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# Development of life cycle water footprints for the production of fuels and chemicals from algae biomass

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## ABSTRACT

This study develops life cycle water footprints for the production of fuels and chemicals via thermochemical conversion of algae biomass. This study is based on two methods of feedstock production – ponds and photobioreactors (PBRs) – and four conversion pathways – fast pyrolysis, hydrothermal liquefaction (HTL), conventional gasification, and hydrothermal gasification (HTG). The results show the high fresh water requirement for algae production and the necessity to recycle harvested water or use alternative water sources. To produce 1 kg of algae through ponds, 1564 L of water are required. When PBRs are used, only 372 L water are required; however, the energy requirements for PBRs are about 30 times higher than for ponds. From a final product perspective, the pathway based on the gasification of algae biomass was the thermochemical conversion method that required the highest amount of water per MJ produced (mainly due to its low hydrogen yield), followed by fast pyrolysis and HTL. On the other hand, HTG has the lowest water footprint, mainly because the large amount of electricity generated as part of the process compensates for the electricity used by the system. Performance in all pathways can be improved through recycling channels.

## 1. Introduction

The water consumption of the entire life cycle of a product needs to be assessed because water is a scarce resource. It is expected that in a few decades it will be challenging to meet basic human needs in terms of access to water for large proportions of the population (Jackson et al., 2001). Preserving natural habitats and systems is also very important, and the removal of resources fundamental to these systems can be damaging (Postel and Richter, 2012). For these reasons, it is important that agriculture and industrial processes do not threaten access to water. In recent years, studies have been conducted to measure the water footprint of many different crops (Gerbens-Leenes et al., 2009; Mekonnen and Hoekstra, 2010). Furthermore, as algae cultivation becomes more common, it is also important to understand all the effects on the environment so that informed decisions on the possibility and scale of production can be made. Over the last few decades, many different types of feedstocks have been studied as candidates for biomass sources in bioenergy production (McKendry, 2002a; Swana et al., 2011), and the different characteristics in each offer a range of characteristics on the final product (McKendry, 2002b). One feedstock that has attracted more interest of late is algae biomass, mainly due to its unique properties and methods of production, including via ponds and photobioreactors (PBRs) (Doucha et al., 2005; Jorquera et al., 2010; Pankratz et al., 2017; Ugwu et al., 2008).

One of the main resources required for alga production, and to a lesser extent its processing, is water (Dismukes et al., 2008; Pate et al., 2011). Depending on the geographical location of the production facility, obtaining the minimum amount of water necessary to produce the biomass can be challenging, and given the high volume required for algae cultivation, the impact is generally considerable (Slade and Bauen, 2013). To reduce water use, the possibility of recycling the water used during the algae life cycle (Yang et al., 2011) or cultivating a species of alga in wastewater from municipal waste to lower the high water requirement during cultivation have been considered (Wang et al., 2016). One important consideration regarding water consumption during algae production is to determine which cultivation method offers more advantages, the most commonly used and better understood algae

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production in ponds or the relatively new technology that uses photobioreactors (PBRs). Recent studies show that some types of PBRs can be economically competitive with ponds (Davis et al., 2016; Ozkan et al., 2012). While there are several studies on the conversion of algae (through thermochemical processes or transesterification) to produce biofuel (Jonker and Faaij, 2013; Nautiyal et al., 2014), there are none on the conversion of algal biomass to diluent and very few on the production of hydrogen from algae through thermochemical conversion. These are the two products of interest and in high demand by the oil sands and chemical industries.

In oil sands applications, the chemicals namely diluent in the form of naphtha and paraffin, are employed to reduce density and to liberate hydrocarbon molecules from bitumen (Rao and Liu, 2013). Diluent, broadly defined as a diluting agent, is a substance that is added to viscous fluid to increase its flow. Diluents have a diverse range of applications, from the drug industry (Ebino, 1999) to the transportation of oil and bitumen extracted in the Canadian oil sands (Alvarez et al., 2009; Hemmingsen et al., 2005). The diluent helps in reducing the viscosity of bitumen to allow efficient transportation through pipeline (Miadonye et al., 2001). In general, they are natural gas condensates, consisting of heavy oil components from lighter compounds but may have lighter fractions (Tipman et al., 2001). Diluent is composed of paraffinic hydrocarbons molecules (Anhorn and Badakhshan, 1994; Mehrotra, 1992). In this regard, a liquid product from pyrolysis in the form of biodiluent has been patented (Pollard et al., 2015). Another patent highlights the use of methods for oil extraction using bitumen through Fischer-Tropsch process (Tessel, 2015). Furthermore, the properties of diluent in relation with naphtha condensates are comparable (Kumar et al., 2017). The aim is to use renewable biomass to produce stabilized bio-crude through HTL and fast pyrolysis, which would be employed as a diluent in oil sands applications. Hydrogen, also versatile, is used by the chemical, metallurgical, glass and electronics industries and has seen an increase in interest from the petroleum refining sector, especially for the refining of heavy oils that contain high amounts of sulfur and hydrogen (Ramachandran and Menon, 1998).

There are studies that explore the water footprint of biofuel production through different conversion pathways (Dominguez-Faus et al., 2009; Gerbens-Leenes and Hoekstra, 2011; Yi-Wen and May 2013). Gerbens-Leenes et al. provide some details of the water footprint of biofuel production from algae (Gerbens-Leenes et al., 2014). Their study focuses on transesterification as the primary method of biomass conversion. Since alga and all its conversion pathways are receiving increased interest as possible environmentally friendly sources of biofuels and other products, this study analyses the requirements of water, an important resource for the sustainability of the production and thermochemical conversion of algae, over the life cycle. A case study for Alberta, a western Canadian province, is conducted in this paper. The semi-arid climate in most of the Canadian provinces and the corresponding low volume of precipitation (Mbogga et al., 2009) dictate that resource use must be well planned to guarantee proper biomass growth. The overall objective of this paper is to analyse the life cycle water consumption of diluent and hydrogen production from algal biomass used as raw material. The specific objectives are to:

- Develop a method to estimate the water footprint for diluent and hydrogen production from algal biomass for four different conversion pathways. These thermochemical conversion methods that can be applied to algal biomass produced either through ponds or PBRs are:
  - o the production of diluent through fast pyrolysis and the hydrotreating of algae feedstock;
  - o the production of diluent through the hydrothermal liquefaction and hydrotreating of algae feedstock;
  - o the production of hydrogen through the gasification of algae feedstock and enrichment of syngas; and
  - o the production of hydrogen through the hydrothermal gasification (HTG) of algae feedstock and enrichment of syngas.
- Conduct sensitivity and uncertainty analyses to study the changes resulting from variations in input parameters on the life cycle water footprints of diluent and hydrogen production from algae.

## 2. Method

Calculating the water footprint from the production of diluent and hydrogen from algal biomass involves an analysis of the life cycle of the biomass from well-to-tank (which means all steps from resource acquisition for biomass cultivation to final production of chemicals of interest, except their consumption). The International Organization for Standardization suggests through their ISO 14040 norms a life cycle assessment framework that consists of a goal and scope definition, life cycle inventory, and impact assessment and interpretation (Standardization, 2006). First, the goal and scope define the system boundaries of the cases that will be analyzed and include details on possible impacts (negative or positive) for industry or government. The life cycle inventory is the part of the study in which all the information necessary for the analysis is assembled and all the input assumptions are made. Finally, the computation and analysis permit the assessment of environmental impacts and a better interpretation of the results of the study. This study adopts a functional unit of 1 MJ of diluent (for the fast pyrolysis and HTL analyses) and 1 MJ of hydrogen (for the gasification and HTG analyses). More specifically, for the resource of interest in this study, the results are presented in terms L of water/MJ of diluent or $H_2$. In other words, the functional unit is the amount of water required to produce 1 MJ of the product of interest in a wheel-to-gate approach. Different base cases were established so that the importance of each variable in the final results could be measured. Once this was done, an uncertainty analysis was conducted through a Monte Carlo simulation to determine the influence of uncertainties of some inputs on the results.

