Alternative Energy Fuels Analysis Support to AFRL/RZPF

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SUMMARY

The purpose of this project was to provide technical analysis support on alternative aviation fuels to the Propulsion Directorate of the Air Force Research Laboratory. The work included (i) developing process flow sheets and associated mass and energy balances for the production of Fischer-Tropsch aviation fuels, and (ii) performing technical assessments of the energy use in algae-based fuel systems, particularly examining the energy demands associated with water management. This final report is organized into two major sections, separately describing the work on Fischer-Tropsch and algae based fuels.

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1. Estimates of Greenhouse Gas Emissions Associated with Conversion of Mixed Coal and Biomass into Liquid Aviation Fuels

1.1 Overview

This work examines liquid fuels production in a coal and biomass to liquids (CBTL) facility. The boundaries for the analysis begin at the gate of the CBTL facility and end at the start of a pipeline used for the transport of carbon dioxide for enhanced oil recovery. The analysis includes production of F-T jet fuel from varying proportions of Illinois No. 6 coal and switchgrass biomass. The focus of the analysis presented here is specifically on understanding differences in greenhouse gas (GHG) emission estimates that arise from two sources:

1. **Differences in plant designs:** Transportation fuels are generally produced and blended in large pools, drawn from products made at different facilities. It is important to determine the extent to which differences in processing conditions (and feedstocks) from different facilities lead to different GHG footprints for the F-T jet fuel produced.
2. **LCA methodological choices**: Although there are a number of guidance documents and standards that constrain the methodological available for performing the life cycle emission estimates (Consoli, et al., 1993; ISO, 2006a,b), there is still significant variability in methodological practices among life cycle assessment practitioners.

Other factors than these may give rise to different GHG footprints for F-T fuels, but a detailed examination of these two primary factors helps to illustrate the challenges to creating markets for products meeting GHG emission requirements.

1.2 Modeling Approach and Data Sources

The following text provides relevant details regarding CBTL facility design, assumptions, characteristics, and data sources considered in this study.

for the CBTL Facility

Several scenarios are included in the CBTL facility, in order to capture potential variations in feedstock input scenarios, CBTL operations, and product outputs. These scenarios are summarized in **Table 1-1**.

Table 1-1: CBTL Facility Scenarios

Scenario Number	Percent Switchgrass Biomass	Percent Illinois No. 6 Coal	Catalyst	Notes
1	0%	100%	Iron	Coal feed only
2	15%	85%	Iron	Baseline scenario
3	30%	70%	Iron	High biomass scenario
4	13%	87%	Cobalt	Cobalt catalyst, similar to baseline scenario
5	13%	87%	Cobalt	Cobalt catalyst, maximize jet fuel production, minimize diesel production

Design for Gasification-Based Production of F-T Jet Fuel

Different feedstocks can be used in the production of F-T fuels. This LC stage considers coal and switchgrass biomass as the primary source materials. A variety of process configurations are possible for converting a coal, biomass, or a co-feed of coal and biomass to F-T liquids (termed coal-biomass to liquids, or *CBTL*). To illustrate, we adopt a process design (and corresponding detailed process simulation results) developed by Tarka and co-workers at NETL for our baseline case. In particular, we adopt the results of Case #7 identified in Table 2-1 of the January 2009 report by Tarka (2009). This particular design uses a co-feed of coal and biomass, and is configured to maximize production of liquid fuels to produce just enough electricity to meet on-site demands. Tarka (2009) does not present detailed mass and energy balances for this design, but he provided these details for use in the present analysis (Tarka, 2010). We refer hereinafter to this design as our baseline design.

Others have proposed plant designs that produce F-T fuels with a major exportable electricity co-product (Larson et al., 2010). The F-T fuels produced from such a power/fuels co-production facility may have a different GHG footprint from the baseline plant design considered here, but the overall approach to the assessment of GHG emissions would be similar to that discussed here. **Table 1-2** provides an overview of key assumptions.

Table 1-2: Key Assumptions for the F-T Jet Fuel CBTL Facility

Primary Subject	Assumption	Basis	Source
CBTL Facility Production Throughput (liquid products)	30,000 Barrels per Day	Assumed reasonable design flow capacity, based on feedstock requirements and study scope and planning	Basis for Study Design
Carbon Dioxide Management Strategy	Carbon Capture for subsequent sequestration and/or beneficial use	Available carbon dioxide management strategies to minimize GHG emissions	Basis for Study Design
Feedstocks Accepted by CBTL Facility	Switchgrass Biomass, Illinois No. 6 Coal	Feedstocks considered in study scope	Basis for Study Design
Products Generated by CBTL Facility	F-T Jet Fuel, Diesel (in some cases), Naphtha, Power (electricity), Carbon Dioxide	Facility design for the CBTL Facility: this suite of products would result from the CBTL process	Engineering Judgment
Fischer Tropsch Catalyst	Iron or Cobalt	Facility design includes the use of either an iron or cobalt catalyst	Basis for Study Design

Facility Design

The distinguishing features of our baseline design are 1) a liquid fuels production capacity of 30,000 barrels per day, 2) a biomass input equal to 30% (by mass) of the combined as-received coal plus biomass input, 3) and capture for storage of CO_2. **Figure 1-1** provides a simplified block diagram for this design.

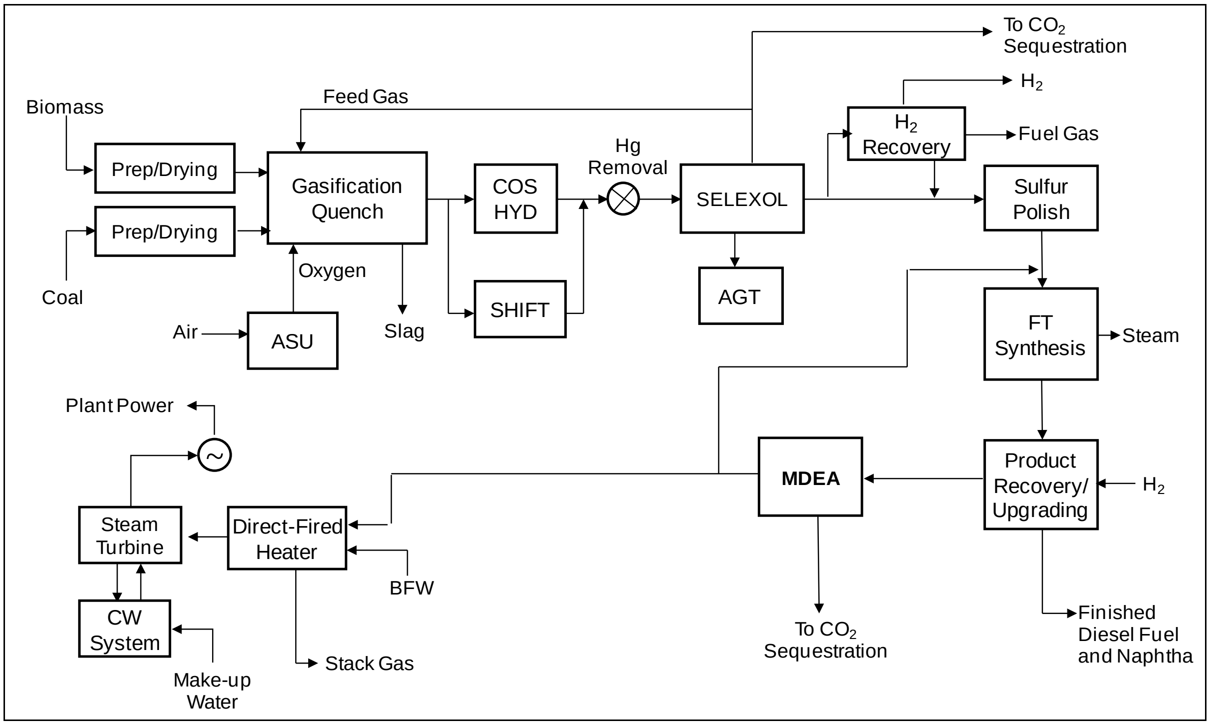

Figure 1-1: Simplified Process Diagram for the Baseline CBTL Facility System

Facility Operational Details

At the CBTL facility gate, bales of switchgrass (15% moisture by weight) arrive by truck and Illinois #6 sub-bituminous coal (11.11% moisture by weight) arrives by rail. Both feedstocks must be prepared for processing by grinding and drying. For switchgrass, a de-baler breaks up the bales into loose grass and uses waste heat from the CBTL facility to dry the biomass to a nominal 10% moisture (by weight). The biomass is then fed to the grinder to reduce its size to one millimeter or less to ensure proper feeding to the gasifier. Finally, before it is fed to the gasifier, it is dried to 5% moisture (by weight) using driers fired with fuel gases produced downstream at the CBTL facility. Coal is unloaded from rail cars and crushed/ground to a size distribution which is 17 percent less than 200 mesh, and also dried to 5% moisture (by weight). The ground and dried feedstocks are fed with oxygen (95% purity) from a conventional cryogenic air separation unit (ASU) into a Shell-type entrained flow gasifier operating at 42 bar (615 psia) pressure and 1308^{o}C (2388^{o}F). This high-temperature entrained flow gasifier design was selected by NETL engineers because high-temperature processing can ensure that tars are completely destroyed and methane production from the gasifier is minimized. Moreover, among several entrained-flow gasifiers available commercially, the Shell-type design is the only gasifier with any substantial commercial operating experience with co-firing biomass (at the Buggenum IGCC plant in the Netherlands). Ash leaves the gasifier as molten slag, and a direct contact water quench spray system is used to cool the exiting syngas. The quench also serves to remove entrained particulate matter and contaminants.

Syngas leaving the quench is split into two streams. One stream goes to a water gas shift (WGS) reactor, which shifts the ratio of H_2 to CO in the syngas via the WGS reaction: $CO + H_2O \leftrightarrow$

$CO_2 + H_2$. The syngas leaving the gasifier has a H_2:CO ratio of 0.4, whereas the downstream iron catalyst FT synthesis unit requires a value of 1 or 1.1. The impact of varied biomass usage, which affects the ratio of H_2:CO produced in the gasifier, will be examined via scenarios with 0%, 13% or 15%, and 30% of the mass fed to the gasifier consisting of biomass. Some syngas bypasses the WGS to a carbonyl sulfide (COS) hydrolysis unit that converts COS into hydrogen sulfide (H_2S), a sulfur compound that can be readily removed from the gas stream in the downstream acid gas removal (AGR) unit. (Any COS passing through the WGS is hydrolyzed by reactions in that unit.) The two streams are then re-combined and cooled before passing through activated carbon filters to remove mercury and then to a two-stage acid gas removal system (designed using a Selexol™ physical absorption system).

The Selexol™ unit selectively removes H_2S, which would otherwise poison downstream catalysts, as well as CO_2. CO_2 is removed to enable more efficient and less capital-intensive downstream syngas conversion to liquids. The pure stream of CO_2 available from the Selexol unit can be vented to the atmosphere or, as in our baseline design, dried and compressed to 150 bar (2200 psia) for pipeline transport as a supercritical fluid to an injection site for storage. The captured H_2S is fed to a Claus/SCOT system for acid gas treatment (AGT) and recovery of elemental sulfur.

The synthesis gas exiting the Selexol™ unit may still contain 1 to 2 ppmv H_2S – too high a concentration for the sulfur sensitive Fischer-Tropsch catalyst. Sulfur polishing reactors are used in which zinc oxide reacts with the H_2S to form solid zinc sulfide to reduce the H_2S concentration to less than 0.03 ppmv.

Following the AGR, hydrogen is recovered from a portion of the clean synthesis gas to be used in hydrotreating and hydrocracking in the downstream Fischer-Tropsch upgrading section. Hydrogen recovery is via membrane and pressure swing adsorption (PSA) systems.
The clean synthesis gas is finally fed to the Fischer-Tropsch (FT) synthesis unit, where it is heated and then fed to the bottom of the slurry-bed FT synthesis units operating at about 220^{o}C (428^{o}F). The gas bubbles up through a heavy liquid hydrocarbon in which the iron-based catalyst particles are suspended. Heat generated by the FT reactions is efficiently removed by steam-generation inside tubes embedded in the slurry bed. Because iron-based FT catalysts promote the WGS reaction along with the FT reactions, the syngas is only required to have an H_2:CO ratio of 1:1 to 1.1:1. This is less than that of other FT catalysts, such as cobalt, which require higher ratios of 2.1:1, as will be described below. The relatively low temperature of the base case FT reactor design helps optimize production of long-chain hydrocarbons that can be selectively hydrocracked into liquid fuels, with some fuel gas production.The raw liquid products are sent to the recovery/upgrading sub-system, where hydrogen (recovered from upstream) is used in hydrocracking and hydrotreating operations, resulting in the production of diesel, naphtha, and fuel gas. The liquid products are 70% by volume finished diesel and 30% by volume naphtha. Alternatively, the liquid products could be separated into F-T jet fuel , diesel and naphtha, as described later in this paper. As the yield and life cycle GHG emissions from the finished fuels will vary with the desired product slate, variations on the F-T plant configuration will also be examined via separate scenarios and sensitivity analyses. The F-T jet fuel contains no sulfur can be blended up to 50% by volume with petroleum-derived fuels in order to create aviation gas that

meets military specifications. The naphtha generated by the plant is suitable as a chemical or gasoline feedstock, and the diesel can be used in any diesel engine..

The F-T reactor also produces a tail gas stream containing CO_2, unreacted H_2 and CO, and light hydrocarbon gases (C_4 and below). This stream is passed through a standard methyldiethanol amine (MDEA) unit for CO_2 removal (a single CO_2 absorber and solvent regenerator), and the resulting CO_2 stream is dried and compressed to 150 bar for pipeline transport as a supercritical fluid to an injection site for storage. In combination with capture of CO_2 upstream, about 91% of the CO_2 produced at the plant is capture and stored.

Following the MDEA unit, the hydrogen-rich stream can be split into a recycle stream (with a maximum possible split about ¾ of the gas being recycled) that is returned to the F-T reactor, and a fuel gas stream. In the baseline scenario, all of this stream is used for heating, for drying the biomass and coal, and for power generation. The power island consists of a steam generator, steam turbine generator, cooling water system, and associated auxiliaries. In the base case configuration, the power unit generates just enough electricity to meet all of the plant's onsite electricity needs.

Table 1-3 summarizes the performance for this CBTL facility (Tarka, 2009). Also shown are results (Tarka,2009), for similar plant designs utilizing biomass input fractions of 0 and 15%.

Table 1-3: Characteristics of the Baseline CBTL Facility with Two Additional Feed Scenarios, (Tarka, 2009)

CBTL Facility Parameter, Iron Catalyst	Fraction of Biomass Input (% as received basis)		
	0 *	15	30
Coal input (at 100% capacity), metric t/day, as-received	11,571	10,335	8,994
Coal input, MWth HHV	3,624	3,237	2,818
Biomass input (at 100% capacity), metric t/d, as-received	0	1,824	3,855
Biomass input, MWth HHV	0	355	751
Biomass energy input (% of total HHV energy input)	0	9.9%	21%
Total liquids production rate (at 100% capacity), bbl/d	30,000	30,000	30,000
Diesel production rate, bbl/d	20,562	20,575	20,575
Diesel energy content, MWth LHV (HHV)	1,254 (1,344)	1,255 (1,345)	1,255 (1,345)
Naphtha production rate, bbl/d	9,438	9,425	9,425
Naphtha energy content, MWth LHV (HHV)	540 (579)	539 (578)	539 (578)
Power generated, MW (equals process demand**)	270.4	271.7	272.2
Total plant energy efficiency, % HHV basis	53.0	53.5	53.9
CO2 captured (at 100% capacity factor), metric t/d	14,534	14,550	14,530
CO2 emissions from plant, metric t/d	1,183	1,093	1,123
Number of gasifier trains	7	7	8
Number of FT reactor trains	6	6	6
* Scaled linearly from NETL results for 50,000 bbl/day plant. ** Process power demand included de-baling of as-received switchgrass and grinding of the biomass to 1 mm or smaller particles.			

The results shown in **Table 1-3** are for process designs that produce only diesel and naphtha as liquid products. Since the present analysis is focused on production of an F-T jet fuel, estimates have been made of how much F-T jet fuel (meeting military specifications for JP-8 fuel) might be produced if the liquid products from the upgrading section of the plant were separated into an FT jet fuel fraction, a diesel fraction, and a naphtha fraction (see **Appendix A**). The result is a volume yield of F-T jet fuel of 53% of total liquids (**Table 1-4**). This yield seems reasonable by comparison to results of de Klerk (2008), who has made a detailed estimate of 77% volumetric output fraction of jet fuel from a low-temperature F-T unit designed to maximize F-T jet fuel production. For a plant designed with motor gasoline production in mind, the F-T jet fuel fraction ranges from 37 to 61% (de Klerk, 2008).

The results shown in the right-hand column of **Table 1-4** (for 30% biomass input) correspond to our baseline F-T jet fuel production scenario. In this Table, the energy content of the product streams was calculated using group contribution methods (as described in **Appendix B)** and the modeled carbon distribution discussed in **Appendix A.** This reflects the differences in the molecular makeup of the fuel products that result from the different processing scenarios considered in this work, and allows for consistent comparisons to be made between processing scenarios.

