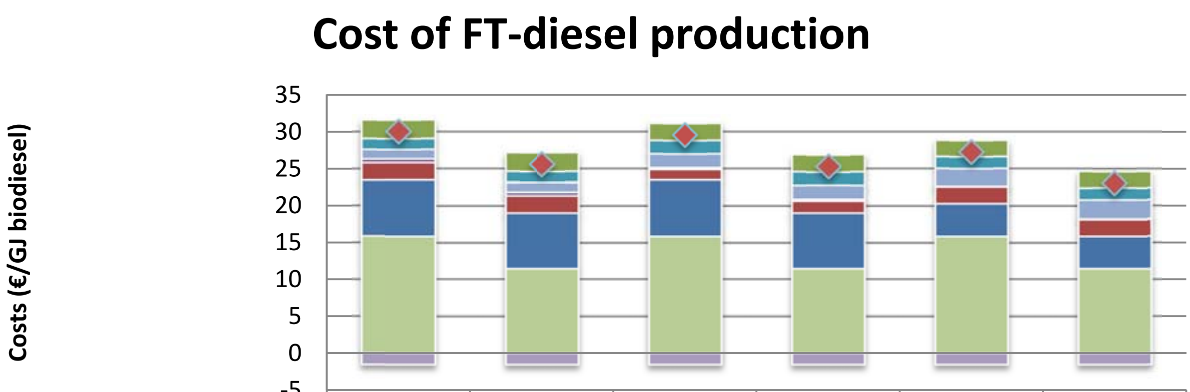
Table 10 - Results cases

[19] From fossil resources

[20] Assuming 83.8 g $CO2_{eq}$ / MJ for diesel as is prescribed by the RES directive; this figure includes the emissions from the production of the fossil diesel (Renewable Energy Directive 2009/28/EC).

3.2.1 **Costs**

The costs of the production of 1 GJ FT-diesel for the six examined case studies are depicted in Figure 20. The costs for Cultivation were derived from the Updated Billion Ton Study (US DoE, 2011) and are found to be nearly equal, the highest cultivation costs (for stover) are only 16% higher than the cultivation costs for the lowest cost found (for woody biomass). The next cost, the cost for Harvesting and Collection, consists of the costs for harvesting, bailing / bundling and collection. The Harvesting and Collection costs for switchgrass are 23% higher than the costs for stover due to different equipment used during harvesting (windrower versus combine).



	StoverPTL 400	StoverPTL 2000	SwitchPTL 400	SwitchPTL 2000	WoodyPTL 400	WoodyPTL 2000
Cultivation	2.55	2.55	2.33	2.33	2.20	2.20
Harvesting and Collection	1.46	1.46	1.80	1.80	1.60	1.60
Preprocessing	1.32	1.32	1.89	1.87	2.38	2.60
Storage	0.48	0.48	0.25	0.25	0.08	0.08
Handling and Queuing	0.00	0.00	0.00	0.00	0.00	0.00
Remote Transport	2.35	2.35	1.41	1.62	2.27	2.27
Long Range Transport	7.61	7.61	7.61	7.61	4.44	4.44
FT Plant	15.85	11.41	15.85	11.41	15.85	11.41
FT (Credits)	-1.57	-1.57	-1.57	-1.57	-1.57	-1.57
Total	30.04	25.60	29.56	25.32	27.27	23.04

Figure 20 - Cost of FT-diesel production per component of the FT-diesel supply chain[21]

[21] Remote Transport consists of the operations to transport the biomass from Field to Depot and from Depot to Terminal. Long Range Transport is the intermodal transportation of the biomass from Terminal to the FT-plant. FT Plant includes all the operations in the FT plant, including: storage, preprocessing, handling & queuing and end-conversion. FT (Credits) are the savings from excess electricity from cogeneration in the FT-plant.

The costs for Harvesting and Collection for the chains for FT-diesel from woody biomass are in between these values (€ 1.60 / GJ FT-diesel) and have higher costs for both harvesting and collection but don't require baling / bundling of the feedstock. The Preprocessing costs are the highest for Case 5-6 (feedstock type woody biomass) and are almost twice as high as the Preprocessing costs for stover. This is explained by the additional costs for field side shredding and grinding of the woody biomass, which is not required for both stover and switchgrass. The Storage costs are far lower for woody biomass (€ 0.08 / GJ FT-diesel) due to the higher density of the feedstock during fieldside storage compared to switchgrass (€0.25 / GJ FT-diesel) and stover (€ 0.48 / GJ FT-diesel). According to the defined supply chains by INL in the BLM Model, no handling and queuing operations are required for the supply chain considered from field- to terminal gate. The required handling and queuing operations at the FT-plant (such as pellet crumbling) are included in the costs for the FT-plant in the model by van Vliet et al. There is an apparent difference in the costs for remote transport (Field-Depot, Depot-Terminal) between the cases for stover and switchgrass although the bulk densities are assumed to be the same during the remote transport (192 kg/m^3). The difference is explained by the number of depots used in each supply chain. For SwitchPTL400 a fixed number of 8 depots were specified to be used, while for StoverPTL400 the required amount of depots is internally calculated by the INL BLM Model which results in 7 depots being used. Hence, due to the lower number of depots being used for the stover cases the distance between field-depot and depot-terminal is larger and accordingly the costs for remote transportation are also higher. The costs for long range transportation for the cases for stover and switchgrass are found to be identical at €7.61 for all four cases. This is explained by a number of factors. First of all, for both stover and switchgrass the export terminal was assumed to be located in Kansas City and the FT-plant in Rotterdam, hence the start and end of the long range transportation route is the same for the cases for stover and switchgrass. Since the feedstock was densified into a uniform format (pellets) the density of the transported biomass is identical. Lastly the same FT-plant was selected, with for all four cases the same conversion efficiency. The costs for the long range transportation for Case1-4 consist of the costs of loading the pelletized feedstock at the terminal, transport over 2023km by IWW Class 6 vessel, transloading form IWW Class 6 onto Ocean Handysize vessel, transport over 8933 km by ocean vessel, transloading from ocean Handysize onto train, transport over 14 km by train and finally unloading. The costs for long range transport for the woody biomass cases are much lower with €4.44 although the transported commodity and the final conversion efficiency in the chain are the same as for the stover and switchgrass cases. The difference is explained by the assumed location of the export terminal, Savannah. Since Savannah is located near the coast the pelletized biomass can directly be loaded onto an ocean Handysize vessel, inland transportation by IWW Class 6 vessels, as used for the herbaceous biomass cases, is not necessary. In addition the distance between Savannah and Rotterdam is considerably smaller than the distance between Kansas City and Rotterdam. The costs for final conversion of the pelletized biomass into Fischer-Tropsch diesel in the FT-plant are identical between all three cases with the same type and size conversion plant (Advanced FT 400$MW_{th\ input}$) at €15.85 per GJ FT-diesel produced, which was expected since the format of the delivered feedstock (pellets, 610 kg/ m^3, 10% moisture content) is the same. When a larger, but otherwise identical, conversion plant is selected (Case 2, 4, 6) with a capacity of 2000$MW_{th\ input}$ instead of 400$MW_{th\ input}$ the costs per GJ FT-diesel produced drop by 28% to €11.41 due to economies of scale. The revenue of excess electricity exported to the grid are however the same for all six cases per GJ of FT-diesel produced (€1.57) and are unaffected by the scale of the conversion plant as assumed by van Vliet et al. (2009). This suggests that there is no apparent effect of the scale of the plant on the conversion efficiency, the energy consumption (and savings) will be discussed in the next paragraph.

For all six demonstrated cases, there are two distinct contributors to the total costs of the FT-diesel supply chain: first of all the costs for conversion (Stover: 38-48%, Switchgrass: 39-48%, Woody: 43-52%) and second the costs for long range transportation (Stover: 25-30%, Switchgrass: 26-30%, Woody: 16-19%). The most economic supply chain (considering the same scale of the FT-plant) is the supply chain for the production of FT-diesel from woody biomass (€ 27.27 / 23.04 per GJ). The costs for supply from switchgrass are 8-10% higher (€ 29.56 / 25.32 per GJ) and the most expensive is the supply from stover (€ 30.04 / 25.60 per GJ).

To put the costs of the supply chain into perspective, the results can be compared with the current price of the supply of 1GJ diesel from fossil resources. The current price of crude oil is $108.48 per barrel. Considering an energy density of 37MJ per liter, a barrel contents of 119.24 liter per barrel, an exchange rate of 1.30 EU/USD and an assumed refinery costs of 10% this amounts to 21 € /GJ diesel. To recall, the found ranges for the cases were 23.04-30.04 € / GJ FT-diesel. The supply of FT-diesel from woody biomass (WoodyPTL2000) can therefore be considered as nearly cost effective and would become cost effective at a crude oil price of 121$/bbl.

The study by van Vliet et al. (2009) also considers a chain for the production of synthetic diesel from woody biomass using pellets as an intermediate. In order to be able to compare the cost of the supply chain for Case 6 (WoodyPTL400) from this study with the results found by van Vliet the costs from the study by van Vliet have been converted and expressed in €(2012) / GJ of FT-diesel[22]. According to the study van Vliet et al. the total costs for the supply of one liter FT-diesel from Latin America Eucalyptus are €(2005) 0.64 as is depicted in Appendix VI: Figure 27 or €(2012) 22.07 / GJ. The costs found in this study for the supply from woody biomass are found to be considerably higher with 27.27 € / GJ. The difference in total costs found is mainly explained by the costs found for long range transportation of the pelletized feedstock. According to the study by van Vliet these costs amount to 0.70 € / GJ[23], while according to this study the costs are 4.44 € / GJ.

