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Techno-economic analysis of solar integrated hydrothermal liquefaction of microalgae

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HIGHLIGHTS

- Hydrothermal liquefaction and concentrated solar power provide integrated biofuel technology.
- Heat kinetics and energy efficiency Aspen plus modelling of CSP and HTL.
- Microalgae biofuel minimum fuel sales price of \$1.23/kg.

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ABSTRACT

Integration of Hydrothermal Liquefaction (HTL) of microalgae biomass with concentrated solar power thermal processing (CSP) for bio-oil production is a potential processing pathway for energy efficient generation of renewable biofuels. Solar HTL infrastructure avoids additional bolt-on components of conventional solar parabolic trough systems used for electricity production including heat transfer fluids, counter current heat exchangers, fluid transfer interconnectivity and electrical power control systems. The absence of such capital intensive additional equipment considerably reduces the production costs of solar HTL biofuels compared to electricity generation from conventional CSP power systems. An economic and market appraisal of variance and system economic resilience is presented. It is hypothesised that the combination of nutrient recycling with HTL/CSP unification has the potential for economically sustainable microalgae bio-oil production. A microalgae biofuel minimum fuel sales price of \$1.23/kg has been modelled. Further experimental work would be able to validate this integrated model.

1. Introduction

As the demand for energy intensifies amid growing concerns for drastic climate change, biofuels are needed more than ever as an alternative to fossil fuels. Third generation renewable liquid biofuels derived from microalgae could potentially supplement incremental global energy demand. Microalgae grow rapidly, produce energy dense lipids, are able to utilise marine, freshwater and wastewater, grow on non-agricultural land and remediate waste or atmospheric carbon dioxide. Microalgae biomass feedstock for HTL bio-oil production benefits from reduced energy requirements for complete dewatering [1–20].

This paper begins with an introduction and review of current literature, the HTL process and heat integration using CSP are discussed, then we calculate costs of microalgae derived bio-crude production from a 1-ha site using a 100 m long parabolic CSP trough. Working methodology considers established CSP thermodynamics, heat transfer, present day market prices and the mass of engineering equipment and associated capital expenditure (CAPEX). Finally, this theoretical forecast of a commercial operation is compared to industrially functioning global electricity CSP and evaluates how this new techno-economic analysis (TEA) can make strides from being present-day theory to the development of a new future scenario of commercially implemented technology.

The energetics of the HTL process are dominated by the energy required to heat the reactor, 6.51 MJ (kg microalgae)$^{-1}$ [21]. Careful consideration of the EROEI (Energy Returned on Energy Invested) of HTL as a function of reaction temperature is required [22]. A sensitivity analysis of base case parameters indicated that modelled systems were particularly sensitive to the extent of heat integration from HTL suggesting that optimisation of heat integration is necessary for minimisation of lifecycle greenhouse gas emissions [23]. HTL oil yields reported for higher temperatures (>200 °C) exceed the lipid content of the biomass, which

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indicates conversion of other cellular constituents (e.g., protein, carbohydrate, algaenan) by HTL reaction processes [24,25].

Reaction times are a crucial factor for economical operation of HTL, short reaction times will reduce bio-oil yield whereas long reaction times may lead to higher gas and compromised bio-oil yield [26]. 30 min is the most appropriate HTL reaction time for *Enteromorpha prolifera* [27] and *Dunaliella* [20]. A hydrothermal liquefaction techno-economic analysis of a modelled 2000 dry tonne per day processing facility using defatted microalgae indicates that 66% external electricity should be supplied with an overall energy efficiency of 56% [28]. The well to pump lifecycle comparison of fossil energy use and greenhouse gas emissions were higher for HTL bio-oil than lipid extracted renewable diesel production on account of net heat energy input to establish the operational process conditions, however HTL used 1.8-fold less biomass than the lipid extracted renewable diesel production pathway [29]. The amount of energy required to dry algal biomass to levels typical of terrestrial crops for solvent based oil extraction would exceed the energy content in the algal oil [30]. The energy required for microalgae and biogas production from *Nannochloropsis* has been calculated to be as much as 8–11 times more than the bio-gas energy yield [31]. A trade-off between high algal oil yields and high energy recovery via catalytic hydrothermal gasification of the aqueous HTL solubles is amplified by using *Escherichia coli* grown on aqueous HTL solubles for secondary HTL, boosting the oil yield per unit of microalgae biomass and suggesting that recovery and recycling of aqueous phase product from HTL is instrumental to overall lifecycle economics [32].

