Accepted Manuscript

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PII: S0960-8524(14)01564-8
DOI: http://dx.doi.org/10.1016/j.biortech.2014.10.132
Reference: BITE 14175

To appear in: *Bioresource Technology*

Received Date: 27 August 2014
Revised Date: 24 October 2014
Accepted Date: 27 October 2014

Please cite this article as: Malik, A., Lenzen, M., Ralph, P.J., Tamburic, B., Hybrid life-cycle assessment of algal biofuel production, *Bioresource Technology* (2014), doi: http://dx.doi.org/10.1016/j.biortech.2014.10.132

Hybrid life-cycle assessment of algal biofuel production

Arunima Malik[1*], Manfred Lenzen[1], Peter J. Ralph[2], Bojan Tamburic[2]

[1]ISA, School of Physics A28, The University of Sydney NSW 2006, Australia

[2]Plant Functional Biology and Climate Change Cluster, University of Technology Sydney NSW 2007, Australia

[*]Corresponding author. E-mail: amal9110@uni.sydney.edu.au; Tel: +61 2 9351 5451; Fax: +61 2 9351 7726

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.

Keywords: microalgae; algal biofuel; life-cycle assessment; input-output analysis; sustainability

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 & 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 & 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 & 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 of algal cultivation is improved non-polar lipid productivity, i.e. high algal biomass productivity using algal cells with a high lipid content (Griffiths & 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 & 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 & 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 & 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 considered. 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 & 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 IO table of Australia; or for multiple regions, such as the IO table featuring all Australian states, or a table featuring different nations. Multi-regional input-output (MRIO) tables are spatially explicit representations of economies, and thus demonstrate the interconnections between industries in different regions. Developing MRIO tables is a labour- and resource-intensive task. Data needed for constructing such tables are often incomplete and fragmented. Recently, a group of Australian researchers have developed a cloud computing platform for the compilation of large-scale MRIO tables for Australia (Lenzen et al., 2014). Featuring unprecedented regional and sectoral detail, the Australian Ecology Virtual Laboratory (IELab) is the first of its kind, globally. Lenzen et al. (2014) constructed a detailed MRIO table for Australia consisting of 19 Australian regions and 344 industry sectors. This table was utilised to analyse the economic, social and environmental impacts of the algae biofuel supply chain using hybrid LCA. The Western Australian region of the MRIO table was chosen as the case study region.

Input-output tables are often coupled with data on economic, social and environmental indicators, such as energy use. These indicators are termed physical accounts or satellite accounts. For this work, the satellite accounts for employment, energy and greenhouse gas (GHG) emissions are based on data from the Australian Bureau of Statistics (ABS), Bureau of Resources and Energy Economics (BREE) and the Department of Climate Change and Energy Efficiency (DCCEE), respectively (ABS, 2012b; BREE, 2013; DCCEE, 2011). The economic stimulus satellite account was constructed by adding the intermediate use of goods and services by all industries in the economy (ABS, 2011; ABS, 2012a).

2.2 Data on algae bio-crude production

This hybrid LCA requires monetary inputs to cover the costs associated with cultivating, harvesting and processing microalgae. It draws on three main sources of information: (i) the open-pond infrastructure cost data collated during the US Department of

Energy's Aquatic Species Program by Sheehan et al. (1998); (ii) the energy flows described in an LCA by Liu et al (2013), which are based on real data from pilot plants operated by Sapphire Energy in New Mexico; and (iii) biomass to bio-crude production using hydrothermal liquefaction, following Jena and Das (2011). A small on-site laboratory for algal maintenance and process optimisation has also been included in the model, based on the bioreactors and facilities available at the University of Technology, Sydney (Tamburic et al., 2014). The specific values used for productivity, energy demand, infrastructure, equipment and chemicals are shown in Table S1. The data were adjusted for the year 2013 by converting from US$ to AU$ using the current conversion rate of 1 US$ = 1.08 AU$. The cost of transporting the bio-crude from the algae production plant to the BP Kwinana Oil Refinery was estimated using a forestry-based transport model (Lambert, 2006), and updated for the density of bio-crude. A distance of 50 km was assumed between the algal production plant and the oil refinery.

Data were also collected for physical indicators such as employment, energy use and greenhouse gas emissions. For a 740 ha algae production plant, the labour required was estimated to be 29.6 full-time equivalent (FTE) people (WorleyParsons, 2012). Energy consumption was estimated by extracting the monetary input of different energy sources (e.g. petrol and diesel), and converting the monetary value into joules by using energy content factors (DRET, 2011). Similarly, greenhouse gas emissions were calculated using carbon content factors that convert energy units into carbon dioxide equivalent values (DCCEE, 2012).

