

Net energy ratio of photobiohydrogen generation

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Abstract:

We estimate the energy content, the operational energy inputs, and the net energy ratio (NER) of an industrial tubular photobioreactor used for the photosynthetic production of H₂ by microalgae. The calculated H₂ output of the photobioreactor is based on a range of algal photosynthetic H₂ generation efficiencies, and on the application of standard theory for tubular solar collectors. Small diameter reactors have a low NER as the mixing energy becomes large. For a tubular photobioreactor, low density polyethylene (LDPE) film and glass have significantly higher NERs than rigid polymers such as polymethyl methacrylate (acrylic). Using a hypothetical improved microalgal H₂ generation efficiency of 5 %, a NER ~ 6 can be obtained for LDPE film and for glass. For mechanical and assembly reasons LDPE film is the material of choice. These results show that photobiohydrogen could be a viable H₂ generation technology.

1. INTRODUCTION

One avenue of research for the sustainable production of hydrogen is the exploitation of the photosynthetic process of microbial algae *in vivo* ("photo-bio-hydrogen") (Das & Nejat Veziroğlu, 2001; Melis, 2002; Hallenbeck & Benemann, 2002). When some microalgae are subjected to specific physiological conditions, the photosynthetic electron transport that regularly is committed to sugar biosynthesis and other bioreductive processes (Buchanan et al, 2000) is diverted towards the reduction of protons and the release of H₂ (Melis, 2002; Melis et al, 2000). This physiological activity has been proposed as the basis of a sustainable industrial source of H₂ (Melis, 2002).

Chlamydomonas reinhardtii is an eukaryotic unicellular model organism for photosynthesis and photosynthetic H₂ production (Melis et al, 2000; Melis et al, 2004). This swimming green microalga has fully sequenced nuclear, chloroplastic and mitochondrial genomes (Shrageer et al, 2003). Research using *C. reinhardtii* is also facilitated by extensive mutant collections. Although the *C. reinhardtii* photosynthetic H₂ generation process is used here as an example, the net energy analysis applies to any form of photosynthetic hydrogen generation (Das & Nejat Veziroğlu, 2001).

There have been a number of preliminary studies of the economics of photobiohydrogen. These were reviewed by Benemann (2000), who emphasized the need for costings based on detailed rather than conceptual engineering designs. Only with a very inexpensive bioreactor material could the system be economic, even with improved algal efficiencies (Amos, 2004).

An energy metric such as the net energy ratio (NER) gives a monetary-independent analysis for the viability of an energy generation process. It is the relationship, calculated for the lifetime of the system, between the energy output (in this case the energy content of the H₂ produced) and the energy content of all the materials with which the plant is constructed (their 'embodied energy') plus the energy needed for all the operations (Spitzley & Keoleian, 2004). Thus for an energy generation system to be sustainable its net energy ratio should be greater than 1, and as high as possible. The NER has previously been estimated for H₂ production via steam methane reformation (Spath & Mann, 2001) and electrolysis of water with electricity derived from wind energy (Spath & Mann, 2004). As photosynthetic biohydrogen production is still at the laboratory or prototype stage a comprehensive net energy analysis is not possible. However, an upper limit for the NER can be obtained by considering the major energy inputs and hypothetical H₂ outputs of the system.

Here we consider an outdoors non-thermostated tubular photobioreactor, and a protocol in which the algal biomass maintained in the photobioreactor generates hydrogen directly via photosynthesis (Hallenbeck & Benemann, 2002). We estimate the energy content of the main materials involved in the photobioreactor, and the energy needed to stir the culture (via pumping) and to compress the collected H₂. The reactor energy content has a major influence on the result, and the

net energy analysis favours larger diameter, thin-walled designs. Rigid acrylic tubes are shown to be a poor choice for H₂ producing photobioreactors. Instead, with either glass or low density polyethylene (LDPE) film reactors the system is potentially viable, providing that specific constraints on photosynthetic conversion rates, microbial H₂ generation phase stabilities, and H₂ collection efficiencies are met.

