

Using wastewater and high-rate algal ponds for nutrient removal and the production of bioenergy and biofuels

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ABSTRACT

This paper projects a positive outcome for large-scale algal biofuel and energy production when wastewater treatment is the primary goal. Such a view arises partly from a recent change in emphasis in wastewater treatment technology, from simply oxidising the organic matter in the waste (i.e. removing the biological oxygen demand) to removing the nutrients – specifically nitrogen and phosphorus – which are the root cause of eutrophication of inland waterways and coastal zones. A growing need for nutrient removal greatly improves the prospects for using new algal ponds in wastewater treatment, since microalgae are particularly efficient in capturing and removing such nutrients. Using a spreadsheet model, four scenarios combining algae biomass production with the making of biodiesel, biogas and other products were assessed for two of Australia's largest wastewater treatment plants. The results showed that super critical water reactors and anaerobic digesters could be attractive pathway options, the latter providing significant savings in greenhouse gas emissions. Combining anaerobic digestion with oil extraction and the internal economies derived from cheap land and recycling of water and nutrients on-site could allow algal oil to be produced for less than US\$1 per litre.

Key words | algal oil, biodiesel, biogas, microalgae, nutrients, wastewater

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INTRODUCTION

In a special issue of this journal published in 1995, Bill Oswald stated 'because they are economical reactors, properly designed ponds for waste management will grow in importance in the 21st century'. According to Oswald, this heightened importance would come from a growing need for water and nutrient recycling and animal feed production (Oswald 1995). He realised that paddle-wheel-mixed algal growth ponds are not only cost-effective for wastewater oxidation, but also are very efficient for capturing solar energy and reclaiming nutrients and energy from organic wastes.

Several recent reports show that algal biomass rich in lipids can be a cheap pathway to biofuels when the oil extraction is intimately associated with wastewater treatment and several other production processes (see Lundquist *et al.* 2010; Batten *et al.* 2011a, b). Oswald recognised that a change in emphasis in wastewater treatment technology is on the horizon, one that shifts the emphasis

from oxidising the organic matter in the waste (i.e. removing the biological oxygen demand) to removing and recovering the nutrients – specifically nitrogen (N) and phosphorus (P) – which are the root cause of the eutrophication of inland waterways and coastal zones.

In the future, truly progressive wastewater treatment plants will view themselves as recovery plants for recovering water, nutrients, metals and energy. This growing need for water and nutrient removal and recovery greatly improves the economic potential of using algal ponds in wastewater treatment, because microalgae are particularly efficient in capturing and removing nutrients. Research has shown that high-rate algal ponds, when fed clarified domestic wastewater supplemented with CO₂, can remove nutrients to concentrations similar or better to those achieved in mechanical treatment technologies. Recent laboratory experiments showed nutrient removals of >98% for ammonium and >96% for phosphorus with mixed culture

microalgae grown on CO₂-supplemented primary waste effluent (Woertz et al. 2009).

In this paper, the lifetime net present values (LNPVs) and carbon footprints of four alternative processing scenarios – which combine high-rate algal biomass production with the production of biogas, biocrude, animal feed and several other products – are discussed and compared. The scenarios were assessed for incremental development of Melbourne Water’s wastewater treatment plants using a spreadsheet model developed by CSIRO. This model assesses costs, benefits, greenhouse gas emissions and carbon credits that may accrue to Melbourne Water by using their wastewater for production of algae as a source of energy, fuel and other co-products.

In the next section, the system for integrating the algal growth is described. In later sections, the technical details of the processing of the algae and the results of the four processing scenarios are summarised and compared. Estimates of LNPVs and carbon footprints confirm that tradeoffs will

be inevitable, since the pathway with the best LNPV (under certain conditions) also displays the worst carbon footprint.

INTEGRATION OF ALGAL BIOMASS

Melbourne Water manages the Eastern and the Western Treatment Plants (WTP). Between them they process the majority of sewage produced in Melbourne. Only scenarios for the WTP are discussed in this paper. The WTP is located on about 10,500 hectares of land and processes about 400 ML/day using covered and polishing lagoons and embedded activated sludge (see Figure 1). The on-site power comes from two 1.3 MW Deutz engines and five 1.0 MW Jenbacher engines. Since two additional 1.0 MW Jenbacher engines were added, the plant is now biogas limited in winter only.

