Feasibility Study of Large Scale Photosynthetic Biohydrogen Production

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A method of industrial production of hydrogen through microalgal photosynthesis is being developed. The technology involves renewable energy and materials principles. Preliminary technical design and economical analysis shows that H_2 could be produced at a cost of ~AUD$5-10/kg. This price is similar to other fossil-fuel-independent methods. The size of the concept unit plant is 1 km^2, involving a novel plastic film tubular photobioreactor containing 1.5x10^8 L of culture, with the water being recyclable. Using an optimized microalga strain, the plant would yield up to 10^6 kg of H_2 p.a. (equivalent to a net 1.5x10^4 MWh/year, considering a 75% H_2 collection efficiency and a fuel cell efficiency of 50%).

1. INTRODUCTION

Hydrogen is expected to become a major fuel/energy carrier towards the middle of this century. To be sustainable, methods to produce H_2 relying on renewable sources of energy will be fundamental (Grant, 2003; ACIL Tasman Pty Ltd, 2003). H_2 can be produced in a number of ways (Norbeck et al, 1996; ACIL Tasman Pty Ltd, 2003), either by using fossil fuels, electricity, or solar heat, or by exploiting the photosynthesis process of microbial algae *in vivo* ("photo-bio-hydrogen") (Cammack et. al, 2001; Melis, 2002; Hallenbeck and Benemann, 2002; ACIL Tasman Pty Ltd, 2003). In the latter the (main) source of energy is sunlight.

Photosynthesis is the biological process to transform light into biochemical energy. This takes place inside algae and plant cells in chlorophyll-containing biological membranes (e.g. in the chloroplast). A main step in the process is the photolysis of water, the same as in some non-biological systems of H_2 production. In normal conditions in algae and all plants, following the breakdown of the water molecule, a photosynthetic electron transport chain further transforms the energy of light into biological energy via the synthesis of sugars with the fixation of CO_2.

However, in some algae and in the absence of oxygen (a fundamental requirement (Cammack et. al, 2001), the photosynthetic electron transport is diverted from its usual CO_2 fixation role to the reduction of H^+, generating H_2 that is released as a by-product. The catalytic action of the enzyme hydrogenase is needed. Hydrogenases are synthesised only in the absence of O_2 (anaerobiosis). Moreover, their stability also requires anaerobiosis. Thus, in those conditions, the intact algal cell can become a complete H_2 production unit.

Why use sunlight as an alternative source of energy? Because it is inexpensive, safe, and has low geographical limitations. Why use a biological system to transform light energy into H_2? Because, if properly selected and manipulated, a biological system (e.g. a photosynthetic microbe) functions as a catalytic unit that self-reproduces (exponentially, very fast, and cheap), self-regulates (e.g. can adapt to light intensity and quality), and self-repairs (allowing for an "always as new" unit). Moreover, due to the evolution capacity of biological systems, mutants can be designed or selected as to specifically adapt the organism to a multidimensional variety of environments. Most of these individual characteristics and all of them combined are never found in non-biological industrial systems.

Thus, *in vivo* photo-bio-hydrogen production could be an excellent method for sustainable energy conversion, completely independent of fossil fuels and environmentally safe. Because it is "low-tech", both in the industrial plant construction and in its operation, it would be a choice for local level, remote areas, and the developing countries of the world.