2.3 Input-output based hybrid LCA

To undertake a hybrid LCA, bottom-up process data on algae bio-crude production (Section 2.2) were hybridised with top-down IO data obtained from the IELab (Section 2.1). Figure 1 shows the process of hybridisation. The process data were compiled into a column vector of inputs needed for algal bio-crude production. This column vector was inserted into the case study region of the MRIO table – Western Australia. The inputs and outputs of an industry or commodity should always be equal to ensure the IO table is balanced. For balancing the augmented IO table, a row was inserted into the WA region, and populated with data for the sale of crude oil – assuming that bio-crude produced at the algae biofuel plant will have the same sales structure as crude oil. The augmented row was scaled down according to the total inputs needed for algae bio-crude production. Malik et al. (2014) offer a detailed description of the hybridisation process.

2.4 Footprint calculations

Leontief (1966) formulated a set of linear equations that can be used for calculating economic, social and environmental footprints. To enumerate both the onsite (direct) and supply chain (indirect) impacts of the algae biofuel industry, the individual components of the augmented MRIO table need to be recognised. Suppose the size of the intermediate transactions matrix **T** is N x N, where N is the row and column dimension of the $\mathbf{T}$ matrix. The final demand matrix $\mathbf{y}$ is N x K (Fig. 1). Then, the total gross output $\mathbf{x}$ of an economy can be calculated as follows:

$$\mathbf{x} \quad = \mathbf{T}\mathbf{1}^{N} + \mathbf{y}\mathbf{1}^{K}, \tag{1}$$

where $\mathbf{1}^{N}$ and $\mathbf{1}^{K}$ are row summation operators of sizes N x 1 and K x 1, respectively. The size of $\mathbf{x}$ is N x 1.

To calculate the proportions $\mathbf{A}$ of inputs purchased by the biofuel industry, each element of the transactions matrix $\mathbf{T}$ was divided by the total output $\mathbf{x}$ of the receiving sector, as $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$, where the hat symbol represents diagonalisation of the total output matrix. $\mathbf{A}$ is called the matrix of input coefficients, or the direct requirements matrix. The fundamental input-output (IO) equation was derived by substituting $\mathbf{T} = \mathbf{Ax}$ into equation (1), and applying simple matrix operations to obtain $\mathbf{x} \quad = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{I}$ is a N x N identity matrix, and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse capturing all direct and indirect links between different economic sectors, and thus enumerating the total impacts across supply chains.

The fundamental IO theory was extended to include physical indicators such as employment, economic stimulus, energy use and greenhouse gas emissions (see $\mathbf{Q}$, Fig. 1). The direct economic, social and environmental impacts of algae bio-crude production per dollar of bio-crude output were calculated similar to $\mathbf{A}$. The direct impacts were calculated as $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$, where $\mathbf{Q}$ is the satellite account containing the indicators P x N, and P is the row dimension of the satellite block – 4 indicators in this study. The $\mathbf{q}$ matrix provides the direct impacts of algae bio-crude production. The total (direct + indirect) impacts can be enumerated as $\mathbf{m} = \mathbf{qL}$, where $\mathbf{m}$ is the multiplier that contains the direct and indirect impacts of algae bio-crude production. The size of **m** is P x N.

The total multiplier **m** was decomposed into contributions from different industry sectors $\mathbf{q}\#\ \mathbf{L}\mathbf{y}^*$, where # denotes element-wise multiplication, and $\mathbf{y}^*$ is the final demand vector containing only one non-zero element. This non-zero element corresponds to the total monetary final demand for the biofuel industry. The Leontief's inverse can be written as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots + \mathbf{A}^n$. $\mathbf{q}\#\ \mathbf{L}\mathbf{y}^*$ now becomes:

$$\mathbf{q}\#\mathbf{y}^* + \mathbf{q}\#\mathbf{A}\mathbf{y}^* + \mathbf{q}\#\mathbf{A}^2\,\mathbf{y}^* + \mathbf{q}\#\mathbf{A}^3\,\mathbf{y}^* + \cdots + \mathbf{q}\#\mathbf{A}^n\,\mathbf{y}^*, \quad (2)$$

where # denotes element-wise product. Equation (2) allows impacts to be decomposed according to different layers of the supply chain. For example, $\mathbf{q}\#\mathbf{y}^*$ part of the equation corresponds to the direct impacts of the algal biofuel industry. The impacts of the suppliers of the biofuel industry are enumerated using $\mathbf{q}\#\mathbf{A}\mathbf{y}^*$; the suppliers of suppliers using $\mathbf{q}\#\mathbf{A}^2\,\mathbf{y}^*$, the suppliers of suppliers of suppliers using $\mathbf{q}\#\mathbf{A}^3\,\mathbf{y}^*$, and so on. Equation (2) therefore allows the enumeration of impacts throughout the infinite supply chains of the biofuel industry.