Melbourne Water plans to integrate the growth and harvesting of algae biomass with the operation of their

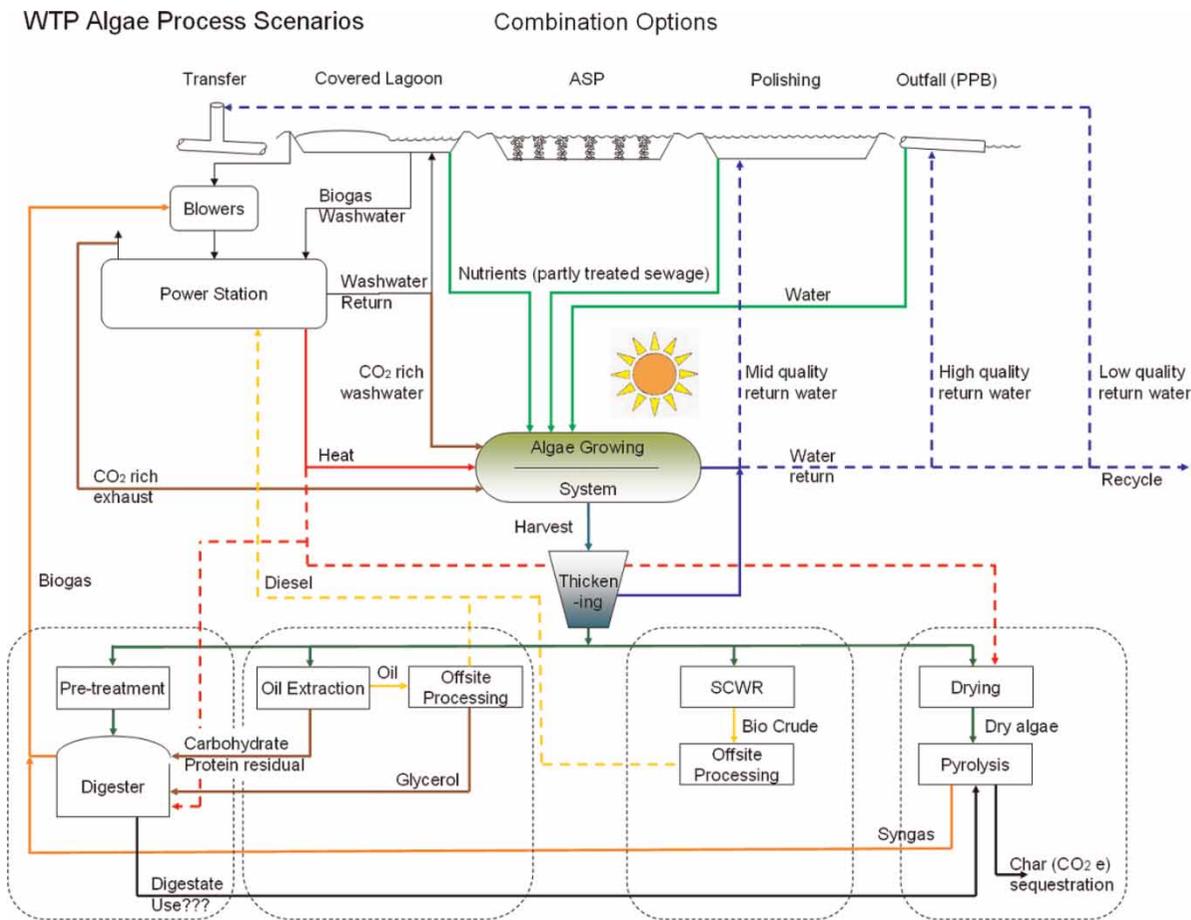


Figure 1 | Schema of proposed algae production and system integration at the Western Treatment Plant (Source: Ken Baxter, Energy Manager, Melbourne Water, 100 Wellington Pde, East Melbourne 3002; or PO Box 4342, Melbourne, VIC 3001; www.melbournewater.com.au).

treatment plants. Anaerobic digestion (AD), oil extraction, a super critical water reactor (SCWR), gasification and/or pyrolysis may be combined in this integrated processing system. The new high-rate algal growth ponds will be separated from their existing treatment processes. Figure 1 depicts the system proposed by Melbourne Water for linking water and nutrient offtake from their WTP with its on-site power station and the proposed algae biomass production facility. The four scenarios to be assessed are shown in the same figure.

In addition to a suitable strain of alga, the key inputs required to grow algae profitably in an industrial setting are: (1) *inexpensive land* (preferably at least 400–500 hectares); (2) *an inexpensive water supply* (preferably recyclable); (3) *warm sunlight and high solar radiation* (preferably all year round); (4) *sustainable sources of CO₂* (preferably nearby); and (5) *inexpensive nutrients* (preferably recyclable). For Melbourne Water, the problem amounts to finding an ecologically benign system of technologies that can co-locate and co-produce profitably, producing a lower cost to their customers and a lower carbon footprint overall, under the conditions imposed by integration of the algal growth system with their existing plant.

SYSTEMS FOR ALGAL GROWTH AND PROCESSING

Algal growth possibilities

In terms of the key inputs mentioned above, (1), (2), (4) and (5) are satisfied. As well as these, several other factors contributed to Melbourne Water's interest in algae:

1. a need for additional biogas for the power station in winter;
2. availability of water, CO₂, N and P at little or no extra cost to them; and
3. possibilities for recycling the water and removing/recycling the nutrients.