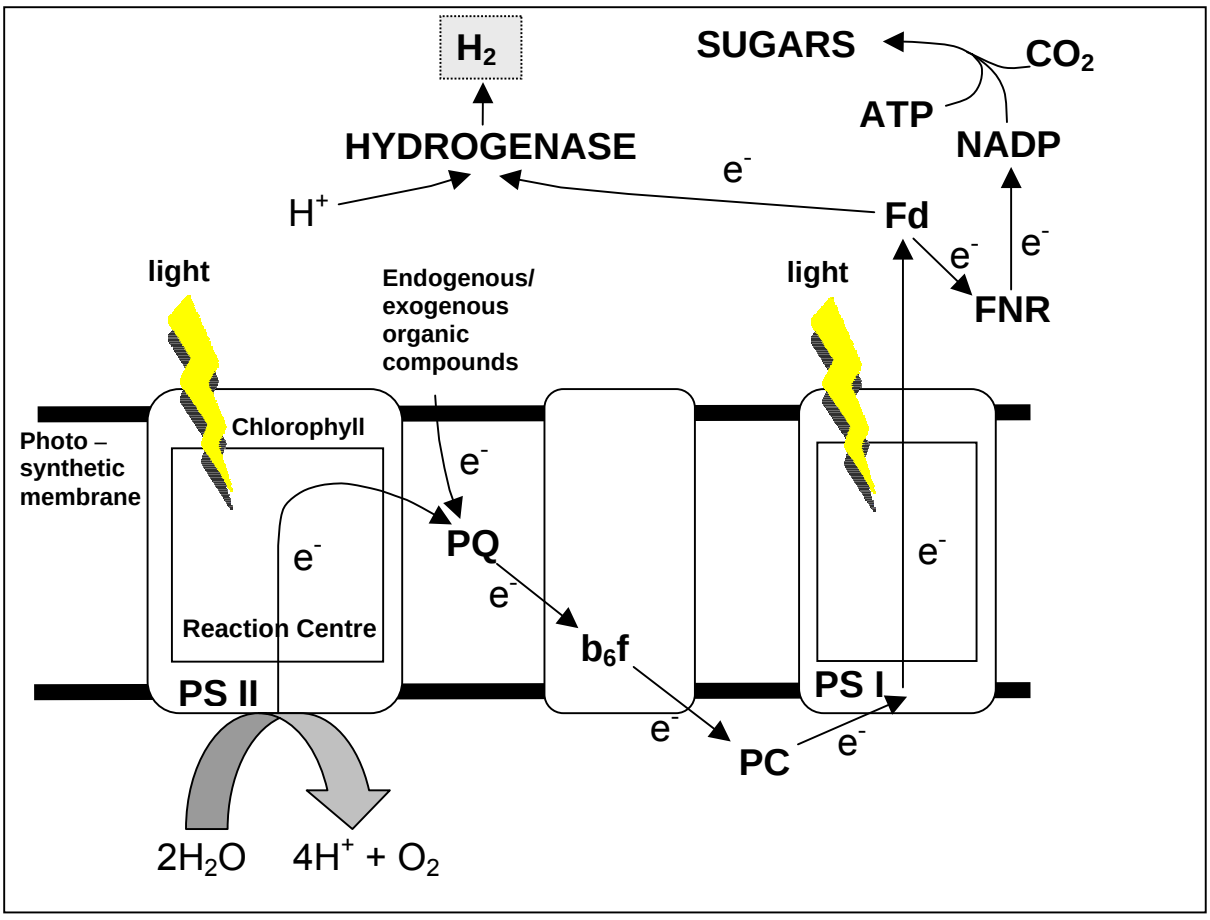

Figure 1. Photosynthetic electron transfer in the chloroplast of the unicellular green alga *Chlamydomonas reinhardtii* and the alternative H_2 production pathway. PS I and PS II are Photosystems I and II, respectively. PQ, PC, Fd and NADP (plastoquinone, plastocyanin, ferredoxin, and nicotinamide-adenosine-dinucleotide-phosphate, respectively) are electron carriers. b_6f (cytochrome b_6f complex), FNR (ferredoxin-NADP reductase), and hydrogenase are redox enzymes. ATP (adenosine triphosphate) is a biochemical high-energy intermediate. In normal conditions a linear electron transfer is established that maintains CO_2 fixation for the synthesis of sugars. In the absence of O_2 (see text for conditions) the photosynthetic electron transport is diverted at the level of Fd towards the synthesis of H_2, which is evolved as a by-product.

2. PHOTOSYNTHESIS AND THE MICROBIOLOGY OF PHOTOSYNTHETIC HYDROGEN PRODUCTION

Photosynthesis takes place in photosynthetic membranes which are lipid bilayers that osmotically and electrically isolate two liquid phases. In the photosynthetic membranes, light is absorbed by pigment/protein complexes called photosystems. There are two photosystems, Photosystem I (PSI) and Photosystem II (PSII). They contain chlorophyll, other pigments, and redox cofactors. By absorbing light the reaction centre of PSII becomes extremely oxidant and is able to split water into protons, electrons and oxygen, the latter being finally released to the atmosphere as a by-product of the reaction. Through the metabolic network, those protons and electrons are used for all bioenergetic and biosynthetic requirements, and this is the way that sunlight energy enters the Biosphere. Interestingly, those protons and electrons cannot immediately recombine to form H_2 because they take different routes in the photosynthetic apparatus (Figure 1). PSI cannot photo-oxidize H_2O but, using light, can further energize electrons originally derived from the photolysis of H_2O by PSII. As shown in Figure 1, both photosystems absorbe light and sustain electron transport from high potential (i.e. low energy) redox donors to low potential (i.e. high energy) redox acceptors. Water-derived electrons energized by light are transported along and across the photosynthetic membrane and together with ATP, that is the fundamental biochemical energetic intermediary, are used to make sugar from CO_2.

