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Hybrid life-cycle assessment of algal biofuel production

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HIGHLIGHTS

- For the first time, hybrid LCA undertaken for algal bio-crude production.
- Breakthrough integration of multi-region input–output and process data performed.
- Employment, stimulus, energy and GHG impacts assessed for algal bio-crude supply chain.
- Algal bio-crude supply chains will generate new jobs and stimulate economic growth.
- Algal bio-crude production is net carbon-negative.

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ABSTRACT

The objective of this work is to establish whether algal bio-crude production is environmentally, economically and socially sustainable. To this end, an economic multi-regional input–output model of Australia was complemented with engineering process data on algal bio-crude production. This model was used to undertake hybrid life-cycle assessment for measuring the direct, as well as indirect impacts of producing bio-crude. Overall, the supply chain of bio-crude is more sustainable than that of conventional crude oil. The results indicate that producing 1 million tonnes of bio-crude will generate almost 13,000 new jobs and 4 billion dollars' worth of economic stimulus. Furthermore, bio-crude production will offer carbon sequestration opportunities as the production process is net carbon-negative.

1. Introduction

Sustainability encompasses social and economic development, as well as environmental protection. It is also the key global driver for natural resource management. The availability of natural resources is limited; hence their consumption by humans often results in environmental degradation. For example, fossil fuels are considered unsustainable because they are non-renewable, and they emit greenhouse gases upon combustion. Anthropogenic greenhouse gas emissions are the main driving force behind Earth's changing climate. Growing concern over fossil fuel use has driven investment in initiatives aimed at promoting alternative energy sources that are renewable. Biofuels are one such alternative, which have received significant attention in the past decade. Biofuels are categorised into first-, second- or third-generation, depending on the feedstocks that are used to produce them.

First-generation biofuels are typically produced from food crops such as sugarcane, corn and palm. The development of this type of biofuel market results in food price hikes, driving the "food vs. fuel" debate (Pimentel et al., 2009). Second-generation biofuels derived from lignocellulose and forest residues remove the food conflict; however, the conversion processes needed to generate such fuels are still in their infancy (Brennan and Owende, 2010). Third-generation biofuels, derived from photosynthetic microalgae have great potential as sustainable fuels of the future (Leite et al., 2013). Microalgae have many advantages over other feedstocks, since they can: (i) grow at much faster rates with higher yields of oil due to their simple structure and lower nutritional requirements than higher plants (Brennan and Owende, 2010); (ii) grow in saline or brackish water (Gao et al., 2013), thus minimising competition for freshwater resources; (iii) grow on marginal or barren land (Lam and Lee, 2012), thus avoiding competition with food production; and (iv) sequester carbon dioxide for growth (Li et al., 2008), so that algal biomass production can be coupled with flue gas emissions from coal-fired power stations.

The production of biofuels from microalgae involves three major steps: cultivation, harvesting and chemical processing. Algal cultivation makes use of photosynthesis to convert light energy into chemical energy stored within algal cells. The primary goal

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of algal cultivation is improved non-polar lipid productivity, i.e. high algal biomass productivity using algal cells with a high lipid content (Griffiths and Harrison, 2009). Light availability is a key parameter for efficient biomass production, and algal cultures also require sources of carbon (carbon dioxide), nitrogen and phosphorus (fertiliser) for growth. Commercial microalgal cultivation is mostly carried out in large outdoor ponds, where the key to success is to choose the algal species that performs best under local environmental conditions (light, temperature, salinity and pH) (Larkum et al., 2012). The main challenges during algal harvesting are the large volumes of water involved, with low biomass density (circa 0.2–2.0 g L^{-1}) and the small size of algal cells (typically 10–30 μm) (Borowitzka and Moheimani, 2013). In the first instance, sedimentation or flotation can be used to concentrate the algal suspension into an algal sludge. Further dewatering requires the use of energy-intensive processes such as centrifugation and filtration, which make a large contribution (20–30%) towards the overall cost of bio-crude production (Molina Grima et al., 2003). Dry biomass has traditionally been chemically processed to biodiesel by lysing the algal cells and separating out triacylglycerol molecules (TAGs), then converting them to alkyl esters (biodiesel) by transesterification (Georgianna and Mayfield, 2012). An alternative approach is to process semi-dry biomass by hydrothermal liquefaction to produce "bio-crude", which can later be distilled into its fractions at a refinery (Delrue et al., 2013; Jena and Das, 2011). Even though algae itself are considered a sustainable feedstock and possess many benefits, a comprehensive assessment of algae to bio-crude conversion should be undertaken to determine the overall sustainability of the bio-crude production process. A well-established technique called life-cycle assessment can be used for assessing the impacts of bio-crude production.