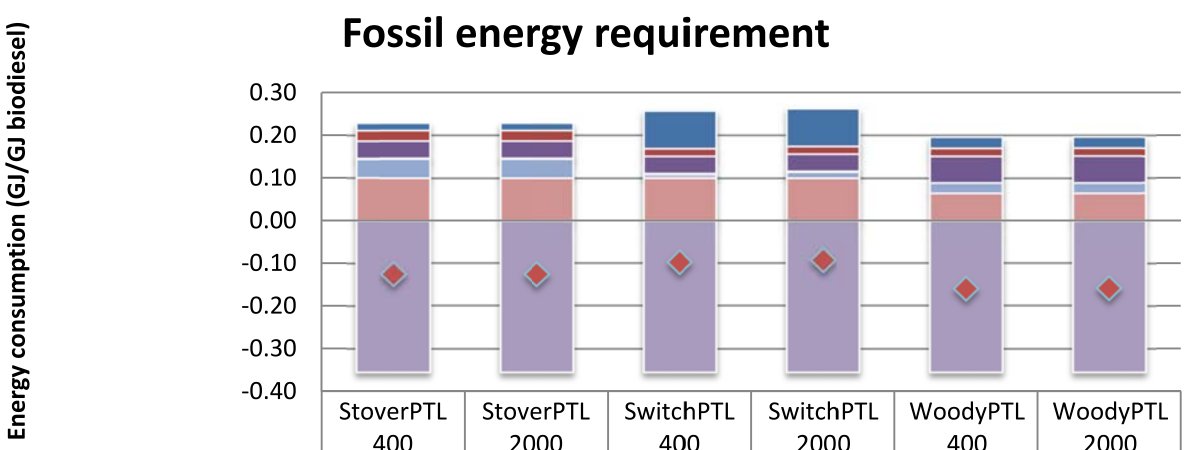
The distances per mode of traveled assumed by van Vliet et al. are 12000 km by ocean bulk carrier and 300 km by IWW. For WoodyPTL400 the distances per mode in this study, when optimizing for cost, are found to be 7255 km by ocean bulk carrier and 14 km by train. The differences in transportation distances are explained by the location of the source of the biomass, Latin America for the study by van Vliet and South-East U.S. in this study. So even though the assumed transportation distance is nearly twice as high in the study by van Vliet, the long range transportation costs are 86% lower. This is mainly explained by the found low costs for transportation by ocean bulk carrier, the model by van Vliet determines the costs of the transportation of pellets by ocean bulk carrier to be € 3.43 / tonne [24]which is quite low. To put this cost into perspective, the freight rates published in Argus Media (Figure 28) for transportation of pellets on the route Mobile-ARA over a distance of 8900 km are € 18.50 / tonne (Argus Media, 2012). Based on the low transportation costs van Vliet et al. conclude that long

[22] Assumptions: LHV FT-diesel = 43.3 MJ/kg, Density FT-diesel = 780 kg / m^3, Average inflation rate = 2.2%
[23] €(2005) 0.02 / liter in study by van Vliet
[24] €(2012) 4.00 / tonne assuming an average inflation rate of 2.2%

range transport has a minor role in the total cost of the supply chain, even when intermediates need to be shipped over 12,000 km. The results found in this thesis do however indicate that long range transport does have major role in the total cost of the supply chain.

3.2.2 Energy requirements and greenhouse gas emissions

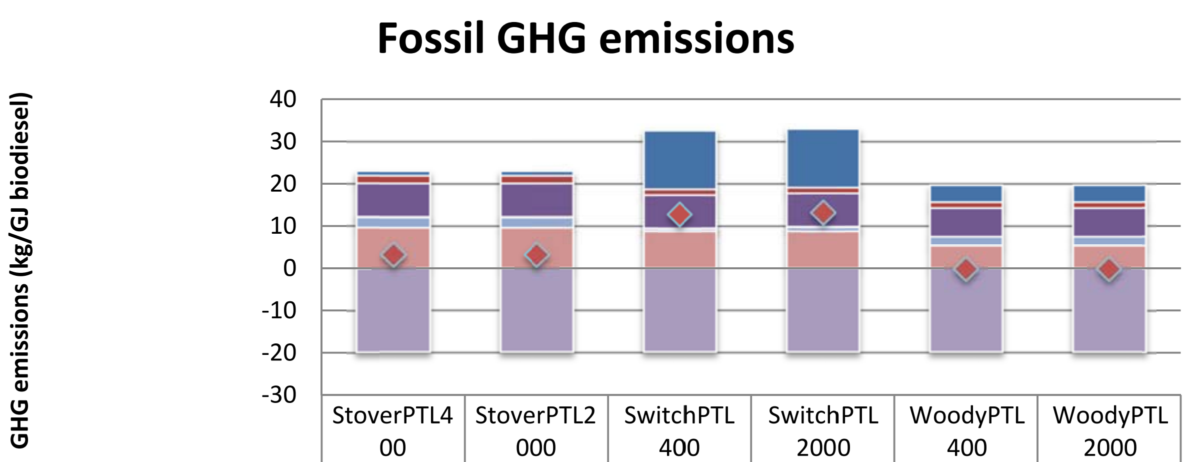
The fossil energy required for the production of 1 GJ FT-diesel for the six examined case studies are depicted in Figure 21, the GHG emissions are depicted in Figure 22. Since fossil energy consumption and GHG emissions are closely related they are described together in this paragraph.



	StoverPTL 400	StoverPTL 2000	SwitchPTL 400	SwitchPTL 2000	WoodyPTL 400	WoodyPTL 2000
Cultivation	0.017	0.017	0.089	0.089	0.026	0.026
Harvesting and Collection	0.025	0.025	0.018	0.018	0.019	0.019
Preprocessing	0.041	0.041	0.040	0.040	0.061	0.062
Storage	0.002	0.002	0.002	0.002	0.000	0.000
Handling and Queuing	0.000	0.000	0.000	0.000	0.000	0.000
Remote Transport	0.043	0.043	0.007	0.013	0.024	0.024
Long Range Transport	0.101	0.101	0.101	0.101	0.065	0.065
FT Plant	0.000	0.000	0.000	0.000	0.000	0.000
FT (Credits)	-0.355	-0.355	-0.355	-0.355	-0.355	-0.355
Total	-0.126	-0.126	-0.098	-0.093	-0.160	-0.159

Figure 21 – Fossil energy requirement for FT-diesel production

The results show that in all examined cases most of the processes do consume energy from fossil resources. For the cultivation of the feedstock the fossil energy required and GHG emitted is the highest for switchgrass (0.089 $GJ_{expfossil}$ / GJ FT-diesel, 13.90 kg $CO2_{eq}$ / GJ FT-diesel). The reason that the fossil energy requirement for the cultivation of switchgrass is more than five times higher than for stover is because switchgrass is a dedicated energy crop whereas stover is considered as an agricultural residue. Since switchgrass is a dedicated energy crop, all fossil energy consumed for cultivation is allocated to the feedstock. For stover however most of the fossil energy consumed and GHG emitted are allocated to the corn grain. But the removal of the stover increases the amount of fertilizer required for the cultivation of the corn grain therefore a fertilizer debit is taken into account for the fossil energy requirement and GHG emitted for the cultivation of stover to account for this fact The fossil energy requirement and GHG emissions are mainly associated with the production of the required fertilizers and pesticides and the diesel consumed by equipment used for the cultivation.



	StoverPTL400	StoverPTL2000	SwitchPTL 400	SwitchPTL 2000	WoodyPTL 400	WoodyPTL 2000
Cultivation	1.07	1.07	13.90	13.90	4.02	4.02
Harvesting and Collection	1.85	1.85	1.36	1.36	1.41	1.41
Preprocessing	7.93	7.93	7.88	7.88	6.80	6.80
Storage	0.15	0.15	0.15	0.15	0.00	0.00
Handling and Queuing	0.00	0.00	0.00	0.00	0.00	0.00
Remote Transport	2.41	2.41	0.57	0.97	2.13	2.13
Long Range Transport	9.62	9.62	8.76	8.76	5.33	5.33
FT Plant	0.00	0.00	0.00	0.00	0.00	0.00
FT (Credits)	-19.85	-19.85	-19.85	-19.85	-19.85	-19.85
Total	3.17	3.17	12.77	13.17	-0.15	-0.15

Figure 22 – Fossil GHG emissions for FT-diesel production

Case 5 and 6 are supply chains with purpose growth wood as a feedstock, the amount of fertilizer and diesel required for the cultivation of this farmed wood is far less than for switchgrass, this explains the lower fossil energy consumption and GHG emitted found for cultivation. The fossil energy consumption for preprocessing, which does include the densification into pellets, is nearly equal for stover and switchgrass but about 50% higher for woody biomass which is mainly explained by the additional (fieldside) shredding and grinding operations required in this supply chain. The stover and switchgrass don't require these operations and are transported in bales from field to depot. The fossil energy required and GHG emitted for remote transportation (Field-Depot, Depot-Terminal) is the highest for stover and the lowest for switchgrass. The fossil energy requirement and GHG emitted for remote transportation of the biomass for the cases with switchgrass as the feedstock increases when selecting a larger FT-plant. The reason for this is that when the scale of the FT-plant is increased, the demand for biomass increases. This means more acres haves to be harvested and more acres harvested means that the draw radius for transport between field and depot increases; this is because there are a fixed number of depots specified (8). This in turn increases the fuel consumption of the trucks, which explains the increase in energy consumption and GHG emitted for remote transportation. The reason that this is not applicable to the other herbaceous supply chains (FT-diesel from stover) is because the number of depots for those cases is internally computed by the INL Model which results in no significant increase in transport distance between field and depot.

