AN ENERGY EFFICIENT PROTOCOL TO COMPENSATE NET EVAPORATION IN OPEN-POND MICROALGAL MASSIVE CULTURES AND OBTAIN MAXIMAL STEADY-STATE PRODUCTIVITIES

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ABSTRACT

Industrial growth of microalgae in open ponds can be strongly limited by evaporation. This is specially the case of cultures in highly evaporative areas where production plants would be placed due to other important considerations. We present a mathematical model to calculate native solutes and exogenous nutrient concentrations as affected by net evaporation. The model takes into account the periodic compensatory addition of new feedstock water and the eventual recycling of the culture medium. We find that for a selected species and growth conditions even in locations where the net evaporation is very high (e.g. 250 $mm.month^{-1}$), a protocol of harvesting 10 % of the pond volume per day, and replacing this volume and the evaporated water with new feedstock water is sufficient to maintain the solute concentrations at a level only 24 % higher than the original ones. In the case of a plant dedicated to the production of biodiesel, the pro-rated to lifetime embodied energy of all the piping systems and the pumping energy involved in the protocol can be a small fraction of the microalgae energy yield as crude oil. This protocol should prove particularly useful for the exploitation of marine microalgae growing in open ponds with seawater-based growth medium.

INTRODUCTION

Solar radiation can be harvested as biomass, a sustainable source of energy, by exploiting natural photosynthesis (Larking, Ramage et al. 2004). Some microalgae have the highest productivities of biomass and oil (Chisti 2008; Sheehan, Dunahay et al. 1998) and should become the basis for a new "agriculture".

However, a particular feature of microalgae industrial cultures is that all the nutrients needed for biomass generation are provided by the feedstock water and by the addition of fertilizers (Andersen 2005), here called "exogenous nutrients", whereas, in most cases, classical crops draw a good part of the nutrients from the native soil content (Taiz and Zeiger 2006). Furthermore, microalgal industrial plants should be placed in areas of adequate insolation, moderate temperatures, and easy provision of water. But also, very importantly for the rational use of soil resources, they should be located in classically non-productive land, which typically involves areas of high potential evaporation and low rainfall. Moreover, the extended microalgal growth infrastructure has to be simple and cheap which suggests the use of open ponds (Richmond 2004; Borowitzka 2005; Benemann and Pedroni 2007). This, however, implies significant water loss through evaporation. Using new feedstockwater (fresh or marine) to compensate for evaporation is the cheapest, most sensible approach, as we show below.

Any energy efficient engineering solution for the technology needs to minimize both the embodied energy of the plant (Burgess and Fernández-Velasco 2007) and the operational energy to maximize the Net Energy Ratio (NER) (Bailey 1981; Prueksakorn and Gheewala 2008). The embodied energy includes all the energy contained in the plant materials and the energy involved directly or indirectly in the construction of those materials and of the full plant. In this particular case, the operational energy includes the pumping energy needed to bring feedstock water from its reservoir (source) to the plant. In this paper we keep a broad view of what an ecologically sound water feedstock reservoir could be. Although we favour the case of the ocean for the exploitation of marine microalgae, other suitable reservoirs could be, in principle, rivers or underground aquifers. Our analysis applies equally well to all of them.

In this paper we provide a mathematical model to predict the native solute and exogenous nutrient concentrations as affected by net evaporation, utilising climatological information and manipulating the periodic input of original feedstock water in combination with the harvesting regime. We show that even in locations where the net evaporation is very high (e.g. 250 mm.month^{-1}), a protocol of harvesting 10 % of the pond volume per day and replacing this volume and the evaporated water with new feedstock water maintains the solute concentrations at a level only 24 % higher than the original ones. This protocol proves to be energy efficient as, under those conditions of evaporation and management, the total energy required for daily additions of feedstock water and the pro-rated to lifetime embodied energy involved in all the piping systems is only 10.7 % of the daily microalgal energy yield as crude oil, in the case of a plant located 10 km horizontally and 100 m vertically from the feedstock water reservoir, and in the absence of water recycling.