2. NET ENERGY RATIO DEFINITION

For any energy generation system (renewable or fossil fuel), there are many alternative figures of merit which express the net energy generation of the system over its lifetime; these are discussed in detail by Spitzley & Keoleian (2004), and by Richards & Watt (in press). The metric used here is the net energy ratio (NER), which can be defined as "the ratio of the total energy production to the primary non-renewable energy requirements associated with the system life cycle" (Spitzley & Keoleian, 2004). 'Primary' energy is hereafter used to refer to the HHV (higher heating value) energy content of fossil fuels extracted from the earth (including any losses), plus the energy required to extract and deliver them to their point of use (Spitzley & Keoleian, 2004; Boustead, 2005). The system energy requirements include not only direct inputs (such as the primary energy required to generate and deliver the electricity required for pumping), but also the life cycle energy input involved with the system materials. The energy input for a material or fabricated item is called its energy content (or 'embodied energy'), and is the total energy required for its manufacture, including the calorific value of any organic raw materials. The latter component must be included as it represents a real use of resources (Boustead, 2005). There can be considerable variation in estimates of the energy content of materials, in part due to real differences in production methods, but also due to the methodology used for the estimation (Lenzen & Munksgaard, 2002)

The net energy ratio has been also called the "energy yield ratio", as it gives the output or yield from fossil fuel inputs (Richards & Watt, in press; Guerzenich et al, 1999). The definition is not unambiguous, as there can be differing interpretations of the input and output energy terms. For example, the output energy can be given as the gross or net calorific value of a fuel, as a converted energy output (e.g. electrical or mechanical), or as the primary energy displaced or saved by renewable energy generation (Richards & Watt, in press). For this work we define the NER output energy term as the HHV energy of the collected hydrogen, and the input energy term as the primary energy requirement of the system over its lifetime.

Considering a system made up of n separate components, the net energy ratio can then be written as in Richards & Watt (in press) as:

$$NER = \frac{E_{H_2,Y} L_{system}}{\sum_{i=1,n} (E_{in,i} L_{system} / L_i)} \quad (1)$$

$E_{H_2,Y}$ is the annual HHV energy output of the system, L_i is the lifetime in years of component i , and $E_{in,i}$ is the total primary energy input associated with component i . In the case of a direct energy input (e.g. for pumping) $E_{in,i} / L_i$ is the annual energy input, written as $E_{in,i,Y}$. For a material $E_{in,i}$ is its energy content, as explained above. L_{system} is the system lifetime in years, i.e. the period after which the full system, its design, or the most important of its elements becomes obsolete and will not be replaced or re-applied. Values of 20 and 25 years are typically used in life cycle analyses of established technologies such as solar and wind energy (Guerzenich et al, 1999; Lenzen, 1999). A lifetime of 20 years is assumed here for the biohydrogen plant.

We consider a biohydrogen plant whose main component is an array of tubular photobioreactors; a major energy input will thus be the energy content of the photobioreactor materials.

3. PHOTOBIOREACTOR DESIGN, MATERIALS AND ENERGY CONTENT

Algal photobioreactor designs are reviewed in Pulz (2001), and tubular and flat plate systems are compared in Richmond et al (1993), Tredici & Zitelli (1998), and Weissman et al (1988). We consider only single layer horizontal tubular reactors, but the energy content and net energy ratio analysis could

be applied to other configurations by making the appropriate changes to the reactor mass per unit of aperture area and to the conversion and collection efficiencies (all defined below).

A horizontal tube of inside diameter D , length L , wall thickness t , and wall density ρ , has a mass given by $\rho\pi DtL$. The geometrical projection of this tube section onto the plant surface area is the aperture area A_a , equal to DL . The photobioreactor mass per unit aperture area m/A_a is then independent of the tube diameter and given by:

$$m/A_a = \rho\pi t \quad (2)$$

A wide variety of materials have been used for tubular photobioreactors. Those considered here are glass, low density polyethylene film (LDPE), and clear acrylic (polymethyl methacrylate, PMMA, also known by the trade names Plexiglas® and Perspex®). The energy content of each of the chosen materials is considered below.