From the details, it is apparent that the fossil energy consumption and GHG emitted for the long distance intermodal transportation from terminal to FT-plant for pelletized woody biomass from Savannah are lower than for the herbaceous cases from Kansas City. This is mainly due to the fact that the transporting distance to the Netherlands is smaller.

The energy and GHG emission savings from excess electricity from cogeneration do not change when selecting a larger scale plant and are for all six analyzed cases -0.355GJ / GJ FT-diesel, -19.85 kg CO_2eq / GJ FT-diesel produced. This is due to the fact that efficiency increases as a result of the scale of the FT-plant are not included in the model developed by van Vliet et al. and therefore not part of the developed modeling tool in this thesis.

The main contributors to the fossil energy consumption are Long Range and Remote Transport for the supply chain from stover, Cultivation and Long Range Transport for the supply chain

from switchgrass and Preprocessing and Remote Transport for the supply chain from woody biomass. For the GHG emissions the largest contributors are for the supply chains from stover and woody biomass Preprocessing and Long Range Transport and for the supply chain from switchgrass Cultivation and Long Range Transport.
For all six biofuel production chains, a negative fossil energy consumption was found. The lowest negative fossil energy consumption was found for the supply chain from switchgrass. With respect to GHG emissions only negative emissions were found for the supply chains from woody biomass, the chains for stover and switchgrass do emit greenhouse gasses from which the chain for FT-diesel from switchgrass is performing the worst by far.

With an overall found range for the GHG emissions of -0.15 - 13.17 g $CO2_{eq}$ / MJ FT-diesel produced the found emissions for the six case studies fall within the ranges found by other studies as collected in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, depicted in Appendix VI: Figure 29. This figure shows the ranges of GHG emissions from other bioenergy system LCAs. The six cases studies fall within the category 'Lignocelulose FTD' with a range of -5 – 20 g $CO2_{eq}$ / MJ (IPCC, 2011).

For the supply chain for FT-diesel from woody biomass (WFSD1) the JRC study finds a total energy consumption of 1.09 – 1.29 MJ_{exp} / MJ FT-diesel (Appendix VI: Figure 30) from which 0.06 MJ is consumed from fossil resources (JRC, 2011). In the JRC study however there has been not been credited for electricity production, the transportation distance between terminal and refinery is assumed to be only 50km (by truck) and the feedstock is not densified into pellets. In order to compare the results from the JRC study with the chain for woody biomass (WoodyPTL2000) from this study the savings from excess electricity from cogeneration, the long range transportation costs and the preprocessing costs (mainly densification into pellets) have to be ignored. Ignoring these figures the results for the fossil energy consumption of the WoodyPTL2000 supply chain are 0.069 MJ_{exp} / MJ FT-diesel which is close to the figure found by the JRC study of 0.06 MJ_{exp} / MJ FT-diesel. With respect to the GHG emissions the JRC study finds a figure of 6.9 g $CO2_{eq}$ / MJ FT-diesel with a range of 5.4 - 18.8 g $CO2_{eq}$ / MJ FT-diesel where this study finds a considerably lower figure of - 0.15 g $CO2_{eq}$ / MJ FT-diesel. This difference is mainly explained by crediting for electricity exported to the grid.

3.3 Sensitivity analysis

The results of the case studies in Figure 20, Figure 21, Figure 22 show that a large share of the total costs, energy consumption and GHG emissions of the supply chain of FT-Diesel are related to the transportation of the biomass from the terminal to the FT conversion plant. The costs for long distance intermodal transportation are mainly influenced by the time charter rates, fuel prices and chosen vessel size. From the graph in Figure 23 it is apparent that the time charter rates and fuel prices have been fluctuating highly between 2007 and 2011. To determine how robust the conclusion is that a large share of the total costs of the FT-diesel supply chain are associated with the transportation of the biomass three sensitivity analyses have been performed targeted on the parameters that are assumed to have a large impact on the costs, energy consumption and GHG of the intermodal transport of biomass. All sensitivity runs were performed for supply chains with woody biomass as the feedstock.

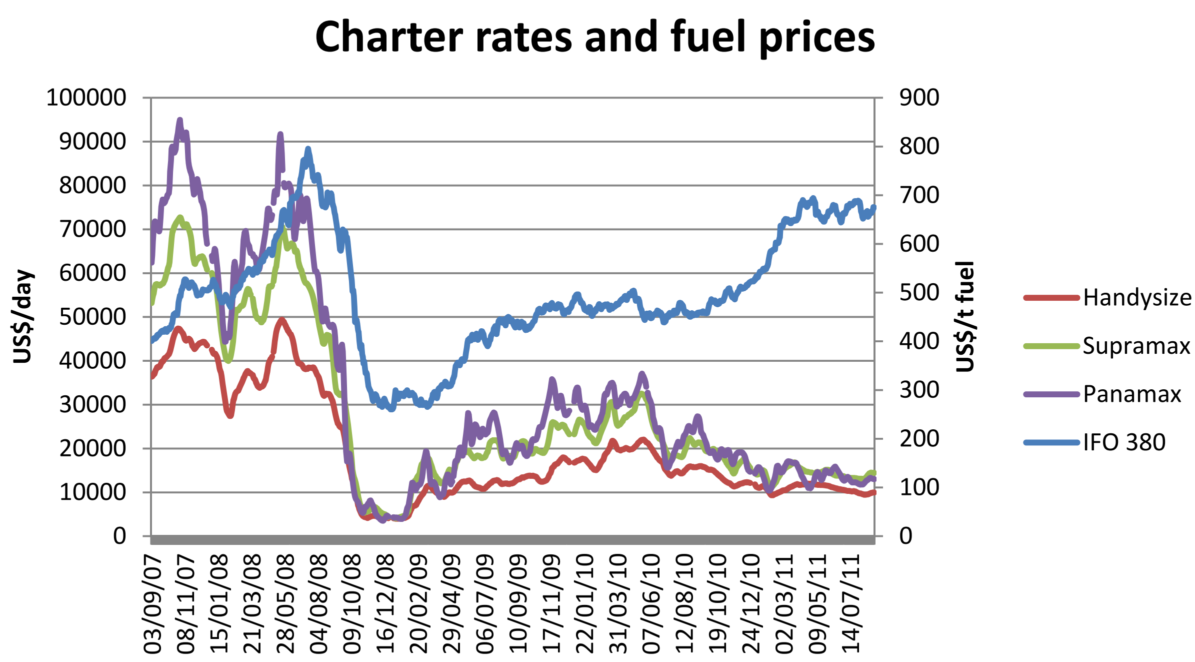


Figure 23 - Charter rates and Fuel prices (Hoefnagels et al., 2011)

The first two sensitivity analyses were performed by additionally running the model for respectively the lowest and highest time charter rates and lowest and highest fuel prices that occurred in the period 2007-2011, the assumed charter rates and fuel prices can be found in

Table 11 and Table 12. The third sensitivity analysis was performed by running the model with the specifications of two other types of ocean vessels: Supramax (37000 t) and Panamax (53400 t), the specifications are summarized Table 13.

	WoodyPTL400 Base 2007-2011	*WoodyPTL400 LowTCRates 2007-2011*	*WoodyPTL400 HighTCRates 2007-2011*
Time charter rates (€/h)	453.86	125.33	1568.16

Table 11 - Time charter rates Handysize 2007-2011

	WoodyPTL400Base 2007-2011	*WoodyPTL400 LowIFO380 2007-2011*	*WoodyPTL400 HighIFO380 2007-2011*
Fuel prices (€/GJ)	13.44 (719.31 \$/t)	4.92 (260.36 \$/t)	14.86 (795.24 \$/t)

Table 12 - Fuel prices IFO380 2007-2011

	WoodyPTL400Base Handysize	*WoodyPTL400 Supramax*	*WoodyPTL400 Panamax*
Time cost (€/h)	595.46	829.29	971.38
Variable cost (€/km)	0	0	0
Fuel type	IFO380	IFO380	IFO380
Fuel consumption full (MJ/kg)	1761	2185	2553
Fuel consumption empty (MJ/kg)	1466	1742	1987
Maximum load (t)	26000	37000	53400
Maximum load (m3)	43333.33	61666.67	89000
Speed (average) (km/h)	26.48	26.67	26.67

Table 13 - Ocean vessel properties by type

The results of the analysis, the costs of the supply chain for 1 GJ of FT-diesel from woody biomass at different time charter rates, fuel prices and types of ocean vessel can be found in Table 14 to Table 16, the details per supply chain component can be found in Appendix V.