Table 1-4: Summary Characteristics of Baseline CBTL Facility, With Adjustments to Liquid Fuel Production Estimates to Disaggregate F-T Jet Fuel Production

CBTL Facility Parameter, Iron Catalyst	**Fraction of Biomass Input (% as-received wt basis)**		
	0%*	**15%**	**30%(Baseline)**
Coal input (at 100% capacity), metric t/day, as-received	11,546	10,312	8,974
Coal input, MWth HHV	3,624	3,237	2,818
Biomass input (at 100% capacity), metric t/d, as-received	0	1,820	3,874
Biomass input, MWth HHV	0	355	751
Biomass energy input (% of total HHV energy input)	0	9.9%	21%
Total liquids production rate (at 100% capacity), bbl/d	30,000	30,000	30,000
F-T jet fuel production rate, bbl/d	15,941	15,941	15,941
F-T jet fuel energy content, MWth LHV (HHV)	984 (1056)	984 (1056)	984 (1056)
F-T Diesel production rate, bbl/d	10,765	10,765	10,765
F-T Diesel energy content, MWth LHV (HHV)	688 (739)	688 (739)	688 (739)
F-T Naphtha production rate, bbl/d	3,294	3,294	3,294
F-T Naphtha energy content, MWth LHV (HHV)	183 (197)	183 (197)	183 (197)
Power generated, MW (equals process demand)*	270.4	271.7	272.2
Total plant energy efficiency, % HHV basis	55	56	56
CO_2 captured (at 100% capacity factor), metric t/d	14,555	14,553	14,532
CO_2 emissions from plant, metric t/d	1,184	1,094	1,123
Number of gasifier trains	7	7	8
Number of F-T reactor trains	6	6	6
* Assumption is no impact on power generation or consumption with the different F-T upgrading process.			

Designs for F-T Jet Fuels Production

Table 1-3 and **Table 1-4** show how the variation in GHG emissions for different biomass input fractions. Additional alternative process designs may lead to different estimates for GHG emissions than for the baseline design as well. This section contains data for alternative scenarios for producing F-T jet fuel that explore the impact of (1) different FT synthesis catalyst, and (2) different F-T synthesis and upgrading process configurations. We briefly discuss each of these scenarios here.

To explore impacts on GHG emission estimates of a different F-T catalyst, we have developed a separate process design for F-T jet fuel production using a cobalt F-T catalyst. For this case, we used a 13% biomass input fraction. The cobalt process configuration (**Figure 1-2**) differs from the iron-based design (**Figure 1-1**) following the gasifier section. When a cobalt F-T catalyst is used, the F-T reactor produces a high molecular weight, waxy product (F-T wax) rather than the mixture of F-T wax, F-T diesel, and F-T naphtha range products that are typical of a process using an iron F-T catalyst. As with the iron catalyst case, the wax from the cobalt catalyst F-T reactor undergoes upgrading via hydrocracking and isomerization to produce lighter products. There is flexibility in choosing the process configuration within the F-T synthesis and upgrading area. It would be designed to maximize investment return for some assumed market conditions. The upgrading section design shown in **Figure 1-2**, for which details are described by Allen, et al. (2010), represents a design that might be implemented under market conditions that promote maximizing F-T jet fuel production.

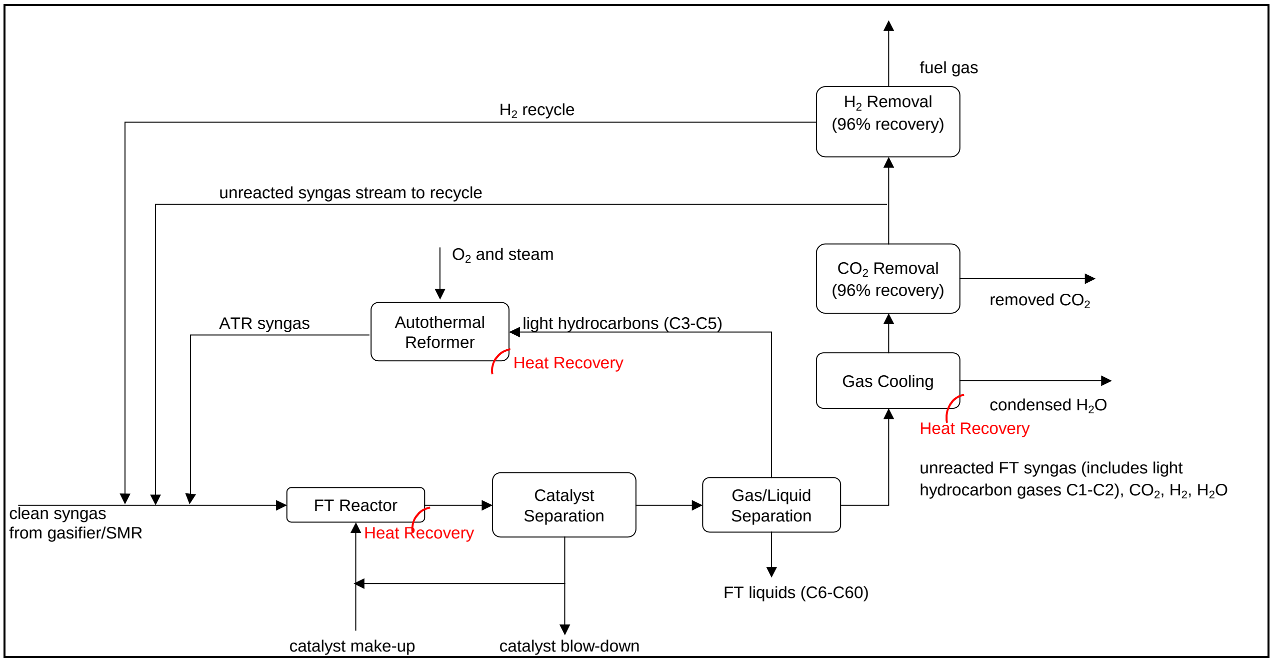

Figure 1-2: Alternative Processing Configuration for F-T Jet Fuel Bendstock Synthesis (Co-Catalyst)

To provide a consistent basis for comparison with the iron-based catalyst systems shown in **Table 1-4**, the cobalt-based systems should be designed to generate enough power onsite to meet all process power needs without any excess power for export. Detailed heat integration was not carried out as part of the design of the cobalt-based systems, but estimates of the potential steam turbine power generation using available heat and fuel-gas streams as inputs were made. Boiler feedwater pressurized to about 23 bar would be preheated to about 220^{o}C in a syngas cooler, following the water gas shift, and in a raw F-T product cooler. The heat from the exothermic F-T synthesis process would be used to evaporate the water, and the fuel gas streams available from the F-T refining area would be burned to superheat the steam. We estimate conservatively that the power output for this design would be of the order of 250 MWe. Although there are uncertainties involved in this estimate, including the assumption that the onsite power demands for a cobalt-based system design would be comparable to those for the iron-based system design (**Figure 1-1**) producing the same level of liquid fuels, we conclude that it is likely that the cobalt-based system could be designed to be energy self-sufficient, with no net power exports, if 50% of the unreacted syngas stream shown in **Figure 1-2** is recycled to the F-T reactor. Accordingly, our system design with a cobalt catalyst utilizes a 50% recycle rate.

Also, in order to provide a consistent basis for comparison with the iron-based catalyst process, the same coal and biomass feeds were applied in both cases (Switchgrass and Illinois #6). The feedstocks studied by Allen et al (2010) were slightly different from the feedstocks of the Tarka's iron-based catalyst research (2009): the mass fraction of carbon in the coal (dry basis) and the switchgrass fed to the gasifier in Allen et al (2010) were 0.73 and 0.39, respectively, while in Tarka they were 0.72 and 0.4226. It was assumed that the H_2:CO ratio and the overall CO yield in the gasifier output estimated by Allen et al (2010) for the cobalt-based catalyst study would remain constant so long as the ratio of carbon in coal to carbon in biomass remained constant. Thus, the case that is described as 15% biomass (by mass, wet basis) in Allen et al (2010) has been adjusted so that its coal and biomass inputs reflect the iron case feeds, and it is identified as 13% biomass in the descriptions of the cobalt case in this work. The values for higher heating value for the coal and biomass in the iron cases were applied to the cobalt cases as well.

The results in the column of **Table 1-5** labeled "13%" are for the overall plant performance using a cobalt F-T catalyst and producing the same product slate as in the iron catalyst case (fuel gas, naphtha, F-T jet fuel, and diesel). Overall energy efficiency is 2-3% lower than for the iron catalyst case (15% biomass in gasifier feed case in Table 1-4), although this difference is likely simply due to differences in the details of the allocation of recovered heat and the use of fuel gas. The volumetric fraction of liquid output that is F-T jet fuel is 58% for the system using the cobalt F-T catalyst versus 53% for the iron F-T catalyst. This is expected since the cobalt catalyst case study emphasized production of F-T jet fuel, while the iron catalyst study sought to maximize production of diesel.

The results in the column of **Table 1-5** labeled "13% max SPK" are for a scenario where the hydrocracker is operated such that all hydrocarbons that are heavier than jet fuel are recycled and the only products are F-T jet fuel, naphtha, and fuel gas. Such a configuration maximizes the production of F-T jet fuel and may be desirable if the market value of F-T jet fuel is sufficiently high.

As shown in **Table 1-5,** along with F-T jet fuel has 9% lower GHG emissions than the scenario where only naphtha, fuel gas, and F-T jet fuel are produced in the wax upgrading section. In addition to variations in the wax upgrading section, shown in Table 1-5, F-T jet fuel output is 36% higher with this process configuration than for the configuration where diesel is produced as well as fule gas, naphtha, and jet fuel.

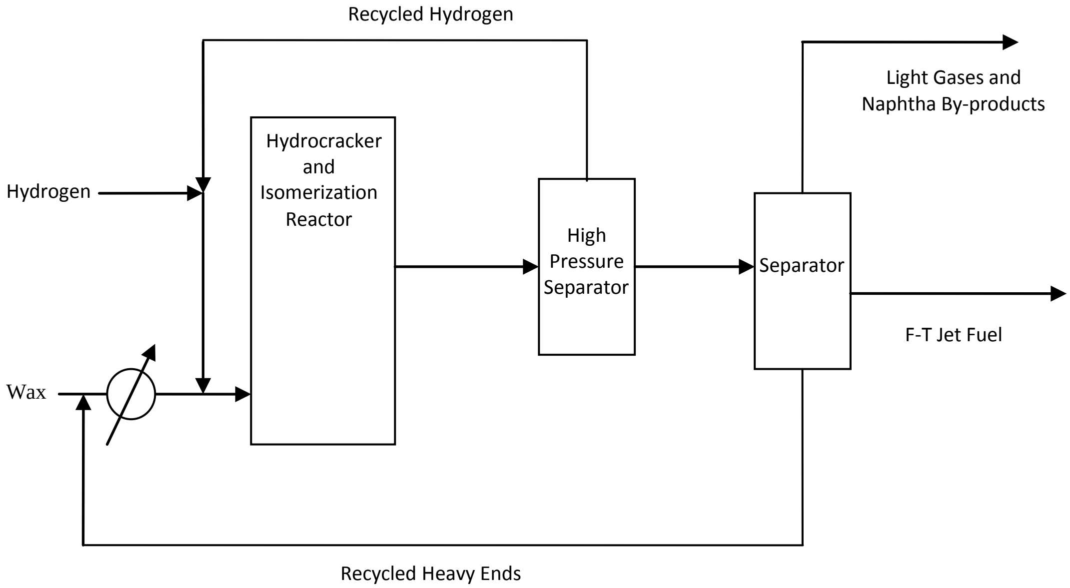

Figure 1-3: Configuration of Wax Upgrading Unit

As shown in **Table 1-5**, there are many other process configurations that could be considered. For example, different levels of unreacted syngas leaving the F-T reactor could be recycled. In the primary cobalt catalyst configuration (**Figure 1-2**), 50% of the unreacted syngas exiting the F-T reactor is recycled back to the reactor and the remainder is used to generate electricity and steam for onsite consumption. Increasing the recycle rate would decrease the amount of fuel gas available for electricity and steam production (which might require electricity and/or steam to be imported). Conversely, decreasing the recycling rate may generate excess electricity that could be exported to the grid.

Another processing scenario that could have been examined is varying the carbon number distribution of the products produced by the either the F-T iron or F-T cobalt catalyst by changing the F-T reactor conditions. A wide variety of carbon number distributions have been observed in F-T waxes (Shah et al, 1988). Examining the greenhouse gas footprints of these processing scenarios would provide additional information about the variability of the footprints depending on the details of processing configurations. These calculations were not performed since detailed data on the impact of reactor conditions on product carbon number distributions are not publicly available for commercial F-T reactors.

Table 1-5: Processing Scenarios Involving a Cobalt F-T Catalyst

CBTL Facility Parameter, Cobalt Catalyst	Fraction of Biomass Input (% as Received Basis)	
	13%	13% Max F-T Jet Fuel
Coal input (at 100% capacity), metric t/day, as-received	10,790	10,701
Coal input, MWth HHV	3.377	3,353
Biomass input (at 100% capacity), metric t/d, as-received	1,616	1,601
Biomass input, MWth HHV	315	313
Biomass energy input (% of total HHV energy input)	8.5%	8.4%
Hydrogen input, metric t/day	18	26
Hydrogen input, MWth LHV (HHV)	25 (29)	36 (42)
Total liquids production rate (at 100% capacity), bbl/d	30,000	30,000
F-T jet fuel production rate, bbl/d	17,370	23,591
F-T jet fuel energy content, MWth LHV (HHV)	1,079 (1,1159)	1,465 (1,574)
F-T Diesel production rate, bbl/d	8,303	0
F-T Diesel energy content, MWth LHV (HHV)	530 (569)	0
F-T Naphtha production rate, bbl/d	4,327	6,409
F-T Naphtha energy content, MWth LHV (HHV)	242 (261)	358 (386)
Power generated, MW (equals process demand)	-	-
Total plant energy efficiency, % HHV basis	53%	53%
CO_2 captured (at 100% capacity factor), metric t/d	14,703	14,578
CO_2e emissions from FT processing, metric t/d	1,366	1,490

Modeling Variables

The results for the operation of the CBTL facility were generated using Aspen models of the CBTL process. The output from the Aspen model runs could not be parameterized to allow greenhouse gas emissions to be correlated with specific inputs to the CBTL process. Consequently, quantitative uncertainty analyses and sensitivity analyses could not be performed for Stage 3a.

One variable was allowed to be uncertain in the evaluation of this stage, however. This variable is the amount of CO_2 captured for Enhanced Oil Recovery (EOR) per kg of F-T jet fuel produced. In **Table 1-6**, the best estimate, minimum value, maximum value, and most likely value are presented for this variable. The best estimate is based on the Aspen modeling and is around 91% of the total CO_2 generated in the CBTL process. For this analysis, it was assumed that the amount captured could be 10 percent less than the best estimate or 1 percent more than the best estimate. Since a 91% capture efficiency is already fairly high, it was assumed that it would be difficult to improve this value significantly. However, it is possible for the CO_2 capture system to perform worse than the design basis. The amount of CO_2 emitted to the atmosphere was adjusted as necessary to ensure that the total mass of CO_2 generated by the CBTL is conserved. **Table 1-6** also provides the best estimate, minimum value, maximum value, and most likely value for variables used to assess the greenhouse gas emissions form construction of the CBTL.

While the CBTL process could not be parameterized, the Aspen model was modified to determine the inputs and outputs for five different configurations of the CBTL (i.e., five different operational scenarios for the CBTL). These five scenarios allow greenhouse gas emissions for different configurations of the CBTL to be compared.

Table 1-6: Key Modeling Variables for CBTL (LC Stage #3a)

Variable Name	Units	Best Estimate	Minimum	Maximum	Most Likely	Distribution	Discussion
Input Parameters-CBTL Operation							
CO2 Captured for EOR	kg/kg F-T jet fuel	7.646	6.881	7.722	7.646	Triangular	The best estimate is from Aspen modeling. Minimum is 10 percent less than best estimate. Maximum is 1% more than best estimate.
Input Parameters-CBTL Construction							
Steel, Cold Rolled per kg F-T Jet Fuel Produced	kg/kg F-T jet fuel	2.95E-03	2.66E-03	4.43E-03	2.95E-03	Triangular	Assumes that material use is -10% to +50% of best estimate
Steel, Pipe Weld., BF (85% Rec.) per kg F-T Jet Fuel Produced	kg/kg F-T jet fuel	2.53E-04	2.28E-04	3.79E-04	2.53E-04	Triangular	Assumes that material use is -10% to +50% of best estimate
Cast Iron Parts per kg F-T Jet Fuel Produced	kg/kg F-T jet fuel	4.81E-05	4.33E-05	7.21E-05	4.81E-05	Triangular	Assumes that material use is -10% to +50% of best estimate
Aluminum Sheet per kg F-T Jet Fuel Produced	kg/kg F-T jet fuel	2.96E-05	2.66E-05	4.44E-05	2.96E-05	Triangular	Assumes that material use is -10% to +50% of best estimate
Concrete, Mixed 5-0 per kg F-T Jet Fuel Produced	kg/kg F-T jet fuel	1.66E-02	1.49E-02	2.49E-02	1.66E-02	Triangular	Assumes that material use is -10% to +50% of best estimate
Diesel Used to Install NGCC	kg/year	1.41E+06	1.26E+06	2.11E+06	1.41E+06	Triangular	Assumes that diesel use is -10% to +50% of best estimate
Construction Period for NGCC	Mo	20	18	30	20	Triangular	Assumes that construction period is -10% to +50% of best estimate
Area of 30,000 bbl/day CBTL	Acres	40	36	50	40	Triangular	Assumes that area necessary is -10% to +25% of best estimate
Fraction of Installation Inputs and Outputs Assumed to Apply to De-Installation		0.10	0.05	0.25	0.10	Triangular	Assumed based on best engineering judgment

1.3 Data Quality Assessment

The results of unit process data quality evaluation are provided in **Table 1-7**. Data quality indicators and lifecycle significance determinations are listed for each unit process included in the model.