It is necessary to consider the unit operations involved in algal biomass production, thermochemical conversion through fast pyrolysis, hydrothermal liquefaction, hydrothermal gasification or conventional gasification, and hydrotreating to obtain diluent (in the cases of fast pyrolysis and HTL). The basic unit operations for

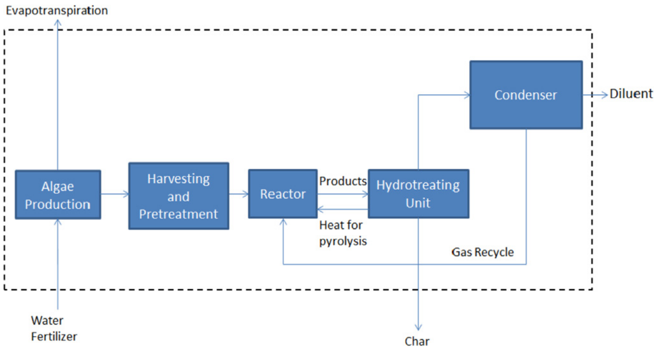

Fig. 1. System boundary for pyrolysis.

fast pyrolysis and HTL are the production and dewatering of algal biomass, drying (for fast pyrolysis only) and thermochemical conversion of the feedstock, and hydrotreating to produce diluent. The conversion pathway for fast pyrolysis is shown in Fig. 1 and for HTL in Fig. 2. For gasification and HTG, the unit operations are cultivation and dewatering, drying (for gasification only) and thermochemical conversion, and hydrogen production. The conversion pathway for thermal gasification and hydrothermal gasification is presented in Figs. 3 and 4, respectively. In both fast pyrolysis and HTG, it is assumed that the cultivation and conversion facilities are closely located and that the impact of transportation between units is negligible. This analysis uses data gathered from the literature on the cultivation and conversion of algal biomass (and other types of biomass, when case studies for algae are not conclusive), information obtained from industry, and information obtained through models developed by the authors in Aspen Plus (Aspen Plus, 2009). Some key assumptions were made for the analysis conducted in this paper. First, it was assumed that the algae production facility capacity is 2000 dry tonnes of biomass per day; this figure is used in earlier studies on large-scale biomass-based systems (Berndes, 2002; Moazami et al., 2012). Second, the thermochemical conversion plants have the infrastructure to use everything that is produced as it becomes available. Third, the production facilities and conversion plants are adjacent to each other and the impact of biomass transportation is negligible. Fourth, the inoculum systems of ponds have a negligible contribution to the overall water consumption of the process. Fifth, the electricity input to each stage of the process indirectly contributes to the overall water consumption, since water is required for energy generation. And last, water loss due to evaporation in PBRs is negligible, considering that PBRs are closed systems (versus open ponds).

A water footprint assessment for algae cultivation was conducted for two options. The first is the use of raceway ponds, which is currently the most common method of algae cultivation and consists of a recirculation channel where the feedstock, immersed in a liquid solution, is guided through the channel, thereby avoiding sedimentation (Chisti, 2007). The other method is the use of photobioreactors (PBRs), an innovative technology in which biomass is cultivated in enclosed systems, which increases the level of control the operator has over the parameters and makes it possible to maximize biomass production (Singh and Sharma, 2012). Of the four thermochemical conversion pathways considered in this study, two are for the production of diluent and two for hydrogen. In this study, the life cycle water footprint refers to both direct and indirect consumption of water during the processes used to produce algal biomass and to convert it to diluent or hydrogen. Direct consumption of water is defined as the total amount of water required during the entire biomass production phase and the subsequent thermochemical conversion processes, such as losses due to evaporation or blowdown of water at the steam generation or cooling stages. Indirect consumption refers to the amount of water used during fertilizer production (ammonia and diammonium phosphate, in this case) and electrical energy input for the various unit operations (Singh and Kumar 2011). Surface or ground water can be used as sources for both direct and indirect uses.

## 3. Water requirement inventory

Water requirements calculated in this inventory are categorized based on the unit operations that make up the entire production pathway of algal biomass to diluent or hydrogen.

### 3.1. Production of biomass

This section presents the input parameters related to the production of algae feedstock for the two main methods of algae cultivation, ponds and photobioreactors.

### 3.1.1. Ponds

Raceway ponds are very common in the algae facilities currently in operation (Chiaramonti et al., 2013). Hence there are many studies that explore in depth the operating conditions and production optimization methods in ponds (Borowitzka, 1999; Chiaramonti et al., 2013; Lee, 2001; Moheimani and Borowitzka, 2006). However, most of the literature in this area concentrates on facilities built in warm locations with high solar radiation all year and generally good conditions for algae cultivation in an open-air setting (Pankratz et al., 2017). This study considers a pond

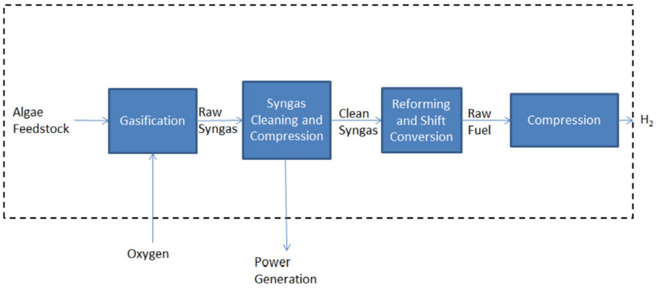

**Fig. 3.** System boundary for gasification.

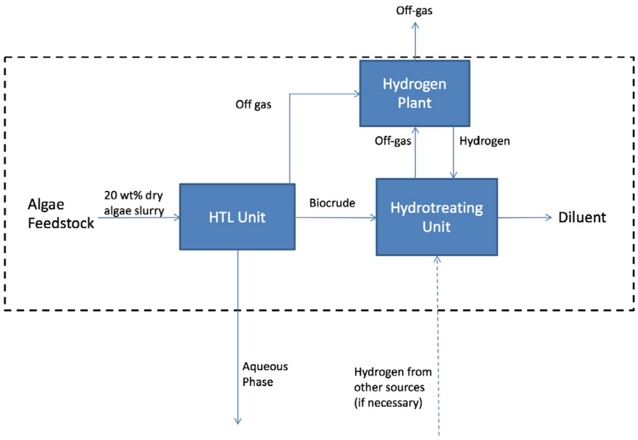

**Fig. 2.** System boundary for hydrothermal liquefaction.

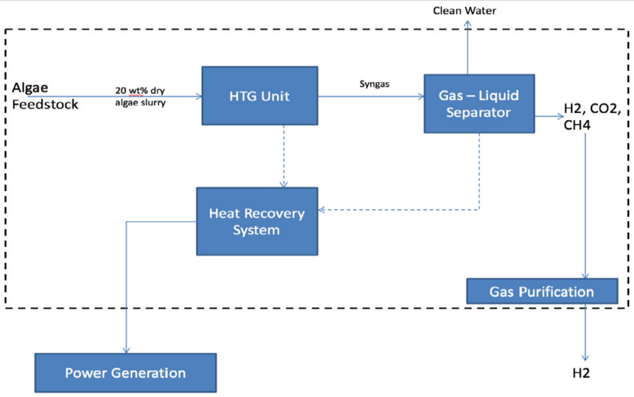

**Fig. 4.** System boundary for hydrothermal gasification.

facility in central Alberta, Canada, and assumes that production is limited to the warm months of the year, approximately 175 days. For ponds, some of the main sources of water loss are transpiration and evaporation, system blowdown, and losses during harvesting and drying. While some of these losses can be mitigated (for example, through water recycling feeds designed for the system), evapo-transpiration is a challenge in the dry climates and low precipitation rates in Alberta (Mbogga et al., 2009). Hence water replacement rates may be relatively high in this cultivation method. To estimate the average evaporation during summer, it was assumed that summer conditions in Alberta are similar to late spring/early autumn in Arizona (where detailed data on algae cultivation are available), so that an average evaporation rate can be adopted for this study. The evaporation data from Arizona were compared with data measured in the Wabamun Lake area in Alberta (Hage, 1978).

For our study, we assumed a large-scale facility capable of producing 2000 T of dry algae/day, with the same basic characteristics of operation and production described in a recent study (Davis et al., 2016). Daily alga production is assumed to be 25 g/m$^2$/d in a facility divided into farms of 20.2 million m$^2$ dedicated to pond cultivation only and a total footprint per farm (including processing and storage) of 30.8 million m$^2$. A design with 400,000 m$^2$ modules containing 50 raceway ponds of 8000 m$^2$ each is also assumed. The media in these ponds would be mixed by paddlewheels and the alga concentration kept at 0.1 g/L, or 0.01 wt %. An inoculum system is also part of the design; its goal is to guarantee the production of a high-concentration media for insertion into the ponds, which maintains the culture at the desired concentration. This inoculum system is negligible in size compared to the main system and does not account for a considerable percentage of the water consumption. The data for the water footprint analysis of algae cultivation in ponds were acquired from multiple sources, from industry partners to extensive studies of algae cultivation. Empirical data for what can be expected in Alberta, such as evaporation rate and number of days of harvest per year, help more accurately estimate water requirement. The calculated water footprint for the production of algae through ponds was 1564 L of water/kg of algae. The details of algae cultivation in raceway ponds as reported by (Davis et al., 2016) or derived from their data are provided in Table 1.

It is also important to consider the water footprint of the electricity consumption of the facility. In this case, the highest energy-consuming equipment are the pumps used to carry the algae solution through the ponds, the paddlewheels used to stir the ponds, and the drying apparatus used to increase the algae concentration to 20% dry weight before it is sent for thermochemical conversion. The drying consists of pumps, membranes for the first and most basic phase of the dewatering process, and centrifuges that guarantee the desired 20 wt%. The water consumption factor is adopted based on data for Alberta, Canada, where most of the electricity generation is coal-based. For ponds, the processes that require the highest amounts of water are the initial filling of the modules, water loss to evaporation, and blowdown.