MATERIALS AND METHODS

Growth of *Nannochloropsis salina* and outdoors growth simulation

The marine microalga *Nannochloropsis salina* strain CS-190, CSIRO, Hobart, Australia, was grown in f_2 medium (Andersen 2005) in standard laboratory conditions continuously illuminated and bubbled with CO_2 (5 % v/v in air). A simulation for the growth in a close to natural irradiance conditions was prepared by interspacing 16 h of no growth (i.e. “night conditions”) per each 8 h of growth (i.e. “day conditions”) using an actual growth curve obtained under continuous light. This simulation was subsequently modified to represent the pseudo steady-state growth in which a culture growing in the late linear phase is partially harvested each day by the withdrawal of 10 % of the total volume. An 8 h period of linear growth (maximal rate) is followed by a harvest and addition of new feedstock water that brings the volume to the standard value (e.g. equivalent to 300 mm pond depth) and causes a 10 % dilution. This dilution is followed by a period of no growth. The three phases, totalling 24 h, were repeated for many cycles representing the pseudo steady-state culture.

Simulation of solute concentration dependence on evaporation and its compensation

The simulations were generated in Microsoft Excel 2003 using Visual Basic 6.3.

From the universal dilution formula (Harris 1991) by expressing all water volumes as a function of the pond height (h_p) the actual concentration of any solute [S_i] in the feedstock water at time t (in days) contained by a pond that is subjected to net evaporation, and in which water is taken for harvesting and replaced by recycling this volume back to the pond, or by the addition of fresh feedstock water, or by a combination of the two in varying degrees, can be expressed as:

$$[S_i]_t = \frac{\left((h_p - h_e - h_h + h_r) \left(\frac{h_p}{h_p - h_e} \right) [S_i]_{t-1} + (h_h - h_r + h_e)\ [S_i]_0 \right)}{h_p} \qquad (1)$$

Where h_p is the initial operational pond height, h_e is the evaporation per day, h_h is water taken each day for harvesting, h_r is the water harvested culture recycled to the pond each day, $[S_i]_0$ is the concentration of any native solute in the original feedstock water or exogenous nutrient added at time zero, in relative units, by definition unity and $[S_i]_{t-1}$ is the concentration of any solute in the pond the previous day. To generate the solute concentration time curves shown in Fig. 1 this formula is applied iteratively. The concentration of any solute $[S_i]_t$ is calculated after harvesting and "re-topping" with new feedstock water and/or recycled water, to maintain the pond height (h_p) constant.

We calculate the concentration of exogenous nutrients as affected by the addition of new feedstock water to replace the culture withdrawn for harvesting, in an evaporation compensated regime and maintaining the pond height (h_p) constant. The change in concentration of exogenous nutrients does not include the resultant one from the assimilation by the microalgae. Exogenous nutrients are lost only when the culture is withdrawn for harvesting. In Fig. 1, equation (2) is applied iteratively.

$$[N_i]_t = \left(1 - \frac{h_h - h_r}{h_p} \right) [N_i]_{t-1} \qquad (2)$$

where $[N_i]_t$ and $[N_i]_{t-1}$ are the concentration of any exogenous solute at any given day (t) and the concentration of any exogenous solute the previous day, respectively.

Energy content of piping infrastructure and pumping energy

The energy content of the piping infrastructure was calculated as in (Burgess and Fernández-Velasco 2007), considering the mass of the pipe, the specific energy content and the lifetime of each material, as per specifications in Table I.

The energy required to pump water from the feedstock reservoir to the plant border and within the plant ('in-plant') can be calculated by combining the standard expressions for pressure loss through a pipe (Potter and Wiggert 1991) with the energy required for vertical displacement. Here we consider that the hydraulic efficiency of the pump is 0.75. Values for pipe inner surface roughness for concrete, PVC and steel are 0.5, 0.005 and 0.05 mm respectively (Bhave 1991).

RESULTS

Plant and external piping system design

We have modelled a microalgae growth and harvesting plant to estimate the embodied energy of both the 'in-plant' and the external piping infrastructure, and all the energy required for pumping. The 'in-plant', which is a square of 1000 ha includes 1740 growth ponds of 50 m x 100 m and includes general infrastructure immediately associated with it (e.g. piping lines and service roads). Ponds are connected in columns (both inlet and outlet) by pipes with a diameter of 0.44 m (total 181.5 km in pipe length) and columns are connected to a main feeder manifold of 1.5 m diameter (total 6.32 km in pipe length (see Table 1). The external piping system (connecting the 'in-plant' with the feedstock water reservoir) has a diameter of 1.5 m and is analysed independently of the in-plant' and involves two pipes, one for the incoming new water and the other for returning used water to the reservoir. External to the 'in-plant' are also all the auxiliary facilities, which are not considered here. Because the power needed for pumping is approximately inversely proportional to the square of the pipe diameter, for the external piping system we chose one of the largest pipe diameters available for all the three pipe materials here discussed; i.e. 1.5 m.