Analysis of the lifecycle uncertainty significance of processes shows that the composite construction process for the CBTL plant is very slightly above the significance threshold for the jet fuel production lifecycle.

The operation of the CBTL facility is of significance (5.72%) in the baseline lifecycle of jet fuel. Because quality scores for source reliability and completeness are low for the CBTL facility operation, a detailed explanation of quality indicator choices is provided in **Table 1-8**.

Table 1-7: Unit Process DQI and Significance Check

Process Level	Unit Process	DQI	Lifecycle Significance of Process (%)
1	Coal and Biomass to Liquid Facility, Operation	4,4,2,2,3	5.72%
1	Coal and Biomass to Liquid Facility, Construction	2,2,3,2,3	0.12%

Table 1-8: LC Stage #3a Qualitative Assessment of Data Quality

Quality Metric	Qualitative Assessment of Stage-Level Data Quality
Source Reliability	SCORE varies from 1-4; a variety of data sources were used. This part of the assessment was done using process models that ensured mass and energy balances. However, since there are a limited number of commercial FT units in existence with an even more limited number of commercial cobalt catalyst FT units, important variables, such as yields of liquid fuels from synthesis gas, were in many cases estimated based on best available data and/or expert opinion and/or personal communication. Wax characterization assumed for the cobalt-catalyst FT reactor was based on a wax produced in a bench scale reactor. There were no detailed wax characterization data for the iron catalyst FT reactor and it was assumed to match the profile of known iron catalyst waxes. Data sources for gasifier yields and synthesis gas compositions were more readily available and are expected to be more robust than those used for the FT columns. The data are primarily secondary in nature. Data were expected to represent an industry average except that the coal fed to the gasifier was specifically Illinois #6. Primary Data: Primary data (data directly from industrial scale integrated gasifiers and FT synthesis processes) were not available. Analyses were based on process simulations, based on secondary data. Secondary Data: Tarka, Thomas J. “Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass”, prepared for the Department of Energy, National Energy Technology Laboratory, 2009 available at: http://www.netl.doe.gov/energy-analyses/pubs/CBTL%20Final%20Report.pdf- Process design/configuration and characteristics for baseline CBTL facility, characteristics of coal and biomass feedstocks Allen, et al., 2010: Allen, D.T., Murphy, C., Rosselot, K.S., Watson, S., Miller, J., Ingham, J., and Corbett, W. “Characterizing the Greenhouse Gas Footprints of Aviation Fuels from Fischer-Tropsch Processing”, Final report from the University of Texas to the University

	of Dayton Research Institute, Agreement No. RSC09006, February 9, 2010: Process configuration for FT processing with a cobalt catalyst Shah, PP, GC Sturtevant, JH Gregor, MJ Humbach, FG Padrta, KZ Steigleder. Fisher-Tropsch wax characterization and upgrading, final report. US Department of Energy. Available through NTIS DE88014638. June 6, 1988.– characterization of iron catalyst wax, verification of hydrocracker model
Completeness	SCORE varies 1-4 No attempt was made to assess the statistical representativeness of the yield and product data for the gasifier and FT reactor process units. Data for commercial processes tend to be prioprietary and when they are published reflect the performance of a single production unit operating under a specific set of conditions. Process configurations in ASPENand other modeling tools included complete mass balances of all of the species. When calculating GHG emission estimates, it was assumed that combustion would be complete and the only carbon-containing combustion product would be CO_2.
Temporal Representativeness	SCORE 2 Secondary data collection for this assessment focused on finding the most recent data available in literature sources. Most sources are recent (<5 years old), with Shah et al (1988) being an exception. Shah et al (1988) was the only source of detailed wax and hydrocracker product characterization available. Tarka (2009) is a recent publication but relies on data that was collected over multiple years. The data found are expected to be representative of current conditions for at least some plants in use today.
Geographical Representativeness	SCORE 2 Greenhouse gas emissions for the average US electrical generation grid were applied in the sensitivity analysis. The coal fed to the gasifiers was assumed to be Illinois #6. Otherwise data represent global industry standards.
Technological Representativeness	SCORE 1 to 3 Processing for the conversion of coal and biomass co-feeds to FT liquids is relatively recent, however, FT processing has been used in industrial settings since the 1940s. Even though the process is relatively mature, there are very few commercial installations, so industrial scale data are sparse. The technology assumed for the gasifier was based on the largest gasification unit using a coal biomass co-feed, which is used in an IGCC application. FT processing was based on the current implementation of iron catalyst FT chemistry, with adjustments made to reflect the use of a cobalt catalyst where appropriate.

1.4 Results

This section presents the life cycle greenhouse gas emissions estimates. Quantitative uncertainty analyses were not performed because only one operational parameter, the amount of CO_2 captured in the gasification process was allowed to be uncertain. However, five scenarios reflecting different operating configurations for the CBTL were examined allowing deterministic greenhouse gas emissions from the different scenarios to be compared. A sensitivity analysis was performed on Scenario 2 to examine the influence of construction inputs on the calculated greenhouse gas emissions.

Greenhouse Gas Emissions

Scenarios 1 through 3 involve the use on an iron catalyst with a feedstock comprised of 100% coal for Scenario 1, 85% coal and 15% switchgrass by mass for Scenario 2 and 70% coal and 30% switchgrass by mass for Scenario 3. Scenarios 4 and 5 involve the use on a cobalt catalyst with a feedstock comprised of 87% coal and 13% switchgrass by mass. In Scenario 4, F-T diesel is generated as well as F-T jet fuel and F-T naphtha. In Scenario 5, the process is configured to maximize the production of F-T jet fuel, which reduces the production of F-T diesel.
Table 1-9 through **Table 1-13** present the lifecycle greenhouse gas emissions for Scenarios 1 through 5, respectively. In these tables, the greenhouse gas emissions are presented in terms of

the reference flow for this stage, which is 1 kg of F-T jet fuel ready for transport from the CBTL. These tables present the total emissions of 1) non-biogenic carbon dioxide from operation and construction, 2) biogenic carbon dioxide from operation and construction, 3) methane from operation and construction, 4) nitrous oxide from operation and construction and 5) other greenhouse gases from operation and construction. This last category, other greenhouse gases, captures emissions from greenhouse gases other than carbon dioxide, methane or nitrous oxide, or emissions that are expressed in carbon dioxide equivalents, and cannot be differentiated into the primary greenhouse gases. The second column in these tables presents the actual mass of each constituent emitted. The third through fifth columns present the emissions of each constituent in carbon dioxide equivalents using the global warming potentials for each constituent based on the IPCC 2007, IPCC 2001 and IPCC 1996 estimates, respectively.

The total CO_2e emissions are highest for Scenarios 1 (0% switchgrass, iron catalyst—770 g CO_2e/kg) and 4 (13% switchgrass, cobalt catalyst, normal F-T jet production—760 g CO_2e/kg). The next highest CO_2e emissions are for Scenario 2 (15% switchgrass, iron catalyst—720 g CO_2e/kg), followed by Scenario 5 (13% switchgrass, cobalt catalyst, maximize F-T jet production—630 g CO_2e/kg) and Scenario 3 (30% switchgrass, iron catalyst—600 g CO_2e/kg).

As indicated in **Table 1-9** through **Table 1-13**, operation of the CBTL contributes far more to life cycle greenhouse gas emissions than do construction activities. Operations account for about 98% or more of the total life cycle greenhouse gas emissions for LC Stage 3a, for all study scenarios. The emissions of methane and nitrous oxide are negligible compared to the emissions of non-biogenic CO_2. There are no emissions of biogenic carbon dioxide or the "other GHG" categories in this process.

Table 1-9: Scenario 1 (100% Coal, Iron Catalyst) GHG Emissions (per kg F-T Jet Fuel Ready for Transport)

Greenhouse Gas (GHG)	Mass of GHG Emitted to Atmosphere (g/kg F-T Jet Fuel)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2007 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2001 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 1996 GWP)
Non-biogenic CO_2 – Operation	760	760	760	760
Non-biogenic CO_2 – Construction	12	12	12	12
Non-biogenic CO_2 – Subtotal	770	770	770	770
Biogenic CO_2 – Operation	0.0	0.0	0.0	0.0
Biogenic CO_2 – Construction	0.0	0.0	0.0	0.0
Biogenic CO_2 – Subtotal	0.0	0.0	0.0	0.0
CH_4 – Operation	0.00	0.0	0.0	0.0
CH_4 – Construction	0.00	0.1	0.1	0.1
CH_4 – Subtotal	0.00	0.1	0.1	0.1
N_2O – Operation	0.000	0.0	0.0	0.0
N_2O – Construction	0.001	0.2	0.2	0.2
N_2O – Subtotal	0.001	0.2	0.2	0.2
Other GHG – Operation		0.0	0.0	0.0
Other GHG – Construction		0.0	0.0	0.0
Other GHG – Subtotal		0.0	0.0	0.0
Operation – Total		760	760	760
Construction– Total		12	12	12
Grand Total		770	770	770

Table 1-10: Scenario 2 (15% Switchgrass, Iron Catalyst) GHG Emissions (per kg F-T Jet Fuel Ready for Transport)

Greenhouse Gas (GHG)	Mass of GHG Emitted to Atmosphere (g/kg F-T Jet Fuel)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2007 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2001 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 1996 GWP)
Non-biogenic CO_2 – Operation	700	700	700	700
Non-biogenic CO_2 – Construction	12	12	12	12
Non-biogenic CO_2 – Subtotal	720	720	720	720
Biogenic CO_2 – Operation	0.0	0.0	0.0	0.0
Biogenic CO_2 – Construction	0.0	0.0	0.0	0.0
Biogenic CO_2 – Subtotal	0.0	0.0	0.0	0.0
CH_4 – Operation	0.00	0.0	0.0	0.0
CH_4 – Construction	0.00	0.1	0.1	0.1
CH_4 – Subtotal	0.00	0.1	0.1	0.1
N_2O – Operation	0.000	0.0	0.0	0.0
N_2O – Construction	0.001	0.2	0.2	0.2
N_2O – Subtotal	0.001	0.2	0.2	0.2
Other GHG – Operation		0.0	0.0	0.0
Other GHG – Construction		0.0	0.0	0.0
Other GHG – Subtotal		0.0	0.0	0.0
Operation – Total		700	700	700
Construction– Total		12	12	12
Grand Total		720	720	720

Table 1-11: Scenario 3 (30% Switchgrass, Iron Catalyst) GHG Emissions (per kg F-T Jet Fuel Ready for Transport)

Greenhouse Gas (GHG)	Mass of GHG Emitted to Atmosphere (g/kg F-T Jet Fuel)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2007 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2001 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 1996 GWP)
Non-biogenic CO_2 – Operation	590	590	590	590
Non-biogenic CO_2 – Construction	12	12	12	12
Non-biogenic CO_2 – Subtotal	600	600	600	600
Biogenic CO_2 – Operation	0.0	0.0	0.0	0.0
Biogenic CO_2 – Construction	0.0	0.0	0.0	0.0
Biogenic CO_2 – Subtotal	0.0	0.0	0.0	0.0
CH_4 – Operation	0.00	0.0	0.0	0.0
CH_4 – Construction	0.00	0.1	0.1	0.1
CH_4 – Subtotal	0.00	0.1	0.1	0.1
N_2O – Operation	0.000	0.0	0.0	0.0
N_2O – Construction	0.001	0.2	0.2	0.2
N_2O – Subtotal	0.001	0.2	0.2	0.2
Other GHG – Operation		0.0	0.0	0.0
Other GHG – Construction		0.0	0.0	0.0
Other GHG – Subtotal		0.0	0.0	0.0
Operation – Total		590	590	590
Construction– Total		12.0	12.0	12
Grand Total		600	600	600

Table 1-12: Scenario 4 (13% Switchgrass, Cobalt Catalyst) GHG Emissions (per kg F-T Jet Fuel Ready for Transport)

Greenhouse Gas (GHG)	Mass of GHG Emitted to Atmosphere (g/kg F-T Jet Fuel)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2007 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2001 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 1996 GWP)
Non-biogenic CO_2 – Operation	750	750	750	750
Non-biogenic CO_2 – Construction	11	11	11	11
Non-biogenic CO_2 – Subtotal	760	760	760	760
Biogenic CO_2 – Operation	0.0	0.0	0.0	0.0
Biogenic CO_2 – Construction	0.0	0.0	0.0	0.0
Biogenic CO_2 – Subtotal	0.0	0.0	0.0	0.0
CH_4 – Operation	0.00	0.0	0.0	0.0
CH_4 – Construction	0.00	0.1	0.1	0.1
CH_4 – Subtotal	0.00	0.1	0.1	0.1
N_2O – Operation	0.000	0.1	0.1	0.2
N_2O – Construction	0.001	0.2	0.2	0.2
N_2O – Subtotal	0.001	0.3	0.3	0.3
Other GHG – Operation		0.0	0.0	0.0
Other GHG – Construction		0.0	0.0	0.0
Other GHG – Subtotal		0.0	0.0	0.0
Operation – Total		750	750	750
Construction– Total		11	11	11
Grand Total		760	760	760

Table 1-13: Scenario 5 (13% Switchgrass, Cobalt Catalyst, Maximize F-T Jet Fuel) GHG Emissions (per kg F-T Jet Fuel Ready for Transport)

Greenhouse Gas (GHG)	Mass of GHG Emitted to Atmosphere (g/kg F-T Jet Fuel)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2007 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 2001 GWP)	Mass of GHG Emitted to Atmosphere (g CO_2e/kg F-T Jet Fuel) (IPCC 1996 GWP)
Non-biogenic CO_2 – Operation	620	620	620	620
Non-biogenic CO_2 – Construction	8.2	8.2	8.2	8.2
Non-biogenic CO_2 – Subtotal	630	630	630	630
Biogenic CO_2 – Operation	0.0	0.0	0.0	0.0
Biogenic CO_2 – Construction	0.0	0.0	0.0	0.0
Biogenic CO_2 – Subtotal	0.0	0.0	0.0	0.0
CH_4 – Operation	0.00	0.0	0.0	0.0
CH_4 – Construction	0.00	0.1	0.1	0.1
CH_4 – Subtotal	0.00	0.1	0.1	0.1
N_2O – Operation	0.001	0.2	0.2	0.2
N_2O – Construction	0.000	0.1	0.1	0.1
N_2O – Subtotal	0.001	0.3	0.3	0.3
Other GHG – Operation		0.0	0.0	0.0
Other GHG – Construction		0.0	0.0	0.0
Other GHG – Subtotal		0.0	0.0	0.0
Operation – Total		620	620	620
Construction– Total		8.3	8.3	8.3
Grand Total		630	630	630

Analysis

To determine the influence of the key variables in **Table 1-6** on the calculated CO2e emissions, a sensitivity analysis was performed. The sensitivity analysis was performed on Scenario 2 (the baseline scenario for the study). In the sensitivity analysis, the total CO_2e emission using the IPCC 2007 global warming potentials was calculated for each key variable in **Table 1-6**. **Table 1-14** presents the key variables, their best estimate, their minimum value, their maximum value, and associated minimum and maximum total CO_2e emissions. The Absolute Difference for each key variable is also shown, and key variables are listed from highest to lowest based on their Absolute Difference.

The only variable that influences the total CO_2e emissions is the “amount of CO_2 captured for EOR”. All other key variables have a negligible influence on total CO_2e emissions.

Table 1-14: Sensitivity Analysis Results for Total CO_2e Emissions (Using IPCC 2007 GWP) (g CO_2e/kg F-T Jet Fuel Ready for Transport)

Variable Name	Variable Symbol	Units	Input Values			Results: CO_2e Emissions (g CO_2e/kg F-T jet fuel)		
			Best Estimate	Minimum	Maximum	Minimum	Maximum	Abs. Diff.
CO2 Captured for EOR	CO2_cap	kg/kg F-T jet fuel	7.65	6.88	7.72	1,500	640	840
Steel, Cold Rolled per kg F-T Jet Fuel Produced	Stl_Croll_kg	kg/kg F-T jet fuel	2.95E-03	2.66E-03	4.43E-03	720	720	5.0
Concrete, Mixed 5-0 per kg F-T Jet Fuel Produced	Concrete_5_0_kg	kg/kg F-T jet fuel	1.66E-02	1.49E-02	2.49E-02	720	720	1.4
Construction Period for NGCC	Con_Per_NGCC	mo	20	18	30	720	720	8.00E-01
Diesel Used to Install NGCC	Dies_InstNGCC	kg/year	1.41E+06	1.26E+06	2.11E+06	720	720	8.00E-01
Area of 30,000 bbl/day CBTL	Area_CBTL	acres	40	36	50	720	720	4.70E-01
Fraction of Installation Inputs and Outputs Assumed to Apply to De-Installation	DeIn_Frac		0.1	0.05	0.25	720	720	2.40E-01
Steel, Pipe Weld., BF (85% Rec.) per kg F-T Jet Fuel Produced	Stl_Pipe_BF85_kg	kg/kg F-T jet fuel	2.53E-04	2.28E-04	3.79E-04	720	720	1.70E-01
Cast Iron Parts per kg F-T Jet Fuel Produced	Cst_Iron_Pt1_kg	kg/kg F-T jet fuel	4.81E-05	4.33E-05	7.21E-05	720	720	3.00E-02
Aluminum Sheet per kg F-T Jet Fuel Produced	AlumSht1_kg	kg/kg F-T jet fuel	2.96E-05	2.66E-05	4.44E-05	720	720	1.30E-02

1.5 References

Allen, et al., 2010: Allen, D.T., Murphy, C., Rosselot, K.S., Watson, S., Miller, J., Ingham, J., and Corbett, W. "Characterizing the Greenhouse Gas Footprints of Aviation Fuels from Fischer-Tropsch Processing", Final report from the University of Texas to the University of Dayton Research Institute, Agreement No. RSC09006, February 9, 2010

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Tarka, T., 2009: Tarka, T. "Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass," DOE/NETL-2009/1349, National Energy Technology Laboratory, 14 January 2009.