**Table 1**
Basic operational data for algae cultivation in ponds (Davis et al., 2016).

| Operation | Value | Unit |
|---|---|---|
| Average daily algae production | 0.025 | kg/m$^2$/d |
| Pond cultivation area/farm | 20.2 million | m$^2$ |
| Pond depth | 0.25 | m |
| Pond motion velocity | 0.2 | m/s |
| Volume harvested daily | 20 | % |
| Size of module ponds | 100 | acres |
| Net evaporation rate/day | 0.5 | % |
| Blowdown - replacement of media/day | 0.5 | % |
| Media loss at harvesting | 0.2 | % |
| Number of days of harvest/year | 175 | days |
| Pumping | 0.75 | kW/acre |
| Paddlewheel | 1.35 | kW/acre |
| Pumping to/from dewatering | 1000 | kW/module pond |
| Energy demand (membranes) | 0.04 | kWh/m$^3$ |
| Inlet flow rate (membranes) | 76000 | m$^3$/day |
| Energy demand (centrifuges) | 1.35 | kWh/m$^3$ |
| Inlet flow rate (centrifuges) | 6000 | m$^3$/day |

### 3.1.2. Photobioreactors

PBRs are a promising alternative to ponds; however, there is not much information available on them in the literature. PBRs may be able to optimize algae production and resource allocation, since they allow more control of the operating parameters, such as temperature and light applied to the media (Chiaramonti et al., 2013). They also require a smaller cultivation area than ponds for the same amount of algae produced. PBRs can be designed and built in many different sizes. For this study, a tank size of 6800 L and a daily production of 20 kg of algae, like the one used by HY-TEK Bio, was assumed. This design consists of a hollow tank that has an airlift system to help with the mixture of the media (Singh and Sharma, 2012), with a bubble sparging mechanism containing $CO_2$ for the photosynthesis process. The algae concentration in a system of this type is assumed to be between 3 and 5 g/L, up to 50 times higher than in ponds. Because of the scarcity of data available on this equipment, a consistent set of parameters provided by industry was used and validated with data from various studies (Chen et al., 2011; Li et al., 2007; Rodolfi et al., 2009). The same assumptions were made for PBRs as for a pond producing 2000 T of algae per day. PBRs have negligible losses to evaporation since the culture remains in an enclosed space isolated from the environment. Other losses (i.e., water loss during harvesting) can be mitigated through systems controls. As expected, the water footprint for the cultivation of algae via PBRs is considerably lower than that for ponds; PBRs consume only 25 L of water/kg of algae produced. Table 2 gives the details of the basic operational data for algae cultivation in PBRs.

In terms of electricity consumption, PBRs require considerably more energy than ponds (Davis et al., 2016; Watanabe and Hall, 1996). This is due to the equipment necessary for the proper functioning of the system, such as the compressors to regulate the pressure and the many LED lamps that both transmit light and provide heat to the culture at all times of the day. This equipment would allow the cultivation of algae year round even in cold winter climates like Alberta's. The PBR algae cultivation processes that require the most water are the initial filling of the tanks, replacement of blowdown water, and electricity generation.

**Table 2**
Basic operational data for algae cultivation in PBRs (source: HY-TEK Bio).

| Operation | Value | Unit |
|---|---|---|
| PBR tank size | 6800 | L |
| PBR production/day | 20 | kg/day |
| Volume harvested each time | 10 | % |
| Number of harvests | 10 | #/day |
| Area occupied/PBR | 8 | m$^2$ |
| Blowdown | 6435 | m$^3$/day |
| Harvesting | 2145 | m$^3$/day |
| Compressor - Power/PBR | 6.25 | kW |
| LED lights' power/PBR | 0.9 | kW |
| Chiller for storage power | 10 | kW |
| Chiller for storage power/PBR | 0.01 | kW |
| Airlift system | 3.9 | kW/acre |
| Water consumption factor for electricity generation | 1.08 | L of water/kWh |

**Table 3**
Water requirements for pyrolysis of algae.

| Operation | Value | Unit | Source |
|---|---|---|---|
| Bio-oil cooling[a] | 0.027 | L water/kg bio-oil | (Ringer et al., 2006) |
| Bio-oil vapor cooling[a] | 0.003 | L water/kg bio-oil | (Ringer et al., 2006) |
| Steam condensing[a] | 1.077 | L water/kg bio-oil | (Ringer et al., 2006) |
| Steam system[a] | 0.026 | L water/kg bio-oil | (Ringer et al., 2006) |
| Ash quenching[a] | 0.233 | L water/kg bio-oil | (Ringer et al., 2006) |
| Recycle gas compression | 10400 | kW | This study |
| Feedstock grinding | 5600 | kW | This study |
| Other auxiliary | 1248 | kW | This study |
| Electricity generated | 19600 | kW | This study |

[a] Water consumption derived from the flow rates of the plant described by Ringer et al. (2006).

## 3.2. Fast pyrolysis

Fast pyrolysis is a thermochemical conversion method commonly used to convert biomass to bio-oil. It is a thermal decomposition process that occurs in high temperatures in the absence of oxygen in 0.5–10 s (flash pyrolysis lasts less than 0.5 s and conventional pyrolysis takes 5–10 min). Fast pyrolysis yields relatively high amounts of bio-oil (Demirbas, 2008; Patel et al., 2016). In this method, biomass is dried to a moisture content of <10% to decrease the water content in the fast pyrolysis bio-oil (Wright et al., 2010).

Biomass feedstock that only goes through dewatering leaves the cultivation facility with approximately 20 wt% dry biomass and must go through extra drying before being fed into the fast pyrolysis reactor. Feedstock with a moisture content of 5–10 wt% is preferred for fast pyrolysis (Bridgwater et al., 1999). Other important parameters in the pyrolysis reaction are particle size, temperature, pressure, and residence time. Once prepared, the dried biomass is sent to a fluidized bed pyrolysis reactor at 520 °C (Jones et al., 2009) with particles smaller than 2 mm. Following reaction, bio-char is removed by cyclones, resulting in a bio-oil yield of approximately 59.9 wt% (dry basis) depending on the feedstock (Ringer et al., 2006). For this study, a yield of 26130 kg/hr was estimated using process model (Kumar et al., 2018b). The fast pyrolysis values related to the water footprint generated by the cooling, ash quenching, steam condensing, and steam producing processes are extracted from the literature, given that there is no significant difference in water requirement for this equipment no matter which feedstock is used. Most of the water used in these processes is recycled, but there is an estimated loss of 3% due to factors such as blowdown and evaporation. Steam condensing is the main contributor to the water footprint (Ringer et al., 2006). Water is indirectly consumed through the generation of the electricity necessary to operate the plant during pre-treatment and pyrolysis. For the fast pyrolysis of algae, a process model was developed in Aspen Plus to estimate the entire plant's electricity consumption and generation, and the results for water requirements for algal pyrolysis are provided in Table 3. With the higher heating value (HHV) of diluent at approximately 34 MJ/kg, when all the factors shown in plus the hydrotreating factors (Table 5) are considered and all their contributions are added, the total water footprint from the production of diluent through fast pyrolysis is approximately 0.12 L/MJ of diluent.

## 3.3. Hydrothermal liquefaction

HTL is a thermochemical conversion process that converts biomass to bio-crude in the presence of large amounts of water (Toor et al., 2014). During the process, macromolecules are broken down into small molecules that are unstable and can recombine, with a good portion of the oxygen present in the biomass being removed (Toor et al., 2011). It is a method used to produce diluent and does so through medium temperature and high pressure reaction in a high concentration of water; bio-crude is its main product (Kumar et al. 2017, 2018a; Toor et al., 2014). In hydrothermal liquefaction, biomass is pumped to 18 MPa and passed through heat exchangers to increase the algal stream temperature to 350 °C (Kumar et al., 2017). At this temperature, water exists slightly below the supercritical point, which allows dissolution of biomass organics (Ou et al., 2015). The incoming effluent is fed into the HTL reactor, which converts biomass components into bio-crude. The output from the HTL reactor is filtered to obtain solid residue in the form of bio-char. The filtered effluent passes through a heat exchanger to recover heat before moving to a three-phase separator unit to produce aqueous, bio-oil, and gaseous phases (Zhu et al., 2014). The bio-crude undergoes hydrotreating, where it is deoxygenated (Tews et al., 2014).