An integrated modelling framework has been developed to predict biological cultivation and chemical HTL process pathways as a predictive tool for microalgae to fuel [33]. Whilst many authors' have endorsed HTL nutrient recycling and the energetic transformation and optimisation of biomass conversion processes using HTL, to date there has been no known research on efficient heat delivery for achievement of the operational HTL process conditions, irrespective of the reaction constituents. With the volumetric scale-up of this technology which will be required for industrial quantities of biofuel production, integration of efficient heat delivery is a pre-requisite. Key issues for future R&D of microalgae biofuels include both the utilisation of co-products and development of energy efficient thermo-conversion processes [34].

Various parameters affect product yield of HTL derived bio-oil including microalgae species, feed ratio of solids to liquid, reaction temperature, holding time, heating rate, cooling rate, presence of catalysts and effective product separation [35]. In recent years HTL process development from batch to continuous feed has occurred [36]. Continuous feed systems have advantages of higher feedstock flows and lower process and retention times, lacking uncertainties in heating and cooling rates common in batch run experiments [37]. Development of a continuous feedstock process requires thermal quenching to reduce temperature differentials, ensure preservation of reactant products and optimise the viable and scalable commercial integration into a CSP/HTL production system. Thermal retention, multi-phase flow fluid mechanics and feedback control optimisation within the core of the reaction pressure vessel should be identified to define reaction process boundaries. Microalgae biomass of concentration 10–20% (w/v) is optimal for HTL boundaries of solids loading [38]. A 20% solid content is estimated to be a reasonable trade-off between the capital costs for the HTL system and the costs for dewatering. Higher biomass solid input concentrations to HTL reduce the capital cost and make product separation easier but also incur greater dewatering costs [3]. Solar heat integration as the vector for biomass to biofuel transformation does not jeopardise holistic energetic transformation pathways resulting in a more favourable energy return in the LCA (Lifecycle Analysis) than energy input from fossil fuel generated heat.

Engineering the integration of solar thermal energy for HTL bio-oil rather than electricity generation has not been widely reported by other authors'. The objectives of this study were to investigate a techno-economic analysis (TEA) of factors influencing the unification of HTL and CSP parabolic troughs for the processing of microalgae biomass into bio-oil. CSP parabolic troughs yield a temperature of up to 400 °C with oil as the heat transfer liquid (HTF); the use of molten salts as a HTF can attain a temperature much higher [39] whilst beneficial operational temperature requirements for HTL occur within the range of 250–350 °C [36,40]. A thermodynamic assessment of parabolic troughs [41] with an economic analysis using experimental field trials of microalgae productivity justifies the potential viability of this technology unification. Aspen plus® and custom sizing equations have been used to determine the economic viability of the process. Finally, the influence of estimated parameters on the economic results was assessed *via* sensitivity analysis.

2. Materials and methodology

2.1. Process overview

This sized CSP plant could process 200 kg of daily microalgae biomass in 3 cycles. The schematic diagram of the solar-assisted HTL plant is depicted in Fig. 1, which describes the integration of solar CSP with the tubular HTL reactor aligned along the focal line of the parabolic trough.

A land surface area of a 1 ha site could produce in the region of 180–200 kg biomass per day from a high rate microalgae pond, additional waste biomass and recycled nutrients for secondary biomass growth further supplements HTL microalgae feedstock. Considering a 30% biomass to bio-oil conversion with a ratio of 20% solids to water ratio in HTL, this would provide 1000 l feedstock per day. The HTL reactant volume space replaces the heat transfer fluid (HTF) as used in conventional electricity generating CSP plants. Likewise, HTF molten salt is replaced by microalgae biomass and water as the reactant components of HTL. Reactant inputs and discharge on alternative ends of each linear row of parabolic troughs function as semi-continuous batch processing. A proposed diurnal thermal HTL capacity for 3 h either side of midday permits 3 batch runs per day (Table 4). Estimation of CSP plant size for processing of HTL feedstock is based on the 1000 l daily production of HTL feedstock at 20% (w/v) microalgae – 160 l HTL reaction core volume from 100 m of solar CSP parabolic troughs, with 226 m^2 total solar aperture.

2.2. Process modelling and economics

Fig. 2 depicts the overall methodology employed in this study.

The elements of the methodology used in this study are elaborated in the succeeding tables and equations discussed in this section. Table 1 presents the typical dimensions and thermodynamic outputs of the commercially available CSP parabolic troughs for electricity production, and the methodology used to derive the values in Table 1 is now discussed.

The value of DNI (Direct Normal Irradiance, ie direct sunlight) of 750 W/m^2 is a conservative number, representative of locations with high concentrations of direct sunlight on an average basis (e.g. desert regions of North Africa, the Middle East, and the Americas) or peak levels of direct insolation in more temperate latitudes. For reference, DNI at the top of the earth's atmosphere (the so-called "Solar Constant") is approximately 1380 W/m^2).

Table 1 also includes optical and thermal loss values from a parabolic trough solar concentrating mirror and absorber tube of