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APPENDIX 1.A: CALCULATING THE F-T JET FUEL PRODUCT PORTION FROM AN IRON CATALYST CBTL PROCESS

A life-cycle assessment of the greenhouse gas emissions of diesel produced from a Coal and Biomass to Liquids (CBTL) process using an iron-catalyst F-T column is provided in "Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass" (Tarka, 2009). The products in that analysis are naphtha and diesel, with no F-T jet fuel cut. In order to compare the results of another CBTL analysis with a cobalt-catalyst F-T reactor (Allen et al, 2010), the amount of F-T jet fuel produced in the iron-catalyst case was needed. This Appendix describes how the amount of F-T jet fuel produced in the iron-catalyst case was calculated.
In order to find the portion of naphtha and diesel that could be considered to be F-T jet fuel, knowledge of the composition of the streams is needed. F-T jet fuel must meet military specs for a range of distillation cuts. In a personal communication, Tarka (2010a) provided a carbon number distribution for the output of the F-T column. This carbon number distribution could be related to the modeled output for Case 7 of the report in a separately provided personal communication (Tarka, 2010b).

To determine which products to place in the F-T jet fuel cut, a group contribution method was used to estimate the boiling points for points of the components in the stream that were not experimentally available (Allen, et al., 2010).

Determining the amount of F-T jet fuel in the straight run products (C5-C18) from the F-T reactor was straightforward. The beginning and ending boiling point values were selected so that the stream meets the military specifications for jet fuel (DoD, 2008), as shown in the Table below:

Table 1.A-1: F-T Jet Fuel from Straight Run Product Stream of Iron-Catalyst F-T Reactor

Boiling Point, (Degrees C)	% of Straight Run Products	Cumulative % of F-T Jet Fuel Portion of Straight Run Products	Milspec
230-296	48.0	100.0%	must be at least 90%
206-229	13.3	51.3%	must be at least 50%
184-205	13.6	37.8%	must be at least 10%
169-183	7.2	24.0%	must be less than 90%
158-168	7.3	16.8%	must be less than 50%
130-157	9.3	9.4%	must be less than 10%

Of the straight run products, 98.6% are F-T jet fuel, 0.5% are naphtha, and 1% are diesel. The total straight run flow rate is 37,200 lb/hr, so the naphtha flow rate is 176 lb/hr, the F-T jet fuel flow rate is 36,600 lb/hr, and the diesel flow rate is 358 lb/hr.

The carbon number distribution of the diesel and naphtha output of the hydrocracker was not provided and had to be estimated. All that is known about the wax is that it is 3.2 wt % C19-C24 and the remainder C25+. The fraction of the wax in various carbon numbers has been observed to fit a sigmoidal distribution; a component distribution with μ of 3.51 and σ of 0.17 was used. A distribution of products from the hydrocracker was developed using the hydrocracker model described in Allen et al, 2010. While this model is known to underestimate the production of fuel gas, the modeled distribution compares favorably to the distribution of the products reported from the hydrocracker by Tarka in a personal communication (2010a,b), as shown in **Figure 1.A-1** below:

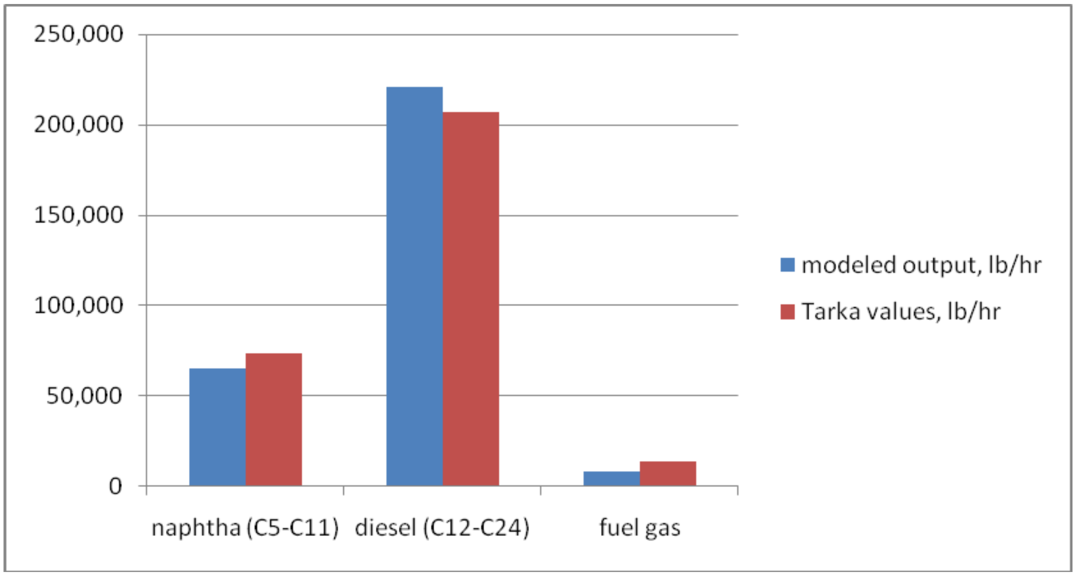

Figure 1.A-1: Modeled Output and Tarka Values for Naphtha, Diesel, and Fuel Gas

Note that the cuts reported by Tarka (2010a,b) were based on carbon number, not boiling point. The values in the figure above are reported based on carbon number for both the modeled case and from Tarka (2009, 2010a,b).

The beginning and ending cuts of the modeled F-T jet fuel stream from the hydrocracker were selected so that the F-T jet fuel stream meets the military specifications for distillation cuts. The stream exhibits the following profile:

Table 1.A-2: F-T Jet Fuel from Hydrocracker Product Stream for Iron-Catalyst F-T Reactor

Boiling Point, (Degrees C)	% of Hydrocracker Output	Cumulative % of F-T Jet Fuel Portion of Hydrocracker Output	Milspec
263-267	3.2	n/a	n/a
230-262	14.1	92.9%	must be at least 90%
206-229	7.7	61.8%	must be at least 50%
184-205	8.0	45.0%	must be at least 10%
169-183	3.6	27.4%	must be less than 90%
158-168	4.5	19.5%	must be less than 50%
130-157	4.4	9.6%	must be less than 10%

The modeled hydrocracker products are 2.8% fuel gas, 10.8% naphtha, 45.5% F-T jet fuel, and 40.9% diesel (mass basis). Because production of fuel gas is underestimated by the model, it is recommended that Tarka's (2009, 2010a,b) value for fuel gas production be used and the remaining products apportioned according to the modeled values. The total output of the hydrocracker is 295,000 lb/hr, so the output of products from the hydrocracker when F-T jet fuel is included as a product is 14,100 lb/hr fuel gas, 31,100 lb/hr naphtha, 132,000 lb/hr jet fuel, and 118,000 lb/hr diesel. The combined flow rates of straight run product from the FT reactor and upgraded wax from the FT reactor are given below.

Table 1.A-3: Combined Flow Rates of Straight Run Product and Upgraded Wax from the F-T Reactor

Stream	Straight Run Output (lb/hr)	Upgraded Wax Output (lb/hr)	Total (lb/hr)
fuel gas	n/a	14,099	14,099
naphtha	176	31,119	31,295
F-T jet fuel	36,638	131,593	168,232
diesel	358	118,224	118,582
total	37,172	295,035	332,207

Appendix 1.A. References

Allen, et al., 2010: Allen, D.T., Murphy, C., Rosselot, K.S., Watson, S., Miller, J., Ingham, J., and Corbett, W. “Characterizing the Greenhouse Gas Footprints of Aviation Fuels from Fischer-Tropsch Processing”, Final report from the University of Texas to the University of Dayton Research Institute, Agreement No. RSC09006, February 9, 2010

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U.S. Department of Defense (DoD). Detail specification: turbine fuel, aviation, kerosene type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37). MIL-DTL-83133F. 11 April 2008.

APPENDIX 1.B: ENERGY CONTENT AND COMBUSTION EMISSIONS OF F-T CBTL FUELS

The heats of combustion for the diesel and F-Tjet fuel streams were estimated based on group contribution methods developed by the Department of Transportation/Federal Aviation Administration (DOT/FAA, 2001). This report provides group contributions for the heats of combustion (higher heating value) for each of the three functional groups in diesel and F-T jet fuel made from upgraded wax:

- -CH3 775 kJ/mol
- -CH2- 670 kJ/mol
- -CH< 518 kJ/mol

In the iron catalyst case, the liquid stream from the FT reactor is largely in the F-T jet fuel range, but contains many olefinic compounds. It was assumed that these alkenes were straight chain with one olefinic bond per molecule. The group contribution of the higher heating value of this structural group (>C=C<) is 781 kJ/mol

The group contribution for the higher heating value of hydrogen is

- -H 190 kJ/mol

LHVs were calculated using the following relationship (DOT/FAA, 1998):

$$\text{LHV (kJ/g)} = \text{HHV (kJ/g)} - 21.96 \text{ (weight fraction hydrogen)}$$

The LHV of the iron catalyst case F-T jet fuel was estimated to be 44.7 MJ/kg and its carbon fraction is 0.850. If all the carbon in this F-T jet fuel is converted to CO2 during combustion, the GHG emissions on an energy basis are

$$(0.850 \text{ kg carbon/kg F-T jet fuel})\times(44 \text{ kg } CO_2/12 \text{ kg C})/(44.67 \text{ MJ/kgF-T jet fuel})$$
$$= 69.8 \text{ g } CO_2/\text{MJ}.$$

For the 13% cobalt catalyst case where diesel is a co-product, this value is

$$(0.848 \text{ kg carbon/kg F-T jet fuel})\times(44 \text{ kg } CO_2/12 \text{ kg C})/(44.80 \text{ MJ/kgF-T jet fuel})$$
$$= 69.4 \text{ g } CO_2/\text{MJ},$$

and for the 13% cobalt case where production of F-T jet fuel is maximized, this value is

$$(0.848 \text{ kg carbon/kg F-T jet fuel})\times(44 \text{ kg } CO_2/12 \text{ kg C})/(44.74 \text{ MJ/kgF-T jet fuel})$$
$$= 69.5 \text{ g } CO_2/\text{MJ},$$

Appendix 1.B References

U.S Department of Transportation/Federal Aviation Administration, Molar Group Contributions to the Heat of Combustion, DOT/FAA/AR-TN01/75, September 2001.

U.S Department of Transportation/Federal Aviation Administration, Heats of Combustion of High Temperature Polymers, DOT/FAA/AR-TN97/8, September 1998.

2. ENERGY BURDENS ASSOCIATED WITH WATER MANAGEMENT IN ALGAE PRODUCTION

2.1 Overview

Microalgae are a potential feedstock for the production of transportation fuels. This work addresses the energy needed to manage the water used in the mass cultivation of saline, eukaryotic algae grown in open pond systems. Estimates of both the direct and upstream energy requirements for obtaining, containing, and circulating water within algae cultivation systems are developed. Potential productivities are calculated for each of the 48 states within the continental US based on theoretical photosynthetic efficiencies, growing season, and total available land area. Energy output in the form of algal biodiesel is compared to total energy inputs required for water management. The analysis indicates that, for current technologies, energy required for water management is seven times greater than energy output in the form of algal biodiesel. While this analysis addresses only known species grown in an open-pond system, the water management requirements of any algae system will be substantial; therefore, it is critical that an energy assessment of water management requirements be performed for any technology system and algal type in order to fully understand the energy balance of algae-derived biofuels.

2.2 Introduction

Microalgae are a potential feedstock for the production of transportation fuels. While there is considerable interest in developing algae technology (Mascarelli, 2009), there are also significant technical challenges and concerns as to whether the energy balance for algae-based fuel production is positive from a life cycle perspective. Of particular concern is the need to provide substantial amounts of water and nutrients to populations of algae undergoing mass-cultivation (Lardon *et al*., 2009, Clarens *et al* l., 2010). Lardon *et al.* (2009) determined that algae grown under nutrient-replete conditions and subjected to dry oil extraction processes have a negative energy balance. Clarens *et al.* (2010) note that the cultivation phase dominates the life cycle of fuel production from algae and recommend that algae ponds be developed in conjunction with waste water treatment operations. Clarens *et al.* (2010) also conclude that, with the exception of land use and eutrophication potential, other biofuel crops have smaller environmental footprints than algae. None of the comprehensive life cycle assessments of algae-based fuels completed to date, however, have addressed another important aspect of algae cultivation, which is the energy needed to manage the large amounts of water associated with high-rate biomass production. This work addresses both direct and upstream energy required to obtain, contain, and circulate water between operations within the cultivation system. Only open raceway pond operations are assessed here, as they are currently the best understood and described technology. As new cultivation systems (such as enclosed photo bioreactors) are developed and better defined, similar analyses should be performed in order to accurately assess the energy balances of these alternative approaches.

Mass cultivation of algae is not new; the first interest occurred during World War II, when these organisms were investigated as a potential source of a number of products including antibiotics and food. In the late 1940's and early 1950's, the Carnegie Institution of Washington sponsored construction of a pilot plant and supplemental laboratory studies. This work is summarized in a report that continues to be a valuable source of information with respect to algae cultivation (Burlew, 1953). Commercial systems designed to produce algae for human consumption were developed in Japan in the 1960's. Microalgae also have a significant role in waste water treatment plants, although in general, the algae are not harvested (Benemann and Oswald, 1996). The concept of cultivating microalgae for conversion to fuel (biogas, rather than biodiesel) was first suggested by Meier in the early 1950's. Between 1978 and 1996, the US Department of Energy (DOE), funded a program to develop fuels from algae through the Solar Energy Research Institute (SERI), which in 1991, became the National Renewable Energy Laboratory (NREL). This effort, known as the Aquatic Species Program (ASP), focused on production of biodiesel from naturally occurring oils within algae and is summarized in a document entitled "A Look Back at the U.S. Department of Energy's Biodiesel from Algae" (Sheehan, *et al*., 1998). In addition to the summary report, there are approximately 30 detailed individual reports that provide a wealth of publicly available data; these reports significantly inform the analysis presented here.

Algae require considerable amounts of water in order to grow and thrive. The organisms themselves are typically 80 to 85% water (Burlew, 1953) and the photosynthetic process results in the dissociation of roughly one mole of water per mole of CO_2 (Williams and Laurens, 2010). This means that approximately 5 to 10 kg of water are "consumed" per kg of dry algae biomass produced. In addition to water incorporated within the cell, most algae grow and reproduce in aqueous suspension. When algae blooms are observed, it appears that there are copious amounts of biomass; indeed a thin suspension of *Chlorella* contains 2×10^{10} individual cells per liter of water (Burlew, 1953). However, the percentage of suspended solids is actually quite low, typically less than 0.5% wet biomass (0.1% dry). Thus for every gram of dry algae biomass generated, more than a kilogram of non-cellular water is required to produce and support it.

Water not only provides a physical environment in which the algae live and reproduce, it also delivers nutrients, removes waste products, and acts as a thermal regulator. Unlike natural environments, mass cultivation systems require that the water be acquired, contained, circulated, and pumped to and between desired locations. All of these activities entail inputs of energy, both direct and indirect, and the amount of energy expended is tightly coupled to the volume of water involved. The volume of water involved depends upon system geometries, losses from the system, and most importantly, the ability to reclaim and reuse water. The latter is affected by the efficiency of the separation process(s), the quality of the return water, and the sensitivity of the specific culture to changes and/or impurities in the return water, including waste products introduced by the algae themselves.

The analysis presented in this work evaluates autotrophic, saline, eukaryotic microalgae grown in a semi-continuous manner. Saline systems are, in general, considered preferable to freshwater systems because they minimize diversion of freshwater from other critical applications such as human consumption and conventional irrigation. Eukaryotic algae typically contain more lipids than prokaryotic (blue-green) algae (Williams and Laurens, 2010), which is critical for biodiesel or biojet feedstocks. At the scale required for significant fuel production, autotrophic mass-cultivation systems must be located outdoors where they are subjected to diurnal cycles of light and temperature; therefore, continuous systems, which require steady-state conditions, are not practical. Semi-continuous rather than batch systems are considered here, as this allows the algae to be harvested on the exponential portion of the growth curve, thereby increasing biomass productivity for a given area and time. The focus is on open raceway pond systems, as demonstrated and described in the SERI reports (e.g., Weissman, *et al*., 1989; Weissman and Goebel, 1987; Neenan. *et a*l., 1986). These systems were demonstrated at relatively large scale, over extended periods of time, and there are significant amounts of publicly available data. Enclosed systems are of interest, but have a number of challenges associated with them including identifying the optimum shape, overcoming light attenuation, controlling temperature, and maintaining levels and distribution of both desirable and undesirable constituents (e.g, Molina, *et al*., 2001; Posten, 2009; Carvalho, *et a*l., 2006).