The economic, social and environmental impacts of algae bio-crude production can also be decomposed according to inputs purchased by the algae biofuel industry. The equation $\mathbf{q}\#\mathbf{y}^*$ gives the direct impacts of bio-crude production, and $\mathbf{q}\mathbf{L}\#\mathbf{A}\mathbf{y}^*$represents the indirect impacts of the industry owing to the purchase of inputs.

Input-output analysis is a powerful tool for analysing complex supply chain networks. However, this technique is based on several assumptions. In particular, the following assumptions apply to this study: a) fixed production structure of industries i.e. the inputs needed for the production of algal bio-crude remain largely constant; b) constant returns to scale; and c) constancy of commodity prices. These assumptions are described in detail elsewhere (Miller & Blair, 2009).

3. Results and Discussion

3.1 Algae biofuel industry – direct and total impacts

The integration of bottom-up process data with top-down multi-regional input-output data allowed the elucidation of both the direct (onsite) and the indirect (supply chain) impacts of bio-crude production. A comparison of the social, economic and environmental impacts of bio-crude production with those of conventional crude oil production provides interesting insights about their relative sustainability (Table 1). The impact intensity results for the social indicator reveal that the production of green-crude requires fewer personnel on-site as compared to conventional crude oil production (Table 1). However, the opposite is true if the entire supply chain is taken into account; this demonstrates the power of hybrid LCA. The supply chain of bio-crude production offers more job opportunities than the crude oil supply chain. In terms of stimulus generation in the economy, both the direct and total impacts of bio-crude production are higher than those of crude oil production. Essentially, this indicates that an algal bio-crude industry will generate more monetary stimulus by stimulating the economy much more than a conventional crude oil industry. For assessing environmental sustainability, energy and greenhouse gas impacts of bio-crude were compared to those of crude oil production. Both the direct and indirect environmental impacts of bio-crude production are significantly lower than those of crude oil production. Overall, the comparison shows that bio-crude production is more sustainable than conventional crude oil production.

The results presented in Table 1 correspond to an algal biofuel industry modelled in the Western Australian (WA) region of the input-output (IO) table. This implies that the biofuel industry is sourcing inputs from the WA region. If the industry is modelled in a different Australian region of the input-output (IO) table, such as Victoria, then the direct impacts would remain the same. However, the total impacts would change, because the inputs in the supply chain would largely be sourced from industries operating in the Victorian region.

In this study, the production of bio-crude and crude oil were compared on a $-per-$ basis. There are two reasons for this choice of comparison: 1) biofuels do not receive any government subsidies in Australia, and hence petrol produced from bio-crude must compete on a $-per-$ basis with the petrol produced from conventional crude oil; and 2) the higher heating value (HHV) of bio-crude is similar to that of crude oil (Brennan & Owende, 2010).

The data in Table 1 present an overall comparison of the impacts of bio-crude production relative to crude oil. To understand the details behind these numbers, the impacts need to be broken down according to different industry sectors, and also inputs bought by the algae biofuel industry for the production of bio-crude.

3.2 Employment and Economic Footprints

The total multiplier **m** was broken down according to different layers of the supply chain. Figures 2a and 2b show the employment and economic footprints of algae bio-crude production, respectively. Production layers are the upstream layers of the supply chain. Layer one signifies the algae biofuel industry itself; layer two includes the suppliers of the biofuel industry; layer three is the suppliers of suppliers; layer four is the suppliers of suppliers of suppliers and so on. The impacts were decomposed according to the final demand $\mathbf{y}^*$ for 1 million tonne of bio-crude. To satisfy the final demand, a total of 13,200 FTE people would need to be employed for algae bio-crude production, and the industry will generate almost 4 billion dollars' worth of economic stimulus (production layer 5 in Fig. 2a and 2b, respectively). The production layer decomposition graph for employment (Fig. 2a) shows that jobs are mainly created in the upstream supply chain of the algae biofuel industry, rather than directly on the industry's premises. In contrast, the opposite is true for economic stimulus, most of which is generated directly onsite ($2.5 billion in Fig. 2b) in comparison to the supply chains.

The decomposition and classification of total impacts according to various industry sectors provides a clear representation of where the impacts lie along the supply chain. The biofuel industry will need to source many inputs from the e*quipment* sector (Figs 2a & 2b) for meeting the capital and operating costs. For the construction of the algal production plant, the industry will hire construction machinery such as cranes, loading machinery and crushing & grinding equipment. The industry will also need to buy paddle wheels for stirring and mixing algae cultures, carbonation equipment for injecting carbon dioxide into the pond, scientific laboratory equipment such as photo-bioreactors and centrifuges for researching and testing algae cultures, pumps for pumping water into the ponds, electrical equipment such as wires, cables, switches and similar items for providing electricity to the algae production plant. The aforementioned items will be purchased from industries in the *equipment* sector, which in turn will need to employ labour for fulfilling the increase in demand – this is reflected in the area under the curve in Fig. 2a and 2b. Increase in demand of a particular product triggers a ripple effect in the economy, which stimulates the growth of other industries. Suppose the biofuel industry buys paddle wheels from an industrial machinery company. For manufacturing paddle wheels, the company will need to source fabricated steel products from a *metals* industry, which in turn will require extra iron ore for the production of steel. Consequently, there will be an increase in demand for iron ore. Therefore, introduction of an algae biofuel industry would become a potential driver of economic growth.