The 'in-plant' piping system is designed for continuous filling and emptying of ponds, to minimize pumping energy and the size of infrastructure. For a plant with the above dimensions, an operational water depth of 300 mm, a climate with 250 $mm.month^{-1}$ net evaporation and a 10 % daily harvesting regime without recycling, the total average input volume of water to the plant is 332 $ML.d^{-1}$ (without water recycling).

Change of pond solute concentration as determined by climate

Sustained net evaporation can strongly affect the microalgal growth medium composition in open ponds (Wheaton 1977; Richmond 2004). Here we develop simulations to quantify these effects. We consider here the solute ("salts") concentration ("salinity") change due to net evaporation and how that change can be affected or governed by additions of new feedstock water, for both the native solutes in the feedstock water and the exogenous nutrients. We do not attempt to account for the natural depletion of native or exogenous nutrients due to the uptake by the cells during growth, as a compensation nutrients re-addition is always required.

Application of Equation (1) shows that in the absence of any manipulation the solute concentrations attained by the culture at the time of harvesting (e.g. ≥ 11 days) deviate from the original feedstock water solute or exogenous nutrient concentrations at the beginning of the culture, to both of which we assign the arbitrary value of 1. The deviations are larger the higher the net evaporation. We consider that the solute concentration of rain water is zero. Uncompensated evaporation identically affects the concentration of the solutes brought at time zero by the feedstock water or as exogenous nutrients. Fig. 1A, curve a shows the case for a location with an average net evaporation of 250 $mm.month^{-1}$, which corresponds to a severely arid zone, as for example close to the shore of central western Australia (Hounan 1961).

The periodical addition of new feedstock water in an amount equal to that lost by net evaporation allows for a slower deviation of the original feedstock water solute concentrations (Equation (1)), with the kinetics changing to a linear behaviour as the daily addition of new feedstock water partially dilutes the feedstock water solutes that have been concentrated by net evaporation, compare curves b and a in Fig. 1A. With this protocol, the concentration of exogenous nutrients is not affected by the net evaporation (first 11 days in curve d).

In comparison, Fig. 1A, curve e, shows a simulated growth curve for *N. salina* in an 8 h light/16 h dark regime (see Materials and Methods). Altogether, this analysis indicates that, for any given microalgal strain, the maximal length of time that can be allowed for the culture to achieve the highest possible cell concentration in the linear growth phase, before a total or first partial harvest is performed, will be determined by its typical growth kinetics and salinity tolerance, and the rate of net evaporation in a given location.

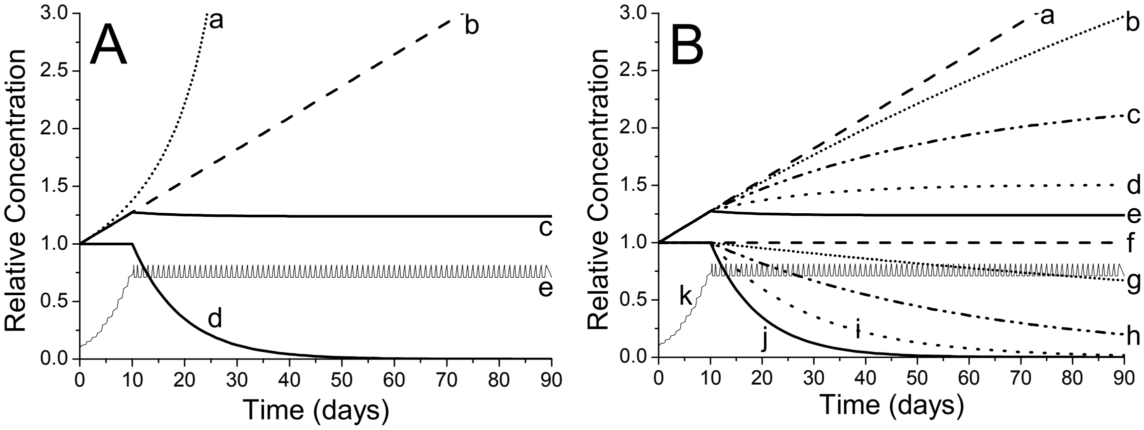


Figure 1 Evolution of the concentration change of the feedstock water solutes ("salts") and exogenous nutrients during the full microalgal culture in an open pond subjected to 250 mm.month^{-1} net evaporation, and under a variety of management conditions. Concentrations are expressed in arbitrary units.