This work considers the amount of water required to support mass cultivation of algae expressed as biomass production per meter squared of light-available surface area over the course of a full calendar year (365 days), or kg/m^2-yr. For purposes of evaluation, the results are assumed to scale up without distortion and are meant to represent the average of a “typical” mass-cultivation system located in the continental United States using currently available and characterized technologies. Rather than describing optimum conditions that are dependent upon highly localized factors, the intent is to examine the energy requirements associated with water management, at a scale that has the potential to have a measureable impact on the US transportation fuel portfolio. In 2008, the US consumed 27,230 trillion (10^{12}) BTUs of petroleum products in the transportation sector (EIA, 2010), equal to 28.7 x 10^{12} MJ per year.

2.3 System Design

The model assesses a system design based primarily on ideas and information presented in Benemann and Oswald (1996) and Weissman and Goebel (1987). The basic assumptions are as follows. The pond system includes a minimum of 10 cultivation (growth) ponds placed side-by-side; each individual cultivation pond has a total surface area of 10,000 m^2. Every cultivation pond consists of two elongated channels, separated by a divider. A single paddlewheel, located at the end of one channel, is used to circulate the water down the channels and around curved connecting ends to create a continuous loop. The channels are designed to hold the algae culture medium (primarily water) at a nominal depth of 0.3 meters. The aspect ratio (length to width) for each channel is taken to be 15. For every cultivation pond, there is a 3 meter deep harvest pond capable of holding at least half the cultivation pond volume. An inoculation system, similar to that described in Benemann and Oswald (1996), is located on site. The system consists of large open inoculum ponds, each equivalent in size and design to a cultivation pond, which feed (inoculate) the cultivation ponds. The large inoculum ponds provide 10% of the makeup water when ponds are refilled after harvest; thus the ratio of large inoculum ponds to cultivation ponds is 1:10. In addition, a small inoculum pond provides 10% of the makeup water to the large inoculum ponds. Shallow evaporation ponds are used to precipitate out salts from water released during the blowdown process (described below).

Microalgae reproduce through cell division with the number of cells typically doubling every 12 to 48 hours (Sheehan, *et al*., 1998). In a semi-continuous system, half the biomass in the cultivation ponds is harvested at a rate equal to the doubling time (e.g., once a day if the doubling time is 1/day or every other day if the doubling time is 0.5/day). The current analysis assumes a relatively fast-growing algae species with a doubling time of 1/day. Therefore, harvesting occurs once daily, between sunset and sunrise, in order to maximize light exposure time. The biomass harvest rate is equal to the growth rate expressed as g/m^2-day, (where meters squared (m^2) is the light-available surface area within the cultivation system and grams (g) is equal to the ash-free dry mass of the algae). It is assumed that the concentration of suspended solids in the harvested medium is identical to that in the cultivation pond at the time of harvest (i.e., the removal process itself does not provide any separation mechanism).

After the culture is removed (harvested) from the cultivation system, algae biomass is separated from the growing medium (water). This poses a technical challenge not only because the volume of water to biomass is extremely high, but also owing to the nearly identical densities (kg/m^3) of algae biomass and water, the small size of the algal cells, and the naturally charged surface of the cells. The separation process needs to be efficient in order to maximize the amount of water that can be returned to the cultivation system and to minimize the water content of the slurry as it is delivered to downstream processes, most of which require at least 10% total solids (as wet biomass). Therefore, if the percent total suspended solids (%TSS) at the time of harvest is equal to 0.1%, the culture must be concentrated by a factor of 100X before it leaves the separation process. In this particular example, 99 kilograms of water must be removed for every 1 kg of wet biomass. It is important to recognize that measures of separation efficiency in terms of concentration factors or percent water reclaimed are meaningful only in the context of the original concentration (%TSS) (i.e., at the start of the harvest operation).

Separation of algae biomass from its aqueous culture can be achieved either by constraining the liquid and allowing the particles to move in response to an external force (e.g., sedimentation and centrifugation) or by constraining the solids and allowing the fluid to move away from the solids (e.g., filtration). Filtration techniques are of interest because they have the potential to remove significant amounts of water with relatively low energy inputs; however, to date, economically viable and reliable means of filtering eukaryotic microalgae remain a technical challenge. This is in large part due to the tendency of small algae cells to clog membranes or screens. In addition, filtration devices typically have short life-spans and are material intensive (Shelef and Sukenik, 1984). The potential effectiveness (and limitations) of both centrifugation and sedimentation processes are described by Stokes law, whereby the time and energy required is inversely proportional to the difference in densities between particles and fluid as well as to the square of the particle diameter, both of which are very small for microalgae. Currently, the most reliable method for harvesting microalgae is to perform a two-stage separation using sedimentation (settling) followed by centrifugation, with a flocculation agent used at the onset of the sedimentation step. This is the approach assumed here. Relatively thorough views of different harvesting technologies, and in particular flocculation methods, are provided by several authors (Benemann and Oswald, 1996; Osborne, 2009; Shelef and Sukenik, 1984; Molina-Grima, *et al*., 2003).

2.4 Algae Productivity

Biomass growth rates determined in laboratory studies are often expressed on a per unit volume basis; however, the more appropriate reporting metric is growth per unit area, where area is that exposed to light. Burlew notes that, "the same yield per unit area can be obtained with almost an infinite number of combinations of volume, depth, and concentration [assuming] the depth and concentration be great enough for optical extinction to occur" (Burlew, 1953). Therefore, in order to translate volumetric growth rates (typically from under artificial light conditions) into meaningful, areal growth rates (typically under natural light) requires knowledge of the area exposed to light and the hours per day that light was applied. There are a multitude of additional problems associated with making such translations, as most of the studies upon which volumetric growth rates are based are conducted indoors, at bench-scale, and under tightly controlled steady-state conditions, none of which are likely to be applicable to mass production systems.

Algae production at a scale capable of having a noticeable impact on transportation fuel supplies will have to occur over broad geographic areas and over as much of the year as possible. Williams and Laurens (2010) address this particular issue by generating a series of curves showing theoretical maximum growth rates (assuming clear skies and the highest photosynthetic efficiencies) as a function of latitude, where growth rate is expressed as ash-free dry mass (grams) per unit of light-available surface area (meters squared) per unit of time (day), or g/m^2-day. The authors note that temperature effects are not taken into account; if they were to be included, the results would reflect decreased photosynthetic activity as well as a shorter, practical growing season. Climate in general, along with other factors that are difficult to systematically quantify, will act to suppress biomass accumulation. Data reported in the literature are used by Williams and Laurens to make an overall adjustment (an effective 43% decrease) to predict actual growth rates, by latitude, in a mass cultivation environment (Williams and Laurens, 2010, Figure 23).

In the current analysis, curve fitting and interpolation is used to generate theoretical maximum algae productivity curves at 5º latitude intervals based on the 30, 40, and 50º N latitude curves presented by Williams and Laurens (2010, Figure 18). The average latitude for each state in the contiguous United States (US), to the nearest 5º, was determined along with an estimate of the average length of the growing season in days per year. The growing season was estimated as the number of days per year where the minimum temperature is greater than 5º C (40º F) and the maximum temperature is less than 35º C (95º F) based on the US Department of Agriculture (USDA) Plant Hardiness Zone Map (USNA, 2003) and the American Horticultural Society Plant Heat-Zone Map (AHS, 1997). The biomass productivity curves were integrated over the length of the growing season to produce an expected annualized, theoretical maximum by state. These values were then reduced by 43%, consistent with the empirically determined decrease presented in Williams and Laurens (2010). This reduction is taken to account for cloudy days, competition for resources (including light) in dense populations, shutdown for preventative maintenance, etc. Each state is assigned a "typical" annual productivity in terms of grams of algae (as ash-free dry mass) per meter square of surface area in the cultivation ponds (Appendix 2.A., Supporting Information, Table 2.A.1). Annualized yields (kg/m^2-yr) are determined by dividing this value by 365 days. The US weighted average is 6.92 kg/m^2-yr, with a range of 4.96 to 9.00 kg/m^2-yr (14 to 25 g/m^2-day, annualized). The average, daily, non-annualized growth rates (i.e., productivity divided by the number of days in the growing season) are higher in the northern states (33.5 g/m^2-day) than in the southern states (29.3 g/m^2-day), as the hours of sunlight per day during the growing season increases with increasing latitude.

The total algae biomass production potential for each state is taken to be the annualized growth rate, as determined above, multiplied by the total "available" land in each state. The amount of "available" land is estimated from data in the USDA, 2007 National Resources Inventory (USDA, 2009) and calculated as the total non-federal, rural land area excluding forested areas, prime pasture, prime rangeland, and all cropland (except that in the Conservation Reserve Program (CRP)). This does not account for other potential limitations to land suitability, such as topography or general availability. It does include wetlands, but not deep bodies of water (lakes and rivers) or territorial (coastal) waters. The maximum total "available" land in the US is thus estimated to be 224 x 10^6 hectares (ha) of land (Appendix 2.A., Supporting Information, Table 2.A.2). The total land required for an algae production facility will include not only that required for primary cultivation, but also space for inoculum systems, harvest systems, access to the ponds or reactors, waste management and storage facilities, infrastructure, and support systems. In the case of open ponds, evaporation ponds must be formed to hold releases from the blowdown process. Raceway ponds, if constructed with earthworks, require land for berm formation. The total area burden for open raceway ponds is taken to be 1.6. This is the ratio of light-available surface area, in the cultivation ponds only, to the area of land occupied to support those ponds. Taking into account the total land required and weighting by each state's potential algae production, results in predicted US annual biomass productivities of 9.3 Tg (megatonnes) for raceway ponds. This translates to 43.2 Mg per occupied hectare of land per year (Mg/ha-yr). The maximum of 56.3 Mg/ha-yr is predicted for Florida.

The biomass productivity values presented above are gross values; there will be losses at subsequent steps, including harvesting. If harvesting is assumed to require a two-step operation with 90% yield (10% losses) at each of these steps, the maximum amount of mass that could be produced annually is reduced to 81% of gross, corresponding to 7.5 Tg/yr or 35.0 Mg/ha-yr. As a point of comparison, the weighted average US production of corn for silage (using the entire plant) in 2009 was 44.9 Mg/ha-yr (based on data from the USDA (NASS, 2010).

2.5 Water Balance

There are two key factors that must be considered in estimating the volume of water necessary to grow algae in a mass-cultivation system. The first is the amount of water needed to support a culture at a target biomass productivity level at any given time. The second is the amount required to replace water that is removed from the cultivation ponds, either as a function of system design or due to natural losses. The flows that are used to determine the water balance for an open raceway pond system are shown in Figure 2.1. Details of the water balance, as described below, are given at the state level in Appendix 2.A, Supporting Information.

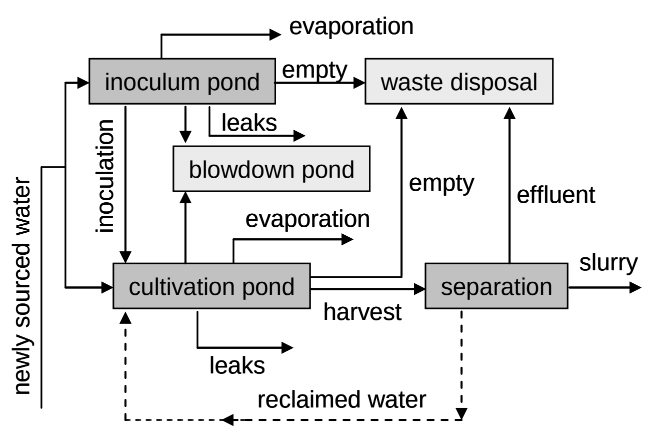

FIGURE 2.1. Flow of water and suspended algae grown in an open-pond, semi-continuous system.

Total water inputs into the cultivation ponds will consist of feed from the inoculum ponds, water reclaimed from harvest, and, if necessary, newly sourced water. Inputs to the inoculum ponds are assumed to be derived only from the small upstream inoculum pond(s) or newly sourced water. The volume of water that must be pumped into the inoculum and cultivation ponds on an annual basis is equal to that lost or removed, which includes complete fills of the ponds, compensation for gradual and intermittent losses, and daily replacement of culture removed due to harvest operations. The general characteristics of these losses are discussed below. In all cases, the values are normalized to the light available surface area of the cultivation ponds only. Details of the methods used to calculate annualized values at the state and national level are presented in Appendix 2.A., Supporting Information.

Complete empty and fill of ponds is expected to occur for cleaning and maintenance as well as at the end and beginning of each growing season. It is estimated that cultivation ponds will need to be drained for maintenance and/or cleaning every 4 months, while inoculum ponds, which are more sensitive to contamination, are assumed to be drained for cleaning and subsequently refilled every 2 months. The fill volume for a 0.3 meter deep raceway pond is simply 0.3 m^3/m^2. The weighted US average volume required to fill both cultivation and inoculum ponds is calculated to be 0.81 m^3/m^2-yr, where area (m^2) refers only to cultivation ponds.

The net amount of water lost due to evaporation depends on the climate, particularly temperature, humidity, precipitation, and wind velocity. Each of these will vary from site to site and over the course of a year. Pan evaporation data, multiplied by 0.7, can be used to estimate evaporation from large, shallow bodies of water (Univ. of Arizona, 2010). This method correlates well to average annual free water surface evaporation from shallow lakes in the continental United States (Farnsworth, *et al*., 1982). Based on these maps, the lowest evaporation rate from open algae ponds would occur in the state of Maine, with estimated evaporative losses of 0.0014 m/day; the highest rate, at the state level, would occur in Arizona, with estimated losses of 0.49 m/day. The US average is 0.0034 m/day, or 0.76 m^3/m^2-yr over an average 222 day growing season. In the design assessed here, the total surface area of uncovered inoculum ponds is 10% of the cultivation ponds. Applying a multiplier of 1.1 for the inoculum ponds, the typical evaporative losses are thus estimated to be 0.84 m^3/m^2 of cultivation pond area per year.

Another potential source of water loss is leaks from the pond to the surrounding soil, although the degree to which this phenomenon is inevitable is not known. Weissman *et al*. (1989) report loses of 0.11 to 0.36 cm/day from a lined pond. In this analysis, it is assumed that better designs and materials can minimize this problem and the lower value, equivalent to 0.0011 m^3 of water per m^2 of cultivation pond area per day, is assumed. Weighting the value by 1.1 to account for inoculum ponds, 0.27 m^3/m^2-yr is expected to be lost due to leaks.

Uncovered ponds lose a significant amount of water through evaporation and act as solar concentrators of dissolved salts. This effect may be counteracted with a process referred to as blowdown, in which the culture medium is removed from the pond and replaced with freshwater (as that is what is preferentially evaporated). Even freshwater algae will require this process, although on a smaller scale than species adapted to saline environments. The blowdown process releases a portion of the inoculation or cultivation pond water; an equal volume of new makeup water is added to the pond in order to control the water chemistry. Weissman and Goebel (1987) specify a blowdown rate equal to 14% of evaporative losses for saline species. For average evaporative losses of 0.84 m^3/m^2, cultivation and inoculum ponds combined, water removed due to blowdown is thus estimated to be 0.12 m^3/m^2-yr.

The amount of water removed from the cultivation ponds (and which therefore must be replaced) during the harvesting operation depends upon the harvesting strategy used. In the current model, it is assumed that algae are grown in a semi-continuous mode in which half the pond volume is removed after sunset and an equal amount of water is delivered to the pond by sunrise. The total water that must be replaced due to harvesting is, therefore, half the volume (0.3 m^3) or 0.15 m^3/m^2-day, equal to 33.2 m^3/m^2-yr for the US when annualized.

The average volume of water per unit area that must be added annually to lined cultivation ponds growing a saline-water species of algae in the continental US ($V_{TOTAL\ input}$, per equation S1, Appendix 2.A., Supporting Information) is estimated to be equal to 35.0 m^3/m^2-yr. The make-up water delivered to the cultivation ponds will consist of feed from the inoculum ponds, water reclaimed from harvest, and newly sourced water as needed. The average volume of water per unit area that must be added annually to the inoculum ponds is similarly calculated to be 3.9 m^3/m^2-yr, where m^2 refers to the surface area of the cultivation ponds. The total for the system is then 38.9 m^3/m^2-yr. All water fed to the inoculum ponds is assumed to be newly sourced.

Although this analysis assumes that most of the water is reclaimed, newly sourced water will be required in some instances. In addition to saline water, this includes freshwater needed to compensate for water lost to evaporation or removed during the blowdown process. The weighted average freshwater requirement for the US is equal to 0.96 m^3/m^2-yr. The volume (driven by different evaporation rates and season lengths) ranges from 0.26 m^3/m^2-yr in Maine to 1.65 m^3/m^2-yr in Arizona. In addition, both cultivation and inoculum ponds are expected to be filled with newly sourced saline water after being drained for cleaning or maintenance. In order to protect the viability of the culture and the chemistry of the medium, all of the makeup water added to the inoculum ponds to offset that removed during inoculation of downstream ponds is also assumed to be newly sourced. These activities represent the minimum amount of newly sourced saline water that will be required. If there are shortfalls in the amount of water that can be reclaimed from harvest, additional newly sourced water will be needed. The US weighted average minimum newly sourced saline water requirement is equal to 4.55 m^3/m^2-yr. The range is from 3.29 m^3/m^2-yr in the northern states, where the growing season is short, to 6.28 m^3/m^2-yr in Florida.