Like any industry or company, the algae biofuel industry will also need *business services* such as banking, insurance, accounting services and property services for running and managing the business. Furthermore, the industry will require computer and technical services for maintaining the IT infrastructure, and computer assisted controls for growing, maintaining and harvesting algae. Once the algae are harvested and converted to bio-crude, the biomass would need to be transported to the Oil refinery on B-double trucks, which will create job opportunities for skilled drivers. Repairs and maintenance of any industrial machinery such as pumps and harvesting equipment will be managed by the industrial machinery and repairs industries that fall under the *trade* category.

Figures 2a and 2b illustrate that certain sectors experience a considerable increase in labour requirements and economic stimulus, whilst others do not. The reason lies in the demand for goods and services by the algae biofuel industry. As explained in the previous paragraphs, sectors such as *equipment and business services* are more positively impacted than sectors such as agriculture or forestry. Nonetheless, Figure 2a shows that almost all sectors experience an increase in labour requirements. However, the proportion of labour requirements or stimulus generation for a certain sector depends on how significant it is in the supply chain of the algae biofuel industry. Overall, the industry will create new jobs and initiate development in all industrial sectors of the economy.

3.3 Energy footprint

Cultivating then harvesting algae, and ultimately extracting bio-crude, involves a high electricity demand. During cultivation, energy is required to mix and aerate the culture in order to ensure that all algal cells receive access to sufficient sunlight and carbon dioxide. Harvesting of algae involves the energy-intensive dewatering of the algal biomass from a dilute suspension. Chemical processing of algal biomass into bio-crude involves supercritical temperatures in a high-pressure environment.

Energy consumption in the supply chain of the biofuel industry is reflected in the production layer decomposition graph (Fig 3a). The *utilities* sector is responsible for supplying electricity to every industry, home or business. In addition to *utilities*, two other sector categories – *equipment* and *transport services* - are prominent in production layer two (Fig. 3a). The *equipment* category includes scientific laboratory equipment, construction machinery, pumps and other industrial machinery, whereas the *transport services* category includes industry sectors responsible for road transport. In the third and subsequent layers, *mining* and *metals* categories become more evident. The *mining* sectors include coal for producing electricity, and also construction materials that are bought by the *equipment* sectors for constructing machines. The *metals* sectors are responsible for providing iron and steel products, structural metal products and other fabricated metal products. These products are bought by the *equipment* sectors in the second production layer to meet an increase in demand for machinery or other equipment used by the algal biofuel industry in layer one.

In addition to production layer decomposition analysis, the total impacts were also decomposed according to inputs bought by the biofuel industry. Fig 3b shows the top five suppliers of the biofuel industry that contribute to indirect energy use. As expected, the electricity sector is responsible for the majority of energy consumption, followed by the industrial machinery & equipment sector that also consumes electricity for constructing machines. This analysis – commonly known as commodity breakdown – allows the evaluation of the industry's supply chains to highlight the sectors that are responsible for the overall impacts.

3.4 Carbon footprint

Production of bio-crude involves growing then harvesting algae, and processing the harvested algae to obtain bio-crude. Algae require carbon dioxide to carry out photosynthesis for growth. Therefore, when algal production is coupled with a carbon-emitter, algae can provide opportunities for greenhouse gas mitigation. On the other hand, algae harvesting and processing requires electricity, which is a potential source of carbon emissions. In this paper, the amount of carbon dioxide emitted and the amount sequestered was analysed to determine if algae bio-crude production is a net carbon-positive or a net carbon-negative process. Figure 4a shows that the amount of carbon dioxide sequestered in algae bio-crude production is significantly more than the amount emitted. For every tonne of bio-crude produced, almost 1.5 tonnes of carbon dioxide are sequestered from the atmosphere, whereas only 0.5 tonnes are emitted. This result demonstrates that bio-crude production is a carbon-negative process, with net carbon savings of 1 tonne of carbon dioxide per tonne of bio-crude production. The net carbon savings can be increased by reducing the amount of carbon emitted during the bio-crude production process. Similar to energy consumption, the main sectors responsible for carbon dioxide emissions are *utilities*, *mining*, *metals*, *equipment* and *transport services*. Figure 4b shows the top five suppliers of the algae biofuel industry that contribute to carbon dioxide emissions. The greatest carbon emissions result from the use of electricity for harvesting and processing algae. Developing more energy-efficient bio-crude production processes would increase the net carbon savings.