A) Growth medium is not recycled. a) Solute (feedstock-water-provided or an exogenous nutrient) concentration in the absence of any manipulation; no harvesting. b) Feedstock water solute concentration in the presence of daily additions of new feedstock water to the pond, to exactly compensate the average net evaporation; no harvesting. c) Feedstock water solute concentration in a pond in which two regimes of new feedstock water additions are applied. In the first one, first 11 days, new feedstock water is daily added as for curve b. In the second one, during the pseudo steady-state phase generation of biomass combined with daily partial harvest (10 %), new feedstock water is added to compensate for daily evaporation (as for the first regime) and also to replace the volume of culture that is withdrawn daily from the pond for harvesting. The supernatant of this harvested volume is discarded. d) Exogenous nutrient concentration resultant from the same protocol described for curve c; the nutrients are added at time zero. e) Simulated growth curve of *N. salina* describing, as biomass concentration, the initial biomass build-up (first 11 days with no harvesting), and the following phase that includes growth interspaced with daily partial harvesting which maintains the cell concentration in a pseudo steady-state.

B) Growth medium is recycled in various percentages. a-e) The same as Panel A, curve c, but the withdrawn volume for harvest is recycled in the following percentages: a) 100 %, b) 95 %, c) 80 %, d) 50 % and e) 0 %. f-j) Exogenous nutrient concentration resulting from various harvesting regimes in which the withdrawn volume for harvest is recycled in the following percentages: f) 100 %, g) 95 %, h) 80 %, i) 50 % and j) 0 %. Curves e, j and k in Panel B are identical to curves c, d and e in Panel A.

Periodic partial harvest matched with new feedstock water re-additions stabilises solute concentrations against net evaporation

Once an optimum cell density is reached through growth, a program of periodic (e.g. daily) partial harvesting should follow involving the withdrawal of a fraction of the total volume (e.g. 10 %) and the separation of the cells from the growth medium, e.g. by centrifugation. In our model (Fig. 1) this occurs at day 11. The corresponding supernatant (the growth medium separated from the cells) can be discarded, by returning it to the water feedstock reservoir (e.g. the ocean or the river), or it can be recycled in variable amounts. An identical amount of new feedstock water needs to replace the supernatant discarded in order to maintain the pond height constant.

For the same climate of 250 mm.month^{-1} net evaporation, Fig. 1A, curve c shows the evolution of the concentration of the feedstock-water originated solutes during the complete process of biomass growth since inoculation (time zero) and the pseudo steady-state process resulting from growth and daily harvesting (10 %) which starts after an optimal cell density is reached; equation (1) is used. This allows the maximal compensation achievable while maintaining a constant pond volume. During the period of biomass build-up (Fig. 1A, curve e) the feedstock-water originated solutes concentration increases linearly, as partially compensated by the daily addition of original feedstock water, i.e. the same protocol as for curve b is used. However, when the daily harvesting starts, the feedstock water solute concentrations decrease to finally stabilise in a level 1.24 times higher than the concentrations in the original feedstock water. This halt of the concentration process and its partial reversion result from the addition of feedstock water to compensate for net evaporation and for the partial withdrawal of culture, keeping the total culture volume constant.

The kinetics of concentration of exogenous nutrients have a different pattern, as shown by equation (2). During the biomass build-up in any regime of net evaporation that concentration remains constant (Fig. 1 A, curve d), because the total pond volume is kept constant through the daily additions of feedstock water in amounts identical to the average net evaporation. However, a washout of the initially present exogenous nutrients starts during the periodic harvesting in the pseudo steady-state phase (the nutrients assimilated by the microalgae are not considered, see above). The kinetics of this washout is independent of the net evaporation regime as it results only from the percentage of daily culture withdrawal.