Several electron carriers link PS II and PS I (see Figure 1) and all these are embedded in or loosely associated with the photosynthetic membrane. Protons released from H_2O and accumulated in one side of the photosynthetic membrane (which enclose a topologically closed space) create an energy-rich proton gradient that is used for the synthesis of ATP. For a comprehensive introduction to bioenergetics and photosynthesis see e.g. Nelson and Cox (2005) and Raghavendra (1998).

Some microalgae in anaerobiosis can generate H_2 using light as energy source (Ghirardi et al., 2000), see Figure 1. This process involves (a) oxygen-sensitive hydrogenases which are synthetised only in anaerobiosis and (b) totally or in part, the Photosystem II-to-Photosystem I electron transfer chain (Melis et al., 2000). A variety of other functions participate in the generation of H_2, e.g. the catabolism (degradation) of endogenous carbohydrates and proteins, and the assimilation of exogenous organic substrates (Figure 1). This potential for H_2 photoproduction in microalgae opens the door for possible industrial applications for the sustainable production of H_2.

Photosynthetic H_2 metabolism is intensively studied in the unicellular green alga *Chlamydomonas reinhardtii.* This microalga has the approximate size of a red blood cell (diameter ~6 µm). *C. reinhardtii* is eukaryotic, i.e. it is highly evolved, containing membrane-surrounded subcellular compartments: a) nucleus (depository of genetic information), b) chloroplast (site of light energy conversion by photosynthesis), and mitochondria (site of transformation of biochemical energy by cell respiration). *C. reinhardtii is* a well-known model organism for photosynthesis and H_2 production (Melis et al., 2000; Rochaix, 1995; Davies and Grossman, 1998; Grossman, 2000) that has fully sequenced nuclear, chloroplastic and mitochondrial genomes (Shrager et al. 2003). There is an extensive mutant collection available for this microalga. Beyond its photosynthetic capacity, *Chlamydomonas* can also assimilate, and respire or ferment exogenous organic substrates and grow fine irrespectively of the presence or absence of light (this allows non-photosynthetic mutants to grow). The ability of assimilating organic substrates also relates to the photosynthetic H_2 generation (see below). *Chlamydomonas* swims (speeds of ~25 cm/h), facilitating the even distribution of cells in a photobioreactor of industrial dimension. This is a clear advantage over the prokaryotic (i.e. without membrane-surrounded subcellular compartments) cyanobacteria (or blue-green algae) which are not motile. *Chlamydomonas* has a low duplication time (~6 h in several optimal conditions at 25 ºC), allowing for a fast growth for industrial purposes.

3. THE BIOTECHNOLOGY OF PHOTOSYNTHETIC HYDROGEN PRODUCTION

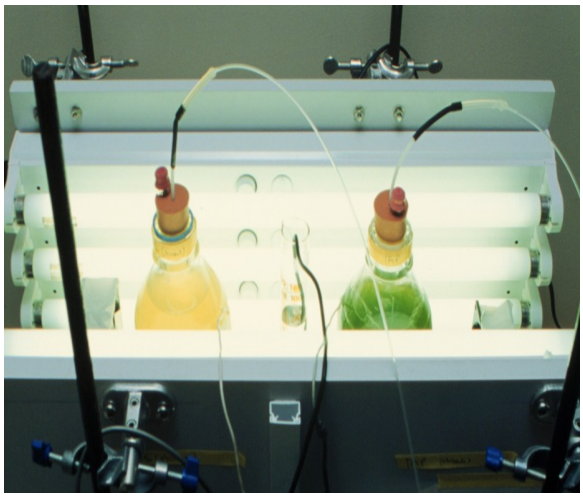

Figure 2. 1 L bottle bioreactor experimental set-up for H_2 production using a sulphur starvation treatment, showing tubbing for gas collection (ending inside an underwater inverted graduated cylinder). Two physiological treatments are shown.