3.1 Glass

Glass photobioreactors for biohydrogen production are considered in Tredici & Zitelli (1998) and Benemann (2000). A large scale glass photobioreactor system (for biomass production only, total volume 700 m³) has been installed at Klotze, Germany (Pulz, 2001; Janssen et al, 2003). In the present study the glass tubes are assumed to be made from 1.6 mm wall thickness borosilicate (Pyrex) glass, which is commonly used in solar hot water collectors. A selection nomograph for the minimum thickness of a borosilicate glass tube (determined by its diameter and the working pressure) is given by Barloworld Scientific (2006).

Various estimates of the energy content of glass were found in the literature. They range between 13.0 and 18.6 MJ.kg⁻¹ for window glass (Weir & Muneer, 1998), to 15.9 MJ.kg⁻¹ for float glass and 26.2 MJ.kg⁻¹ for toughened glass (Baird et al, 1997). The value used here is 25.0 MJ.kg⁻¹, taken from a study on solar thermal collectors (Lenzen, 1999). Solar collector tubes are typically sold with a 10 year warranty, which would represent a lower limit to their expected lifespan. The glass tubes are taken here to have a lifespan equal to the plant service lifetime of 20 years.

3.2 Low Density Polyethylene Film (LDPE)

Tubular photobioreactors made from polyethylene "sleeves" have been described in a number of articles (e.g. Cohen & Arad, 1989; Merchuk et al, 2000), and used commercially (Olaizola, 2000). A generic design for a polymer film reactor is given in Tredici et al (1998). LDPE film is widely used as a greenhouse covering (Hussain & Hamid, 2004), which application has the same requirements as a photobioreactor: high visible light and near infra red transmission, low UV transmission, and low cost. Variants of the basic LDPE polymer which are also used as greenhouse films include LDPE/EVA (ethyl-vinyl acetate) copolymers and LDPE/LLDPE (linear LDPE). The main disadvantage of any of these materials is their short lifespan: even with the addition of UV stabilizers the maximum life of LDPE greenhouse film used as a greenhouse covering is 3 years (Hussain & Hamid, 2004). Research is currently being carried out at ANU into the usable lifetime of LDPE photobioreactors. Here we use the value of 3 years, which is considered appropriate as the thermal cycling amplitude is lower for a photobioreactor material than a greenhouse covering, as it is limited by the culture thermal mass. Trials have shown that standard 180 µm greenhouse film is suitable as a photobioreactor material, and that thickness is used in our calculations.

Estimates of the energy content of LDPE film are 78.1 MJ.kg⁻¹ (Boustead, 2005) and 74.0 MJ.kg⁻¹ (Lenzen, 1999). We use the value of 78 MJ.kg⁻¹, for consistency with the acrylic data (see below) also obtained from Boustead (2005).

3.3 Rigid acrylic (PMMA)

Clear acrylic tubing has been used in a number of prototype photobioreactor systems, with outer diameters in the range of 30 to 60 mm and wall thickness 3 to 5 mm (e.g. Ación Fernández et al, 1997; Molina et al, 2001; Tredici & Zitelli, 1998). Material with 1.6 mm (1/16") wall thickness is also available as a standard product, but only in diameters up to 25 mm. As the energy required for mixing by pump-driven circulation of the culture varies with D^3 (see below) such small diameter tubes are considered to be unsuitable for a large scale biohydrogen plant. A wall thickness of 5 mm is also assumed to be too costly (and to have too high an energy content), so that in this study a 3 mm thickness is used. The energy content of PMMA is estimated at 131.4 MJ.kg⁻¹ (Boustead, 2005). The

lifespan of acrylic in outdoor conditions is at least 10 years (Blaga, 1980), and is set here to the plant service lifetime of 20 years.

3.4. Photobioreactor energy content

The energy content, lifespan and density data for the three materials are summarized in Table 1. Equation (2) is used to calculate from those data the absolute and the lifespan-weighted energy contents of the photobioreactor per unit of plant aperture area.