In order to save exogenous nutrients and to minimize energy in the pumping of new additions of feedstock water, the harvest-derived supernatant could be recycled almost totally or partially. Fig. 1B shows a simulation for the same climate of 250 mm.month^{-1} of net evaporation; equation (1) is used. Whereas water recycling from the harvested volume determines higher steady-state concentration of feedstock water solutes, it minimizes exogenous nutrient washout. For example, after 50 days of total culture in a regime of 80 % water recycling the exogenous nutrient washout is not higher than 54 %, independently of the net evaporation as indicated above, whereas the original feedstock solute concentration in the extreme climate condition of 250 mm.month^{-1} net evaporation is 1.85 times the native one.

Embodied energy of piping infrastructure and overall pumping energy costs

While the protocol of compensating for high evaporation rates allows placement of the production plant in any desert area, the embodied energy of the infrastructure needed to bring the feedstock water from a distant source ("feedstock water reservoir") to the plant as well as the pumping energy costs must be kept reasonably low. For our calculations we have selected an extreme case of monthly evaporation in Australia, i.e. 250 mm.month^{-1}. Besides considering protocols with 50 and 80 % water recycling (Fig. 2C), we have also considered the case of a non-recycling protocol (Figs. 2B and C).

Fig. 2A shows the lifetime pro-rated energy content of the full piping system. These results are shown in comparison with the energy content of the crude oil (150 $L.ha^{-1}.d^{-1}$) produced by a microalga as *N. salina* on a daily basis, i.e. 5,400 $MJ.ha^{-1}.d^{-1}$ (Lewin 1985; Kulkarni, Dalai et al. 2007). We have expressed both input and output energy parameters on a per hectare basis prorated from the model plant described above. Table I shows the properties of each material.

Table I Material properties, piping requirements and 'in-plant' pumping energy

Material	Material energy content ($MJ\ kg^{-1}$) [1]	Material lifespan (yr) [6] [7]	Material density ($kg\ m^{-3}$)	Pipe diameter (m) [3] [4] [5]	Wall thick-ness (mm) [2]	In-plant total pipe length (km)	In-plant lifespan-weighted energy content ($MJ\ ha^{-1}\ day^{-1}$)	In-plant pumping energy ($MJ\ ha^{-1}\ day^{-1}$)
Concrete	2.5	20	2400	1.5, 0.44	95, 55	6.32, 181.5	15.15	17.99
Steel	40.0	50	7800	1.5, 0.44	12, 10	6.32, 181.5	71.89	13.32
PVC (buried)	75.2	80	930	1.5, 0.44	40, 16	6.32, 181.5	13.84	12.45
Hybrid	40.0, 75.2	50, 80	7800, 930	1.5, 0.44	12 16	6.32, 181.5	- 13.84	12.45

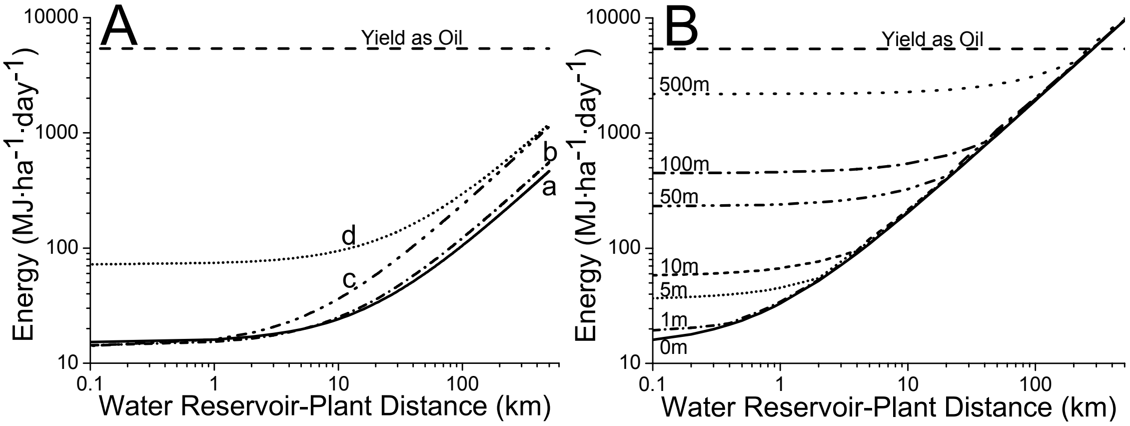
[1] (Lenzen 1999), [3] (Humes 2001), [2] (Standards-Australia 2003), [5] (Uni-Bell 2007), [6] (Rosenberg, Gaidis et al. 1977), [7] (Vinyl-Institue 2008). Where two values are given, they correspond to the two piping components ('in-plant' and external) described for the full piping system. The 'hybrid' has PVC pipes 'in-plant' and steel pipes for the external piping system.