Hydrothermal liquefaction happens at medium temperatures and high pressures and generates mainly the liquid product known as bio-crude but also gases and an aqueous phase (Akhtar and Amin, 2011). In this study, it is assumed that 2000 T (dry basis) of biomass is processed. A diluent yield of 28600 kg/hr was estimated on AspenPlus for the HTL case (Kumar et al., 2018b). Since for HTL no extra drying is necessary after cultivation, the feedstock fed into the HTL reactor is 20% dry content. Thus about 80% of the water can be recycled after the cooling and depressurization of the reaction effluents (Jones et al., 2014). The remaining water is sent to a wastewater treatment plant. The direct water footprint generated by HTL is affected by the cooling system and the boiler feed water, since these systems consume high amounts of water. Zhu et al., (2014) show that the differences in water requirement for the cooling system and boiler feed are negligible regardless of feedstock, and thus in this study we used their water consumption values for the cooling system and boiler feed. HTL also indirectly requires water for the electricity necessary to operate the equipment. However, electricity can be generated by burning the methane-rich off-gas, and this energy can be used in the HTL system, thereby reducing indirect water consumption (Zhu et al., 2014). Table 4 shows the water requirements for HTL of algae. With the higher heating value (HHV) of diluent at approximately

**Table 4**
Water requirement for the HTL of algae.

| Operation | Value | Unit | Source |
|---|---|---|---|
| Cooling water make-up | 4.32 | L water/kg diluent | (Zhu et al., 2014) |
| Boiler feed water make-up | 0.72 | L water/kg diluent | (Zhu et al., 2014) |
| Water purged/day | 1.17 | L water/kg algae | (Zhu et al., 2014) |
| Feed pre-treatment | 4.3 | MWe | This study |
| Steam reforming | 1.28 | MWe | This study |
| Other auxiliary | 0.11 | MWe | This study |
| Electricity generation | −1.9 | MWe | This study |
| Water consumption factor for electricity generation | 1.08 | L water/kWh | (Environment Canada, 2013; Statistics Canada, 2014) |

**Table 5**
Water requirement for hydroprocessing after the pyrolysis of algae.

| Operation | Value | Source |
|---|---|---|
| Cooling water required (L water/kg diluent)[a] | 0.08 | (Hsu, 2012) |
| Boiler feed required (L $H_2O$/kg diluent)[a] | 0.82 | (Hsu, 2012) |
| Natural gas (MJ/kg diluent)[a] | 12.18 | (Hsu, 2012) |
| Electricity (kWh/kg diluent)[a] | 0.410 | (Hsu, 2012) |
| Water use factor (L $H_2O$/kWh) | 1.08 | (Environment Canada, 2013; Statistics Canada, 2014) |

[a] Derived based on the values for hydroprocessing bio-oil to biodiesel.

**Table 6**
Parameters of hydroprocessing after the HTL of algae.

| Operation | Value | Unit | Source |
|---|---|---|---|
| Light hydrocarbons | 0.008 | wt% | This study |
| Diluent | 0.815 | wt% | (Davis et al., 2011) |
| Electricity | 3.8 | MWe | This study |
| Water consumption factor for electricity generation | 1.08 | | (Environment Canada, 2013; Statistics Canada, 2014) |

34 MJ/kg, when all the factors shown in plus the hydrotreating factors (Table 6) are considered and all their contributions are added, the total water footprint from production of diluent through HTL is approximately 0.20 L/MJ of diluent.

### 3.4. Upgrading of bio-oil/bio-crude

The bio-oil and bio-crude produced during fast pyrolysis and HTL, respectively, go through the hydroprocessing phase to remove oxygen and increase the stability and heating values of the products, which make them more attractive commercial options. These reactions use hydrogen and a catalyst (Jones et al., 2009), which contribute to the water footprint of the process, due to the steam reforming involved in the production of hydrogen. The most traditional hydroprocessing method is the one used to convert bio-oil/bio-crude to biofuel, which requires hydrotreating or hydrocracking, depending on the thermochemical conversion pathway (Hsu, 2012; Patel and Kumar 2016; Singh and Kumar 2011; Singh et al., 2014; Wong et al., 2016). However, for the production of diluent, only hydrotreating is required. Conditions for the hydrotreating of fast pyrolysis and HTL products are slightly different, since they have different characteristics. The water requirements for the hydrotreating of bio-oil generated through fast pyrolysis are shown in Table 5.

For upgrading bio-crude from HTL, the body of knowledge is still limited. Studies have been conducted in this area are by (Elliott, 2007; Elliott et al., 2015; Kumar et al., 2017; Tews et al., 2014). No large-scale facility has been built for this purpose, but the hydrotreating process for HTL products is in theory simpler than the hydrotreating process for fast pyrolysis products, since bio-crude has a lower oxygen content than bio-oil (Baker and Elliott, 1986). Bio-crude goes through only one hydrotreating step and requires less energy and reactant than the hydrotreating of bio-oil (Zhu et al., 2011), which requires two steps. In the developed process model, the hydrotreating of bio-crude involves a reaction of hydrogen in a fixed bed reactor at temperatures around 400 °C; around 78–85% of the product has diluent properties. The main parameters of the reaction are given in Table 6.

### 3.5. Gasification

The gasification of biomass is a thermochemical conversion process that converts feedstock into gaseous products through reactions in high temperatures (up to 850 °C) and atmospheric pressure. Biomass enters the system at 5–10% moisture content. Oxygen (or steam) and a catalyst agent are also used in the reaction (Turn et al., 1998). Gases such as $CH_4$, $H_2$, $CO_2$, and CO are produced from the gasification reaction, as are tar and char. The hydrogen concentration can be increased through reforming and shift conversion (Rapagnà et al., 1998). In this study, the estimated hydrogen yield through gasification is 6475 kg/hr. An earlier study of the gasification process and the current status of production and water

**Table 7**
Water requirement for the gasification of algae.

| Operation | Value | Unit | Source |
|---|---|---|---|
| Cooling water and utilities[a] | 1.78 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Steam system and power generation[a] | 0.49 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Gas clean-up and compression[a] | 1.48 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Gasification and tar reforming[a] | 0.05 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Drying and handling[a] | 20.96 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Feed handling and drying | 742 | kW | (Spath et al., 2005) |
| Gasification, tar reforming, quench | 3636 | kW | (Spath et al., 2005) |
| Compression and sulfur removal | 21,871 | kW | (Spath et al., 2005) |
| Steam methane reforming, shift and PSA | 630 | kW | (Spath et al., 2005) |
| Hydrogen compression | 3899 | kW | (Spath et al., 2005) |
| Steam system and power generation | −25,583 | kW | (Spath et al., 2005) |
| Steam system and power generation - required | 660 | kW | (Spath et al., 2005) |
| Cooling water and other utilities | 1110 | kW | (Spath et al., 2005) |
| Miscellaneous | 3255 | kW | (Spath et al., 2005) |
| Water consumption factor for electricity generation | 1.08 | L $H_2O$/kWh | (Environment Canada, 2013; Statistics Canada, 2014) |

[a] Water consumption derived from the flow rates of the plant described by Spath et al. (2005).

**Table 8**
Water requirements for the hydrothermal gasification of algae.

| Operation | Value | Unit | Source |
|---|---|---|---|
| Cooling, steam, and HTG reaction | 8.06 | L $H_2O$/kg $H_2$ | (Matsumura, 2002) |
| Tar reforming | 0.049 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Gas clean-up and compression | 1.23 | L $H_2O$/kg $H_2$ | (Spath et al., 2005) |
| Hydrogen/syngas ratio | 9.3 | | This study |
| Total plant power requirement | 74662 | kW | This study |
| Generated power | −92,462 | kW | This study |
| Grid electricity requirement | 17,800 | kW | This study |
| Water use factor | 1.08 | L $H_2O$/kWh | (Environment Canada, 2013; Statistics Canada, 2014) |

use in a hydrogen plant gives details on losses due to blowdown and evaporation. These losses are assumed to remain constant for the entire stream (from drying to output of final product) and are estimated to be around 2.2% of the flow (Spath et al., 2005). The indirect water footprint from the electricity required to operate the equipment in the plant can be offset by the electricity generated in the steam plant, which uses off-gases from the gasification process. It is estimated that of the approximately 35 MWe necessary to operate the facility, only about 10 MWe need to be extracted from the grid. The details of the water requirement for the different operations involved in the gasification of algae are provided in Table 7.

With the higher heating value (HHV) of hydrogen at approximately 34 MJ/kg, when all the factors shown in Table 7 are considered and their contributions are added, the total water footprint from the production of hydrogen through gasification is approximately 0.19 L/MJ of hydrogen.

### 3.6. Hydrothermal gasification

HTG is a thermochemical conversion pathway that uses the benefits of supercritical conditions of water in a solution as a reactant, making water itself a reaction partner to the feedstock. First, the bonds between the biomass macromolecules are broken through hydrolysis, then new molecules are formed in the presence of a catalyst agent (Kruse, 2009). The reaction normally happens at intermediate temperatures (300–410 °C) and high pressures (12–34 MPa), while the biomass initial concentration remains between 10 and 30 wt% (Waldner and Vogel, 2005) (for this study it is assumed to be 20 wt% after the cultivation phase). Generally, the product yield (syngas) from HTG is considerably higher than from gasification, and in this case was estimated at 9285 kg/hr. Syngas is then purified into $H_2$. The syngas is cleaned using Selexol and then sent to water-gas shift reactors to enrich $H_2$. A co-generation facility for power generation is also commonly built with the HTG plant (Fang and Xu, 2014; Gasafi et al., 2008; Verma et al., 2015). The co-generation plant uses off-gases from processing areas to produce electricity (Gasafi et al., 2008).

In terms of the direct water consumption, it was assumed that the tar reforming and gas compression phases had footprints comparable to their counterparts in the gasification pathway. The cooling system, steam feed, and HTG reaction estimates are taken from Matsumura, whose study considers different types of biomass (Matsumura, 2002). These values are assumed to have a negligible difference compared to those for algae biomass. The indirect water footprint from electricity consumption was estimated through the developed process model for all the equipment necessary to run the plant. Interestingly, the power generation possible in an HTG facility is so high that it compensates for the power requirement of the entire plant, making it possible to sell energy to the grid and consequently lead to a slightly negative water footprint in terms of the balance between electricity consumed and generated. Table 8 gives the details of the water requirement for different operations for the HTG of algae.