	WoodyPTL400 Base 2007-2011	*WoodyPTL400 LowTCRates 2007-2011*	*WoodyPTL400 HighTCRates 2007-2011*
Costs (€ /GJ FT-diesel)	27.27	26.47	29.97
Energy consumption (GJ / GJ FT-diesel)	-0.16	-0.16	-0.16
GHG Emissions (kg CO2eq / GJ FT-diesel)	-0.15	-0.15	-0.15

Table 14 – Results sensitivity analysis: time charter rates

	WoodyPTL400Base 2007-2011	*WoodyPTL400 LowIFO380 2007-2011*	*WoodyPTL400 HighIFO380 2007-2011*
Costs (€ /GJ FT-diesel)	27.27	27.04	27.71
Energy consumption (GJ / GJ FT-diesel)	-0.16	-0.16	-0.16
GHG Emissions (kg CO2eq / GJ FT-diesel)	-0.15	-0.15	-0.15

Table 15 – Results sensitivity analysis: fuel prices

	WoodyPTL400Base Handysize	*WoodyPTL400 Supramax*	*WoodyPTL400 Panamax*
Costs (€ /GJ FT-diesel)	27.27	27.10	26.75
Energy consumption (GJ / GJ FT-diesel)	-0.16	-0.17	-0.18
GHG Emissions (kg CO2eq / GJ FT-diesel)	-0.15	-0.87	-1.73

Table 16 – Results sensitivity analysis: ocean vessel size

The sensitivity analysis found, that from the extremes in the time charter rates and from the extremes in the fuel prices for IFO380 (in the period 2007-2011), the costs of the supply chain for FT-diesel from woody biomass are most sensitive to the time charter rates. The difference in costs of the entire supply chain between the lowest and highest charter rates in the 2007-2011 period are more than 13%. The level of the time charter rates and fuel price for IFO380 seem to have no effect on the energy consumption and GHG emissions of the supply chain. In this specific case the export terminal has been located in Savannah and the FT-plant in Rotterdam. Both cities have a port and therefore the biomass is primarily transported by ocean carrier, for which no alternative mode of transport exists. In case the terminal was located inland and the biomass first had to be transported to the port, many alternatives routes could have been considered by the Network Analyst to determine the least cost distance route. When the Network Analyst would select a new least cost distance route as a result of new charter rates or fuel costs, possible even using other modes of transport, the energy consumption and GHG emissions are expected to change with the time charter rates and fuel costs for IFO380. In addition it is likely that the time charter rates and fuel costs in that case will have a less substantial effect on the total costs of the supply chain of FT-diesel as was seen for this specific analyzed case.

The final sensitivity analysis performed focused on the effect of the ocean vessel size on the performance of the supply chain. As expected the costs, energy consumption and GHG emissions are lower with the choice of a larger ocean vessel.

From the tables in Appendix V it is clear that although the time charter rates and fuel costs for IFO380 do have an effect on the total costs of the supply chain even when considering the lowest values in the period 2007-2011 the intermodal transportation costs remain to be a significant part of the total costs of the supply chain.

4 Discussion

In this thesis, different production chains of synthetic fuel produced in a Fischer-Tropsch plant located in the Netherlands using various sources of lignocellulosic biomass have been investigated. These sources include different types of solid biomass from different geographic regions in the US densified into pellets before long distance transport. These chains have been investigated using a newly developed modeling tool (BLCM-UU) based on three different models each with its own strengths and weaknesses.

- The Biomass Logistic Model (BLM) developed by INL,
- The Intermodal Transport Network Model (BIT-UU) developed by the UU,
- The Fischer-Tropsch Conversion Model developed by van Vliet et al. (2009).

The combination of the three models allows for discrete modeling of most of the processes related to FT-synfuel production. Especially, considering long distance inter-continental supplies chains to transport the feedstock between terminal and FT plant, the inclusion of the intermodal transportation networks significantly improves the BLM Model.
Comparing the results of the supply chains of the combined models provides insight in the cost structure, potential cost reductions (for example due to economies of scale), and transport (through detailed depiction of intermodal, geographic explicit transport). It provides the opportunity to compare the performance (in terms of costs, energy consumptions and GHG emissions) of multiple alternative supply chains from various feedstock and source and demand regions. Due to its ability to address for both geospatial details and details of logistic processes the developed modeling can be used to study the effects of densification (unprocessed, chips, pellets, torrefaction) and the effects of new technologies on the overall performance of the supply chain. The modeling tool is flexible enough to change individual processes in the supply chain and even move processes up or down the supply chain with the exception that end-conversion into FT-diesel is always required to take place as the final step in the supply chain.

Although with the combination of the models, most weaknesses of the individual models have been mitigated, there are still a number of important limitations to this analysis approach:

One concurrent biomass source for supply assumed: The developed BLCM-UU explicitly assumes that only one concurrent type of feedstock is used for the production of FT-diesel**.** This limitation is a result of the inability of the INL BLM Model (used to model multiple biomass logistics operations in the BLCM-UU) to model multiple concurrent supply chains. In practice, a mix of different feedstock types from multiple source regions is often used. For the conducted case studies the U.S. was considered to be the single supply region for biomass for the production of FT-diesel in the Netherlands since it is a key source area biomass for the Netherlands (Lamers et al. 2011, Cocchi et al. 2011).

Accuracy of modeling of intermodal transfers: Due to the lack of data about the exact locations and details of the intermodal transfer facilities in Europe, a rather simplified approach has been taken to model the intermodal transfers of biomass in Europe. Intermodal transfers are assumed to take place at centroids of a NUTS-3 region and are assumed to be possible between all modes of transport that have a node in that region. This may lead to an underestimation of costs, energy consumption and GHG emissions of the intermodal transporting component of the supply chain.

No distinct modes of transport for Europe and U.S.: The properties of the Inland Waterway vessels in the United States are assumed to be equal to the properties of the Inland Waterway Class 6 vessels for Europe. This assumption was also made due to the lack of data about the specifics of the Inland Waterway vessels in the United States. The same applies with respect to trucks and trains.

Limited modeling of maritime logistics: The maritime logistics have been highly simplified in the developed modeling tool. First of all only one type of concurrent type of ocean vessel is assumed when determining the least cost route from export terminal to FT-plant. This can either by a Handysize, Supramax or Panamax size vessel. Second of all, the tool does not take harbor dues and waiting times for locks into account. Thirdly the tool does not consider the accessibility of the ports for different sizes of ocean bulk carriers into account.[25]

[25] These issues have been addressed in the context of another study ‘Capacity Study for Solid Biomass Facilities’ for the Port of Rotterdam.

Crediting for electricity co-production favors supply chains with a high export of electricity: Most Fischer-Tropsch plants produce surplus electricity and consume additional biomass to that effect. Since the developed modeling tool studies the production of FT-diesel, the surplus electricity is considered to be a byproduct. Following the approach by van Vliet et al. (2009) the total costs of the supply chain were credited for the benefits of exporting electricity to the grid. [26] However due to this approach supply chains with a high electricity export to the grid are favored. An alternative to crediting for the benefits of electricity exported to the grid would be subtracting the additional biomass used for the generation of the surplus electricity using the efficiency of a wood powered electricity station as proposed in the JRC study (JRC, 2011).

[26] By using baseline electricity generation in Western Europe as a reference.

5 Conclusion

To provide further insight in the biomass supply chain for the production of FT-diesel from field-to refinery gate in terms of costs, energy consumption and GHG emissions a modeling tool (BLCM-UU) was developed during this master thesis. The strengths and weaknesses of this approach and implementation, the development of an integrated modeling tool to study the biomass supply chain, has extensively been addressed in the discussion chapter.

The BLCM-UU was designed by integrating, modifying, redesigning and extending three existing models: the INL BLM Model, the BIT-UU Model and the van Vliet FT Conversion Model. These three models are all detailed on different components of the biomass supply chain, but aggregated on the other parts. The strengths of the models have been combined and integrated into one single modeling framework that is capable of addressing discrete logistic process details while also being capable of maintaining geographic explicit transport details of inter-continental supply chains. Thereby the BLCM-UU creates the opportunity to provide insight in the key opportunities and sensitivities of all discrete logistic processes related to the supply and conversion to FT-synfuels including long distance inter-continental biomass feedstock supply chains.

To demonstrate the analyses capabilities of the BLCM-UU several case studies have been performed in this thesis with supply in the United States and demand in the Netherlands. During the analysis of the case studies, the BLCM-UU has proven to be able to cope with different supply regions, feedstock types, routes and specifics of the operations in the supply chain. In addition the results have been proven to contain enough details to explain differences in the costs, energy consumption and GHG emissions of the supply chains when changing the specifics of the supply chain.

Regarding the cost of FT-synfuel production with different types of biomass sourced from the different geographic sources in the U.S., the performed case studies (using the BLCM-UU) show that:

- From the three included types of biomass (Stover, Switchgrass, Woody) based on the assumptions in this thesis the supply chain for the production of FT-diesel from woody biomass is the most economic of the examined supply chains.
- The costs for densification into pellets (included in the costs for preprocessing) are low compared to the total costs of the supply chains at only 4-11%.
- The size of the FT-plant has a clear effect on the total costs of the supply chains due to economies of scale, reducing the costs by 14-16% when moving from a 400MW_{th} to a 2000MW_{th} conversion plant.
- The two main contributors to the total costs of the supply chain are the costs for conversion in the FT-plant (38-52%) and the costs for long distance, intermodal transportation between the export terminal and the FT-plant (16-30%). The costs for long distance, intermodal transportation could further be reduced by processing the feedstock into torrified pellets instead of conventional pellets. This would increase the energy density of the feedstock and thus lower the costs for transportation. However torrefaction would induce costs, energy consumption and GHG emissions. The ability to study the net effect of torrefaction on the overall performance of the supply chain could easily be added to the BLCM-UU. Another way to lower the costs of transportation is by moving the FT-plant near the production site of the feedstock and transporting the bioenergy as liquid biofuel to the demand location.
- Transportation is an important determinant in the overall performance of FT-diesel supply chains with long distance transportation between terminal and refinery. Even when considering the lowest values for the period 2007-2011 for the fuel price of IFO380, the time charter rates or when considering a larger ocean vessel, the long range transportation remains the second most important determinant in the total costs of the supply chain for woody biomass.
- Considering the current crude oil price of $108.48 per barrel (21 € / GJ diesel) the supply of FT-diesel from woody biomass can be considered as nearly cost effective and would

become cost effective at a crude oil price of 121$/bbl. The ranges found for the six cases are 23.04-30.04 € / GJ FT-diesel. Thereby, even when considering supply chains with long distance transportation from terminal to refinery, FT-diesel production in Europe might become cost effective in the future and contribute to the RES 2020 targets of 20% renewable energy in 2020 (Renewable Energy Directive 2009/28/EC).