The amount of water that can be reclaimed after the harvest operation depends upon the incoming biomass density and the concentration factors at harvest. The estimated average biomass density for US at harvest is 210 g/m^3, equal to 0.021 wt% AFDM, or roughly 0.1% total suspended solids (TSS). The settling ponds are assumed to concentrate the biomass by a factor of 10 to produce a slurry containing 2.10 kg/m^3 AFDM (1.1% TSS); 29.9 m^3/m^2-yr of effluent is available for return to the cultivation ponds; the subsequent centrifugation step provides a negligible amount of effluent. As 30.0 m^3/m^2-yr is the required water volume input needed to compensate for the harvest operation, the remaining 0.11 m^3/m^2-yr must be supplied to the cultivation ponds as newly sourced water. The total volume of newly sourced saline water that must be provided to the system (inoculum plus cultivation ponds) is thus 4.66 m^3/m^2-yr, with the remaining 34.2 m^3/m^2-yr (88%) provided by recycled water.

2.6 Energy to Acquire New Water

The 2008 Farm and Ranch Irrigation Survey (USDA, 2010) was used to estimate the amount of energy required to pump freshwater from both surface and groundwater sources using the current mix of electric and diesel pumps. The weighted average value for the continental US is estimated to be 1.35 MJ per m^3 of water pumped. If the annual amount of newly sourced freshwater pumped to algae ponds is 0.96 m^3/m^2-yr, the energy to supply this volume is 1.29 MJ/m^2-yr. Energy is also required to produce and deliver both diesel fuel and electricity. The factors for upstream energy production (ratio of upstream energy use to energy delivered) are assumed to be 2.57 for electricity and 0.18 for diesel (ANL, 2009). When weighted according to the proportion of pump type and state-level algae production potential, the total upstream energy for energy to acquire freshwater is equal to 2.95 MJ/m^2-yr. (See Appendix 2.A., Supporting Information for greater detail).

It is assumed that all water for saline systems is sourced as groundwater. The depths to saline aquifers in the US are estimated based on a US Geological Survey map (Alley, 2003) and an average is assigned to each state. The range in depth is 75 to 380 meters, with deeper aquifers located primarily in the southeast and the High Plains. The weighted US average is 180 meters deep. As no information for New England is provided on the map, the US average is assumed for these 6 small states. Data from the Farm and Ranch Irrigation Survey suggest that the energy to pump water at these depths converges to a value of approximately 0.02 MJ per m^3 of water per meter of depth (independent of pump type), which is roughly equivalent to the theoretical value of work required (mass * gravity * height) with an overall efficiency of 50%. The total energy to supply 4.66 m^3/m^2-yr of saline water at an average depth of 180 m thus equals 16.8 MJ/m^2-yr. The proportion of diesel to electric pumps is taken to be the same as for freshwater pumping. Based on this, the upstream energy requirements are 34.5 MJ/m^2-yr.

2.7 Water Circulation

Circulation within the algae culture helps ensure optimum exposure to light. In addition, it acts to retain culture suspension, distribute nutrients, and minimize thermal gradients. Paddlewheels are relatively energy efficient as compared to other pumping systems and induce minimal mechanical damage to the algal cells. The amount of energy required to power the paddlewheel used for mixing depends upon the area and depth of the water, the roughness of the pond surface, the nominal mixing speed, and the efficiency of the pump. The general formula used to determine the amount of mixing power required is based on Weissman *et al*. (1989) for a plastic surface, which results in a predicted value of 0.197 watts/m^2; (see Appendix 2.A., Supporting Information, equation 2.A.1, for details.). If the circulation system is run an average of 12 hours per day during the growing season, the total energy required is 1.89 MJ/m^2-yr. The system is assumed to be powered by electricity. The upstream energy associated with producing and delivering this electricity is estimated to be 4.84 MJ/m^2-yr.

2.8 Energy to Pump Water between Ponds

A semi-continuous system that cultivates algae characterized by a growth rate of one doubling per day, will be harvested once per day. In the harvest operation, half the water volume in the cultivation ponds is pumped to the separation operation and an equal amount must be pumped in to replace it. A portion of the cultivation pond makeup water is taken from the inoculum ponds, which therefore also experiences a 50% turnover on a daily basis. The total amount pumped out of the inoculum and cultivation ponds is 36.9 m^3/m^2-yr. The volume pumped out of the settling ponds and sent either to centrifuge, returned to the cultivation ponds, or sent to waste is equal to the volume removed at harvest, or 33.2 m^3/m^2-yr. The volume pumped out of centrifuge and sent either to downstream processing or waste is 3.3 m^3/m^2-yr. The water pumped into inoculum ponds and cultivation ponds is here assumed to be taken directly from primary sources; however, if this is not the case and storage is required, up to an additional 36.9 m^3/m^2-yr of pumping could be required. The total volume pumped is thus equal to 110 m^3/m^2-yr with intermediate storage, or 73.5 m^3/m^2-yr without storage.

The energy required to pump water within the system is estimated by assuming a differential head of 25 meters (requiring an operating pump pressure of 35 psi). This is consistent with the sizing of discharge pumps used in US agriculture (USDA, 2010, Table 19) and accounts for friction losses as well as small (less than 3 m) differences in elevation. All pumping is assumed to be completed using an electric pump with an overall efficiency of 50%; the density of the medium is taken to be the same as water. Direct energy requirements are thus calculated to be 36.0 MJ/m^2-yr and upstream energy is 92.4 MJ/m^2-yr, or a total of 128 MJ/m^2-yr, with no intermediate storage.

2.9 Water Containment

The algae culture medium, consisting primarily of water, must be contained in such a way as to maximize the light-available surface area and to create an impermeable boundary between the culture and the land upon which it is located. The latter is necessary in order to prevent loss of algae or release of nutrient-enriched saline water to the surrounding environment. All four pond types (i.e., inoculum, cultivation, harvest, and evaporation) must be lined. Algae cultures are also subject to predators and invading species. For this reason, covered systems are often considered desirable. In the current analysis, only the small inoculum pond is taken to be covered, as it is the most vulnerable and most valuable. The contribution to material consumption in this instance is quite small and therefore ignored in the following analysis.

The inoculum and cultivation ponds are assumed to be constructed of earthwork berms, lined with high density polyethylene (HDPE) plastic film that is 2.0 mm thick and which has a density of 950 kg/m^3. The floors, walls, and channel dividers are all covered. Although the water is only 0.3 meters deep, the earthwork constructed walls must be 0.7 m high for reasons of stability (Benemann and Oswald, 1996). In addition, the plastic must anchored in the earthworks and there must be overlap of adjoining sheets. The lifetime of the plastic on the floors is estimated to be 10 years, while that used on the walls and the evaporation ponds will last only 5 years, due to increased light exposure, thermal cycling, and pests. Total HDPE input is estimated to be 0.31 kg/m^2-yr (see Appendix 2.A., Supporting Information). The upstream energy required to produce HDPE is taken to be 101.0 MJ/kg (Hischier, 2007), giving an embodied energy of 31.3 MJ/m^2-yr for containing the culture in the cultivation and inoculum ponds and the blowdown effluent in the evaporation ponds.

The settling ponds used for harvesting are taken to be constructed of ordinary concrete with a density of 2380 kg/m^3 that is assumed to last the lifetime of the cultivation system, or 20 years.

The total mass of concrete required is estimated to be 1.61 kg/m^2-yr (see Appendix 2.A., Supporting Information) and upstream energy to produce general use concrete is taken to be 1,675 MJ/m^3 concrete (Prusinski, *et al*., 2004), or 0.70 MJ/kg. Thus upstream energy is equal to 1.13 MJ/m^2-yr.

2.10 Discussion

The energy flows addressed in the above analysis consider only those related to the delivery and management of water during the mass cultivation of algae in open pond systems. Direct energy inputs are estimated to be 56.0 MJ/m^2-yr and upstream energy inputs (attributable to the production of energy and construction materials) are 167 MJ/m^2-yr, for a total energy burden of 223 MJ/m^2-yr (US weighted mean). Total energy inputs are dependent primarily on the number of operational days per year with a secondary dependency on depth to saline aquifers and the type of pump used; a minimum value of 139 MJ/m^2-yr and a maximum value of 321 MJ/m^2-yr are predicted for Maine and South Carolina, respectively. The total does not include energy inputs for the production and delivery of nutrients (carbon, nitrogen, and phosphorus) nor does it account for energy (direct or upstream) used to concentrate the biomass slurry beyond that which can be achieved through settling ponds (2% wet or 0.4% dry biomass). As downstream processes are expected to require biomass concentrations that exceed these values by at least an order of magnitude and currently available dewatering technologies, such as centrifugation and/or natural gas drying, are extremely energy intensive (Murphy, *et al*., 2010), this energy requirement is non-trivial. The energy inputs for conversion of the algae biomass into a fuel, including oil extraction and transesterification, are also not included in the above energy balance. Energy inputs for nutrient supply and fuel production are expected to be positively correlated with biomass productivity.

Energy outputs from the system depend primarily upon biomass production, separation efficiency, composition of the biomass, and final products. The potential average (weighted mean) productivity in the continental US is estimated in the above analysis to be 6.9 kg/m^2-yr. However, given a two-stage harvesting and separation process with 90% efficiencies at each, only 5.6 (90% * 90% * 6.9) kg/m^2-yr will actually be realized. The target product in the current analysis is assumed to be biodiesel produced through transesterification of triacylglycerols (TAG), which are neutral lipids found within algal cells. Maximum lipid fraction is limited by non-lipid content (proteins and carbohydrates), which are needed to maintain basic cell functions, including reproduction and photosynthesis. The TAG fraction of the lipids is also limited, as polar lipids are required to keep membranes intact. Although algae have been shown to produce high levels of lipids in general and TAG in particular under short-term conditions of stress (light or nutrient deprivation), such approaches also result in decreased biomass accumulation and are in general not considered to be a viable, long-term cultivation strategy (Sheehan, *et al*., 1998). Normal lipid contents, as reported in the literature, typically range between 20% and 30% and the percent of these lipids that are TAG is generally about 20% (Benemann and Oswald, 1996, Williams and Laurens, 2010, Griffiths and Harrison, 2009; Hu, *et al*., 2008) as a percent of dry weight. In the current analysis, the US annual mean values are optimistically assumed to be 35% lipids, 40% of which are TAG. If 100% of the TAG is converted to biodiesel with an energy value of 38 MJ/kg, the energy yield is equal to 29.8 MJ/m^2-yr. Dividing this energy output by the total inputs above (223 MJ/m^2-yr) gives an energy return on energy investment of 0.13. That is, it takes 7.5 times as much energy to manage the water in an algae cultivation system as is expected to be produced as biodiesel. This is a very approximate estimate and does not include a number of energy inputs; however, the overall goal of the analysis presented in this work is to demonstrate that energy requirements for water management are substantial. Even if it were possible to convert all of the algal biomass into fuel, the energy required just for water management is equal to the heating value of the total biomass (Neenan. et al., 1986).

Figure 2.2 compares the potential energy output from algae-based biodiesel to the inputs estimated above. As can be seen, the biggest demand is due to pumping between ponds, which is driven by the harvest technology and rate. The harvest rate in a semi-continuous system is driven by the growth rate of the algae, thus the harvest rate can be decreased only by using a slower growing algae or by switching to a batch system, which will result in an overall decrease in mean productivity (g/m^2-day). The most promising means of addressing this issue is likely to be a harvest technology that provides some degree of separation of the biomass from the growing medium (water). Belt filtration/removal has been proposed, but it will still require energy to move the belt (and apply a pressure differential if that is part of the technology); the filters are likely to require frequent cleaning and/or replacing, and the energy embodied in the belts will need to be accounted for. Even with a filtration system, it is unlikely that the %TSS in the slurry would be much greater than that obtained in settling ponds (2%); consequently, centrifuge and/or drying to separate out water may still be required.

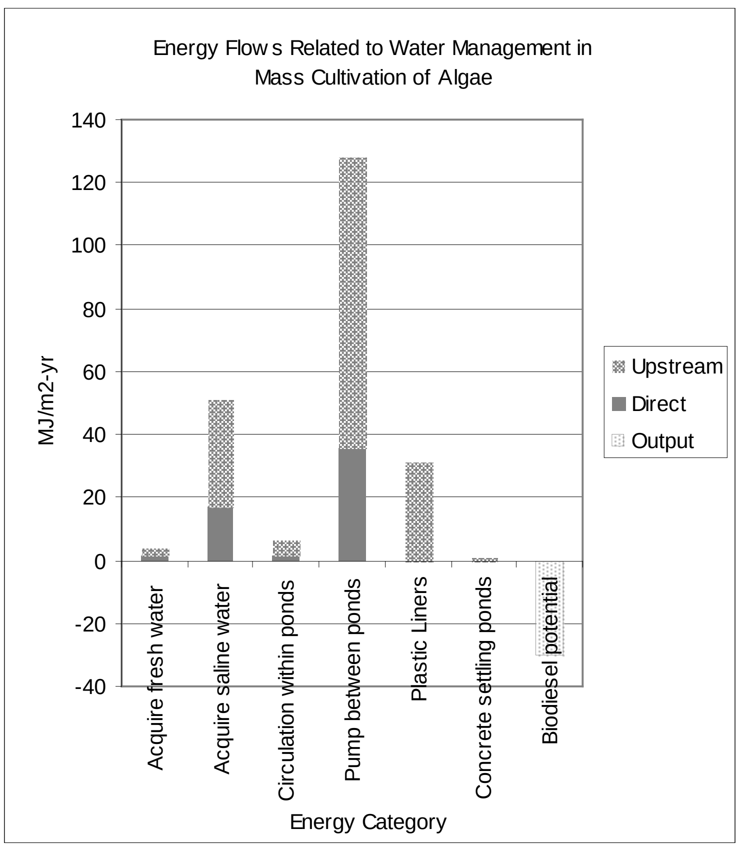

FIGURE 2.2. Weighted mean US average of annualized energy inputs vs. potential energy output in the form of algae-based biodiesel from TAG.

Energy to acquire saline water is the second largest contributor to input requirements. This could be reduced if water is not pumped from deep underground aquifers. If the energy required to obtain saline water from surface sources is similar to that used to pump fresh surface water (0.63 MJ/m^3, direct plus upstream, in the continental US), a total energy savings of 48 MJ/m^2-yr could be realized. However, it is unclear that adequate volumes, capable of supporting large scale fuel production, can be reasonably obtained from surface sources.

The third largest contributor to energy inputs is that embodied in the plastic liners of the ponds. Unlined ponds are likely to be unacceptable from an environmental perspective due to potential losses of saline and/or nutrient enriched water as well as non-native algae. Lining the bottom of the pond with clay would decrease the embodied material energy by approximately 75%, but would also increase the circulation energy required by a factor of 2 to 3 for a net savings of less than 10 MJ/m^2-yr. Preliminary estimates of tube-style photobioreactors suggest that embodied energy is greater than that for plastic lined open ponds, even if potentially higher biomass productivity is considered.

The above analysis addresses only open pond systems growing a known algae species. However, regardless of the technology or species, given that algae must be grown in an aqueous system, the total direct and embodied energy needed to manage the water used in cultivation, including acquisition, movement, and containment, must be accounted for. In addition, if algae-based fuels are to be an important contributor to the US energy portfolio, the energy inputs and outputs must be evaluated over broad geographic areas and annualized over a full calendar year rather than for isolated, optimal conditions.

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APPENDIX 2.A: SUPPORTING INFORMATION

2.A.1. Algae Productivity

Table 2.A.1. Estimates of potential algae yields and productivity (as ash-free dry mass) in the continental US. Maximum productivity is calculated from Maximum "Available" Land, as given in Table 2.A.2.