Land not required for treatment purposes is leased for agricultural uses. A remaining concern for algal growth at their sites is that the average temperature in Melbourne is 14.8 °C and sunlight-hours range between 3.4 hours per day in June (winter) and 8.1 hours in January (summer). Such conditions do not prevent algal growth, but they do reduce the growth rate of most strains (unless the growth medium is heterotrophic).

In the model to date, the walls and base of the ponds are unsealed. Thus, some water will be lost by percolation

through the soil. Also, some CO₂ will bubble off from the surface. Benemann & Oswald (1996) have shown that the capital costs of a pond system increase significantly if the pond is lined. If an unlined pond does not satisfy the rules of the Environmental Protection Authority, then the extra costs of sealing the ponds will be added to the spreadsheet calculator at a later date. A cheaper alternative could be a thin-film system (Doucha & Livansky 2009).

The standard method of mixing and circulating the algae in a raceway pond is using paddle wheels. Considered by some to be the only viable economic option (although blow jets are another), paddle wheels are standard practice for the cyanobacterium *Spirulina's* production. Paddle-wheel mixing is assumed here for all scenarios. The capital costs and operating costs assumed for building the ponds and the paddle-wheel infrastructure are given in Table 1.

Harvesting and dewatering possibilities

The harvesting and dewatering of the algal biomass can be the most expensive stage of all the processing steps to industrial production, accounting for one third or more of total capital costs (Griffin & Batten 2009; Campbell et al. 2011). The processes involved may include centrifugation, flocculation, filtration and screening, gravity sedimentation, flotation and electrophoresis techniques (Uduman et al. 2010). Several of these processes are highly energy intensive, adding significantly to both the operating costs and the greenhouse gas emissions. Low cell densities, limited light penetration, small sizes and the unusual shapes of some algal cells make oil extraction and the recovery of biomass even more difficult and costly.

Because the choice of harvesting technique is dependent on the properties and uses of the microalgae (e.g. size, shape, density and the target products), the process usually involves two stages – (1) bulk harvesting and (2) dewatering or thickening. In the model, the initial concentration of algae in the ponds is assumed to be only 0.5 g/L. Bulk harvesting using flocculation and flotation separates the biomass from the bulk suspension, resulting in a concentration of 40 g/L. Dewatering lifts this to 35% solids (dry weight). Minimising the cost of each stage is crucial to the economic production of microalgal biomass. Some species are much easier to harvest than others, so the total cost will depend crucially on strain selection. For example, *Spirulina* lends itself to microfiltration because of its filamentous nature and long spiral shape. This is cost-efficient and energy-efficient for this alga (Benemann &

Table 1 | Capital and operating costs for the Proposed Raceway Pond System

Capital item	Capital cost (A\$/hectare)	Operating item	Operating cost (A\$/hectare/year)
Land purchase	0	Carbon supply (power)	217
Site preparation and pond construction	14,400	Phosphorus and nitrogen supply	5,000
Pond paddle wheels – capital	18,600	Pond paddle wheels – electrical	167
Pipelines and pumps for water reticulation	5,000	Electrical pumps – oils and other	42
Pipelines and pumps for carbon supply	3,000		
Harvesting/dewatering:		Harvesting/dewatering:	
Settlement tank	63,000	Flocculants (tank)	9,700
Flotation system	13,000	Flocculants (flotation)	170
Vacuum drum filter	1,600	Power	287
Gas scrubbing (if and when required)	1,250	Costs of generating electricity	1,640
Other structures and instrumentation	7,000	Credits from generating electricity	-6,560
Engineering and contingencies	38,000	Labour and Insurance	792
TOTAL CAPITAL	164,850	NET OPERATING	11,455

Source: Griffin (2009).

Oswald 1996). But the same harvesting method will not be cost-efficient for many other species and strains of algae.

In the model, flocculation (using a polyelectrolyte or alum) followed by flotation are the only harvesting options included. Harvesting by flocculation is superior to other harvesting technologies because it caters for the treatment of very large quantities of microalgal culture and can be applied to a wide range of species and strains (Uduman *et al.* 2010). For dewatering, two options are included: (1) rotary vacuum drum filters or (2) centrifugation. Rotary vacuum filters are relatively cheap. Centrifugation is more reliable, but at the expense of being more expensive and energy intensive.

The additional capital and operating costs for harvesting and dewatering of the algae (when required) are given in Table 1. Further explanation of how these costs have been estimated can be found in Griffin (2009) – obtainable from the first author.