With the higher heating value (HHV) of hydrogen at approximately 142 MJ/kg, when all the factors shown in Table 8 are considered and their contributions added, the total water footprint from the production of hydrogen through HTG is approximately 0.05 L/MJ of hydrogen.

## 4. Results and discussion

Base case scenarios were developed to understand the water footprints of each cultivation method coupled with each conversion pathway. We compared algae cultivation methods and thermochemical conversion pathways according to their final results for the unit operations and the final water requirement for each base case scenario. We then varied the values of some input variables within a specified range so that the most significant ones could be identified. Lastly, an uncertainty analysis was conducted through a Monte Carlo simulation to estimate changes in results from the uncertainty of the inputs.

### 4.1. Base case scenario

The base case scenarios give the details of individual unit operations: biomass production and dewatering, harvesting, bio-oil or bio-crude production followed by hydrotreating (fast pyrolysis or HTL) or hydrogen production (gasification and HTG). Different process unit operations for diluent production through fast pyrolysis and HTL, respectively, are listed in Tables 9 and 10 shows the results of water use efficiency for the unit operations in the

**Table 9**
Life cycle water footprint for the conversion of algae biomass to diluent.

| Unit operation (L $H_2O$/MJ diluent) | Pond cultivation followed by pyrolysis | PBR cultivation followed by pyrolysis | Pond cultivation followed by HTL | PBR cultivation followed by HTL |
|---|---|---|---|---|
| Biomass production | 137.67 | 2.24 | 133.95 | 2.18 |
| Biomass harvesting and fertilization | 0.007 | 0.001 | 0.008 | 0.002 |
| Conversion | 0.071 | 0.071 | 0.19 | 0.19 |
| Hydroprocessing | 0.046 | 0.046 | 0.013 | 0.013 |
| Total | 137.79 | 2.36 | 134.15 | 2.20 |

**Table 10**
Life cycle water footprint for the conversion of algae biomass to hydrogen.

| Unit operation (L $H_2O$/MJ hydrogen) | Pond cultivation followed by gasification | PBR cultivation followed by gasification | Pond cultivation followed by HTG | PBR cultivation followed by HTG |
|---|---|---|---|---|
| Biomass production | 141.94 | 2.31 | 99.43 | 1.61 |
| Biomass harvesting and fertilization | 0.001 | 0.001 | 0.001 | 0.002 |
| Conversion | 0.19 | 0.19 | 0.05 | 0.05 |
| Total | 142.13 | 2.50 | 99.48 | 1.66 |

production of hydrogen through gasification and HTG, respectively.

The difference in water consumption for algae cultivation compared to every other unit operation is huge. In fact, it is more than 99% of the total consumption whether ponds or PBRs are used. Hence, any future system modelling aiming for lower water consumption rates must focus primarily on the cultivation side. The results show much higher water consumption in the algae biomass derived from pond cultivation than from PBRs. This was expected since photobioreactors offer a more controlled setting, where evaporation is negligible. Waste through blowdown and harvest are also significantly lower in PBRs than in ponds. On the other hand, the water footprint of PBRs from electricity use is considerably higher than that of ponds. This could be due to the high electrical demand for the equipment used in PBR cultivation (i.e., lighting, compressors, etc.). The higher electricity consumption in PBRs, however, is not enough to compensate for the high water footprint from the cultivation of algae in ponds. It is noticeable that the footprints of the thermochemical conversion methods are very small compared to the footprint of the cultivation phase. This is because the standard for any thermochemical plant design includes many opportunities for water recycling, and the concentration of algae in the solution that enters the plant is considerably higher than during cultivation. It is clear from the results that water consumption mitigation steps are important in the algae thermochemical conversion life cycle. Work by Yang et al. suggests means of achieving some reduction goals and reducing water consumption by up to 80% (Yang et al., 2011). Some measures that could mitigate the water footprint of algae cultivation include designing a system that includes feedback piping (to recycle water to other parts of the system) and developing a more efficient system that does not require large amounts of water.

The electricity consumption is less than the electricity generated for hydrothermal gasification, which causes a water footprint of −0.015 L $H_2O$/MJ hydrogen. This causes the water consumption footprint of HTG to be lower than in the other thermochemical conversion pathways. This is because the power generation of the hydrogen plant works in conjunction with the HTG facility. The water consumption footprint of gasification and HTG is generally lower per unit of energy produced because the higher heating value of hydrogen (142 MJ/kg) is much higher than that of diluent, a low energy product of approximately 34 MJ/kg.

### 4.2. Other scenarios – sensitivity analysis

The effects of the main inputs and contributing factors on the study results were analyzed by introducing different scenarios within specified ranges. Table 11 list all the considered scenarios in this study for an analysis of ponds and PBRs.

Figs. 3–6 show the sensitivity analysis results for the four thermochemical conversion methods and two cultivation options.

The results presented in the base case scenarios clearly show that biomass cultivation is the unit operation with the highest water footprint, in an order of magnitude of almost 1000:1 to any other variable. Therefore, it makes sense that any sensitivity

**Table 11**
(a) Scenarios for sensitivity analysis of ponds, (b) Scenarios for sensitivity analysis of PBRs.

| a. Scenarios for sensitivity analysis of ponds | |
|---|---|
| 1 | Decrease in pond depth design by 10% |
| 2 | Increase in pond depth design by 10% |
| 3 | Decrease in evaporation rate/day by 10% |
| 4 | Increase in evaporation rate/day by 10% |
| 5 | Decrease in replacement of media by 10% |
| 6 | Increase in replacement of media by 10% |
| 7 | Decrease in media loss at harvesting by 10% |
| 8 | Increase in media loss at harvesting by 10% |
| 9 | Decrease in the number of days of harvest/year by 10% |
| 10 | Increase in the number of days of harvest/year by 10% |
| 11 | Decrease in product yield (for all thermochemical conversion methods) by 10% |
| 12 | Increase in product yield (for all thermochemical conversion methods) by 10% |

| b. Scenarios for sensitivity analysis of PBRs | |
|---|---|
| 1 | Decrease in PBR tank size by 10% |
| 2 | Increase in PBR tank size by 10% |
| 3 | Decrease in media loss at harvesting by 10% |
| 4 | Increase in media loss at harvesting by 10% |
| 5 | Decrease in the number of harvests/day by 10% |
| 6 | Increase in the number of harvests/day by 10% |
| 7 | Decrease in electricity consumption by 10% |
| 8 | Increase in electricity consumption by 10% |
| 9 | Decrease in harvest volume by 10% |
| 10 | Increase in harvest volume by 10% |
| 11 | Decrease in product yield (for all thermochemical conversion methods) by 10% |
| 12 | Increase in product yield (for all thermochemical conversion methods) by 10% |

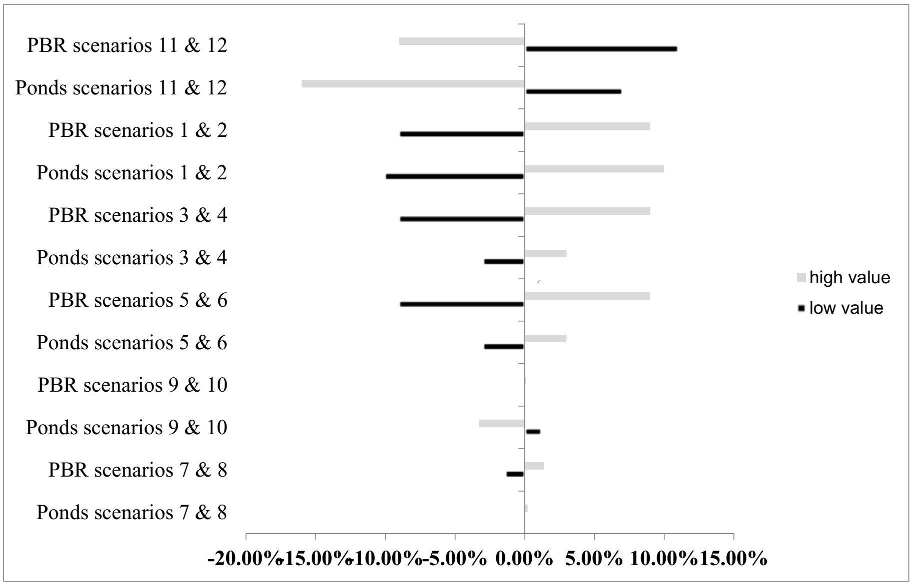

**Fig. 5.** Sensitivity analysis for algae conversion to diluent via pyrolysis.

analysis should focus on cultivation parameter variations and their impacts in final outputs. Since large design changes to a system are not always practical (Weissman et al., 1989), for this sensitivity analysis it was assumed that none of the input variations were below −10% or above 10%.