There are "Direct Biophotolysis" and "Indirect Biophotolysis" strategies proposed for the industrial production of H_2 using a photosynthetic microorganism (Hallenbeck and Benemann, 2002). In the "Direct" ones H_2 is directly generated during illumination via photosynthesis. This involves keeping the microorganism continuously in anaerobiosis in a photobioreactor. The advantage of the Direct strategies is that the industrial operation would require little manipulation, but with the problem to be resolved of an efficient and economical photobioreactor. Photobioreactors require a closed system to collect the gas, and shallow structures in order to let sufficient light to the algae in the deep portion of the culture. The latter requirement necessarily calls for a very large industrial plant extension.

In the "Indirect" ones, H_2 would be generated in the dark by fermentation of endogenous reserves that had been accumulated during previous photosynthetic conditions. This involves the growth of the microalga outdoors, its harvest, and its incubation in a dark fermentor that involves much lower volumes than a photobioreactor. Its disadvantage is the various manipulations needed.

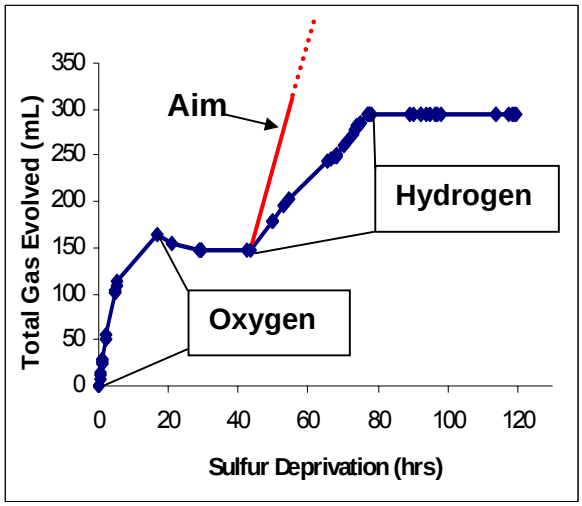

Figure 3. Total gas evolution after sulphur starvation showing the first O_2 evolution phase and the H_2 production phase. The experiment is with a 1L bioreactor as in Figure 2. Gases are identified by gas chromatography.

The current better defined biotechnological process is one of the "Direct" type (Melis et al., 2000; Tsygankov et al., 2002). It involves a normal photosynthetic growth phase followed by a sulphur starvation treatment that leads to the photodestruction of most of the PSII population. Figure 2 shows an experimental setup where *C. reinhardtii* cells are incubated under sulphur starvation for the photogeneration of H_2. The lack of the essential nutrient sulphur inhibits protein synthesis and, thus, the normally photo-damaged PSII centres cannot be repaired. Instead, in normal conditions, protein synthesis maintains a steady state level of PSII. That low level of PSII centers allows for a low O_2 evolution capacity, such that the rate of mitochondrial O_2 uptake by respiration becomes faster than the rate of chloroplastic O_2 evolution, which normally is 10 fold higher than the rate of respiration. Immediately after the start of the sulphur starvation treatment there is still O_2 evolution (this is due to internal sources of sulphur), but lasts only for 20 h (Figure 3). Thus, in the absence of sulphur the required anaerobiosis is established which allows for the generation of H_2 (Figure 3). However, the system is active for only ca. 50 hs, the protocol requires complex manipulation of the microalgal culture (to maintain H_2 production from a same culture periodic additions and depletions of sulphur have to be performed), and necessarily needs the use of exogenous organic substrates (see Figure 1).

Because the "Direct Biophotolysis" approach is the most ambitious in terms of efficiency of both energy conversion and industrial manipulations, we are exploring in detail its feasibility and optimization to achieve a more efficient and stable system (see "Aim" trace in Figure 3), simplify the industrial process, and make it more cost-effective.

4. TECHNICAL AND ECONOMIC FEASIBILITY ANALYSIS

A preliminary investigation to evaluate the technical and economic feasibility of a large scale photobiohydrogen production plant using *C. reinhardtii* has been carried out. A possible technology approach and the main costs of production involved in developing and operating such a plant have been established, and compared to the projected cost of photosynthetic hydrogen production with the costs of other means of generating hydrogen using renewable energy[1]. Notably, none of the reviewed papers in the area includes a detailed consideration of the technical challenges which arise in scaling up from laboratory to full production (as opposed to a prototype scale).