In a log/log form, Fig. 2A shows that the lifetime and area pro-rated embodied energy of the total piping system ('in-plant' and external) made of concrete or PVC (buried) are almost identical whereas one made of steel involves a higher embodied energy. At the 'in-plant' level (zero reservoir-to-plant distance in Fig. 2A) it is five times higher (Table I), whereas at the external piping system level (e.g. 500 km in Fig. 2A) it is two-fold higher. The thickness of the wall of the steel pipe is almost the same for the large diameter pipes used in the external piping system as for the small diameter pipes which dominate the contributions in the 'in-plant' system (Table I). Instead, there is a larger difference in the wall thickness of both the PVC and concrete pipes between the 'in-plant' and the external system (Table I). This is the reason why the ratio of embodied energies depending on pipe material is not the same for the 'in-plant' contribution and the external piping system contribution. Fig. 2A also shows that for feedstock water reservoir to plant distances of up to 100 km the lifetime pro-rated energy content of the full piping system ('in-plant' and external) is only a small portion of the energy content of the daily production of crude oil, i.e. 5.5 % for the case of a steel pipe and ~2 % for the cases of PVC or concrete ones.

Fig. 2B shows the daily pumping energy costs as a function of both vertical and horizontal distances of the plant to the feedstock water reservoir and in comparison with the energy content of the crude oil produced by the microalgae on a daily basis. We have combined both the external-to-the-plant pumping energy with the 'in-plant' pumping energy. The 'in-plant' pumping energy ranges between 12 and 18 $MJ.ha^{-1}.day^{-1}$ depending on the pipe material surface roughness (see Table 1).

The external pumping energy involves a round-trip in the reservoir-to-plant trajectory. Depending on the combination of external piping system length and vertical distance of the plant to the feedstock reservoir (e.g. ocean) frictional losses in the external piping may result in the water flowing unacceptably slowly back to the reservoir and, thus, power needs to be invested for the return of the water in those circumstances.

For vertical distances ≥ 10 m above the reservoir, and for any feedstock water reservoir to plant distances, the 'in-plant' pumping energy (Table I) is a small fraction (≤ 20 %) of the overall energy pumping costs. At short distances to the feedstock water reservoir the total pumping energy required is dominated by the vertical pumping energy, whereas at long distances the total pumping energy is dominated by the horizontal pumping component. Fig. 2B shows that for horizontal distances of 100 km and vertical distances of 100 m the daily pumping energy required to circulate water 'in-plant' and in the external piping systems is 38 % of the daily energy yield as crude oil.



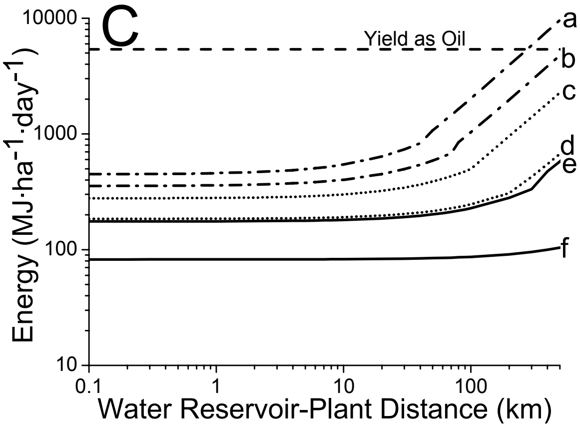


Fig. 2 Lifetime pro-rated energy content of the full piping system ('in-plant' and external) and total energy pumping costs (both 'in-plant' and external components) as a function of the distance between the water feedstock reservoir and the plant. Results are expressed for a plant of 870 ha total water surface (see text). Pipe dimensions and material properties are shown in Table I. The external piping system involves two independent pipes for inlet and outlet.