From the results, it is noticeable that five inputs for ponds and five for PBRs were significant when varied by 10%. Only two areas did not change the results significantly, media harvesting for ponds and harvest volume for PBRs. Almost all input variables chosen for the sensitivity analysis directly affect the results, meaning that a positive variation to the input led to an increase in water footprint. The only exceptions were the yield of the desired product and the yearly cultivation period for ponds. Unlike in ponds, where water footprint-related electricity consumption is minor, the electricity consumption of PBRs is a matter of concern. In fact, the sensitivity analysis showed a minor contribution of the electricity consumption to the outcome of the water footprint in PBRs (a variation of around 1.5%). This variation might not be as high as the ones generated by some other inputs, but it was significant enough to be considered in the uncertainty analysis.

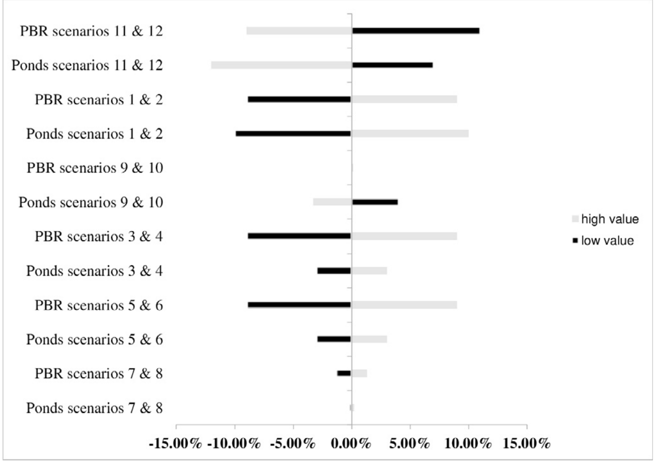

**Fig. 6.** Sensitivity analysis for algae conversion to diluent via HTL.

### 4.3. *Uncertainty analysis*

For this study, an uncertainty analysis was conducted using a Monte Carlo simulation. The simulation was done through a ModelRisk software execution (as described by (Habibi, 2017; Vose et al., 2007) that randomly selected variables within the established range of 100000 iterations. When the relationship between variables is known and there are uncertainties in both published and estimated information, a triangular probability distribution is commonly adopted, since in a distribution of this type the central value is estimated while the maximum and minimum values are fixed. This distribution is used for every input considered in the uncertainty analysis. The triangular distribution also assumes that the majority of the data is centered around the estimated value.

Uncertainty is commonly estimated by identifying the significant inputs through sensitivity analyses and then assigning a suitable uncertainty to each based on the information available. In this study, significant inputs with known estimated uncertainty ranges were varied during the Monte Carlo simulation. Significant inputs with unknown uncertainty had ranges of ±10% attributed to them. Table 12 shows the water use efficiency values for diluent from fast pyrolysis and HTL at various percentiles. Table 13 shows the water use efficiency values for hydrogen from gasification and HTG, also at various percentiles. The low deviation from the median of each case can be seen by calculating the difference between the median and the values on both extremes for a particular case. For example, for the fast pyrolysis of algae grown in ponds, the deviations for the 5% and 95% extremes from the median are −9.81% and 10.88%, respectively. For the gasification of algae produced in photobioreactors, the deviations for the 5% and 95% extremes from the median are −10.38% and 11.63%, respectively. With all the uncertainties in the variables considered in the Monte Carlo simulation, the results on the 50% mark were very close to the results obtained in the base case scenarios. There were some (negligible) deviations of a few percentile points from the original cases. It is also noticeable from Tables 12 and 13 that the spread of results is concentrated around the median. Therefore, the results of this study for the base case scenarios can be considered accurate considering the uncertainty of the inputs used.

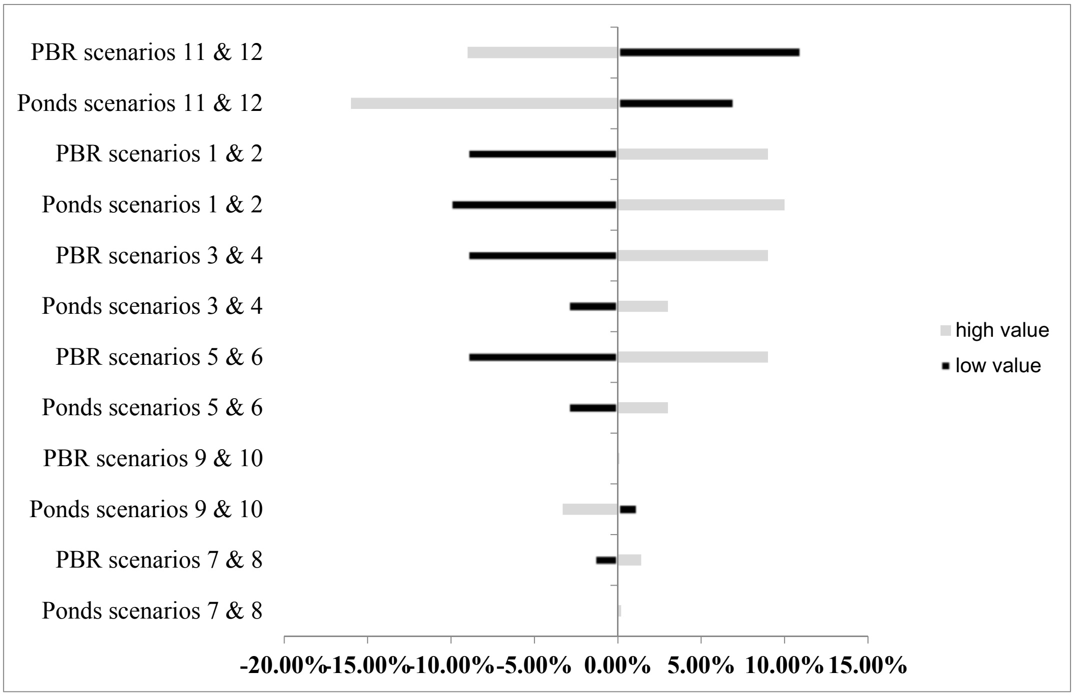

**Fig. 7.** Sensitivity analysis for algae conversion to hydrogen via gasification.

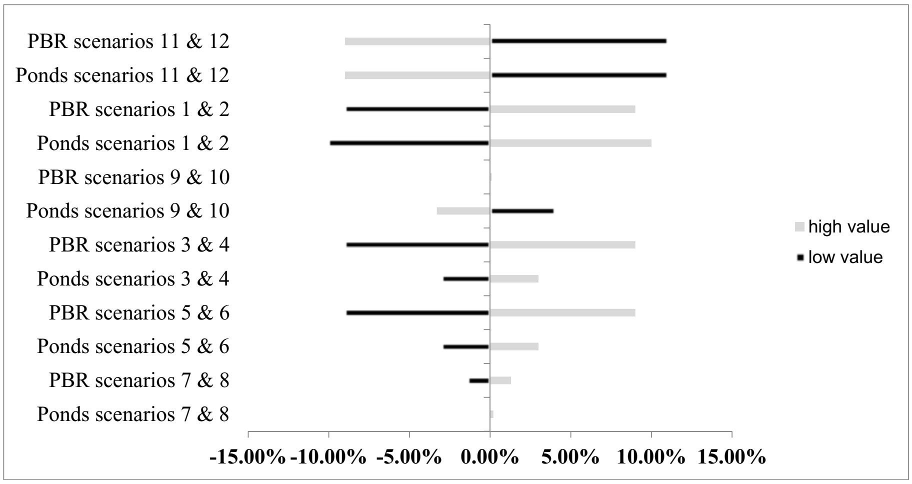

**Fig. 8.** Sensitivity analysis for algae conversion to hydrogen via HTG.

**Table 12**
Percentile values of uncertainty distribution plots for diluent production.

| Percentile | Water use efficiency of diluent production via fast pyrolysis and hydroprocessing | | Water use efficiency of diluent production via HTL and hydroprocessing | |
|---|---|---|---|---|
| | Ponds L $H_2O$/MJ diluent | Photobioreactors L $H_2O$/MJ diluent | Ponds L $H_2O$/MJ diluent | Photobioreactors L $H_2O$/MJ diluent |
| 5% | 124.09 | 2.10 | 121.60 | 1.95 |
| 15% | 128.78 | 2.18 | 125.44 | 2.02 |
| 25% | 131.75 | 2.23 | 127.76 | 2.07 |
| 50% | 137.60 | 2.33 | 133.99 | 2.16 |
| 75% | 143.67 | 2.43 | 139.83 | 2.26 |
| 85% | 146.94 | 2.48 | 142.90 | 2.30 |
| 95% | 152.44 | 2.56 | 148.18 | 2.37 |

## 5. Conclusion

Water may be abundant in many locations, but it is a very valuable resource. Since other uses of water take priority over biomass production, it is important to reduce water consumption in this activity. The cases of algae cultivation explored in this study