Regarding the energy consumption and GHG emissions of FT-synfuel the model results show that for the performed case studies:

- Most processes of the supply chain do consume energy from fossil resources and emit GHG.
- The fossil energy required and GHG emitted for cultivation of switchgrass are five times higher than for stover, due to the fact that switchgrass is considered as a purpose growth feedstock and stove is considered a residue.
- The fossil energy consumption for the preprocessing of woody biomass is 50% higher than for stover and switchgrass due to additional energy consumption for field side shredding and grinding.
- The distance between the export terminal and the FT-plant as well as whether they are located near the coast are important determinants in the energy consumption and GHG emissions of the long range transport.The main contributors to the fossil energy consumption are Long Range and Remote Transport for the supply chain from stover, Cultivation and Long Range Transport for the supply chain from switchgrass and Preprocessing and Remote Transport for the supply chain from woody biomass. For the GHG emissions the largest contributors are for the supply chains from stover and woody biomass Preprocessing and Long Range Transport and for the supply chain from switchgrass Cultivation and Long Range Transport.

- For all six chains a negative fossil energy consumption is found. The lowest negative fossil energy consumption is found for the supply chain from switchgrass (-0.093 to -0.098 GJ / GJ FT-diesel).
- With respect to GHG emissions [27]only negative emissions were found for the supply chains from woody biomass (-0.15 kg $CO2_{eq}$ / GJ FT-diesel), the chains for stover and switchgrass do emit greenhouse gasses from which the chain for FT-diesel from switchgrass is performing the worst by far (12.77-13.17 kg $CO2_{eq}$ / GJ FT-diesel).

Considering a GHG emission factor of 83.8 g $CO2_{eq}$ / MJ for fossil diesel[28] all six cases (range: -0.15 – 13.17 g $CO2_{eq}$ / MJ FT-diesel) can be considered as robust GHG emission savers and meet the required reduction of 60% with respect to diesel production from fossil sources required by the RES Directive (Renewable Energy Directive 2009/28/EC). For the stover cases the reduction is 96%, for switchgrass 84-85% and for woody biomass 100% (see Table 10 for GHG emissions in kg $CO2_{eq}$ / GJ FT-diesel). The RES Directive however prescribes, that for calculating emission savings, the emissions from a biomass electricity plant must be used as a reference instead of the emissions from baseline electricity generation in Western Europe. The latter was used in this thesis. However, even when not crediting for the GHG emissions avoided due to the export of electricity to the grid, the GHG emissions of all six analyzed cases are considerably lower than for the production of diesel from fossil resources. Without crediting the emissions are: 23.02 g $CO2_{eq}$ / MJ FT-diesel for StoverPTL400 and StoverPTL2000, 32.62 g $CO2_{eq}$ / MJ FT-diesel for SwitchPTL400, 33.02 g $CO2_{eq}$ / MJ FT-diesel for SwitchPTL2000 and 20.00 g $CO2_{eq}$ / MJ FT-diesel for WoodyPTL400 and WoodyPTL2000. Based on these figures the reduction is 73% for stover, for switchgrass 61% and for woody biomass 76%.
Since in each of the examined supply chains long distance transportation takes place and each chain meets the 60% reduction required by the RES Directive, it can be concluded that long distance transportation does not have to be a barrier for biofuel production chains in Europe with a feedstock supply source at a distant location.

[27] The effect on carbon stock changes have not been included in the developed modeling tool, this was outside the scope of this study.
[28] The use of the figure 83.8 g $CO2_{eq}$ / MJ for diesel is prescribed by the RES directive; this figure includes the emissions from the production of the fossil diesel (Renewable Energy Directive 2009/28/EC).

The modeling tool (BLCM-UU) could further be improved by incorporating seasonal fluctuations of charter rates into the modal, since distance traveled by ocean carrier is often a major part of intercontinental transport of biomass and seasonal fluctuations of the charter rates are strong. Finally further research should focus on the validation and calibration of the modeling tool developed in this thesis. This would require the gathering of an enormous amount of process details (especially for the parts that originate from the INL BLM Model) and empirical data about existing supply chains which is a resource consuming process and well beyond the reach of this master thesis.

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6.2 Data sources

- RRG GIS Database: Transport networks, shipping routes and seaports of European countries.
- Eurostat Database: Labor cost transportation sector, availability forestry residues and products of European countries.
- RITA National Transportation Atlas Database: Transportation facilities, transportation networks, and associated infrastructure of the United States.
- EC GISCO database: Sea harbors in European countries.
- SeaRates.com: Distances between sea harbors worldwide
- Results REFUEL project: Spatial distribution of energy crops within countries of the EU-27
- TRANS-TOOLS V2 model: Network data for road, rail and inland waterways, toll charges

Appendix I Programmatic Interface

Programmatic Interface

The BLM Model has been developed by INL using the Business Simulation software PowerSIM Studio. The UU BITS Model on the other hand has been developed in ESRI's ArcGIS Network Analyst. The use of different software packages makes it difficult to construct a bidirectional link between the two models. The solution found in this master thesis is to use the by PowerSIM supported Visual Basic scripting language for exporting and importing data into the INL BLM Model and the by ArcGIS supported Python scripting language for exporting, importing data and controlling the Network Analyst module. Unfortunately the two scripting languages are not able to interface directly. To solve this problem the Windows Scripting shell was used as an intermediate.

VB-script (PowerSIM):

The VB-script accepts the following inputs from the (extended) INL BLM Model:
a two-dimensional array containing the mode specific parameters in metric units; the selected case number; an array containing fuel cost; a Boolean value that specifies whether the ArcGIS Module should be enabled; the Dollar-Euro exchange rate; an array containing labor costs

First the script checks the supplied Boolean value to determine whether the module should be enabled or that the Network Analyst module will not be used in this specific scenario. If the module is enabled the script continues and retrieves the Source (Terminal) and Destination (Refinery) locations ids as has been specified by the user in the Excel control input file. Then the script concatenates the fuel costs, the mode specific parameters, the labor costs and the source and destination ids into a single list.

Programmatic Interface (continued)

Next the VB-script invokes the Python-script through the Windows Scripting shell and passes the concatenated list as an argument. The final part of the script retrieves the results of the Network Analyst module and feeds it back into the INL BLM Model.

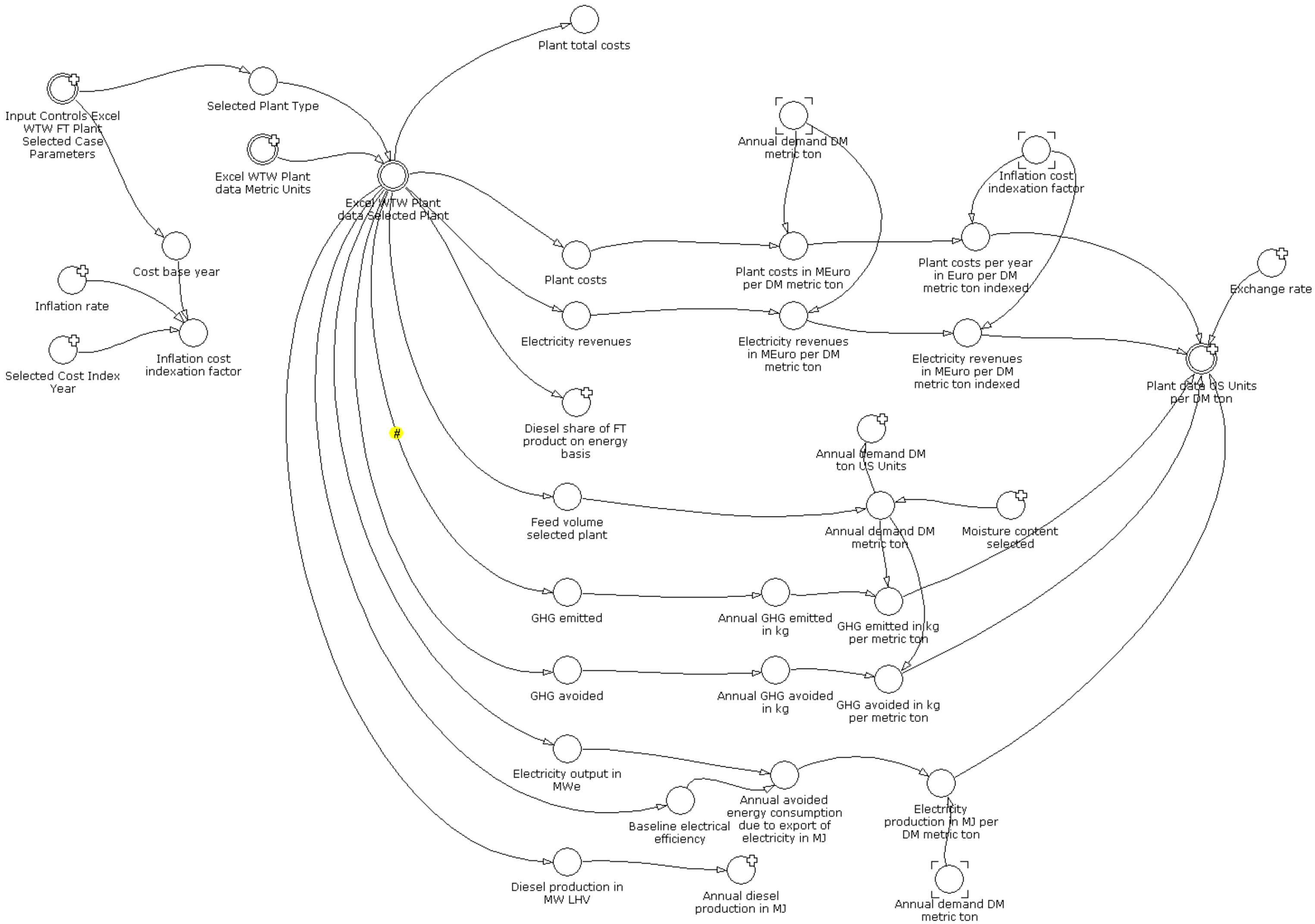
Python-script:

First the necessary licenses for the Network Analyst are checked out and the geodatabase (described in the next chapter) is selected as the workspace. From this workspace the network dataset that is used for the analysis is specified.