ASSESSING THE FOUR CONVERSION SCENARIOS

Anaerobic digestion for biogas purposes

AD is the conversion of organic wastes into a biogas, which consists primarily of methane (CH₄) and carbon dioxide (CO₂), with other gases such as ammonia and hydrogen sulphide. Studies on AD of algae reported in the literature are

few, despite the fact that this was originally proposed fifty years ago in a paper by Oswald & Golueke (1960). Those two authors integrated large-scale raceway pond cultivation of microalgae with wastewater treatment, followed by fermentation of the algal biomass to produce methane fuel. A useful overview of the current knowledge in this field can be found in a review paper by Sialve *et al.* (2009).

A key issue which arises with digestion of algae is the relatively low carbon (C) to nitrogen (N) ratio found in most algal species and the difficulty anaerobic bacteria sometimes experience in breaking down the algal cell wall. The low C:N ratio can lead to the accumulation of high ammonia levels in the digester which can then exert an inhibitory effect on methanogenic bacteria. Mixing of the algal sludge with other material such as waste activated sludge (included as an option in the model) or waste paper can overcome this problem. Yen & Brune (2007) claim they have achieved a C:N ratio in the optimal range (20 to 25) and an improvement in methane production by adding shredded waste paper to algal biomass. Disruption of the algal cell walls by heat or physical forces can also improve methane generation from algal digestion, but it is questionable whether this process actually produces a net energy gain.

While a theoretical approach can be taken to estimating the amount of methane and ammonia which can be generated by AD of algae, the approach taken in the model is to base calculations on the relatively sparse experimental data reported in the literature. On this basis, Sialve *et al.*

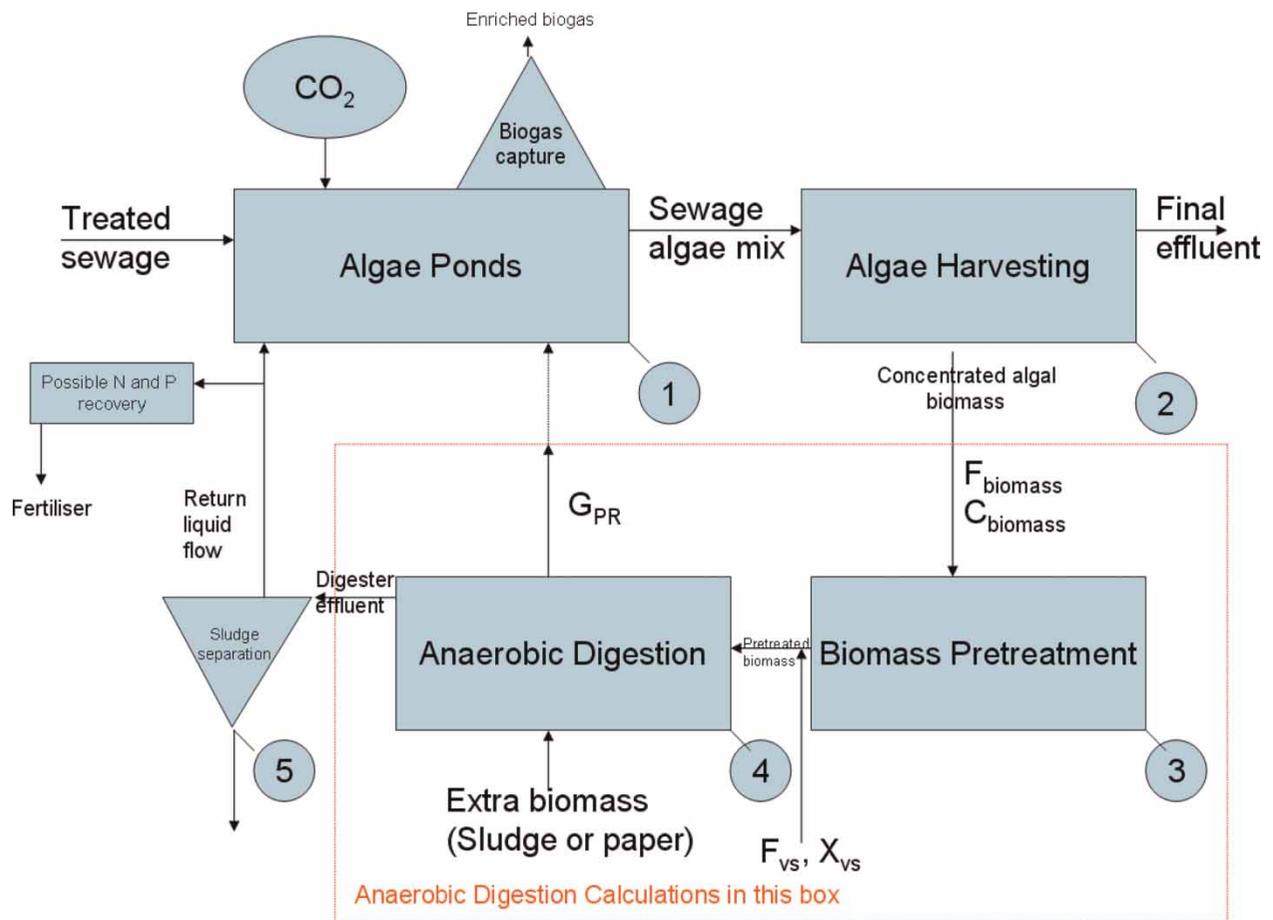


Figure 2 | Schema of anaerobic digestion.