**Table 13**
Percentile values of uncertainty distribution plots for hydrogen production.

| Percentile | Water use efficiency of hydrogen production via gasification | | Water use efficiency of hydrogen production via HTG | |
|---|---|---|---|---|
| | Ponds L $H_2O$/MJ diluent | Photobioreactors L $H_2O$/MJ diluent | Ponds L $H_2O$/MJ diluent | Photobioreactors L $H_2O$/MJ diluent |
| 5% | 129.25 | 2.23 | 89.28 | 1.48 |
| 15% | 133.64 | 2.31 | 92.63 | 1.53 |
| 25% | 136.44 | 2.36 | 94.77 | 1.57 |
| 50% | 141.87 | 2.47 | 98.94 | 1.64 |
| 75% | 147.46 | 2.58 | 103.33 | 1.71 |
| 85% | 150.54 | 2.63 | 105.68 | 1.75 |
| 95% | 155.58 | 2.71 | 109.70 | 1.80 |

present challenges considering the high amount of water used in the production of diluent and hydrogen. The process that requires the most water is the cultivation phase, which is responsible for more than 99% of consumption. This study develops life cycle water footprints including the detailed unit operations involved in pathways. The study also shows that a viable cultivation method based on photobioreactors uses less water than ponds to produce algae. While PBRs are more expensive and complex than ponds, they offer savings in water consumption, nutrients, and land required, which could make them a feasible alternative. In all pathways studied, the water footprint for algae cultivated in PBRs was less than 25% of that for ponds. The difference between different thermochemical conversion methods when the same cultivation method is considered tends to be small, though not negligible. The thermochemical conversion pathway with the lowest water footprint was HTG, with about 60% of the footprint of HTL (the one with highest footprint).

In the future, with increasing demand from industry for products derived from biomass with a lower carbon footprint, algae are one of the likeliest prospects. Some of the technologies discussed in this paper are still novel and can be improved on many levels (economic, resources required, efficiency, etc.). The results presented in this study will help others understand the resource allocation necessary for algae cultivation and processing, which in turn will help to make better choices on areas to invest or formulate policy.

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## References

Akhtar, J., Amin, N.A.S., 2011. A review on process conditions for optimum bio-oil yield in hydrothermal liquefaction of biomass. Renew. Sustain. Energy Rev. 15 (3), 1615–1624.

Alvarez, G., Poteau, S., Argillier, J.-F., Langevin, D., Salager, J.-L., 2009. Heavy Oil−-Water interfacial properties and emulsion stability: influence of dilution. Energy Fuel. 23 (1), 294–299.

Anhorn, J., Badakhshan, A., 1994. MTBE: a Carrier for heavy oil transportation and viscosity mixing rule applicability. J. Can. Petrol. Technol. 33 (04).

Aspen Plus, 2009. Aspen technology. Inc., Version 11.

Baker, E.G., Elliott, D.C., 1986. Catalytic Hydrotreating of Biomass-derived Oils. Pacific Northwest Lab, Richland, WA (USA).

Berndes, G., 2002. Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. Global Environ. Change 12 (4), 253–271.

Borowitzka, M.A., 1999. Commercial production of microalgae: ponds, tanks, tubes and fermenters. J. Biotechnol. 70 (1), 313–321.

Bridgwater, A., Meier, D., Radlein, D., 1999. An overview of fast pyrolysis of biomass. Org. Geochem. 30 (12), 1479–1493.

Chen, C.-Y., Yeh, K.-L., Aisyah, R., Lee, D.-J., Chang, J.-S., 2011. Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: a critical review. Bioresour. Technol. 102 (1), 71–81.

Chiaramonti, D., Prussi, M., Casini, D., Tredici, M.R., Rodolfi, L., Bassi, N., Zittelli, G.C., Bondioli, P., 2013. Review of energy balance in raceway ponds for microalgae cultivation: Re-thinking a traditional system is possible. Appl. Energy 102, 101–111.

Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol. Adv. 25 (3), 294–306.

Davis, R., Markham, J., Kinchin, C., Grundl, N., Tan, E.C., Humbird, D., 2016. Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing through Dewatering for Downstream Conversion. NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Demirbas, A., 2008. Biodiesel. Springer.

Dismukes, G.C., Carrieri, D., Bennette, N., Ananyev, G.M., Posewitz, M.C., 2008. Aquatic phototrophs: efficient alternatives to land-based crops for biofuels. Curr. Opin. Biotechnol. 19 (3), 235–240.

Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: a drink or drive issue? Environ. Sci. Technol. 43 (9), 3005–3010.

Doucha, J., Straka, F., Lívanský, K., 2005. Utilization of flue gas for cultivation of microalgae Chlorella sp.) in an outdoor open thin-layer photobioreactor. J. Appl. Phycol. 17 (5), 403–412.

Ebino, K., 1999. The importance of the diluent for airway transport of toluene diisocyanate following intranasal dosing of mice. Inhal. Toxicol. 11 (3), 171–185.

Elliott, D.C., 2007. Historical developments in hydroprocessing bio-oils. Energy Fuel. 21 (3), 1792–1815.

Elliott, D.C., Biller, P., Ross, A.B., Schmidt, A.J., Jones, S.B., 2015. Hydrothermal liquefaction of biomass: developments from batch to continuous process. Bioresour. Technol. 178, 147–156.

Environment Canada, 2013. Water Withdrawal and Consumption by Sector Data. Government of Canada. Retrieved June 10, 2017, from https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=5736C951-1.

Fang, Z., Xu, C.C., 2014. Near-critical and Supercritical Water and Their Applications for Biorefineries. Springer, pp. 441–475.

Gasafi, E., Reinecke, M.-Y., Kruse, A., Schebek, L., 2008. Economic analysis of sewage sludge gasification in supercritical water for hydrogen production. Biomass Bioenergy 32 (12), 1085–1096.

Gerbens-Leenes, W., Hoekstra, A.Y., 2011. The water footprint of biofuel-based transport. Energy Environ. Sci. 4 (8), 2658–2668.

Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H., 2009. The water footprint of bioenergy. In: Proceedings of the National Academy of Sciences, vol.106, pp. 10219–10223 (25).

Gerbens-Leenes, P.W., Xu, L., de Vries, G.J., Hoekstra, A.Y., 2014. The blue water footprint and land use of biofuels from algae. Water Resour. Res. 50 (11), 8549–8563.

Habibi, R., 2017. Applications of Vose ModelRisk software in simulated data. Asian J. Econ., Bus. Account. 2 (1), 1–10.

Hage, K.D., 1978. Natural and enhanced evaporation from lake Wabamun, Alberta. Can. Water Resour. J./Revue canadienne des ressources hydriques 3 (3), 49–61.

Hemmingsen, P.V., Silset, A., Hannisdal, A., Sjöblom, J., 2005. Emulsions of heavy crude oils. I: influence of viscosity, temperature, and dilution. J. Dispersion Sci. Technol. 26 (5), 615–627.

Hsu, D.D., 2012. Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing. Biomass Bioenergy 45, 41–47.

Jackson, R.B., Carpenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L., Running, S.W., 2001. Water in a changing world. Ecol. Appl. 11 (4), 1027–1045.

Jones, S.B., Valkenburt, C., Walton, C.W., Elliott, D.C., Holladay, J.E., Stevens, D.J., Kinchin, C., Czernik, S., 2009. Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: a Design Case. Pacific Northwest National Laboratory (PNNL), Richland, WA (US).

Jones, S., Zhu, Y., Anderson, D., Hallen, R.T., Elliott, D.C., Schmidt, A., Albrecht, K., Hart, T., Butcher, M., Drennan, C., 2014. Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading. Pacific Northwest National Laboratory, pp. 1–69.

Jonker, J.G.G., Faaij, A.P.C., 2013. Techno-economic assessment of micro-algae as feedstock for renewable bio-energy production. Appl. Energy 102, 461–475.

Jorquera, O., Kiperstok, A., Sales, E.A., Embiruçu, M., Ghirardi, M.L., 2010.

Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresour. Technol. 101 (4), 1406–1413.

Kruse, A., 2009. Hydrothermal biomass gasification. J. Supercrit. Fluids 47 (3), 391–399.

Kumar, M., Oyedun, A.O., Kumar, A., 2017. Hydrothermal liquefaction of biomass for the production of diluents for bitumen transport. Biofuels. Bioprod. Biorefining 11 (5), 811–829.

Kumar, M., Olajire Oyedun, A., Kumar, A., 2018a. A review on the current status of various hydrothermal technologies on biomass feedstock. Renew. Sustain. Energy Rev. 81 (Part 2), 1742–1770.

Kumar, M., Oyedun, A.O., Kumar, A., 2018b. A Comparative Analysis of the Production of Diluents from the Thermochemical Conversion of Algae (Submitted).

Lee, Y.-K., 2001. Microalgal mass culture systems and methods: their limitation and potential. J. Appl. Phycol. 13 (4), 307–315.

Li, X., Xu, H., Wu, Q., 2007. Large-scale biodiesel production from microalga Chlorella protothecoides through heterotrophic cultivation in bioreactors. Biotechnol. Bioeng. 98 (4), 764–771.

Matsumura, Y., 2002. Evaluation of supercritical water gasification and biomethanation for wet biomass utilization in Japan. Energy Convers. Manag. 43 (9), 1301–1310.