A) Lifetime pro-rated embodied energy content of the full piping system for concrete (a), PVC (b) and steel (d) pipe materials. Also shown (c) is the case of a hybrid system with PVC in the 'in-plant' and steel in the external piping system.

B) Daily pumping energy costs as a function also of the plant height above the feedstock water reservoir level. Calculations are based on feedstock reservoir to plant roundtrip distance and are performed considering a net evaporation of 250 $mm.month^{-1}$, a 10 % daily harvesting with no recycling, a piping system as described for curve c in Panel A, a pumping efficiency of 0.75.

C) Daily pumping energy costs as a function also of net evaporation and different recycling regimes for a height of 100 m above the feedstock water reservoir. We consider 10 % daily harvesting. Calculations are performed considering cases with no net evaporation and with a recycling of 0 (b), 50 (d) and 80 (f) %, or with a net evaporation of 250 mm.month^{-1} with recycling of 0 (a), 50 (c) and 80 (e) %. Curve a is identical with curve "100 m" in Panel B. All other details as in Panel B.

As discussed above, any recycling of water will save nutrients and pumping energy. Fig. 2C shows the case of a production system working at 100 m above the feedstock water reservoir level with various percentages of recycling and with or without the need to compensate for strong evaporation. The 'in-plant' pumping energy component is not altered by recycling because water needs to be equally pumped into the ponds either from the recycled effluent or from the external inlet pipe. Fig. 2C shows the expected strong benefit of reducing the pumping energy by recycling. For example, this can be appreciated by comparing curve "50 m" in Panel B and curve "e" in Panel C. By recycling the water 80 % a plant placed 100 m above the feedstock water reservoir could operate with a performance equivalent to another one placed at 50 m above the reservoir but in which there is no recycling.

DISCUSSION

The energy content of the piping system and the pumping energy described fully in Fig. 2 are summarized in Table II, where a preliminary Net Energy Ratio (NER) is presented. At this stage we foresee that the piping system energy content is one of the main components to the total embodied energy of this technology, and that the pumping energy is the main operational energy requirement. Table II shows that the pumping energy is the most important of the two demands, unless the plant is far away from the feedstock water reservoir and a recycling regime is used.

The possibility of achieving relatively high NER values (~10), allowing for the most significant inputs and for challenging geographical scenarios gives an ample margin for the accommodation of the energy input involved in other infrastructure needs.

Table II Preliminary NER of a microalgae for crude oil production plant placed at 100 m above the feedstock water reservoir and under net evaporation of 250 mm.month^{-1}, as a function of different recycling regimes and different distances from the feedstock water reservoir. The Energy Content is that of the full piping system only (no other infrastructure). The hybrid PVC 'in-plant' and steel in external piping system is used. The dimensions of the full piping system suffice both the flows in a recycling and non-recycling regime. The plant crude oil daily production is equivalent to 5,400 MJ·ha^{-1}·day^{-1}.

	No Recycling		50 % Recycling		80 % Recycling	
Water reservoir to plant distance	10km	100km	10km	100km	10km	100km
Pumping Energy (MJ·ha^{-1}·day^{-1})	544	2026	300	498	181	228
Energy Content (MJ·ha^{-1}·day^{-1})	36	238	36	238	36	238
NER (preliminary)	9.3	2.4	16.1	7.3	24.9	11.6

Summarizing, we believe that the energy analysis here presented demonstrates the energy soundness of very large scale industrial production of biofuels (e.g. biodiesel) or other materials through microalgal photosynthesis and using feedstock water from a horizontally and vertically distant source; in particular allowing the exploitation of desert areas and the use of sea water as the main growth medium component.

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BRIEF BIOGRAPHY OF PRESENTER

Mishka Talent is a final year undergraduate student at the Australian National University undertaking an engineering degree, majoring in Sustainable Energy Systems, and a science degree, majoring in Sustainability. He has completed his engineering honours investigating microalgae as a source of biodiesel for developing countries. He concentrated in mechanical and energetic related issues. This original idea has evolved and he is now researching other aspects of microalgal technology, including practical problems to outdoor growth and the development of Geographic Information System methodologies to identify terrestrial areas most suitable for large-scale microalgae production. He will continue to dedicate his career to renewable fuel generation and other sustainability issues.