Table 1. Characteristics of photobioreactor materials and the energy content of tubular photobioreactors.

Densities are taken from Matweb (2005) while references for all other data are given in the text.

Material	Material energy content (MJ.kg ⁻¹)	Material lifespan
Glass	25	20
LDPE	78	3
Acrylic	131	20

Table 1 shows that acrylic tubes involve the highest energy content per aperture area, whereas LDPE tubes the lowest. After normalization by the expected lifetime, glass and LDPE tubes share a similar lifespan-weighted energy content, around 5-fold lower than for acrylic tubes. The choice of favourable values for the lifetime and wall thickness of glass and acrylic tubes (in Table 1) strengthens the conclusion that LDPE is the preferred material.

3.5. Balance of system energy inputs and losses

Analogous to most economic feasibility studies of photobiohydrogen, we argue that the photobioreactor materials represent the major energy input to the system over its lifetime. Because of their long lifespan and/or relatively minor contribution of some system components (site preparation, building infrastructure for operations control, manifolds, H₂ collection system, etc.) we neglect their effect on the lifespan-weighted energy content per unit area of the photobioreactor system. With these simplifications, an upper limit for the NER is obtained. The energy inputs which are considered most significant are discussed below.

3.5.1. Mixing energy

Culture mixing is fundamental in maintaining an homogeneous suspension of cells; in optimizing light absorption; and in facilitating gas exchange, the distribution of nutrients, and the dispersion of secreted/excreted substances. Mixing in tubular reactors is commonly achieved by use of a turbulent flow regime, with a Reynolds number of at least 10,000 (Molina et al, 2001). However the productivity benefits (in terms of biomass growth) due to turbulent mixing have been questioned (Weissman et al, 1998), and the use of a motile photosynthetic microbe such as *C. reinhardtii* may also diminish the importance of turbulence in the maintenance of an homogenous culture.

The standard expressions for pressure drop due to turbulent flow in a pipe (White, 1999) can be manipulated to give the input electrical power P per square metre of aperture area as a function of the photobioreactor tube diameter and the Reynolds number:

$$P / A_a = \frac{0.124 \mu^3 \text{Re}^{2.75}}{\eta_p \rho^2 D^3} \quad (3)$$

where μ is the viscosity ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$), ρ the density ($\text{kg}\cdot\text{m}^{-3}$), D the tube inside diameter (m), η_P the pump efficiency, and A_a the tube aperture area (m^2). As all energy inputs in Equation (1) must be primary energies, allowance must be made for the delivered electrical efficiency. η_{elec} is defined as the electrical conversion efficiency allowing for distribution losses and the energy required to extract the primary fuel used for generation. The annual gross primary energy input in megajoules per square metre is then (for a pump continuously in operation, i.e. 100 % duty cycle):

$$E_{mix,Y} / A_a = \frac{3.91 \times 10^{-6} \mu^3 \text{Re}^{2.75}}{\eta_P \eta_{elec} D^3} \quad (4)$$

The value of η_{elec} depends on the scale of generation and the mix of fuels; for coal fired generation it is typically ~ 0.3 (Boustead, 2005). The specific mixing energy as a function of photobioreactor tube diameter is shown in Table 2, for a flow with Reynolds number $\text{Re} = 10,000$. The diameters ≥ 0.09 m are chosen as they correspond to commercially available PVC fittings used in our prototype system. No allowance has been made for pressure drops in manifolds and fittings, so that the calculated values are low estimates of the complete system mixing energy requirement.

Table 2. Primary mixing energy input per unit of aperture area and per year as a function of tube diameter.

Equation (4) is applied using values of $\text{Re} = 10,000$, $\eta_{elec} = 0.3$, $\rho = 1000 \text{ kg}\cdot\text{m}^{-3}$, $\mu = 0.001 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$, and $\eta_P = 0.5$.