(2009) report data from a number of studies that provide design parameters – such as operating temperature, hydraulic retention time, digester loading rate and methane yield and composition. A key starting place is the volatile solids content of the algae. From this one can use the digester loading rate and the specific methane generation rate to calculate important design parameters such as digester residence time and total methane generation rate. This is the approach taken to the model's input–output calculations, which are based mostly on information contained in Sialve *et al.* (2009).

The key processes are shown in Figure 2. Model calculations start with an estimation of the total flow of algae (F_{biomass}) produced at the algae harvesting stage (see Figure 2) and end with the methane production rate (G_{PR}) and potential energy outputs (heat and electricity). The associated calculations are sufficient to proportion the digester and associated equipment, as well as the energy requirements and outputs. Further technical details

and an example calculation can be found in Batten *et al.* (2011a).

The calculation of capital and operating costs was based on the design parameters mentioned above. Capital cost estimates are currently based on digester loading capacity, although more reliable estimates may be derived from the digester volume. Recent data on capital cost versus digester volume may be included in a future version of the model (see Lundquist *et al.* 2010).

Oil extraction and anaerobic digestion of the residual biomass

After harvesting and dewatering, oil can be extracted. The algal cells may be gently pressed or harshly disrupted, and the oil can be extracted with organic solvents (e.g. hexane) or with environmentally benign but more expensive solvents. This solvent decision highlights one of the many situations where there is a potential clash, yet an obligatory

choice, between a good economic and a good environmental option. The current model assumes that the biomass will be pressed and then the oil extracted with hexane. Another repercussion of this choice is that using hexane prevents the residual biomass from being used as stockfeed. Instead it must be fed to the digester for energy purposes.

Melbourne Water will not transesterify at the WTP, only extract the oil. Nevertheless, two possible ways of using the oil are allowed for in the model: *transesterification* or *direct use*. Direct use assumes that on-site diesel engines can use the algal oil without the need for it to be converted into biodiesel. Alternatively, it may be used in vehicles that have been modified to operate on pure vegetable oil.

Because the algae is combusted and thus releases CO₂ back into the atmosphere, one cannot claim the CO₂ that is sequestered by the algae as a carbon mitigation measure. However, it is legitimate to claim the CO₂ savings (as carbon offsets) from the diesel fuel that has been replaced by algal oil or biodiesel. This carbon offset is included in the model and amounts to 2.94 kg CO₂ per kg of diesel fuel.

Super critical water reactor

A SCWR can be used on its own to liquefy biomass to a viscous oil, or as a first step to gasification (see section on Gasification). According to Matsumura *et al.* (2005), super critical water (SCW) gasification is a hydrothermal conversion route and a novel gasification route for biomass. It employs water either near or above its critical point ($T = 374^{\circ}\text{C}$ and $P = 22.1\text{ MPa}$), namely SCW as a reaction medium. SCW behaves like an adjustable solvent and its properties are tuneable by manipulating temperature and pressure. Under SCW, biomass is rapidly decomposed anaerobically and the resulting decomposition products (organic compounds) can be dissolved in SCW, forming a homogenous reaction environment.

The SCWR pathway has been included in the model because it can be more effective than a conventional thermal gasification route for very wet biomass like algae. Use of a SCWR can promote the selective production of energy-rich gases such as H₂, syngas (a mixture of CO and H₂) and methane from the wet biomass. Conversion of algal biomass to oil is also possible under subcritical water by hydrothermal upgrading. For further details of the temperature and pressure conditions leading to the production of various gases, see Kruse (2008).

Some cost advantages of using a SCWR to convert biomass are: efficient processing of biomass with a high moisture content (such as algae); utilisation of different

kinds of biomass as an energy source; complete gasification achieved within a short reaction time; producer gas is available at high pressures in a single step process (avoiding the cost of expensive gas compression); high energy conversion efficiency is achieved by avoiding drying; suppression of the formation of tar and char; selectivity towards CH₄, H₂ or syngas can be controlled with temperature, pressure and proper catalysts; effective purification of product gas; and water recycling and mineral recovery from wet biomass through desalination.