Many researchers have undertaken life-cycle assessment (LCA), e.g. (Gao et al., 2013; Liu et al., 2013), in order to assess the impacts of third-generation biofuels; however there exists no comprehensive analysis of the economic, social and environmental impacts of the entire algal biofuel supply chain. Conventional LCAs are limited by a methodological boundary consisting of cut-off points that reduce the scope of the assessment (Lenzen, 2000). Only activities included within the system boundary are assessed, whereas the ones that fall outside the boundary are not counted. Consider, for example, the supply chains that support biofuel production. An assessment in which these supply chains are truncated results in an incomplete coverage of impacts (Lenzen, 2000). To deal with the interconnected nature of supply chains, the Nobel Prize Laureate Wassily Leontief developed a top-down economic technique called input–output analysis (IOA) (Leontief, 1966). This technique relies on national input–output tables that represent the flow of money between various industries within an economy. Leontief recognised the interdependency between the industry sectors, and formulated a set of equations for analysing complex supply chain networks. His theory and equations triggered a new field of life-cycle assessment, known as hybrid LCA.

Hybrid LCA is a powerful technique for analysing the complex supply chains underpinning an industry or a product. It involves coupling the strengths of input–output analysis with conventional process analysis (Heijungs and Suh, 2002). This coupling results in a technique that offers completeness by eliminating system truncation, and specificity by including bottom-up process data. Hybrid LCA has become a well-established technique for analysing the impact of a product, new energy technology, and even biofuels. Acquaye et al. (2011), for example, have employed hybrid LCA to analyse the supply chain of rape oil methyl ester (RMS) biodiesel. To date, a hybrid LCA of bio-crude production involving all three spheres of sustainability – social, economic and environmental – has never been undertaken. This research is the first of its kind to improve on previous conventional life-cycle assessments by following a hybrid approach that guarantees consistency and removes incompleteness by considering the entire supply chain of the industry. For the first time, an integration of economic multi-regional input–output data with engineering process data is undertaken for algal biofuels. Use of this approach allows the comprehensive quantification of employment, economic stimulus, energy consumption and greenhouse gas emissions of the algal biofuel supply chain.

2. Methodology

A sustainable algae biofuel industry requires the algal production plant to be situated close to a carbon-emitter, which acts as a source of the concentrated carbon dioxide required for enhanced algal biomass productivity. In this study, a potential region suitable for algal biomass production was selected and analysed for the employment, economic, energy use and greenhouse gas impacts of future production operations including their supply chains. There are many regions around the world, including parts of Australia, which offer ideal conditions for algal growth. However, to fully exploit the benefits of algae as a promising biofuel feedstock, algal production plants should be established in areas that do not compete with existing land-use activities and freshwater supplies. Western Australia (WA) is of particular interest since it receives abundant sunshine, and its vast uninhabited coastal regions provide access to marginal land, as well as plentiful saltwater supply from the Indian Ocean. The world's largest algae production plant, with a total pond area of 740 ha, is located in Hutt Lagoon, WA (Borowitzka et al., 2012). Even though the microalga *Dunaliella salina* cultivated at this plant is used for producing the nutraceutical beta-carotene and not algal biofuels, the success of this particular industry confirms WA's status as a viable algae production region. Therefore, the Australian state of WA was chosen for modelling a potential algal bio-crude production industry.

In this case study, an algae bio-crude production plant with a total outdoor pond area comparable to the biggest algae plant in the world – 740 ha – was modelled. The location of the algae plant was chosen to be 50 km south of Kwinana, WA. Kwinana is the site of a BP oil refinery and a power station (420 MW). For the hybrid LCA, the process of constructing the 740 ha algae production plant, cultivation of algae, harvesting bio-crude from algae, and subsequently transporting it to the BP oil refinery for processing was appraised.

Two types of data are needed to undertake a hybrid LCA: bottom-up engineering process data and top-down input–output data. The following methodological steps were followed for conducting the analysis:

(1) An appropriate input–output database was chosen for the study (Section 2.1).
(2) Bottom-up process data on the algae biofuel supply chain were collected (Section 2.2).
(3) The input–output table obtained in step 1) was augmented with bottom-up process data collected in step 2) (Section 2.3).
(4) The economic, social and environmental impacts of algae biofuel supply chains were analysed using well-established input–output equations (Section 2.4).

2.1. Input–output data

Input–output analysis depends on input–output (IO) tables that are constructed using national accounts data. IO tables reveal the interdependence between various industry sectors in an economy at a particular point of time. They can be for a single region, e.g. an