Next the source and destination ids are used to retrieve their geographic locations from a supplied layer file. Their locations are added to a separate source and destination feature class. Then the route solving problem is formulated including the specification of which attributes should be optimized for and which attributes should be accumulated. The solving problem is further specified by adding the start and end points (stops) to the problem; these are the nodes on the network that are closest to the terminal and refinery. In addition it is specified that start and end points may only be Terminal Nodes in the U.S. and Centroids in Europe. Then the parameters (including mode specific parameters) that were calculated in PowerSIM are added to the solving problem. This is done by iterating over the rows in a CSV file and checking whether a certain parameter is mapped and how the parameters are mapped form PowerSIM to ArcGIS. This approach makes the modeling of intermodal transport easy to extend by the user, since new parameters added to PowerSIM can with little effort be mapped to ArcGIS. The following part of the script instructs the Network Analyst to solve the routing problem. The resulting layer is saved to an output file and the results, which consist of the accumulated attributes, are passed back to the VB-script through the Windows Scripting Shell.

To provide the user with updates during the run of the script a logging function has been included, to enable debugging several intermediate results are exported by the scripts.

Appendix II Calculation steps INL BLM – van Vliet FT Conversion submodel



Appendix III Assumptions for Case Studies

		Road	*Rail*	*Inland waterways*					*SSS*	*Ocean*
Type		Truck	Rail	IWW CL2 small, dry bulk	IWW CL3 medium, dry bulk	IWW CL4 large, dry bulk	IWW CL5 large, container	IWW CL6 push tug	5000 - 7500 dwt dry bulk	Handysize
Labour	person/v	1.00	0.00	1.28	1.44	2.62	2.62	3.76	0.00	0.00
Time cost	€/h	18.41	0.00	10.30	21.85	72.20	106.68	214.22	123.18	453.68
Variable cost	€/km	0.30	0.06	0.00	0.00	0.74	0.93	17.84	5.71	0.00
Fuel type		Diesel	Diesel	MDO	MDO	MDO	MDO	MDO	IFO380	IFO380
Fuel consumption full	MJ/km	13.41	207.04	219.57	314.45	469.98	469.98	716.80	1430.00	1760.54
Fuel consumption empty	MJ/km	8.39	207.04	177.14	271.81	424.57	424.57	660.89	1430.00	1465.61
Maximum load	t	27.00	1820.00	550.00	950.00	2500.00	2500.00	10800.00	5700.00	26000.00
Maximum load	m3	120.00	4550.00	641.77	1321.28	3136.76	3136.76	14774.28	9500.00	43333.33
Speed (max)	km/h	80.00	0.00	5.42	5.80	6.71	8.64	9.00	28.70	26.48
Load factor		1.00	1.00	0.71	0.85	0.77	0.77	0.83	1.00	1.00
Loaded trips of total trips		0.56	0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.55
Design ratio		225.00	400.00	857.00	719.00	797.00	797.00	731.00	600.00	600.00[29]

[29] Details about the assumptions are described in the IEA Task 40 report.

Appendix IV Results of Case Studies

Cost Summary ($/ DM ton)

	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	4.45	0.65	1.29	0.00	1.95	134.58	0.01
Baling/ Bundling	24.89	4.01	7.45	0.00	11.46	25.27	2.20e-3
Collection	6.04	0.89	0.98	0.00	1.87	25.42	2.21e-3
Total Harvest & Collection	**35.39**	**5.55**	**9.72**	**0.00**	**15.27**	**185.27**	**0.02**
Transportation FROM Field	7.17	1.34	9.01	0.00	10.35	124.18	0.01
Transportation FROM Depot	9.87	1.77	12.47	0.00	14.24	201.91	0.02
Transportation FROM Terminal			79.51	0.00	79.51	753.68	0.08
Total Transportation	**17.04**	**3.11**	**100.99**	**0.00**	**104.10**	**1,079.77**	**0.10**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	12.35	3.08	10.69	0.00	13.77	304.28	0.07
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**12.35**	**3.08**	**10.69**	**0.00**	**13.77**	**304.28**	**0.07**
Storage Fieldside	9.78	2.96	0.76	1.00	4.73	10.92	9.50e-4
Storage Depot	0.21	0.07	0.25	0.00	0.32	3.64	3.17e-4
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**9.99**	**3.03**	**1.02**	**1.00**	**5.05**	**14.55**	**1.27e-3**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**149.26**		**149.26**	**-2,662.46**	-0.17
Total	**74.77**	**14.77**	**271.68**	**1.00**	**287.45**	**-1,078.59**	**0.02**

Table 17 - Results StoverPTL400

Cost Summary ($/ DM ton)

	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	4.40	0.65	1.29	0.00	1.94	134.58	0.01
Baling/ Bundling	24.78	4.00	7.45	0.00	11.46	25.27	2.20e-3
Collection	6.01	0.88	0.98	0.00	1.86	25.42	2.21e-3
Total Harvest & Collection	**35.19**	**5.54**	**9.72**	**0.00**	**15.26**	**185.27**	**0.02**
Transportation FROM Field	6.95	1.32	9.01	0.00	10.33	124.18	0.01
Transportation FROM Depot	9.65	1.75	12.47	0.00	14.22	201.91	0.02
Transportation FROM Terminal			79.51	0.00	79.51	753.68	0.08
Total Transportation	**16.59**	**3.07**	**100.99**	**0.00**	**104.06**	**1,079.77**	**0.10**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	12.27	3.07	10.69	0.00	13.76	304.28	0.07
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**12.27**	**3.07**	**10.69**	**0.00**	**13.76**	**304.28**	**0.07**
Storage Fieldside	9.75	2.96	0.76	1.00	4.72	10.92	9.50e-4
Storage Depot	0.19	0.07	0.27	0.00	0.33	3.64	3.17e-4
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**9.94**	**3.02**	**1.03**	**1.00**	**5.05**	**14.55**	**1.27e-3**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**102.85**		**102.85**	**-2,662.46**	-0.17
Total	**74.00**	**14.70**	**225.28**	**1.00**	**240.99**	**-1,078.59**	**0.02**

Table 18 – Results StoverPTL2000

Cost Summary ($/ DM ton)	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	12.10	2.14	3.38	0.00	5.52	111.08	9.66e-3
Baling/ Bundling	24.89	4.01	7.45	0.00	11.46	0.00	0.00
Collection	6.04	0.89	0.98	0.00	1.87	25.42	2.21e-3
Total Harvest & Collection	**43.04**	**7.04**	**11.81**	**0.00**	**18.85**	**136.49**	**0.01**
Transportation FROM Field	4.69	0.86	5.53	0.00	6.40	55.77	4.85e-3
Transportation FROM Depot	0.00	0.00	8.30	0.00	8.30	0.00	0.00
Transportation FROM Terminal			79.51	0.00	79.51	753.68	0.08
Total Transportation	**4.69**	**0.86**	**93.34**	**0.00**	**94.21**	**809.45**	**0.08**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	15.74	4.58	15.22	0.00	19.80	302.62	0.07
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**15.74**	**4.58**	**15.22**	**0.00**	**19.80**	**302.62**	**0.07**
Storage Fieldside	2.84	0.43	0.76	1.06	2.25	10.92	9.50e-4
Storage Depot	0.21	0.07	0.25	0.00	0.32	3.64	3.17e-4
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**3.05**	**0.50**	**1.02**	**1.06**	**2.57**	**14.55**	**1.27e-3**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**149.26**		**149.26**	**-2,662.46**	-0.17
Total	**66.53**	**12.98**	**270.67**	**1.06**	**284.70**	**-1,399.36**	**-9.84e-3**

Table 19 - Results SwitchPTL400

Cost Summary ($/ DM ton)	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	12.05	2.14	3.38	0.00	5.52	111.08	9.66e-3
Baling/ Bundling	24.78	4.00	7.45	0.00	11.46	0.00	0.00
Collection	6.01	0.88	0.98	0.00	1.86	25.42	2.21e-3
Total Harvest & Collection	**42.84**	**7.02**	**11.81**	**0.00**	**18.84**	**136.49**	**0.01**
Transportation FROM Field	5.96	1.13	7.55	0.00	8.67	95.51	8.31e-3
Transportation FROM Depot	0.00	0.00	8.30	0.00	8.30	0.00	0.00
Transportation FROM Terminal			79.51	0.00	79.51	753.68	0.08
Total Transportation	**5.96**	**1.13**	**95.36**	**0.00**	**96.48**	**849.19**	**0.08**
Preprocessing Fieldside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Depot	12.40	4.37	15.22	0.00	19.60	302.62	0.07
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**12.40**	**4.37**	**15.22**	**0.00**	**19.60**	**302.62**	**0.07**
Storage Fieldside	2.81	0.43	0.76	1.05	2.25	10.92	9.50e-4
Storage Depot	0.19	0.07	0.27	0.00	0.33	3.64	3.17e-4
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**3.00**	**0.49**	**1.03**	**1.05**	**2.58**	**14.55**	**1.27e-3**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**102.85**		**102.85**	**-2,662.46**	-0.17
Total	**64.19**	**13.02**	**226.28**	**1.05**	**240.35**	**-1,359.61**	**-6.38e-3**

Table 20 - Results SwitchPTL2000

Cost Summary ($/ DM ton)