D (m)	0.030	0.040
$E_{mix,Y}$ $/ A_a$ (MJ. $\text{m}^{-2}\cdot\text{y}^{-1}$)	96.6	40.7

Table 2 shows that the energy needed to mix the culture by turbulent flow is strongly dependent on the tube diameter. With diameters ≥ 0.09 m the mixing energy per unit of plant aperture area and year ($E_{mix,Y}$) is only a small fraction of the lifespan-weighted energy content of the photobioreactor constructed with any of the three materials (see Table 1). However with tube diameters ≤ 0.05 m the mixing energy becomes a significant or dominant energy input. The mixing energy can also be compared to the H_2 energy output for a given photosynthetic efficiency. For tubes with diameter ≥ 60 mm, and H_2 production with ≥ 5 % conversion efficiency, the mixing energy is very small in relation to the total yield (see below).

The cost of pumping energy was examined in Weissman et al (1988), where it was concluded that fully turbulent flow in tubes ≤ 50 mm in diameter was not economic for algal biomass production. If the diameter is made large the issue of light penetration into the culture must be addressed (Pulz, 2001; Janssen et al, 2003; Molina et al, 2001). An alternative approach to reducing this energy input is the use of a less turbulent flow regime, as discussed above, and/or a lower duty cycle.

The mixing energy input term in Equation (1) would be significantly reduced if the required electrical energy was derived from an efficient renewable source. We have not made this assumption, as it undervalues the real effect of the mixing energy. An alternative is to regard the mixing energy as a reduction in the energy output, rather than as a separate energy input. A life cycle analysis of hydrogen produced by wind energy / electrolysis deducted the electrical energy needed for compressing the hydrogen and pumping the water from the gross electrical output of the wind turbines (Spath & Mann, 2004). That approach has not been used here, as electricity generation from H_2 is not a necessary component of the system.

3.5.2. Energy for hydrogen storage

In calculating the net energy ratio for an energy generation system, a judgement must be made on what are the boundaries of the system, in particular which energy inputs and losses are ascribed to the system, and which are considered to be part of an external consumption or conversion phase. As it is impractical to store or transport hydrogen at atmospheric pressure, due to its low volumetric energy density, the energy required to compress and store the hydrogen should be included as an input to the biohydrogen system. Part of this input is the energy content of the compression and storage infrastructure. A number of different approaches to hydrogen storage are being developed, but the most common method at present is the use of 20 MPa gas cylinders (Zuttel, 2004). The storage energy input is here calculated for this technology, although it is acknowledged that it is not a viable long term option for a 'hydrogen economy'. The energy input required in practice for compression to 20 MPa is approximately 7 % of the HHV of the hydrogen being compressed (Bossel & Eliasson, 2003), and we set the total storage energy input (including the materials energy contents) to 10 % of the HHV hydrogen output.

4. HYDROGEN OUTPUT

The hydrogen production rate at a particular site will depend on biotic-related factors such as the characteristics of the microbial strain and the protocol of microbiological manipulations, and on abiotic factors such as ambient temperature and incident solar radiation. A general analysis of tubular collectors is given in Perez et al (1995), including expressions for the loss due to mutual shading and the interception of ground reflected and diffuse radiation. The amount of direct beam solar radiation intercepted by a tubular collector is equal to that received by a one axis tracking collector of width equal to the tube diameter (Perez et al, 1995). We make the simplifying assumptions that the plane of the reactor (containing the tube axis) is near horizontal, the tube axis is oriented north-south, mutual shading between tubes is small, and that the total radiation received is approximately equal to the global radiation on an east-west oriented tracking planar collector. Various factors which affect the H₂ production rate are listed below.

Photosynthetic hydrogen generation efficiency (η_{PS}) The photosynthetic efficiency is defined here as the ratio of the hydrogen chemical energy (HHV) generated per unit of aperture area and time to the energy of the full-spectrum solar radiation incident in the same unit of aperture area and time. The efficiency is assumed to be constant at all light levels (above some minimum threshold – see below), and independent of culture temperature. We are thus considering a hypothetical optimized micro-organism: at present η_{PS} is only of the order of 1 %, and limited by light saturation at medium to high light levels (Hallenbeck & Benemann, 2002; Kosourov et al, 2002). Increasing the conversion rate (ideally to 10 %) and overcoming light saturation is essential if the process is to be economic. The photosynthetic efficiency is also assumed to be independent of the tube diameter, via the culture density being adjusted to achieve maximal conversion of the incident light (Amos, 2004). In practice, however, there will be upper and lower limits on D beyond which the efficiency decreases.