The relatively low efficiency of the photosynthetic process implies the need for a large plant area and, thus, of a manufacturing facility – consisting of photobioreactors, hydrogen extraction equipment, sterilisation facility, pumps, etc. – with a very low cost per unit area.

The scaling-up of a microbiological process from the 1 L level (which is the order of magnitude of the typical volume used at the basic science level) to ~10^8 L, keeping costs low, involves extremely difficult issues. Among others, these are:

- The choice of materials and the construction design of the photobioreactor, including considerations of materials lifespan and their recyclability.
- Methods of constructing and disassembling the photobioreactor.
- The physical stability of the photobioreactor, e.g. in the wind.
- Optimal sunlight orientation, and culture depth (affecting the light path for photosynthesis).

[1] All costs are given in Australian dollars. Where a conversion from US dollars was required, a nominal exchange rate of 1 AUD = US$0.75 was used.

- Passive thermostatisation/thermal equilibrium of the bioreactor with soil and air.
- Culture chemostasis and turbidostasis (chemical and physical actions to maintain the culture in a stable physiological condition and cell density).
- Minimisation of O_2 leakages during the anaerobic phase.
- H_2 diffusion and H_2 recovery.
- Sterilisation of the microbiological medium and bioreactor.
- Sterilisation of disposed culture at the end of the industrial cycle.
- Waste treatment of disposed culture and re-utilisation of water for the same or other purposes.
- Movement of culture volumes by pumping.
- Homogenisation of culture (stirring/pumping).
- Pressurisation and storage of H_2 (although this requirement applies to any other H_2 producing technology).
- Site selection and preparation.
- Environmental safety.

It is clear that many operations easily done and secured in the lab cannot be carried out in the field through the same techniques. Thus, the design has to consider the yield/cost ratio at all levels in order for the project to be realistic.

4.1 Cell culture containment designs and materials

Photobiological hydrogen generation using *C. reinhardtii* requires an airtight containment structure in order to achieve anaerobiosis and collect H_2. At least the upper surface of the container must transmit radiation in the visible and near infra-red parts of the spectrum for photosynthesis; although it should ideally block ultra-violet radiation as this damages the cells. As part of the feasibility study a range of possible materials and designs were considered. The structure could have the general form of a pond or channel with a clear top, or of lengths of tubing. Amongst the materials considered were glass and polycarbonate sheets (such as are used as a cladding on greenhouses), and acrylic in the form of sheets or tubes. All of these materials were rejected as being too expensive. The preferred design is to have tubes made of transparent plastic film, arranged in long parallel lengths. Figure 4 shows a section of the plant in schematic form, with tubes being connected via manifolds to a central pumping station, which also functions as the site for inoculation with culture, injection of nutrients, and other periodic processes. Despite the relatively short lifespan of plastic film compared to rigid materials, a levelised cost analysis showed it to be more economic per unit area as a means of providing a containment structure. It also has the significant advantage of being obtainable in lengths of hundreds of metres, obviating the need for frequent joins and seals.

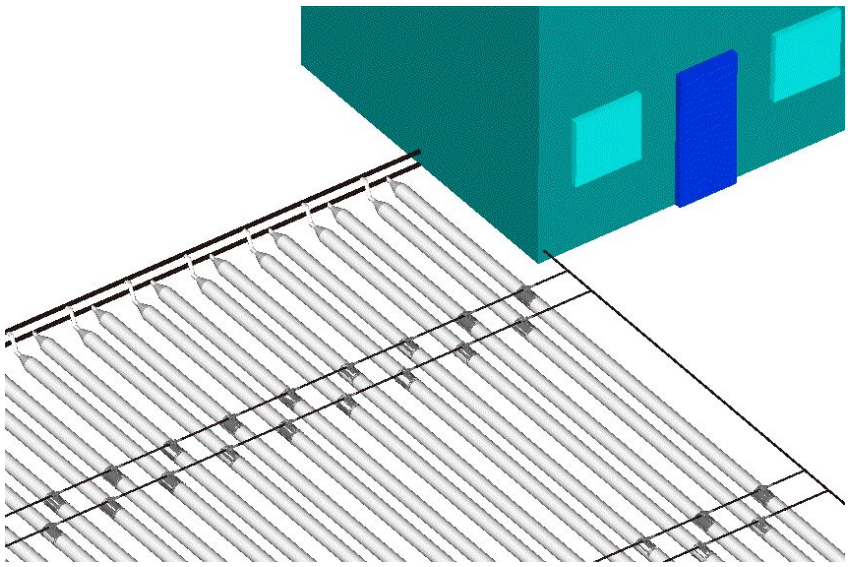

Figure 4. Schematic of plant layout. The large tubes are the alga containing photobioreactor. The thin lines represent the H_2 collection system.