State	Mean Latitude	Growing season	Theoretical Maximum, annualized	Predicted Gross Yield, annualized		Daily Mean Yield, during growing season	Yield per occupied land area		Maximum Productivity	
							Gross	Net	Gross	Net
	ºN	days	g/m^2-day	g/m^2-day	kg/m^2-yr	g/m^2-day	Mg/ha-yr	Mg/ha-yr	Tg/yr	Tg/yr
US (wtd avg)		222	33.2	18.9	6.9	31.5	43.2	35.0	9,321	7,550
Alabama	33	250	37.1	21.2	7.7	30.9	48.3	39.1	57	46
Arizona	34	270	38.8	22.1	8.1	29.9	50.5	40.9	725	587
Arkansas	35	225	34.1	19.5	7.1	31.6	44.4	36.0	65	53
California	37	270	38.0	21.7	7.9	29.3	49.4	40.0	452	366
Colorado	39	175	27.7	15.8	5.8	33.0	36.1	29.2	432	350
Connecticut	41.5	200	30.4	17.4	6.3	31.7	39.6	32.1	3	2
Delaware	39	200	30.8	17.5	6.4	32.0	40.0	32.4	2	2
Florida	28	300	43.3	24.7	9.0	30.0	56.3	45.6	203	164
Georgia	33	250	37.1	21.2	7.7	30.9	48.3	39.1	56	45
Idaho	45	175	27.2	15.5	5.7	32.3	35.3	28.6	128	103
Illinois	40	200	30.7	17.5	6.4	31.9	39.9	32.3	45	37
Indiana	40	200	30.7	17.5	6.4	31.9	39.9	32.3	32	26
Iowa	42	175	27.5	15.7	5.7	32.7	35.7	28.9	69	56
Kansas	38.5	200	30.8	17.6	6.4	32.1	40.1	32.5	273	221
Kentucky	37.5	200	31.0	17.6	6.4	32.2	40.3	32.6	75	61
Louisiana	30	250	37.6	21.4	7.8	31.3	48.9	39.6	81	66
Maine	45.5	150	24.0	13.7	5.0	33.3	31.2	25.3	8	6
Maryland	39	200	30.8	17.5	6.4	32.0	40.0	32.4	11	9
Massachusetts	42.5	190	29.2	16.6	6.1	32.0	38.0	30.8	5	4
Michigan	44	175	27.3	15.5	5.7	32.4	35.5	28.7	52	42
Minnesota	46	150	24.0	13.7	5.0	33.2	31.2	25.2	83	67
Mississippi	33	250	37.1	21.2	7.7	30.9	48.3	39.1	58	47
Missouri	38.5	200	30.8	17.6	6.4	32.1	40.1	32.5	166	135
Montana	47	150	23.9	13.6	5.0	33.1	31.1	25.2	570	462
Nebraska	41.5	175	27.5	15.7	5.7	32.7	35.8	29.0	373	302
Nevada	39	200	30.8	17.5	6.4	32.0	40.0	32.4	147	119
New Hampshire	44	150	24.1	13.7	5.0	33.4	31.3	25.4	3	3
New Jersey	40	200	30.7	17.5	6.4	31.9	39.9	32.3	8	6
New Mexico	34	225	34.3	19.5	7.1	31.7	44.6	36.1	776	629
New York	43	175	27.4	15.6	5.7	32.5	35.6	28.8	43	35

North Carolina	35.5	250	36.6	20.9	7.6	30.5	47.6	38.6	43	35
North Dakota	47.5	150	23.9	13.6	5.0	33.1	31.0	25.1	205	166
Ohio	40.5	200	30.6	17.4	6.4	31.8	39.8	32.2	42	34
Oklahoma	35.5	225	34.1	19.4	7.1	31.5	44.3	35.9	316	256
Oregon	44	190	29.0	16.5	6.0	31.7	37.7	30.5	177	143
Pennsylvania	41	200	30.5	17.4	6.3	31.7	39.7	32.1	40	32
Rhode Island	41.5	200	30.4	17.4	6.3	31.7	39.6	32.1	1	0
South Carolina	34	250	36.9	21.1	7.7	30.7	48.0	38.9	32	26
South Dakota	44.5	150	24.1	13.7	5.0	33.4	31.3	25.4	334	270
Tennessee	35.5	225	34.1	19.4	7.1	31.5	44.3	35.9	75	61
Texas	31	275	40.0	22.8	8.3	30.3	52.1	42.2	2,185	1,770
Utah	39.5	200	30.7	17.5	6.4	32.0	39.9	32.4	228	184
Vermont	44	150	24.1	13.7	5.0	33.4	31.3	25.4	5	4
Virginia	37.5	225	33.8	19.2	7.0	31.2	43.9	35.5	54	44
Washington	47.5	180	27.4	15.6	5.7	31.7	35.6	28.9	126	102
West Virginia	39	200	30.8	17.5	6.4	32.0	40.0	32.4	25	20
Wisconsin	44.5	150	24.1	13.7	5.0	33.4	31.3	25.4	57	46
Wyoming	43	150	24.2	13.8	5.0	33.5	31.4	25.5	377	305

NOTES:

Growing season estimated from the USDA Plant Hardiness Zone Map (USNA, 2003)

Theoretical maximum is calculated based on photosynthetic activity as a function of latitude. Interpolated from Williams and Laurens (Williams and Laurens, 2010), Figure 18; integrated over length of growing season, and annualized to 365 days

Predicted gross yield is the theoretical maximum reduced by 43% to reflect actual productivity under outdoor, mass cultivation conditions (per Williams and Laurens (Williams and Laurens, 2010, Figure 23)

Annualized gross yields and productivity assumes a ratio of 1.6 occupied land area to cultivation pond surface area

Net yield and productivity assumes 90% efficiency at harvest and separation

Maximum productivity is based on maximum “available” land given in Table 2.A.2

All masses are algae ash-free dry biomass

Area in m^2 refers to surface area of the cultivation ponds

Area in ha refers to occupied land area

Table 2.A.2. Estimate of maximum "available" land for mass cultivation of algae in the US. Data from 2007 National Resources Inventory: water area does not include wetlands or territorial waters; cropland does not include CRP (Conservation Reserve Program) lands (USDA, 2009).

State	Total surface area	Federal land	Water area	Developed land	TOTAL	Cropland	Forest land	Prime Pasture	Prime Rangeland	Maximum "Available" Land
	1000 hectares									
US (TOTAL)	784,145	162,658	20,565	45,022	555,900	144,482	164,468	15,069	8,145	223,735
Alabama	13,526	404	522	1,191	11,409	899	8,713	618	1	1,178
Arizona	29,528	12,313	77	812	16,326	305	1,657	16	0	14,347
Arkansas	13,774	1,256	365	732	11,421	2,986	6,109	854	3	1,469
California	41,080	18,874	759	2,498	18,948	3,840	5,823	99	45	9,141
Colorado	26,962	9,630	134	783	16,415	3,079	1,313	44	7	11,971
Connecticut	1,293	6	52	426	809	70	656	15	0	69
Delaware	621	13	117	113	377	170	137	11	0	59
Florida	15,189	1,531	1,268	2,232	10,158	1,166	5,330	56	0	3,607
Georgia	15,273	860	429	1,878	12,107	1,617	8,888	444	0	1,158
Idaho	21,646	13,583	226	367	7,470	2,123	1,625	85	25	3,612
Illinois	14,592	199	296	1,369	12,728	9,676	1,592	322	0	1,138
Indiana	9,372	191	151	990	8,040	5,350	1,550	333	0	807
Iowa	14,575	70	197	766	13,543	10,298	953	364	0	1,928
Kansas	21,311	204	224	848	20,035	10,374	682	565	1,604	6,809
Kentucky	10,467	524	255	847	8,840	2,093	4,286	591	0	1,869
Louisiana	12,698	530	1,588	754	9,826	2,067	5,385	701	8	1,665
Maine	8,485	84	509	344	7,548	151	7,135	15	0	247
Maryland	3,185	68	672	606	1,838	572	938	52	0	276
Massachusetts	2,161	39	148	695	1,278	96	1,048	13	0	121
Michigan	15,115	1,325	454	1,711	11,625	3,174	6,705	280	0	1,466
Minnesota	21,857	1,350	1,273	969	18,265	8,375	6,694	536	0	2,660
Mississippi	12,354	726	360	733	10,534	1,904	6,810	619	0	1,203
Missouri	18,055	777	351	1,186	15,741	5,377	5,030	1,173	17	4,145
Montana	38,085	10,964	421	424	26,277	5,637	2,221	42	23	18,353
Nebraska	20,036	262	193	468	19,113	7,902	333	177	289	10,411
Nevada	28,637	24,228	174	236	3,998	190	126	4	0	3,678
New Hampshire	2,404	309	96	281	1,718	44	1,570	4	0	100
New Jersey	2,111	60	213	748	1,089	197	679	22	0	191
New Mexico	31,494	10,703	62	511	20,218	593	2,203	7	0	17,415
New York	12,691	83	522	1,535	10,551	2,023	7,090	233	0	1,205
North Carolina	13,642	1,015	1,126	1,941	9,559	2,121	6,292	235	0	913
North Dakota	18,312	722	441	394	16,756	9,693	189	57	209	6,608
Ohio	10,702	151	165	1,676	8,710	4,474	2,868	322	0	1,046
Oklahoma	18,105	465	441	832	16,367	3,555	3,030	1,530	1,113	7,140
Oregon	25,156	12,651	335	562	11,608	1,458	5,155	176	126	4,692
Pennsylvania	11,734	293	195	1,765	9,482	1,997	6,309	173	0	1,002

Rhode Island	329	1	61	94	173	7	148	4	0	13
South Carolina	8,069	419	328	1,082	6,240	902	4,519	142	0	676
South Dakota	19,974	1,259	356	390	17,969	6,784	212	118	198	10,658
Tennessee	10,916	527	320	1,230	8,839	1,676	4,789	684	0	1,689
Texas	69,222	1,178	1,670	3,446	62,929	9,714	4,310	2,501	4,453	41,950
Utah	21,990	13,872	729	301	7,088	575	770	45	1	5,696
Vermont	2,490	171	106	159	2,054	219	1,665	18	0	153
Virginia	10,962	1,071	786	1,255	7,849	1,116	5,285	222	0	1,226
Washington	17,820	4,825	625	997	11,373	2,616	5,094	99	17	3,547
West Virginia	6,276	490	73	466	5,246	308	4,253	64	0	621
Wisconsin	14,536	747	523	1,103	12,164	4,056	5,908	382	0	1,818
Wyoming	25,334	11,634	179	276	13,246	861	390	1	5	11,990

2.A.2. Water Balance

Total water inputs into the cultivation system will consist of a mixture of newly sourced water and reclaimed water. The volume of water that must be pumped into the cultivation ponds on an annual basis is calculated as described in expression 2.A.1. Similar calculations are made for inoculum ponds. In all cases, the values are normalized to the light available surface area of the cultivation ponds only.

$$V_{TOTAL\ input} = V_{fill} * freq_{empty} + V_{evap\ loss} + V_{leaks} + V_{blowdown} + V_{harv} \qquad (2.A.1)$$

where

$V_{TOTAL\ input}$ is the volume of water per unit area that must be added to the cultivation ponds annually (m^3/m^2-yr).

V_{fill} is the nominal volume of water required to completely fill the cultivation ponds (m^3/m^2).

$freq_{empty}$ is the frequency with which the pond is emptied for cleaning or maintenance expressed as number of complete volumetric turnovers per year ($year^{-1}$)

$V_{evap\ loss}$ is the annual evaporative loss of water from pond surfaces during the growing season (equal to pan evaporation minus precipitation) per unit area (m^3/m^2-yr)

V_{leaks} is the annual volumetric loss of water due to leaks at the interface between the culture medium and the containment system (m^3/m^2-yr).

$V_{blowdown}$ is the volume of water removed annually per unit area in order to control water chemistry when fresh water is preferentially evaporated from the surface of ponds (m^3/m^2-yr).

V_{harv} is the volume of water removed from cultivation ponds during the harvesting process (m^3/m^2-yr), or feed to downstream ponds in the case of inoculum ponds.

Table 2.A.3. Water balance for cultivation system, in units of m^3/m^2-yr, where volume (m^3) is either water or water plus suspended algae, area (m^2) is surface area of the cultivation ponds, and a year is 365 days.

State	% of US Potential	Annualized rates for cultivation and inoculum ponds									
		Fill (seasonal and post PM)	Evapor-ation	Leaks	Blow-down	Harvest	Total Volume Input	Inoculum Feed	Reclaim from Harvest	Fresh Water, newly sourced	Saline Water, newly sourced
		m^3/m^2-yr									
US Wtd Avg	100%	0.8	0.8	0.3	0.1	36.9	38.9	3.3	29.9	1.0	4.7
Alabama	0.6%	1.1	0.7	0.3	0.1	41.6	43.8	3.8	33.8	0.8	5.5
Arizona	7.8%	1.1	1.4	0.3	0.2	45.0	48.0	4.1	36.5	1.6	5.8
Arkansas	0.7%	0.7	0.7	0.3	0.1	37.5	39.3	3.4	30.4	0.8	4.7
California	4.8%	1.1	1.1	0.3	0.2	45.0	47.6	4.1	36.5	1.2	5.8
Colorado	4.6%	0.7	0.6	0.2	0.1	29.1	30.7	2.6	23.6	0.6	3.8
Connecticut	0.0%	0.7	0.4	0.2	0.1	33.3	34.7	3.0	27.0	0.5	4.3
Delaware	0.0%	0.7	0.5	0.2	0.1	33.3	34.8	3.0	27.0	0.6	4.3
Florida	2.2%	1.1	1.1	0.4	0.2	50.0	52.7	4.5	40.5	1.3	6.4
Georgia	0.6%	1.1	0.7	0.3	0.1	41.6	43.8	3.8	33.8	0.8	5.5
Idaho	1.4%	0.7	0.4	0.2	0.1	29.1	30.5	2.6	23.6	0.5	3.8
Illinois	0.5%	0.7	0.5	0.2	0.1	33.3	34.8	3.0	27.0	0.5	4.3
Indiana	0.3%	0.7	0.5	0.2	0.1	33.3	34.8	3.0	27.0	0.5	4.3
Iowa	0.7%	0.7	0.5	0.2	0.1	29.1	30.6	2.6	23.6	0.5	3.8
Kansas	2.9%	0.7	0.9	0.2	0.1	33.3	35.3	3.0	27.0	1.0	4.3
Kentucky	0.8%	0.7	0.5	0.2	0.1	33.3	34.9	3.0	27.0	0.6	4.3
Louisiana	0.9%	1.1	0.9	0.3	0.1	41.6	44.0	3.8	33.8	1.0	5.5
Maine	0.1%	0.7	0.2	0.2	0.0	25.0	26.1	2.3	20.3	0.3	3.4
Maryland	0.1%	0.7	0.5	0.2	0.1	33.3	34.9	3.0	27.0	0.6	4.3
Massachusetts	0.0%	0.7	0.3	0.2	0.0	31.6	33.0	2.9	25.7	0.4	4.1
Michigan	0.6%	0.7	0.3	0.2	0.0	29.1	30.4	2.6	23.6	0.4	3.8
Minnesota	0.9%	0.7	0.3	0.2	0.0	25.0	26.2	2.3	20.3	0.3	3.4
Mississippi	0.6%	1.1	0.8	0.3	0.1	41.6	43.9	3.8	33.8	0.9	5.5
Missouri	1.8%	0.7	0.6	0.2	0.1	33.3	34.9	3.0	27.0	0.6	4.3
Montana	6.1%	0.7	0.4	0.2	0.1	25.0	26.3	2.3	20.3	0.4	3.4
Nebraska	4.0%	0.7	0.6	0.2	0.1	29.1	30.7	2.6	23.6	0.7	3.8
Nevada	1.6%	0.7	0.8	0.2	0.1	33.3	35.1	3.0	27.0	0.9	4.3
New Hampshire	0.0%	0.7	0.3	0.2	0.0	25.0	26.1	2.3	20.3	0.3	3.4
New Jersey	0.1%	0.7	0.5	0.2	0.1	33.3	34.8	3.0	27.0	0.5	4.3
New Mexico	8.3%	0.7	1.1	0.3	0.2	37.5	39.7	3.4	30.4	1.3	4.7
New York	0.5%	0.7	0.3	0.2	0.0	29.1	30.4	2.6	23.6	0.4	3.8
North Carolina	0.5%	1.1	0.7	0.3	0.1	41.6	43.8	3.8	33.8	0.8	5.5
North Dakota	2.2%	0.7	0.4	0.2	0.0	25.0	26.3	2.3	20.3	0.4	3.4
Ohio	0.4%	0.7	0.5	0.2	0.1	33.3	34.8	3.0	27.0	0.5	4.3
Oklahoma	3.4%	0.7	1.0	0.3	0.1	37.5	39.6	3.4	30.4	1.1	4.7
Oregon	1.9%	0.7	0.5	0.2	0.1	31.6	33.2	2.9	25.7	0.6	4.1

Pennsylvania	0.4%	0.7	0.4	0.2	0.1	33.3	34.7	3.0	27.0	0.5	4.3
Rhode Island	0.0%	0.7	0.4	0.2	0.1	33.3	34.7	3.0	27.0	0.5	4.3
South Carolina	0.3%	1.1	0.7	0.3	0.1	41.6	43.8	3.8	33.8	0.8	5.5
South Dakota	3.6%	0.7	0.4	0.2	0.1	25.0	26.3	2.3	20.3	0.5	3.4
Tennessee	0.8%	0.7	0.6	0.3	0.1	37.5	39.2	3.4	30.4	0.7	4.7
Texas	23.4%	1.1	1.3	0.3	0.2	45.8	48.6	4.1	37.1	1.4	5.9
Utah	2.4%	0.7	0.7	0.2	0.1	33.3	35.1	3.0	27.0	0.8	4.3
Vermont	0.1%	0.7	0.3	0.2	0.0	25.0	26.1	2.3	20.3	0.3	3.4
Virginia	0.6%	0.7	0.6	0.3	0.1	37.5	39.2	3.4	30.4	0.7	4.7
Washington	1.4%	0.7	0.4	0.2	0.1	30.0	31.4	2.7	24.3	0.5	3.9
West Virginia	0.3%	0.7	0.4	0.2	0.1	33.3	34.8	3.0	27.0	0.5	4.3
Wisconsin	0.6%	0.7	0.3	0.2	0.0	25.0	26.2	2.3	20.3	0.3	3.4
Wyoming	4.0%	0.7	0.5	0.2	0.1	25.0	26.4	2.3	20.3	0.5	3.4

2.A.3. Energy to Acquire New Water

Table 2.A.4. Direct and upstream energy requirements to supply newly sourced water to both cultivation ponds and inoculum ponds per unit surface area of cultivation ponds.