System availability (F_A) This is the fraction of the year during which there is hydrogen production. F_A is less than unity as there is no H₂ production during the micro-organism's growth phase to obtain the required biomass (and e.g. for the sulphur starvation two-stage *C. reinhardtii* process also during the early phase of the sulphur-starvation treatment before anaerobiosis is achieved (Melis et al, 2000). F_A also allows for the periods when there is low sunlight and no net photosynthetic H₂ generation. For all calculations we use a hypothetical value of $F_A = 0.8$.

Photobioreactor wall light transmission (T) The transmission coefficient of each of the three materials, at the thicknesses being considered, is of the order of 90 % (Blaga, 1980; Fuller & Cooper, 1983). We set the average PAR transmission in service, for all the materials, to $T = 0.85$, allowing for some loss of transparency due to soiling of the tubes. The wavelength and incidence angle dependence of T is neglected.

Hydrogen collection efficiency (η_{coll}) Hydrogen collection losses may occur due to diffusion through the reactor material and through any joints, and when extracting and separating hydrogen from the culture gas phase. η_{coll} will depend upon the reactor material (H_2 permeability coefficient) and geometry (wall thickness, diameter, length of run to joints or to gas exchange points), and on the flow velocities of the gas and liquid phases. As with the photosynthetic conversion it is essential to obtain a relatively high collection efficiency; we use a hypothetical value $\eta_{coll} = 0.8$. This value is supported by experiments testing the performance of a 3 m long, 15 cm diameter LDPE tube with 180 μm wall thickness.

Incorporating all the above, the annual chemical energy of the hydrogen collected per square metre of photobioreactor aperture is:

$$E_{H_2,Y} / A_a = 365 I_{d,EW} T \eta_{PS} \eta_{coll} F_A \quad (5)$$

where $I_{d,EW}$ is the average daily global radiation on an east-west tracking plane for the site (see above). We calculate the hydrogen output and the NER for a site with moderately high annual solar radiation, using data for Mildura, Australia (lat 34.2° S, long 142.1° E, altitude 50 m). The daily average global radiation on a horizontal plane at that location is 18.6 $\text{MJ.m}^{-2}.\text{d}^{-1}$ and 23.1 $\text{MJ.m}^{-2}.\text{d}^{-1}$ on an east-west tracking plane (Lee et al, 1995). Applying the factors described above, the annual hydrogen output at the site, is 229 $\text{MJ.m}^{-2}.\text{y}^{-1}$ for $\eta_{PS} = 5\%$, and 459 $\text{MJ.m}^{-2}.\text{y}^{-1}$ for $\eta_{PS} = 10\%$.

5. NET ENERGY RATIOS

The net energy ratio, as formulated in Equation (1), can be explicitly written in terms of the dominant system energy inputs (materials energy content, mixing energy, and storage energy) as in Equation (6). E_{PBR} and L_{PBR} are the photobioreactor energy content and lifetime; $E_{mix,Y}$ and $E_{storage,Y}$ are the annual mixing and storage energy inputs.

$$NER = \frac{E_{H_2,Y}}{\left(E_{PBR} L_{system} / L_{PBR} \right) + E_{mix,Y} + E_{storage,Y}} \quad (6)$$

Table 3 shows the NER values, for photobioreactors constructed with the three different materials considered here, as a function of the tube diameter and the photosynthetic H_2 generation efficiency. The NER is shown as a function of photosynthetic efficiency and photobioreactor material, for the case of a 90 mm diameter photobioreactor, in Figure 1.