	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (METU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	10.45	5.20	2.89	0.00	8.09	57.30	4.98e-3
Baling/ Bundling	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collection	10.05	1.50	7.15	0.00	8.65	83.74	7.28e-3
Total Harvest & Collection	**20.50**	**6.70**	**10.04**	**0.00**	**16.74**	**141.04**	**0.01**
Transportation FROM Field	16.26	2.50	12.98	0.00	15.48	182.52	0.02
Transportation FROM Depot	0.00	0.00	8.30	0.00	8.30	0.00	0.00
Transportation FROM Terminal			46.46	0.00	46.46	485.23	0.05
Total Transportation	**16.26**	**2.50**	**67.74**	**0.00**	**70.24**	**667.75**	**0.07**
Preprocessing Fieldside	6.46	0.64	8.52	0.00	9.16	323.32	0.03
Preprocessing Depot	68.83	7.04	8.72	0.00	15.76	136.06	0.03
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**75.29**	**7.69**	**17.24**	**0.00**	**24.93**	**459.38**	**0.06**
Storage Fieldside	0.00	0.00	0.00	0.17	0.17	0.00	0.00
Storage Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**0.00**	**0.00**	**0.00**	**0.85**	**0.85**	**0.00**	**0.00**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**149.26**		**149.26**	**-2,662.46**	-0.17
Total	**112.05**	**16.88**	**244.29**	**0.85**	**262.02**	**-1,394.30**	**-0.04**

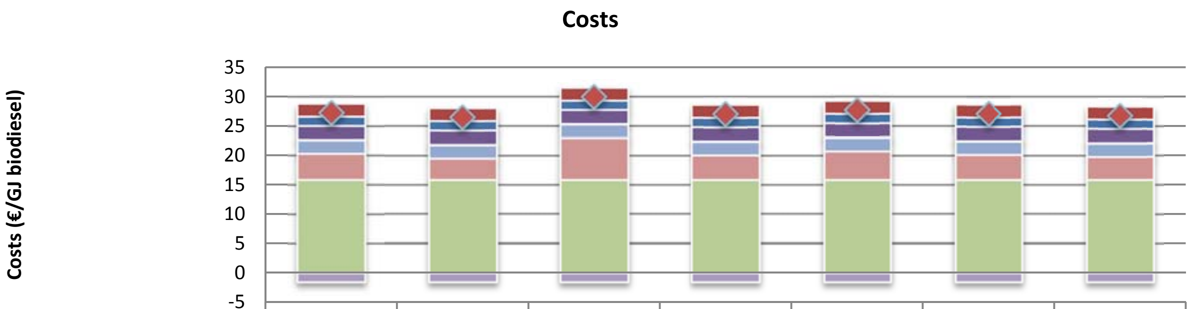
Table 21 - Results WoodyPTL400

Cost Summary ($/ DM ton)

	Installed Capital	Ownership	Operating	DM Loss	Total	MTBU (MBTU/ton)	GHG (ton CO2eq / ton)
Total Grower's Payment					0.00		
Harvesting	10.45	5.20	2.89	0.00	8.09	57.30	4.98e-3
Baling/ Bundling	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collection	10.05	1.50	7.15	0.00	8.65	83.74	7.28e-3
Total Harvest & Collection	**20.50**	**6.70**	**10.04**	**0.00**	**16.74**	**141.04**	**0.01**
Transportation FROM Field	16.11	2.48	12.98	0.00	15.46	182.52	0.02
Transportation FROM Depot	0.00	0.00	8.30	0.00	8.30	0.00	0.00
Transportation FROM Terminal			46.46	0.00	46.46	485.23	0.05
Total Transportation	**16.11**	**2.48**	**67.74**	**0.00**	**70.22**	**667.75**	**0.07**
Preprocessing Fieldside	6.27	0.64	8.52	0.00	9.16	323.32	0.03
Preprocessing Depot	102.05	9.88	8.11	0.00	17.99	141.05	0.03
Preprocessing Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Preprocessing Refinery							
Total Preprocessing	**108.33**	**10.52**	**16.63**	**0.00**	**27.15**	**464.37**	**0.06**
Storage Fieldside	0.00	0.00	0.00	0.17	0.17	0.00	0.00
Storage Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Storage Refinery							
Total Storage	**0.00**	**0.00**	**0.00**	**0.87**	**0.87**	**0.00**	**0.00**
Handling At Depot	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Terminal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling at Refinery							
Total Handling & Queuing	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Total FT Plant			**102.85**		**102.85**	**-2,662.46**	-0.17
Total	**144.93**	**19.70**	**197.26**	**0.87**	**217.83**	**-1,389.30**	**-0.04**

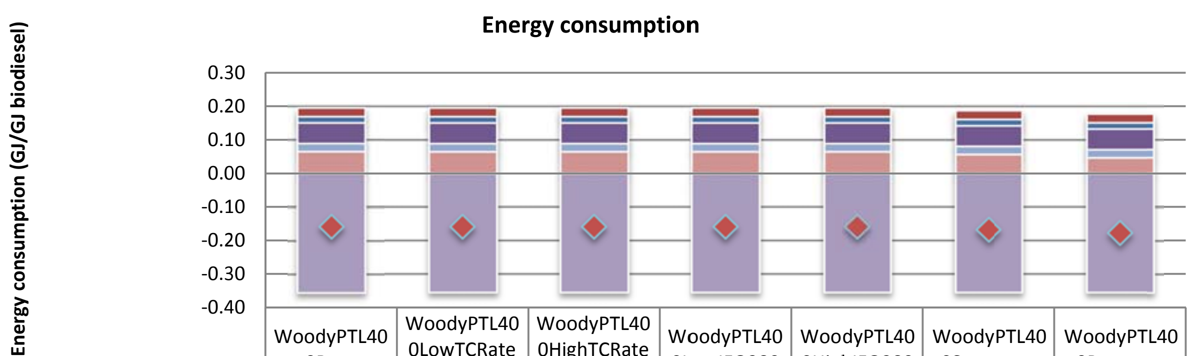
Table 22 - Results WoodyPTL2000

Appendix V Detailed outputs sensitivity analyses



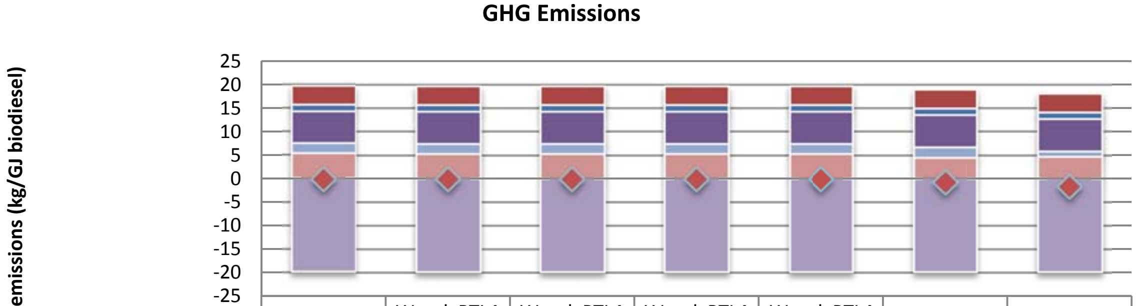
	WoodyPTL400Base	WoodyPTL400LowTCRates	WoodyPTL400HighTCRates	WoodyPTL400LowIFO380	WoodyPTL400HighIFO380	WoodyPTL400Supramax	WoodyPTL400Panamax
Cultivation	2.20	2.20	2.20	2.20	2.20	2.20	2.20
Harvesting and Collection	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Preprocessing	2.38	2.38	2.38	2.38	2.38	2.38	2.38
Storage	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Handling and Queuing	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Remote Transport	2.27	2.27	2.27	2.27	2.27	2.27	2.27
Long Range Transport	4.44	3.65	7.15	4.22	4.89	4.28	3.92
FT Plant	15.85	15.85	15.85	15.85	15.85	15.85	15.85
FT (Credits)	-1.57	-1.57	-1.57	-1.57	-1.57	-1.57	-1.57
Total	27.27	26.47	29.97	27.04	27.71	27.10	26.75

Figure 24 - Fossil energy requirement for FT-diesel production



	WoodyPTL400Base	WoodyPTL400LowTCRates	WoodyPTL400HighTCRates	WoodyPTL400LowIFO380	WoodyPTL400HighIFO380	WoodyPTL400Supramax	WoodyPTL400Panamax
Cultivation	0.026	0.026	0.026	0.026	0.026	0.026	0.026
Harvesting and Collection	0.019	0.019	0.019	0.019	0.019	0.019	0.019
Preprocessing	0.061	0.061	0.061	0.061	0.061	0.061	0.061
Storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Handling and Queuing	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Remote Transport	0.024	0.024	0.024	0.024	0.024	0.024	0.024
Long Range Transport	0.065	0.065	0.065	0.065	0.065	0.056	0.047
FT Plant	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FT (Credits)	-0.355	-0.355	-0.355	-0.355	-0.355	-0.355	-0.355
Total	-0.160	-0.160	-0.160	-0.160	-0.160	-0.168	-0.178

Figure 25 - Fossil energy requirement for FT-diesel production



	WoodyPTL400Base	WoodyPTL400LowTCRates	WoodyPTL400HighTCRates	WoodyPTL400LowIFO380	WoodyPTL400HighIFO380	WoodyPTL400Supramax	WoodyPTL400Panamax
Cultivation	4.02	4.02	4.02	4.02	4.02	4.02	4.02
Harvesting and Collection	1.41	1.41	1.41	1.41	1.41	1.41	1.41
Preprocessing	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Storage	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Handling and Queuing	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Remote Transport	2.13	2.13	2.13	2.13	2.13	2.25	1.18
Long Range Transport	5.33	5.33	5.33	5.33	5.33	4.50	4.71
FT Plant	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FT (Credits)	-19.85	-19.85	-19.85	-19.85	-19.85	-19.85	-19.85
Total	-0.15	-0.15	-0.15	-0.15	-0.15	-0.87	-1.73