A flowchart of the key processes assumed for assessing the SCWR pathway's capital and operating costs is shown in Figure 3. For costing purposes, the gas produced is assumed to be 94% N₂ and 6% light alkanes by mass.

Note the optional products and processes shown in Figure 3. There is a costing for an optional centrifuge to dewater the algae before it goes into the pump and the heat exchanger. If the centrifuge pathway is chosen, several additional cost calculators are made for the centrifuge's capital cost and electricity cost. After degassing, there is a choice between gravity settlement (a relatively inexpensive process) to produce heavy biocrude, or solvent extraction (a more expensive process) to produce light biocrude. Having a density of about 800 kg/m³, the latter is in the range of natural light crude (<870 kg/m³). The former has a density of about 1,025 kg/m³, putting it close to natural extra heavy crude (>1,000 kg/m³). For the price of light biocrude, we have assumed parity with the crude oil price (EAI

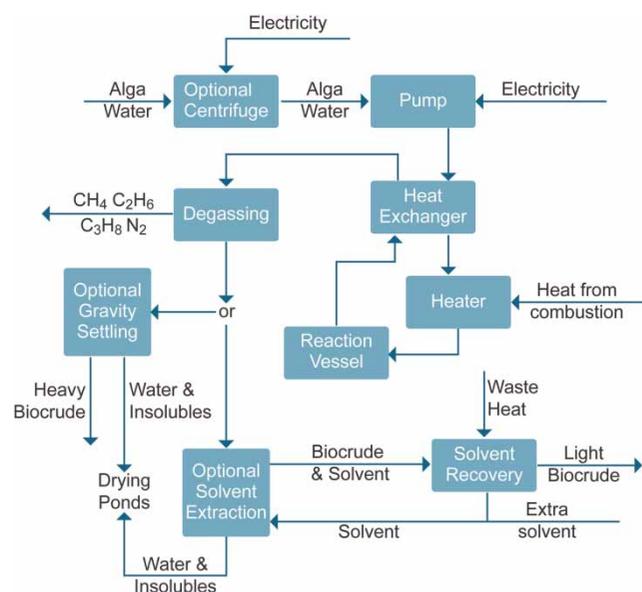


Figure 3 | Flowchart to evaluate capital and operating costs for the SCWR.

2010). For heavy biocrude, the model assumes 85% of the light biocrude price.

Co-products are assumed to be struvite (a good fertiliser) and good quality wastewater that may be returned to the ponds. If solvent is used, another co-product is inorganic carbon. Additional solid waste products may arise, but they have not been assigned any value. Other economic assumptions and technical details pertaining to the SCWR pathway may be found in Batten *et al.* (2011a). Research into SCWR technologies has increased rapidly over the last two decades. Some reactor plants are in operation, but full commercialisation has yet to be realised. To the authors' knowledge, the largest built facilities are pilot-scale plants located in Germany, the Netherlands and New Zealand (for algae processing).

Gasification

Gasification involves the partial oxidation of biomass into a combustible gas mixture at high temperatures (800–1,000 °C). For the purpose of our model, the gas generated is a synthetic gas that consists of carbon monoxide and hydrogen, along with carbon dioxide, methane and other hydrocarbons. Once scrubbed of particulates and organic compounds, it can be combusted to generate electricity. For combustion purposes in the model, algal biomass is considered to be a lignocellulosic material with properties roughly equivalent to that of perennial plants or straw.

Gasification is a robust, proven technology that can be operated either as a simple, low technology system based

on a fixed-bed gasifier, or as a more sophisticated system using fluidised-bed technology (McKendry 2002). Circulating-fluidised-bed (CFB) gasifiers can cope with high capacity throughputs. They are popular in Europe and the USA, so we have included this technology. Because it reduces the heat energy from the gas, air is the oxygen source for the gasification process. If the gasification uses pure oxygen rather than air, the heat-value doubles.

A schematic displaying the key features of the gasification process is shown in Figure 4. The co-product in all gasification of biomass is biochar, because not all the carbon reacts with a reduced oxygen supply. Biochar has a heat value similar to black coal (30 MJ/kg), and the price of the latter has risen recently to about US\$120/tonne.

After dewatering, the gasification pathway represented in the model assumes that a 34% dry weight solids concentration will increase to 50% solids before input into the gasifier. Additional capital expenditure will be incurred in transferring the dewatered algae to the drying area and supplying the infrastructure needed to utilise available free heat. Capital expenditure figures for the construction of the gasifier were derived from two CFB plants in Europe: the Güssing gasifier in Austria (running gas engines) and a Swedish demonstration plant in Varnamo (operating a gas turbine). Further details of both plants may be found in Knoef (2005).