4. Conclusions

Algae bio-crude production is environmentally, socially and economically more sustainable than crude-oil production. In particular, the results indicate that algae bio-crude production process is net carbon-negative. Furthermore, producing 1 million tonnes of bio-crude will generate almost 13,000 new jobs and 4 billion dollars' worth of stimulus in the economy. This study reveals that electricity required for harvesting and processing algae forms a major part of the total energy use. Improvements in the algae to bio-crude conversion process would greatly reduce the energy costs, and thus increase the net carbon savings.

Acknowledgements: This work was financially supported by the Australian Research Council through its Discovery Projects DP0985522 and DP130101293, and by the National eResearch Collaboration Tools and Resources project (NeCTAR) through its Industrial Ecology Virtual Laboratory. NeCTAR is an Australian Government project conducted as part of the Super Science initiative and financed by the Education Investment Fund.

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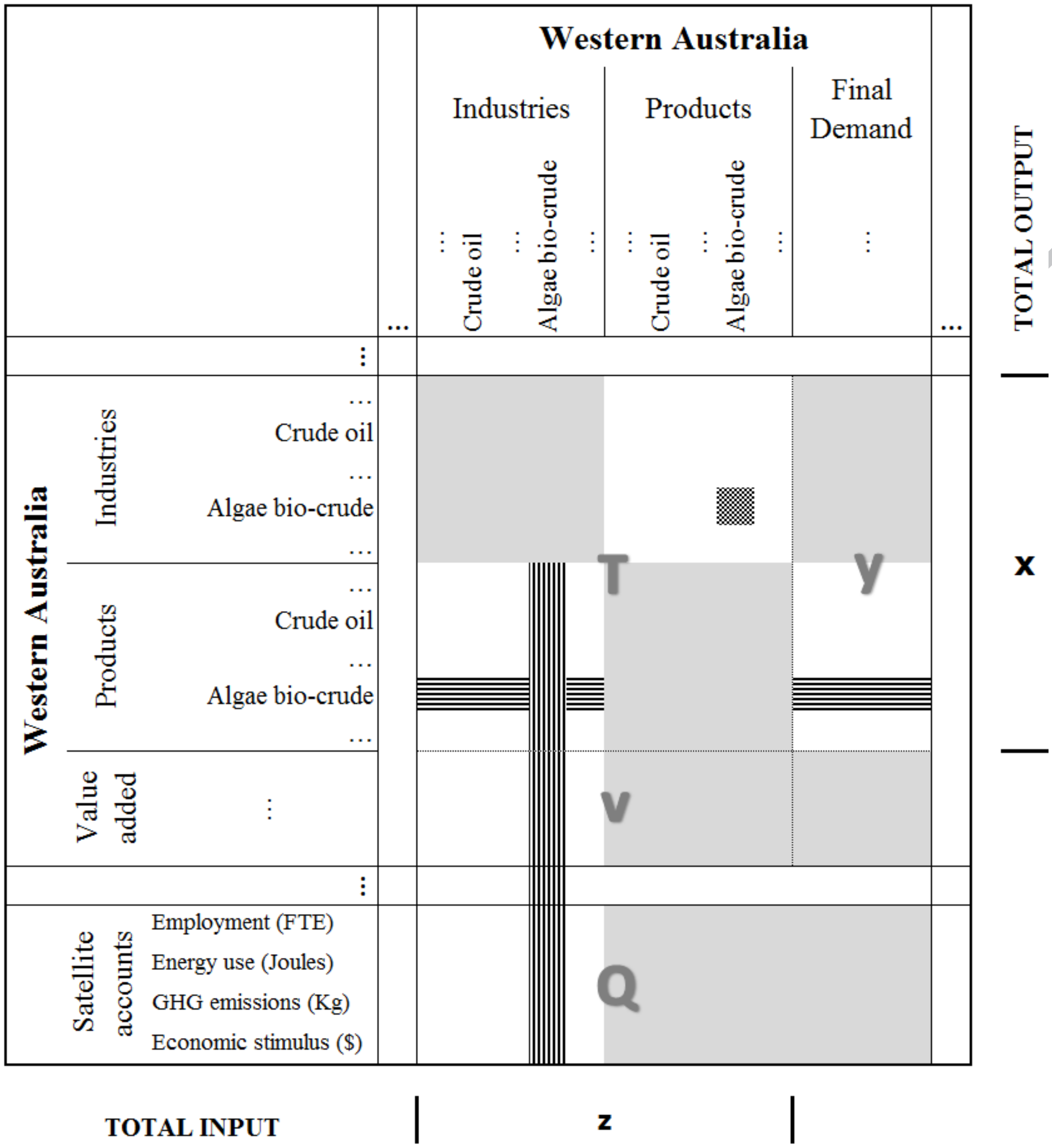
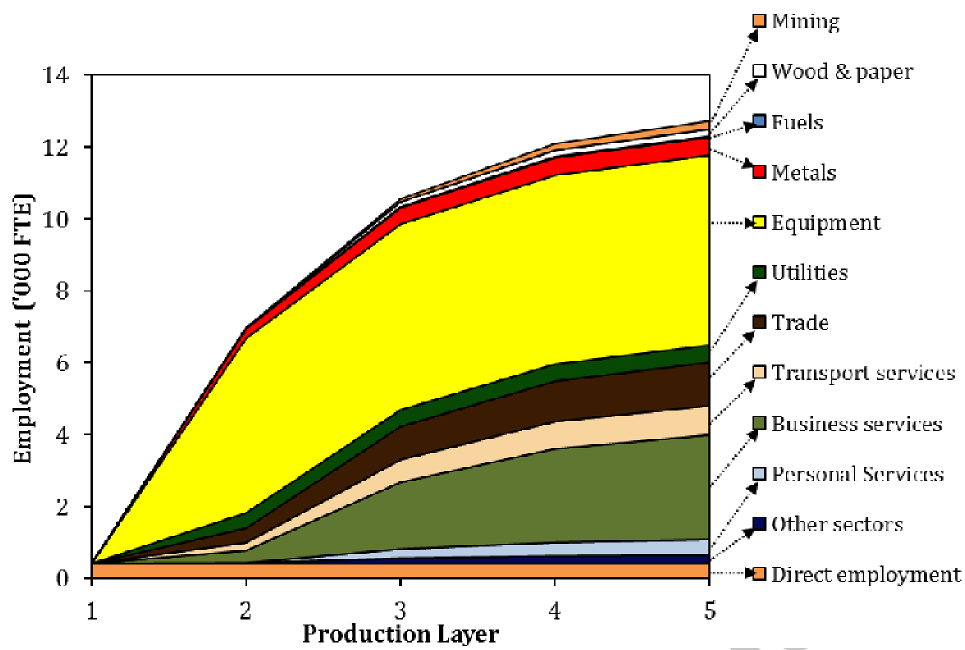