Figure 26 - Fossil GHG emissions for FT-diesel production

Appendix VI Results other studies

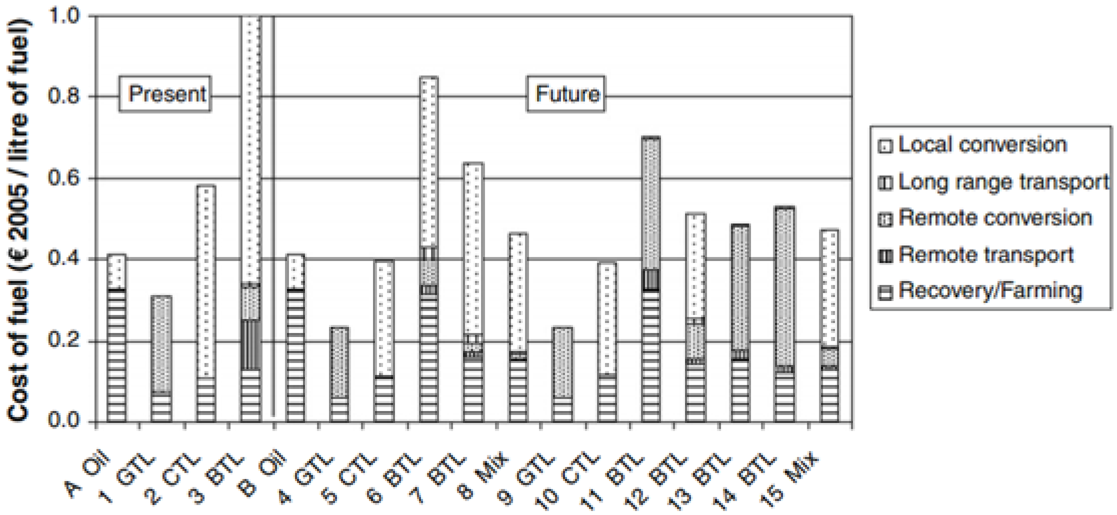


Figure 27 - Breakdown of fuel cost per liter (van Vliet et al., 2009)

Wood Pellet Freight Rates				
Argus wood pellet freight indications, spot cargo				
Route	Tonnage (t)	Units	Rate	+/-
Aveiro-ARA	3,500	€/t	13.50	-0.25
Aveiro-Copenhagen	3,500	€/t	15.75	-0.25
Aveiro-Hull (UK)	3,500	€/t	15.50	-0.25
Riga-ARA	5,000	€/t	18.50	-2.50
Riga-Copenhagen	5,000	€/t	13.00	-1.00
Riga-Stockholm	5,000	€/t	12.25	-1.00
St Petersburg-ARA	3,500	€/t	22.75	-0.25
St Petersburg-Copenhagen	3,500	€/t	16.75	-1.25
St Petersburg-Stockholm	3,500	€/t	15.00	-0.75
Mobile-ARA	25,000	$/t	22.75	0.00
Mobile-ARA	45,000	$/t	18.50	0.00
Savannah-ARA	25,000	$/t	21.25	0.00
Savannah-ARA	45,000	$/t	16.50	0.00
Vancouver-ARA	45,000	$/t	41.00	0.00

Figure 28 - Wood Pellet Freight Rates (Argus Media, 2012)

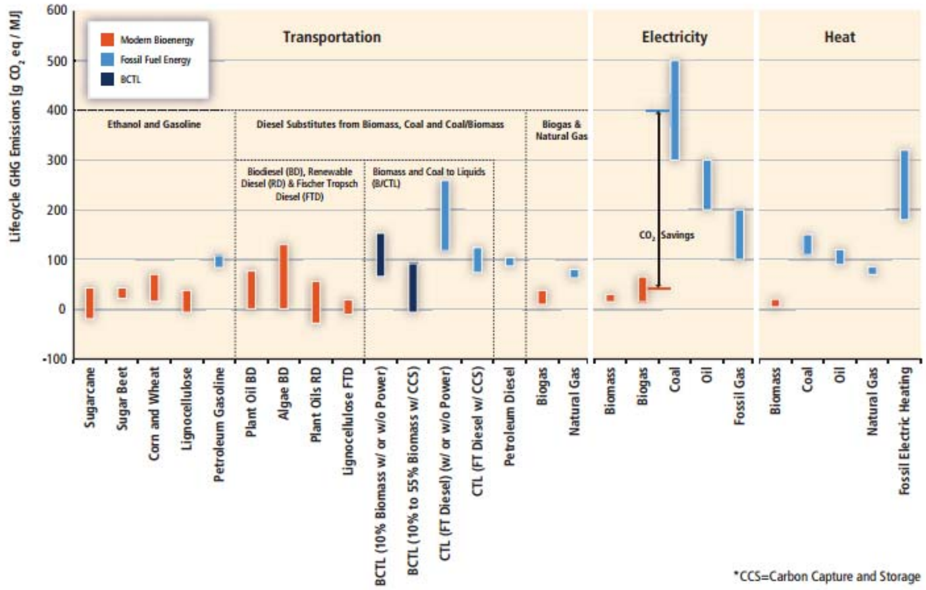


Figure 29- Ranges of GHG emissions per unit energy output (MJ) (IPCC, 2011)

		Standard step	Energy expended (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
GRSD1	**Syn diesel, remote plant, diesel mix**											
	NG Extraction & Processing	1	0.04	0.02	0.07		4.9			1.7	0.13	0.000
	GTL plant	2	0.54	0.49	0.59		13.8			13.8	0.00	0.000
	GTL transport	3	0.04				2.7			2.7	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.0			1.0	0.00	0.000
	Total pathway		0.63	0.57	0.69	0.63	22.4	19.3	25.6	19.1	0.13	0.000
GRSD2	**Syn diesel, remote plant, neat**											
	NG Extraction & Processing	1	0.04	0.02	0.07		4.9			1.7	0.13	0.000
	GTL plant	2	0.54	0.49	0.59		13.8			13.8	0.00	0.000
	GTL transport	3	0.04				2.7			2.7	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total pathway		0.63	0.59	0.69	0.63	22.5	20.1	26.0	19.2	0.13	0.000
GRSD2C	**Syn diesel, remote plant, neat, CCS**											
	NG Extraction & Processing	1	0.04	0.02	0.08		5.3			1.9	0.14	0.000
	GTL plant (CCS)	2	0.67	0.61	0.73		4.2			4.2	0.00	0.000
	GTL transport	3	0.04				2.7			2.7	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total pathway		0.76	0.71	0.82	0.76	13.3	10.5	16.6	9.7	0.14	0.000
KOSD1	**Coal EU-mix, gasifier + FT synthesis**											
	Coal provision	1	0.17				28.7			11.5	0.68	0.001
	Gasifier + FT synthesis	4	0.78				100.3			100.6	0.00	-0.001
	Syndiesel distribution & dispensing	5	0.02				1.1			1.1	0.00	0.000
	Total pathway		0.97	0.89	1.05	0.97	130.1	121.9	138.5	113.2	0.68	0.000
KOSD1C	**Coal EU-mix, gasifier + FT synthesis, CCS**											
	Coal provision	1	0.17				30.0			112.8	0.68	0.000
	Gasifier + FT synthesis + CCS	4	0.86				9.3			0.4	0.00	0.000
	Syndiesel distribution & dispensing	5	0.02				1.1			-98.0	0.22	0.001
	Total pathway		1.06	0.98	1.13	1.05	40.4	32.6	48.4	15.2	0.90	0.001
WWSD1	**Syn diesel, wood waste**											
	Waste collection and chipping	1	0.06				0.8			0.7	0.00	0.000
	Transport (road + sea)	3	0.04				2.9			2.7	0.01	0.000
	Gasifier + FT plant	4	1.08				0.0			0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.2			1.1	0.00	0.000
	Total WTT GHG emitted						4.8	4.6	5.0	4.6	0.01	0.000
	Credit for renewable combustion CO_2						-70.8			-70.8		
	Total pathway		1.19	1.09	1.30	0.07	-66.0	-66.2	-65.9			
WFSD1	**Syn diesel, farmed wood**											
	Wood farming and chipping	1	0.09				5.0			2.5	0.00	0.008
	Road transport	3	0.01				0.7			0.7	0.00	0.000
	Gasifier + FT plant	4	1.08				0.0			0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.2			1.1	0.00	0.000
	Total WTT GHG emitted						6.9	5.4	18.8	4.3	0.00	0.008
	Credit for renewable combustion CO_2						-70.8			-70.8		
	Total pathway		1.19	1.09	1.29	0.06	-64.0	-65.5	-52.1			
BLSD1	**Syn diesel, black liquor**											
	Wood collection and chipping	1	0.05				0.7			0.6	0.00	0.000
	Road transport	3	0.01				0.6			0.6	0.00	0.000
	Black liquor gasifier + FT plant	4	0.83				0.0			0.0	0.00	0.000
	Diesel distribution & dispensing	5	0.02				1.2			1.1	0.00	0.000
	Total WTT GHG emitted						2.4	2.4	2.5	2.4	0.00	0.000
	Credit for renewable combustion CO_2						-70.8			-70.8		
	Total pathway		0.91	0.85	0.97	0.04	-68.4	-68.4	-68.4			

Figure 30 - Detailed results Synthetic diesel JRC WTW Study (JRC, 2011)