MODEL RESULTS

Over the lifetime of the projected scenarios, the best economic return of A\$14 million is achieved by the SCWR

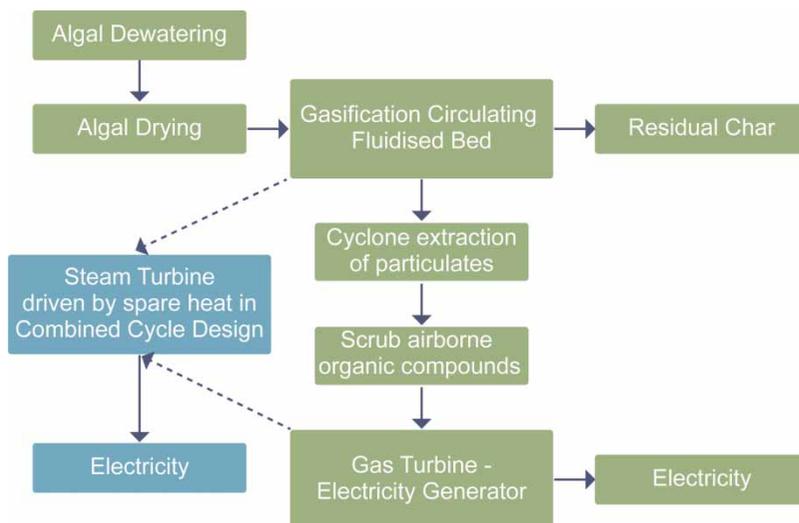


Figure 4 | Schematic of a gasification plant based on a circulating fluidised-bed design.

pathway, followed by the oil extraction pathway with a LNPV of A\$8 million. Under these benchmark conditions, the other conversion pathways achieve negative economic returns. Sadly, gasification is a huge loss-maker with a LNPV of -A\$59 million. However, the picture changes considerably when each pathway's carbon footprint is compared. The SCWR pathway is a net offender, producing additional CO₂-equivalent emissions of 83 kilotons. The other three pathways achieve significant savings in emissions, with the oil extraction pathway performing best with savings of 540 kilotons of CO₂-equivalent emissions.

To see how sensitive these results are to changes in the assumed conditions, we need only change the solvent extraction option in the SCWR pathway. Including solvent extraction corresponds to changing the main product from heavy to light biocrude. Although the latter is more valuable, the costs of producing it are higher.

In Figure 5, the resulting lifetime economic returns from (a) excluding solvent extraction and (b) including solvent extraction are compared. Note that the LNPV changes from +A\$14 million to -A\$24 million. This makes oil extraction the best pathway from an economic viewpoint.

If the algal meal is used for stock feed instead of digesting it, our results alter again and the SCWR pathway is restored to its former position of the most profitable pathway (see Figure 6). These preliminary results confirm that the comparative results are indeed sensitive to the options and underlying conditions assumed for each of the conversion scenarios.

Another point to observe is that each conversion pathway does not produce identical product mixes. Both the sources of revenue and the pathway costs differ (see Table 2). Therefore, any simple comparison of economic returns may be misleading. But some observations can be made, subject to the usual caveats. First, there is no clear winner on both the LNPV and the carbon footprint simultaneously. Our simulations to date have shown that:

- gasification (Scenario 4) is the most expensive option under all conditions;
- combining oil extraction with AD (Scenario 2) performs well on both LNPV and greenhouse gas savings under most conditions examined;

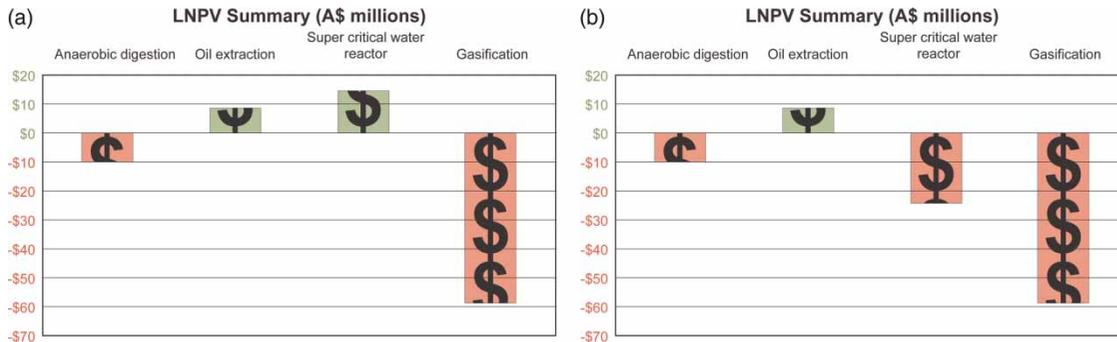


Figure 5 | Changes in lifetime NPV for the SCWR Pathway. (a) Excluding solvent extraction. (b) Including solvent extraction.