The optimum diameter of the tubes is affected by parameters such as the maximum permissible

optical depth of the culture, the relative cost of fittings of different sizes, and the number of tubes required to cover a given area. A diameter in the range of 150 to 250 mm is believed to be ideal, and 200 mm was used for calculating the plant areal cost and production rates. For the feasibility study a plant aperture of 10^6 m^2 was considered, which would have a culture volume of 150 ML. Figure 5 shows a short section consisting of two full size tubes, which were constructed to investigate the mechanical and thermal properties of the tubes.

A small prototype system 8 m long and containing 50 L of culture was also constructed (Figure 6). It consists of a single loop with a 9 cm diameter tube, a pump, and monitoring accessories. *C. reinhardtii* inoculated in the prototype grew well and was maintained alive for more than 2 weeks. Preliminary results using a sulphur starvation protocol showed the achievement of anaerobiosis and the generation of H_2.

Figure 5. 200 mm diameter tubes filled with water.

Figure 6. A 50 L, 8 m long photobioreactor prototype in an greenhouse, inoculated with *C. reinhardtii*.

4.2 Plant output

The maximum measured rate of evolution of hydrogen by a "wild type" strain (i.e. not genetically manipulated) of *C. reinhardtii* is 4 mL H_2 / (litre culture) / hour, for a cell concentration equivalent to 10 µg chlorophyll/mL (e.g. see Figure 2). This rate is only attained during periods of sunlight and only in the hydrogen generation phase, which is taken as 70% of the culture cycle. For a site with an average of 7 hours usable sunlight per day, the annual production rate per litre of culture is then 4 mL H_2 / (litre culture) / hour x 7 hours x 365 days x 70% = 7.15 L H_2 / (litre culture) / year = 0.64 g H_2 / (litre culture) / year. With a plant volume of 150 ML the annual output would be 97 tonnes of hydrogen, which would be further reduced by hydrogen being lost by diffusion before it is collected. It would be necessary to increase the photobiohydrogen conversion efficiency (via genetic construction of "improved" strains of *C. reinhardtii*) by at least a factor of ten, for the technology to become competitive. However, this level of improvement is accepted by the biological research community as reasonable to expect.

In the remainder of the paper it is assumed that the biological improvements in efficiency and duty cycle are achievable and that the net annual output of the plant is 1000 tonnes of hydrogen.

In order to reduce the required capacity of some components of the system, such as the water purification apparatus, the plant would be divided into sections which are in different phases of the *C. reinhardtii* culture cycle at any one time. However the total length of the hydrogen production cycle represents a limitation in this respect, as any single process must be completed in one section of the plant before it is required in the next section. The production cycle is hypothetically taken as being one week of growth followed by four weeks of hydrogen production (this significantly exceeds what has

yet been attained experimentally - at present the process requires two days of cell growth, then two days of sulphur starvation, and finally two days of hydrogen production). An extra five days is also allowed for "sterilizing" the growth medium and pumping it in and out of the reactor tubes at the start and end of the cycle, as well as any maintenance time. Thus any section of the plant would have a complete cycle time of approximately 40 days, with a 70% duty cycle for hydrogen production.

4.3 Liquid growth medium sterilization

In the laboratory the liquid medium used for culturing algae is typically sterilised by heat (autoclave) prior to the inoculation with the alga. *C. reinhardtii* cells can duplicate once every 6 hours in a suitable growth medium, whilst other microbes which may be naturally present in the environment (e.g. in the water) may have a duplication time of as little as 30 to 60 minutes. In scaling up to a full size plant the cost of sterilisation by heat was first considered.