Key:

…	Other regions of the MRIO table	y	Final demand matrix, e.g.: Household consumption ($)
…	Different categories	Q	Satellite accounts matrix
x	Total output		Blank spaces - No data
z	Total input		Sale of algae bio-crude to different industries
T	Intermediate transactions matrix ($)		Inputs needed for the production of algae-biocrude
v	Primary inputs matrix, e.g.: wages and salaries ($)		Total amount of bio-crude produced by the algae biofuel industry

Fig 1 **Hybridisation of algae biofuels data with Australian MRIO data**. Australian multi-regional input-output table was augmented with new rows and columns that were filled with data on algae bio-crude production. The diagram shows a schematic of the Western Australian region of the MRIO table. The table is arranged in a basic supply-use structure (Lenzen & Rueda-Cantuche, 2012).



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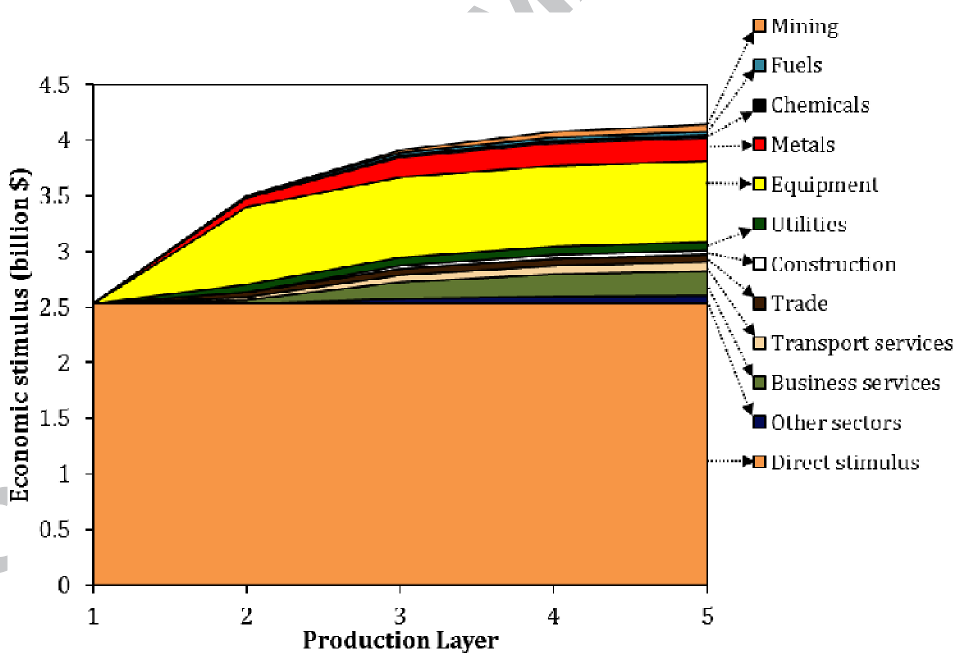