State	% of US Potential	Conventional Crop Irrigation		Fresh water for cultivation of saline algae			Saline water for cultivation of saline algae				
		Electric to Diesel [1]	Energy to Pump Fresh Water [2]	Volume of Fresh Water, newly sourced	Direct Energy to Pump Fresh Water	Upstream Energy to Pump Fresh Water [3]	Mean Depth to Saline Aquifer (visual estimate) [4]	Energy to Pump Saline Water [5]	Volume of Saline Water, newly sourced	Direct Energy to Pump Saline Water	Upstream Energy to Pump Saline Water [3]
			MJ/m^3	m^3/m^2-yr	MJ/m^2-yr	MJ/m^2-yr	meters	MJ/m^3	m^3/m^2-yr	MJ/m^2-yr	MJ/m^2-yr
US Wtd Avg	100%	9.7	1.3	1.0	1.3	3.0	181	3.6	4.7	16.8	34.5
Alabama	0.6%	0.5	3.9	0.8	3.2	3.2	259	5.2	5.5	28.5	28.4
Arizona	7.8%	8.3	0.6	1.6	0.9	2.2	183	3.7	5.8	21.4	49.4
Arkansas	0.7%	0.5	0.6	0.8	0.5	0.5	274	5.5	4.7	25.9	25.2
California	4.8%	4.7	0.9	1.2	1.1	2.5	76	1.5	5.8	8.9	19.2
Colorado	4.6%	31.1	0.9	0.6	0.6	1.5	229	4.6	3.8	17.4	43.3
Connecticut	0.0%	0.2	1.9	0.5	0.9	0.6	180	3.6	4.3	15.4	10.0
Delaware	0.0%	0.3	3.0	0.6	1.7	1.2	381	7.6	4.3	32.6	24.1
Florida	2.2%	0.3	1.3	1.3	1.6	1.2	343	6.9	6.4	44.0	33.6
Georgia	0.6%	1.5	2.4	0.8	2.0	3.2	381	7.6	5.5	41.9	68.1
Idaho	1.4%	49.2	0.8	0.5	0.4	0.9	76	1.5	3.8	5.8	14.6
Illinois	0.5%	1.5	1.5	0.5	0.8	1.4	76	1.5	4.3	6.5	10.5
Indiana	0.3%	1.2	1.5	0.5	0.8	1.2	76	1.5	4.3	6.5	9.5
Iowa	0.7%	1.8	0.9	0.5	0.5	0.8	122	2.4	3.8	9.3	15.8
Kansas	2.9%	1.4	1.9	1.0	1.9	2.9	168	3.4	4.3	14.3	22.8
Kentucky	0.8%	0.5	3.0	0.6	1.7	1.6	137	2.7	4.3	11.7	11.0
Louisiana	0.9%	0.3	1.6	1.0	1.6	1.2	229	4.6	5.5	25.1	19.3
Maine	0.1%	0.0	2.4	0.3	0.6	0.1	180	3.6	3.4	12.1	2.2
Maryland	0.1%	0.2	3.4	0.6	2.0	1.2	381	7.6	4.3	32.6	19.9
Massachusetts	0.0%	0.2	1.2	0.4	0.5	0.3	180	3.6	4.1	14.7	8.3
Michigan	0.6%	1.9	1.8	0.4	0.7	1.2	183	3.7	3.8	13.9	24.4
Minnesota	0.9%	5.5	1.2	0.3	0.4	0.9	76	1.5	3.4	5.1	11.2
Mississippi	0.6%	0.4	1.2	0.9	1.1	0.9	381	7.6	5.5	41.9	36.6
Missouri	1.8%	0.7	1.0	0.6	0.6	0.8	76	1.5	4.3	6.5	7.8
Montana	6.1%	8.7	0.5	0.4	0.2	0.5	213	4.3	3.4	14.3	33.2
Nebraska	4.0%	1.7	2.0	0.7	1.4	2.3	343	6.9	3.8	26.0	43.5
Nevada	1.6%	25.9	1.3	0.9	1.1	2.8	76	1.5	4.3	6.5	16.1
New Hampshire	0.0%	1.3	3.7	0.3	1.1	1.6	180	3.6	3.4	12.1	18.5
New Jersey	0.1%	0.2	3.8	0.5	2.0	1.2	343	6.9	4.3	29.3	18.0

New Mexico	8.3%	20.3	1.1	1.3	1.4	3.4	122	2.4	4.7	11.5	28.2
New York	0.5%	0.2	2.5	0.4	0.9	0.5	305	6.1	3.8	23.2	13.4
North Carolina	0.5%	0.5	3.1	0.8	2.6	2.4	152	3.0	5.5	16.7	15.6
North Dakota	2.2%	7.1	0.8	0.4	0.3	0.7	91	1.8	3.4	6.1	13.9
Ohio	0.4%	0.7	2.1	0.5	1.1	1.4	76	1.5	4.3	6.5	7.8
Oklahoma	3.4%	1.4	1.6	1.1	1.8	2.8	107	2.1	4.7	10.1	15.7
Oregon	1.9%	15.7	0.6	0.6	0.4	0.9	76	1.5	4.1	6.2	15.1
Pennsylvania	0.4%	3.9	2.5	0.5	1.1	2.3	213	4.3	4.3	18.2	37.9
Rhode Island	0.0%	0.3	5.3	0.5	2.4	1.6	180	3.6	4.3	15.4	10.4
South Carolina	0.3%	5.0	1.4	0.8	1.1	2.5	381	7.6	5.5	41.9	90.7
South Dakota	3.6%	6.4	0.8	0.5	0.4	0.8	274	5.5	3.4	18.4	41.3
Tennessee	0.8%	0.4	2.0	0.7	1.4	1.2	320	6.4	4.7	30.2	26.8
Texas	23.4%	7.6	2.1	1.4	3.0	6.9	191	3.8	5.9	22.6	51.7
Utah	2.4%	12.8	0.5	0.8	0.4	1.0	152	3.0	4.3	13.0	31.2
Vermont	0.1%	27.2	1.2	0.3	0.4	0.9	180	3.6	3.4	12.1	30.0
Virginia	0.6%	0.4	3.5	0.7	2.4	2.0	381	7.6	4.7	35.9	29.3
Washington	1.4%	42.9	0.6	0.5	0.3	0.7	76	1.5	3.9	6.0	15.0
West Virginia	0.3%	2.2	0.7	0.5	0.3	0.6	152	3.0	4.3	13.0	23.6
Wisconsin	0.6%	11.3	1.6	0.3	0.5	1.2	76	1.5	3.4	5.1	12.1
Wyoming	4.0%	7.2	0.4	0.5	0.2	0.5	168	3.4	3.4	11.2	25.6

[1] Based on data in Farm and Ranch Irrigation Survey (2008) (USDA, 2010)

[2] Includes both surface and groundwater sources. Estimated from irrigation energy cost per acre, assuming $0.10 kWh and $2.50 gallon of diesel, and average volume of water applied per acre for all crops (USDA, 2010)

[3] Assumes upstream energy multiplier of 2.565 for electricity and 0.18 for diesel (ANL, 2009)

[4] Visual estimate from map in (Alley, 2003); Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont are taken to have average depths of 180 m (US average)

[5] Estimated as theoretical energy (mass*gravity*depth) with an overall pumping efficiency of 50%: 0.0196 MJ per m3 of water per m of depth; consistent with estimates of energy to pump fresh water from 75 meters in Farm and Ranch Irrigation Survey (2008) (USDA, 2010)

2.A.4. Water Circulation

The general formula used to determine the amount of power required for water circulation within the ponds is based on Weissman *et al*. (Weissman, et al., 1989) and is given as:

$$P / A_{pond} = g * \rho_{culture} * (\upsilon_{mixing})^3 * n^2 / (\delta_{water})^{0.33} * \varepsilon_{mixing} \qquad (2.A.2)$$

where

P / A_{pond} is power in watts per meter squared (W/m^2) required to operate the paddlewheel

g is the gravity constant in meters per seconds squared ($9.81\ m/s^2$)

$\rho_{culture}$ is the density of the algae culture in kilograms per meter cubed (kg/m^3), which is estimated to be equal to the density of water ($1000\ kg/m^3$).

υ_{mixing} is the mixing velocity in meters per second (m/s)

n is the Manning number in seconds per cube root meter ($s/m^{0.33}$)

δ_{water} is the depth of the water in meters (m)

ε_{mixing} is the overall efficiency of the mixing system

The nominal system assumes a mixing velocity, υ_{mixing}, of 0.3 m/sec. Typical values for the Manning coefficient, n, are 0.010 for very smooth surfaces such as plastic (Weissman, et al., 1989). The depth of the water is assumed to be 0.3 meters. The overall efficiency of the mixing system is estimated to be 20%. The required mixing power per unit area is thus 0.197 watts/m^2. If the circulation system is run an average of 12 hours per day during the growing season, the total energy required is 1.89 MJ/m^2-yr.

2.A.5. Energy to Pump Water between Ponds

The energy required to pump water within the system is estimated by assuming a differential head of 25 meters (requiring an operating pump pressure of 35 psi). This is consistent with the sizing of discharge pumps used in US agriculture and accounts for friction losses as well as small (less than 3 m) differences in elevation. All pumping is assumed to be completed using an electric pump with an efficiency of 50%, the density of the medium is taken to be the same as water. Energy requirements are calculated as

$$E = V_{medium} * \rho_{medium} * g * dh_{system} / \varepsilon_{system} \tag{2.A.3}$$

where

E is the energy required to pump water in and out of the ponds and centrifuge per m^2-yr

V_{medium} is the volume of the culture medium pumped in m^3/m^2-yr

ρ_{medium} is the density of the culture medium (kg/m^3)

g is the gravity constant, equal to 9.8 m/s^2

dh_{system} is the differential head of the system in meter

ε_{system} is the efficiency of the system

Required energy for V_{medium} equal to 73.4 m^3/m^2-yr is thus equal to calculated as 35.49 MJ/m^2-yr

$$73.4\ m^3/m^2\text{-yr} * 1000\ kg/m^3 * 9.81\ m/s^2 * 25\ m / 50\% = 36.0\ MJ/m^2\text{-yr}$$

2.A.6. Water Containment

Plastic Liners

Cultivation ponds and large inoculum ponds are modeled as open raceway ponds with 1 hectare of water surface area (Figure 2.A.1). The ponds are constructed of earthwork berms and lined with 2 mm thick sheets of high density polyethylene HDPE plastic. The sheets must extend to the top of the berms where they are anchored in the earthworks. Anchoring and overlap of sheets means that total material use is greater than that of total surface area in contact with the culture medium.

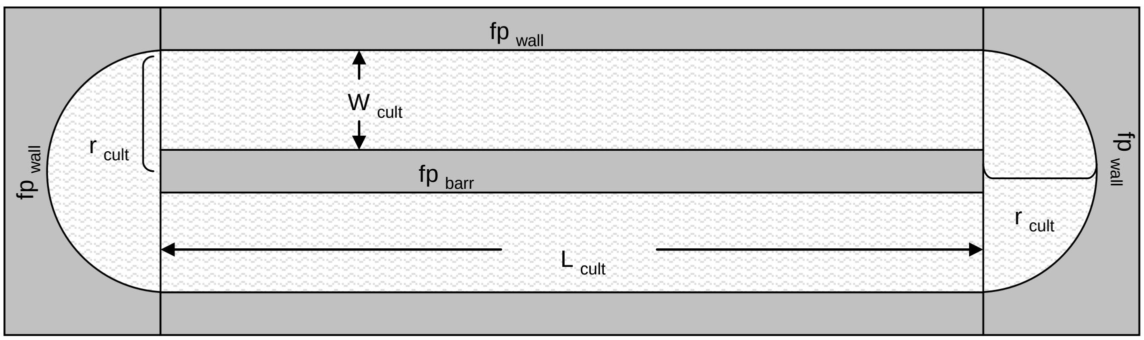

FIGURE 2.A.1: Dimensions of raceway pond (not drawn to scale) are shown above.

The volume of plastic required to line the floor of one modeled 10,000 m^2 pond is calculated as.

$$V_{HDPE\ floor} = \%M_{plastic\ liner} * tx_{liners,\ HDPE} * (\pi * [W_{cult} + fp_{barr}/2]^2 + 2 * W_{cult} * L_{cult}) \quad (2.A.4)$$

where

$V_{HDPE\ floor}$ is the volume of plastic to line the floor of one cultivation pond

$\%M_{plastic\ liner}$ is the percent material usage relative to theoretical minimum, assumed to be 120% to account for overlap, anchoring, and waste

$tx_{liners,\ HDPE}$ is the thickness of the plastic liner, assumed to be 2 mm (0.002 m)

fp_{barr} is the footprint of each channel barrier, equal to 2.8 m in the model design

W_{cult} is the channel width of the cultivation pond, equal to 17 m in the model design

L_{cult} is the channel length of the cultivation pond, equal to 258 m in the model design

$$V_{HDPE\ floor} = 120\% * 0.002\ \text{m} * (\pi * [17\ \text{m} + 2.8\ \text{m}/2]^2 + 2 * 17\ \text{m} * 258\ \text{m}) = 24\ \text{m}^3$$

The density of HDPE is 950 kg/m^3 and the floor lining is expected to last 10 years. An additional 11% will be required for inoculum ponds. Thus for every 1 m^2 of cultivation pond surface area, the mass of HDPE for floor linings is estimated to be

$$(950\ \text{kg/m}^3 * 24\ \text{m}^3 * 1.11) / (10{,}000\ \text{m}^2 * 10\ \text{years}) = 0.253\ \text{kg/m}^2\text{-yr}$$

The volume of plastic required to line the walls of one modeled 10,000 m^2 pond is calculated as.

$$V_{HDPE\ wall} = \%M_{plastic\ liner} * tx_{liners,\ HDPE} * (ISL_{wall} + ISL_{barr}) * h_{pond} \qquad (2.A.5)$$

where

$V_{HDPE\ wall}$ is the volume of plastic to line the walls of one cultivation pond

$\%M_{plastic\ liner}$ is the percent material usage relative to theoretical minimum, assumed to be 120% to account for overlap, anchoring, and waste

$tx_{liners,\ HDPE}$ is the thickness of the plastic liner, assumed to be 2 mm (0.002 m)

fp_{barr} is the footprint of each channel barrier, equal to 2.8 m in the model design

ISL_{wall} is the interior surface length along the walls of the cultivation pond, equal to 634 m in the model design

ISL_{barr} is the interior surface length along both sides of the center barrier of the cultivation pond, equal to 526 m in the model design

h_{pond} is the height of the earthen berm walls and barriers, equal to 0.7 m in the model design

$$V_{HDPE\ wall} = 120\% * 0.002\ m * (634\ m + 526\ m) * 0.7\ m = 1.95\ m^3$$

The lifetime of the plastic on the walls is expected to be less than that used on the bottom of the ponds due to much greater exposure to sunlight, thermal cycling, and pests (insects, rodents, and weeds). It is estimated that this material will need to be replaced once every 5 years. The density of HDPE is 950 kg/m^3 and an additional 11% will be required for inoculum ponds. Thus for every 1 m^2 of cultivation pond surface area, the mass of HDPE for wall linings is estimated to be

$$(950\ kg/m^3 * 1.95\ m^3 * 1.11) / (10{,}000\ m^2 * 10\ years) = 0.041\ kg/m^2\text{-}yr$$

The evaporation ponds used to contain water released during the blowdown process will need to be lined to avoid salinization of the underlying and surrounding soil or release of potentially undesirable microorganisms to the environment. In the model design, there is one blowdown pond per 1 hectare cultivation pond. Each blowdown pond measures 100 x 150 meters and with 0.7 meter high earthen walls.

The volume of plastic required to line the walls of one evaporation pond is calculated as

$$V_{HDPE\ evap} = \%M_{plastic\ liner} * tx_{liners,\ HDPE} * (A_{evap} + 2 * [W_{evap} + L_{evap}] * h_{pond}) \quad (2.A.6)$$

where

$V_{HDPE\ evap}$ is the volume of plastic to line the walls of one evaporation pond

$\%M_{plastic\ liner}$ is the percent material usage relative to theoretical minimum, assumed to be 120% to account for overlap and anchoring

$tx_{liners,\ HDPE}$ is the thickness of the plastic liner, assumed to be 2 mm (0.002 m)

A_{evap} is the area of each evaporation pond, equal to 15,000 m^2 in the model design

W_{evap} is the width of the evaporation pond, equal to 100 m in the model design

L_{evap} is the length of the evaporation pond, equal to 150 m in the model design

h_{pond} is the height of the earthen berm walls and barriers, equal to 0.7 m in the model design

$$V_{HDPE\ evap} = 120\% * 0.002\ m * (15{,}000\ m^2 + 2 * [100\ m + 150\ m] * 0.7\ m) = 36.8\ m^3$$

The lifetime of the plastic is expected to be 5 years. The density of HDPE is 950 kg/m^3 and there is one pond per ten 10,000 m^2 of cultivation ponds. Thus for every 1 m2 of cultivation pond surface area, the mass of HDPE for evaporation ponds is estimated to be

$$(950\ kg/m^3 * 36.8\ m^3) / (10 * 10{,}000\ m^2 * 5\ years) = 0.700\ kg/m^2\text{-yr}$$

The sum HDPE usage is thus the sum of that used for wall linings plus floor linings plus evaporation pond linings or

$$0.253\ kg/m^2\text{-yr} + 0.041\ kg/m^2\text{-yr} + 0.070\ kg/m^2\text{-yr} = 0.36\ kg/m^2\text{-yr}$$

<u>Concrete Settling Ponds</u>

Each harvest pond is assumed to be 3 meters deep; the area is equal to 6% of the cultivation pond area or 600 m^2 per hectare. The dimensions are taken to be 20 by 30 meters to service a 1-ha pond. The thickness of the concrete is assumed to be 0.15 m. The total volume of concrete per harvest pond is thus equal to

$$0.15\ m * [(20\ m * 30\ m + 2 * 3\ m * (20\ m + 30\ m)] * 1\ ha / 10{,}000\ m^2 = 0.0135\ m^3/m^2$$

A typical density for concrete is 2,380 kg/m^3 and the ponds should last the lifetime of the pond, (20 years) giving a final material use rate of 1.61 kg/m^2-yr.

$$(2{,}380\ kg/m^3 * 0.0135\ m^3/m^2) / 20\ years = 1.61\ kg/m^2\text{-yr}$$

2.A.7. References

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