Mbogga, M.S., Hamann, A., Wang, T., 2009. Historical and projected climate data for natural resource management in western Canada. Agric. For. Meteorol. 149 (5), 881–890.

McKendry, P., 2002a. Energy production from biomass (part 1): overview of biomass. Bioresour. Technol. 83 (1), 37–46.

McKendry, P., 2002b. Energy production from biomass (part 2): conversion technologies. Bioresour. Technol. 83 (1), 47–54.

Mehrotra, A.K., 1992. A model for the viscosity of bitumen/bitumen fractions-diluent blends. J. Can. Petrol. Technol. 31 (09).

Mekonnen, M.M., Hoekstra, A.Y., 2010. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products.

Miadonye, A., Doyle, N., Britten, A., Latour, N., Puttagunta, V., 2001. Modelling viscosity and mass fraction of bitumen-diluent mixtures. J. Can. Petrol. Technol. 40 (07).

Moazami, N., Ashori, A., Ranjbar, R., Tangestani, M., Eghtesadi, R., Nejad, A.S., 2012. Large-scale biodiesel production using microalgae biomass of Nannochloropsis. Biomass Bioenergy 39 (Supplement C), 449–453.

Moheimani, N.R., Borowitzka, M.A., 2006. The long-term culture of the coccolithophore Pleurochrysis carterae (Haptophyta) in outdoor raceway ponds. J. Appl. Phycol. 18 (6), 703–712.

Nautiyal, P., Subramanian, K.A., Dastidar, M.G., 2014. Production and characterization of biodiesel from algae. Fuel Process. Technol. 120, 79–88.

Ou, L., Thilakaratne, R., Brown, R.C., Wright, M.M., 2015. Techno-economic analysis of transportation fuels from defatted microalgae via hydrothermal liquefaction and hydroprocessing. Biomass Bioenergy 72, 45–54.

Ozkan, A., Kinney, K., Katz, L., Berberoglu, H., 2012. Reduction of water and energy requirement of algae cultivation using an algae biofilm photobioreactor. Bioresour. Technol. 114, 542–548.

Pankratz, S., Oyedun, A.O., Zhang, X., Kumar, A., 2017. Algae production platforms for Canada's northern climate. Renew. Sustain. Energy Rev. 80, 109–120.

Pate, R., Klise, G., Wu, B., 2011. Resource demand implications for US algae biofuels production scale-up. Appl. Energy 88 (10), 3377–3388.

Patel, M., Kumar, A., 2016. Production of renewable diesel through the hydroprocessing of lignocellulosic biomass-derived bio-oil: a review. Renew. Sustain. Energy Rev. 58 (Supplement C), 1293–1307.

Patel, M., Zhang, X., Kumar, A., 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review. Renew. Sustain. Energy Rev. 53, 1486–1499.

Pollard, A.J., Banasiak, D.S., Ellens, C.J., Brown, J.N., 2015. Methods, Apparatus, and Systems for Incorporating Bio-derived Materials into Oil Sands Processing. Google Patents.

Postel, S., Richter, B., 2012. Rivers for Life: Managing Water for People and Nature. Island Press.

Ramachandran, R., Menon, R.K., 1998. An overview of industrial uses of hydrogen. Int. J. Hydrogen Energy 23 (7), 593–598.

Rao, F., Liu, Q., 2013. Froth treatment in Athabasca oil sands bitumen recovery process: a review. Energy Fuel. 27 (12), 7199–7207.

Rapagnà, S., Jand, N., Foscolo, P.U., 1998. Catalytic gasification of biomass to produce hydrogen rich gas. Int. J. Hydrogen Energy 23 (7), 551–557.

Ringer, M., Putsche, V., Scahill, J., 2006. Large-scale Pyrolysis Oil Production: a Technology Assessment and Economic Analysis. National Renewable Energy Laboratory (NREL), Golden, CO.

Rodolfi, L., Chini Zittelli, G., Bassi, N., Padovani, G., Biondi, N., Bonini, G., Tredici, M.R., 2009. Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor. Biotechnol. Bioeng. 102 (1), 100–112.

Singh, S., Kumar, A., 2011. Development of water requirement factors for biomass conversion pathway. Bioresour. Technol. 102 (2), 1316–1328.

Singh, R.N., Sharma, S., 2012. Development of suitable photobioreactor for algae production – a review. Renew. Sustain. Energy Rev. 16 (4), 2347–2353.

Singh, S., Kumar, A., Jain, S., 2014. Impact of biofuel production on water demand in Alberta. Can. Biosyst. Eng. 56.

Slade, R., Bauen, A., 2013. Micro-algae cultivation for biofuels: cost, energy balance, environmental impacts and future prospects. Biomass Bioenergy 53, 29–38.

Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B., Jechura, J., 2005. Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-heated Gasifier. National Renewable Energy Lab, Golden, CO (US).

Standardization, I.O.f., 2006. ISO 14010:2006 Environmental Management - Life Cyle Assessment - Principles and Framework (Geneva).

Statistics Canada, 2014. Electric Power Generation by Class of Electricity Producer. Government of Canada. Retrieved June 10, 2017, from http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1270007&paSer=&pattern=&stByVal=1&p1=1&p2=35&tabMode=dataTable&csid=.

Swana, J., Yang, Y., Behnam, M., Thompson, R., 2011. An analysis of net energy production and feedstock availability for biobutanol and bioethanol. Bioresour. Technol. 102 (2), 2112–2117.

Tessel, D., 2015. Systems and Methods for Using Gas to Liquids (Gtl) Technology. Google Patents.

Tews, I.J., Zhu, Y., Drennan, C., Elliott, D.C., Snowden-Swan, L.J., Onarheim, K., Solantausta, Y., Beckman, D., 2014. Biomass Direct Liquefaction Options. TechnoEconomic and Life Cycle Assessment. Pacific Northwest National Laboratory (PNNL), Richland, WA (US).

Tipman, R., Long, Y.-C., Shelfantook, W.E., 2001. Solvent Process for Bitumen Separation from Oil Sands Froth. Google Patents.

Toor, S.S., Rosendahl, L., Rudolf, A., 2011. Hydrothermal liquefaction of biomass: a review of subcritical water technologies. Energy 36 (5), 2328–2342.

Toor, S.S., Rosendahl, L.A., Hoffmann, J., Pedersen, T.H., Nielsen, R.P., Søgaard, E.G., 2014. In: Jin, F. (Ed.), Application of Hydrothermal Reactions to Biomass Conversion. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 189–217.

Turn, S., Kinoshita, C., Zhang, Z., Ishimura, D., Zhou, J., 1998. An experimental investigation of hydrogen production from biomass gasification. Int. J. Hydrogen Energy 23 (8), 641–648.

Ugwu, C.U., Aoyagi, H., Uchiyama, H., 2008. Photobioreactors for mass cultivation of algae. Bioresour. Technol. 99 (10), 4021–4028.

Verma, A., Olateju, B., Kumar, A., Gupta, R., 2015. Development of a process simulation model for energy analysis of hydrogen production from underground coal gasification (UCG). Int. J. Hydrogen Energy 40 (34), 10705–10719.

Vose, D., Koupeev, T., Van Hauwermeiren, M., Smet, W., van den Bossche, S., 2007. Help File for ModelRisk Version 5 Vose Software.

Waldner, M.H., Vogel, F., 2005. Renewable production of methane from woody biomass by catalytic hydrothermal gasification. Ind. Eng. Chem. Res. 44 (13), 4543–4551.

Wang, L., Liu, J., Zhao, Q., Wei, W., Sun, Y., 2016. Comparative study of wastewater treatment and nutrient recycle via activated sludge, microalgae and combination systems. Bioresour. Technol. 211, 1–5.

Watanabe, Y., Hall, D.O., 1996. Photosynthetic CO 2 conversion technologies using a photobioreactor incorporating microalgae-energy and material balances. Energy Convers. Manag. 37 (6), 1321–1326.

Weissman, J.C., Tillett, D.M., Goebel, R., 1989. Design and Operation of an Outdoor Microalgae Test Facility. Microbial Products, Inc, Vacaville, CA (USA).

Wong, A., Zhang, H., Kumar, A., 2016. Life cycle water footprint of hydrogenation-derived renewable diesel production from lignocellulosic biomass. Water Res. 102 (Supplement C), 330–345.

Wright, M.M., Daugaard, D.E., Satrio, J.A., Brown, R.C., 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 89, S2–S10.

Yang, J., Xu, M., Zhang, X., Hu, Q., Sommerfeld, M., Chen, Y., 2011. Life-cycle analysis on biodiesel production from microalgae: water footprint and nutrients balance. Bioresour. Technol. 102 (1), 159–165.

Yi-Wen, C., May, W., 2013. The water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process. Environ. Res. Lett. 8 (3), 035015.

Zhu, Y., Tjokro Rahardjo, S.A., Valkenburt, C., Snowden-Swan, L.J., Jones, S.B., Machinal, M.A., 2011. Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels. Pacific Northwest National Laboratory (PNNL), Richland, WA (US).

Zhu, Y., Biddy, M.J., Jones, S.B., Elliott, D.C., Schmidt, A.J., 2014. Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading. Appl. Energy 129, 384–394.