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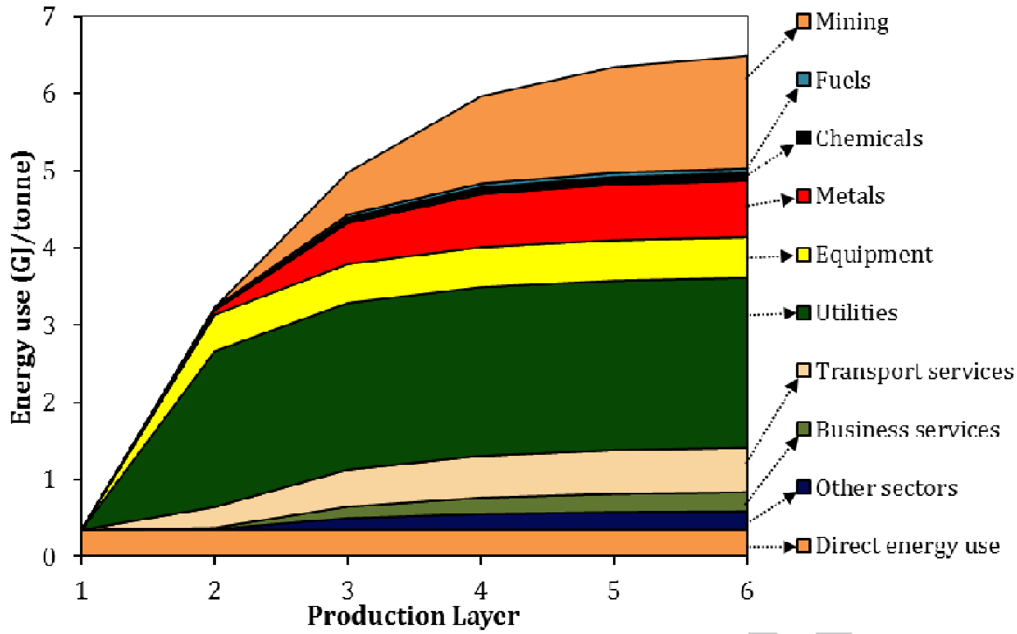
Fig 2a) & 2b) **Employment and economic footprints**: The figure shows the production layer decomposition of total impacts for the social and economic indicator, according to different layers of the supply chain for 1 million tonnes of bio-crude production.



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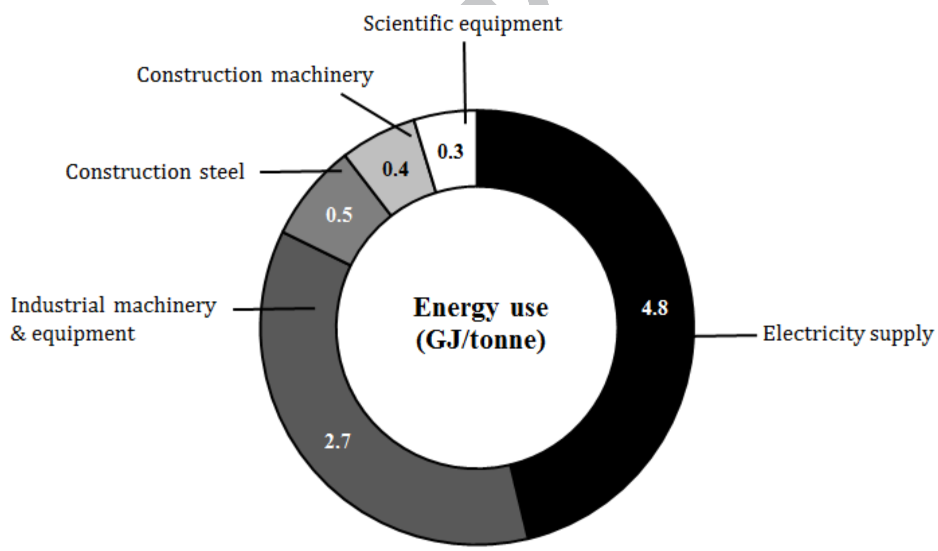
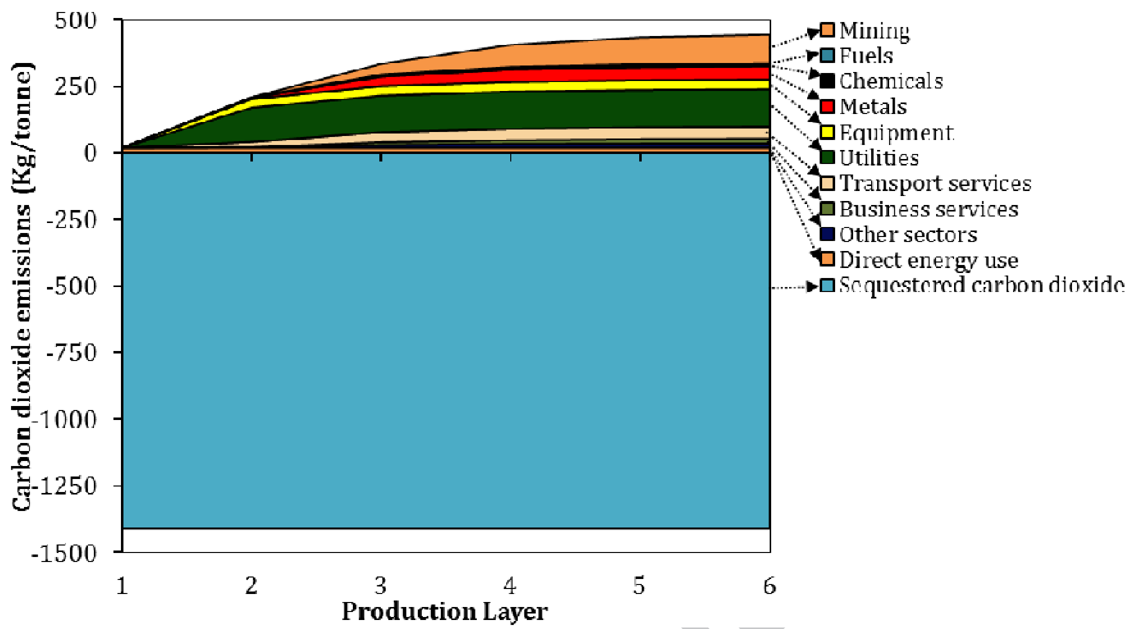