At low tube diameters, the NER is strongly dependent on the diameter (via the mixing energy). The dependence on the material lifespan is less pronounced, as shown in Table 4 where a 90 mm diameter LDPE tube is considered. This arises as the energy input term for the reactor materials varies as the inverse of the lifespan, whilst the mixing energy is proportional to D^3 . The NER value is not a linear function of the materials lifespan or of η_{PS} as there are several terms in the denominator of Equation (6), and the compression and storage energy term ($E_{storage}$) is a function of the H_2 output and, therefore, of η_{PS} . As $E_{storage}$ is set to 10 % of the HHV hydrogen output it limits the maximum achievable NER of the system to 10.

Table 3. The net energy ratio (NER) of tubular photobioreactors as a function of tube material, tube diameter and photosynthetic H₂ generation efficiency (η_{PS}).

Equation (6) is used to calculate the NER. Equations (2), (4), and (5) are used to calculate the photobioreactor lifespan weighted energy content, the annual mixing energy input (a function of tube diameter) and the annual chemical energy of H₂ collected, respectively, all per unit of aperture area. Lifetimes and wall thickness for each material are as in Table 1, mixing energies as in Table 2, and the HHV energy of the collected H₂ as in in the text.

D (m)	Glass (1.6 mm)				LDPE (0.18 mm)				Acrylic (3.0 mm)			
	η_{PS}											
	(%)											
	0.5	1	5	10	0.5	1	5	10	0.5	1	5	10
0.04	0.4	0.8	2.9	4.5	0.4	0.8	3.0	4.6	0.2	0.4	1.7	2.9
0.06	0.8	1.4	4.6	6.3	0.8	1.5	4.7	6.4	0.3	0.5	2.1	3.5
0.09	1.1	2.0	5.5	7.1	1.2	2.1	5.7	7.3	0.3	0.6	2.3	3.8
0.15	1.3	2.2	5.9	7.4	1.4	2.4	6.2	7.6	0.3	0.6	2.4	3.8
0.25	1.3	2.3	6.0	7.5	1.4	2.5	6.3	7.7	0.3	0.6	2.4	3.9

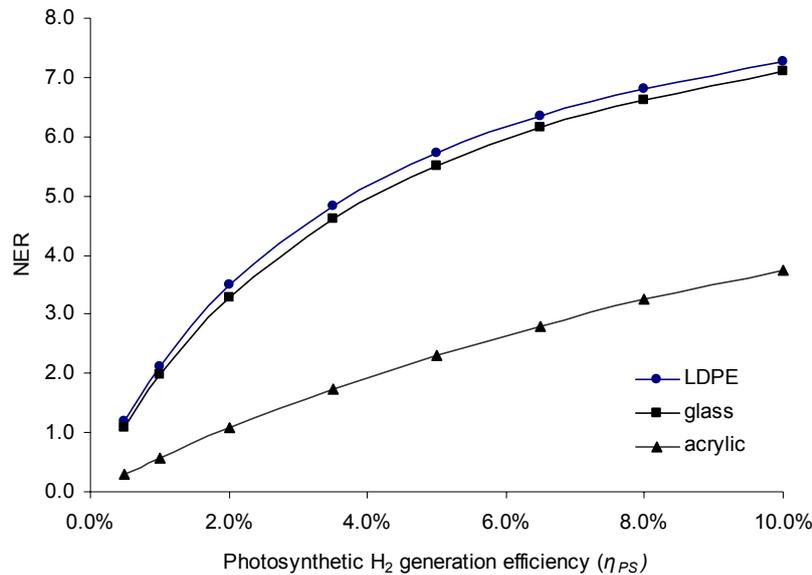


Figure 1. Net energy ratio (NER) as a function of photosynthetic H₂ generation efficiency (η_{PS}) for a photobioreactor diameter $D = 0.09$ m, for LDPE, glass, and acrylic tube materials. NER values calculated as for Table 3.

Table 4. The lifespan-weighted energy content and the net energy ratio (NER) of a LDPE tubular photobioreactor as a function of tube lifespan and photosynthetic H₂ generation efficiency (η_{PS}).

Equations used as in Table 3. A 0.090 m diameter tube, an $\eta_{elec} = 0.3$ and a Re of 10,000 are considered.