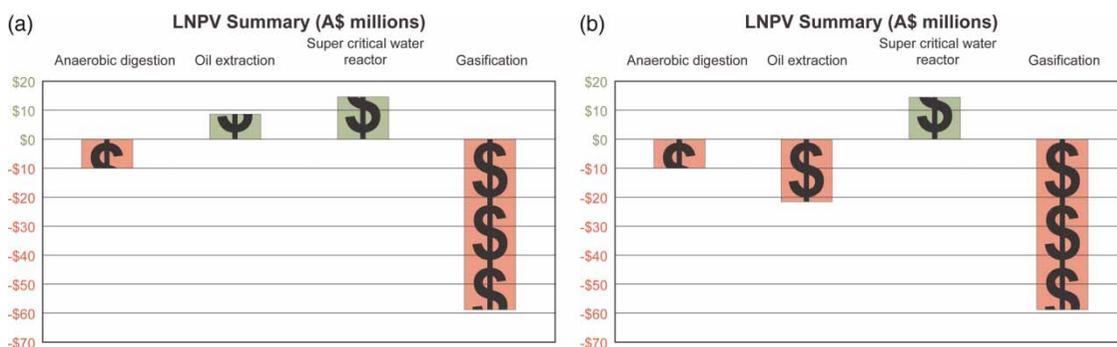


Figure 6 | Changes in lifetime NPV for the oil extraction pathway. (a) Meal digested. (b) Meal used for stockfeed.

Table 2 | Pathway products and costs

Conversion pathway	Product mix (Revenue stream)	Major costs (Expenses stream)
Anaerobic digestion	1. Electricity + RECs 2. Struvite 3. Waste heat	1. Algal ponds 2. Harvesting 3. Digester 4. Activated sludge
Oil extraction plus anaerobic digestion	1. Algal oil 2. Electricity + RECs 3. Struvite 4. Waste heat	1. Algal ponds 2. Harvesting 3. Oil extraction 4. Polyelectrolyte
SCWR	1. Biocrude 2. Struvite	1. Algal ponds 2. Flocculation alum 3. SCWR 4. Electricity
Gasification	1. Electricity + RECs 2. Biochar	1. Algal ponds 2. Harvesting 3. Flocculation alum 4. Gasifier

Note: RECs = Renewable Energy Certificates.

- the SCWR pathway (Scenario 3) is an outright winner in terms of profitability over the life of the project, but its carbon footprint is problematic;
- more reliable lifecycle cost and emissions data are needed for some scenarios before firm conclusions can be drawn.

CONCLUSIONS

This paper started with the observation by several experienced microalgal experts (Lundquist *et al.* 2010) that they did not foresee a favourable outcome for near-term, large-scale biofuels production from microalgae without wastewater treatment as the primary goal. Such a viewpoint reflects two observable facts:

1. The identification of viable ways of producing biofuels from algae profitably is in its infancy and still requires a large amount of R&D.
2. A change in emphasis in wastewater treatment technology is underway, from oxidising the organic matter in the waste to removing and recycling the nutrients.

The growing need for nutrient removal and recovery for environmental and economic reasons does improve the

economic potential of using new algal ponds in wastewater treatment, since microalgae are efficient in capturing and removing such nutrients.

The results presented in this paper go some way towards confirming that observation. Making use of a spreadsheet economic model developed for one of Australia's largest wastewater treatment plants, we have shown that algal oil suitable for the production of biodiesel can be produced for less than US\$1 per litre. With wastewater treatment as the primary goal, this result is achievable by sourcing various qualities of water and nutrients from existing wastewater lagoons, combining them with CO₂ from an on-site power station, then recycling some water and nutrients back into the algal ponds. The profitable algae-to-biodiesel production pathway is not new, combining algal growth ponds with readily available harvesting and dewatering technologies plus AD of the residual algal biomass for energy purposes.

By international standards, producing algal oil for less than US\$1 per litre seems to be an exceptional achievement. Estimated costs of producing algal oil vary widely, but raceway ponds do outperform photobioreactors (USDOE 2009). The profitability of the wastewater strategy discussed in this paper arises from the privileged position that Melbourne Water's WTP enjoys in terms of four of the five key inputs required for the profitable growth and processing of microalgae for industrial purposes:

- available land – at no additional cost;
- a generous, recyclable supply of several qualities of water – at low cost;
- a sustainable source of CO₂ on-site – at little cost; and
- ample and recyclable supplies of N and P – at little cost.

Our spreadsheet model estimated the LNPVs and carbon footprints associated with four processing scenarios. The scenarios combined the production of algal biomass with the ensuing production of biogas, biofuels and other products. Preliminary results show that SCWRs and anaerobic digesters appear to be attractive options, the latter providing significant savings in greenhouse gas emissions. But our results also confirm that tradeoffs will be inevitable, since the most profitable scenario (the SCWR pathway) displayed the worst carbon footprint.

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