b)

Fig. 3 **Energy footprint:** The energy use impacts of algal bio-crude production were decomposed according to upstream production layers, and also according to operating inputs bought by the algal bio-crude industry. Panel a) shows the production layer decomposition of energy consumption, and b) shows the top 5 suppliers of the algal bio-crude industry that contribute to energy consumption.



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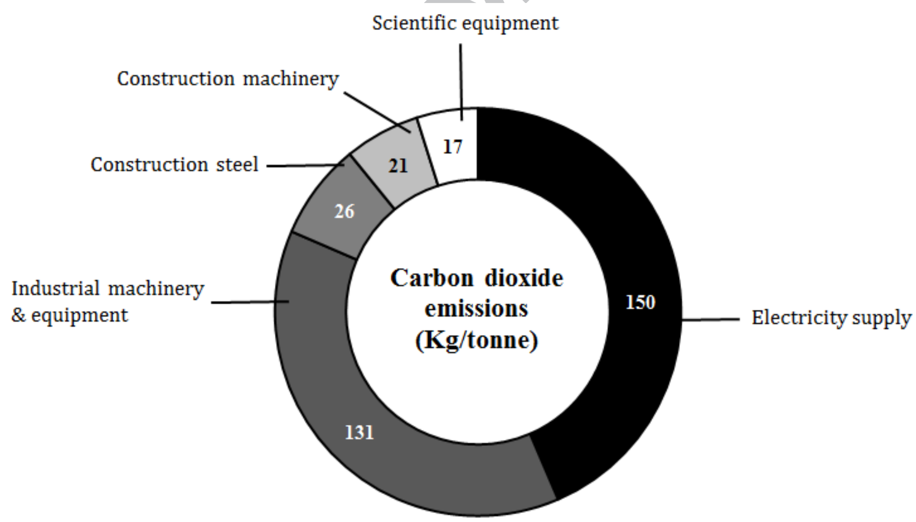

b)

Fig. 4 **Greenhouse gas footprint:** The greenhouse gas impacts of algal bio-crude production were decomposed according to upstream production layers, and also according to operating inputs bought by the algal bio-crude industry. Panel a) shows the production layer decomposition of carbon dioxide (CO_2) emissions, and b) shows the top 5 suppliers of the algal bio-crude industry that contribute to CO_2 emissions.

Table 1: **Impacts of bio-crude and crude oil production.** The table presents the direct and total employment, economic stimulus, energy consumption and greenhouse gas impacts per million dollars of industry output.

Indicator	**Bio-crude**		**Crude Oil**	
	q (direct impacts)	m (total impacts)	q (direct impacts)	m (total impacts)
Employment (FTE per million $)	0.08	2.44	0.48	0.59
Economic stimulus ($ per $)	0.47	0.77	0.11	0.13
Energy use (GJ per million $)	64	1215	3064	3189
Greenhouse gas emissions (tonnes CO_2 per million $)	3.5	83	224	234

5 Highlights for '**Hybrid life cycle assessment of algal biofuel production**' paper:

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 & 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