Lifespan (y)	2.0	2.5
Lifespan-weighted energy content (MJ.m ⁻² .y ⁻¹)	20.3	16.2
NER ($\eta_{PS} = 1\%$)	1.6	1.9
NER ($\eta_{PS} = 5\%$)	4.9	5.4
NER ($\eta_{PS} = 10\%$)	6.6	7.0

The relative contributions of the three energy inputs (energy content of the photobioreactor materials, the mixing energy and the compression and storage energy) depend on the material, the reactor geometry, and on the photosynthetic H₂ generation efficiency. We consider here the particular case of a 0.090 m diameter, 180 μm wall thickness, LDPE tube, with material lifespan of 3 years (as in Table 1); and an η_{elec} of 0.3 and Reynolds number of 10,000 (as in Table 3). The photobioreactor energy content and mixing energy are 13.5 and 3.6 MJ.m⁻².y⁻¹, respectively (see Tables 1 and 2) and are independent of the photosynthetic H₂ generation efficiency. The compression and storage energy depends linearly on the photosynthetic H₂ generation efficiency, and for the case of $\eta_{PS} = 5\%$ is 22.9 MJ.m⁻².y⁻¹ (see above). The compression and storage energy is thus the dominant input in this configuration.

Table 3 shows that an NER > 6 is possible with large diameter polyethylene or glass reactors, which would represent a reasonable return on the primary energy investment. Acrylic reactors have a relatively low NER values and are unlikely to be viable for industrial purposes.

6. DISCUSSION

The net energy analysis imposes some constraints on photobiohydrogen plant design. Photobioreactors made from a relatively thick, rigid polymer such as acrylic perform poorly in net energy terms, whilst polymer film and thin-walled glass tubular photobioreactors are significantly better. In all cases a much improved photosynthetic conversion efficiency is required, compared to the status quo, to achieve a useful net energy production. The photobioreactor "container" (site of biomass production and H₂ generation) is a major system component. To minimize its energy content the wall thickness of the reactor must be kept as thin as possible, but still consistent with the need for mechanical toughness and gas impermeability. All other material and energy inputs must also be kept low.

6.1. Comparison between glass and polymer film tubular photobioreactors

Systems using LDPE film and glass tubular photobioreactors have comparable NER values, so the choice of material must be based on other criteria. The use of glass tubes requires many more connection fittings as lengths of more than a few metres are not produced or, otherwise, are difficult to transport and assemble. Glass tubes also require a supporting structure. The high number of fittings and supporting structures for the glass photobioreactor would reduce the NER values calculated in Table 3. Conversely, film tubes are produced as rolls of hundreds of metres in length and can be placed directly on a simply prepared and leveled surface. Larger diameter tubes have a lower mixing energy input, and can be readily manufactured in LDPE without an excessive increase in thickness (although attention must be paid to the maximum head pressure). The energy content of the relatively few fittings per aperture area would not significantly change the NER values for LDPE in Table 3 and Figure 1.

The most important drawbacks of polyethylene film are its relatively short lifetime (due to weathering), relatively high hydrogen permeability, and susceptibility to punctures. A tubular LDPE film photobioreactor designed specifically for biohydrogen production is being developed at ANU.

7. CONCLUSION

We have examined the major energy inputs and the major factors affecting the efficiency of H₂ generation and collection for an industrial photobiohydrogen plant. The net energy analysis shows that photosynthetic hydrogen generation could be viable in energetic terms if a stable ($F_A \sim 0.8$) algal photosynthetic H₂ generation efficiency of $\sim 5\%$ is achieved. An NER ~ 6 is possible with $\eta_{PS} = 5\%$, which allows a margin for the technology to remain viable once the input and output parameters are refined and the neglected inputs accounted for. A photobioreactor with low energy content is required, for which glass and film can be suitable materials in principle. However, tubular film has the advantage of being produced in long lengths and is less susceptible to breakage than glass. The energy required for mixing can be significant, which favours the use of larger diameter photobioreactors.

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