As noted above, the maximum time that could be taken to purify the entire volume of water is the cycle time of 40 days, so that the requirement is for the treatment of approximately 4 ML per day. In order to reliably kill all spores, the water must be raised to a temperature of 121 ºC, held for 15 to 20 minutes (Gardner and Peel, 1998). To calculate the order of magnitude of the amount of energy required to sterilise 150 ML it is assumed that water from the system enters the sterilisation facility at 20 ºC and passes through a heat exchanger with effectiveness ε = 80%. Then the cold incoming water is raised in temperature by 0.8 x (121 ºC – 20 ºC) = 81 ºC in the heat exchanger, and the temperature must be increased by a further 20º C to achieve sterilisation. The amount of energy required to sterilise 150 ML is then $Q = mc\Delta T = 1.26 \times 10^{13}$ joules. This is a low estimate as it neglects the additional heat required to maintain the temperature for 15 minutes or more, due to heat losses in the system; and also makes no allowance for periods of intermittent operation, which reduce the effectiveness of the heat exchanger. If these factors add approximately 15% to the input heat requirement, and there are nine sterilisations per year (once per 40 day cycle) then the annual heat input is 1.3×10^{14} joule.

Although it would hardly be desirable to burn of large amounts of natural gas as part of a process ultimately intended to reduce greenhouse gas emissions, gas heating is considered as a benchmark for the costs involved in sterilising the water. With a 90% efficient boiler, and a gas price of 1 cent per MJ, the annual cost of gas would be $1,440,000. If the yearly hydrogen production is 10^6 kg then $1.44 / kg is added to the cost of production, even before allowing for the capital and maintenance costs of the boiler and associated sterilisation apparatus.

As an alternative to using natural gas a field of single axis tracking solar troughs was also evaluated as the heat source for sterilisation. Employing a levelised cost analysis of the system, the net additional cost was obtained as approximately $1.20 / kg H_2, which is still undesirably high.

A range of water purification techniques was surveyed to find an alternative to sterilisation. The most cost effective alternative which was found is the use of ultra-violet light disinfection. Suitable commercial units which treat 1 ML per day are available for $17,500, and four such units in parallel would provide sufficient capacity. Allowing for operation and maintenance costs, the input to the hydrogen price of UV disinfection is only of the order of 2 cents per kilogram.

4.4 Stirring of the culture

In the absence of some form of stirring of the algal culture the population of *C. reinhardtii* tends to become inhomogeneous, with a layer of cells which are not swimming sinking to the bottom of the tube. These cells will receive low levels of light and will produce relatively little hydrogen. In general stirring will promote a more homogeneous distribution of the population and maximisation of hydrogen generation. Stirring also reduces thermal stratification, which is undesirable as at temperatures over 35 ºC *C. reinhardtii* ceases to multiply, and at higher temperatures cells die. In the laboratory magnetic stirrers are used to distribute the culture evenly. For a scaled up plant there are the obvious constraints on any stirring mechanism that it must be inexpensive, and require low energy and maintenance inputs.

A solution to the problem is suggested by the requirement that any element of the culture be circulated back to the central pumping station approximately once per day, for processes such as the injection of nutrients (whilst a distributed feeding system would also be possible, it would add to the cost of the plant). The rate of flow which is required to attain this cycle time is found to be relatively high, due to the long lengths of the tubes, and close to the value at which the flow becomes turbulent.

The Reynolds number Re for fluid flow through a cylindrical pipe is defined as:

$$\mathrm{Re} = \frac{\rho V d}{\mu} \tag{1}$$

where μ is the viscosity, ρ the density, V the average velocity (equal to the mass flow rate divided by the cross-sectional area), and d the diameter. The transition to turbulent flow takes place at approximately Re = 2300, which for water in a 200 mm diameter tube corresponds to a velocity of 0.0115 m/s, or a flow rate of 0.36 L/s.

A possible objection to the use of turbulent flow to achieve mixing is that it requires a higher input pump energy than laminar flow. However the pressure head for a flow with Re = 3500, in individual tubes with 1600 m length (out and back), is only 62 Pa. The annual energy consumption of the pump to overcome this pressure head in all tubes is 5000 MJ, which is less than 0.1% of the energy content of the hydrogen output.

4.5 Culture temperature

The population of *C. reinhardtii* ceases to grow at temperatures over 35 ºC, and below 10 to 15 ºC. It has been found experimentally that at 40 ºC cells will begin to die, with only 10 % of the original number still alive after 4 hours at this temperature. At 50 ºC all organisms will die in 90 seconds. Although there is a possibility of developing mutant strains which will tolerate a wider temperature range, experiments and computer modelling are being undertaken to determine the climatic limitations on the system.

4.6 Hydrogen production costs

The cost of other renewable methods of hydrogen production was reviewed to provide a reference point for the economic viability of the proposed system. There are many technologies currently being researched, and the cheapest method at present is wind power driven electrolysis of water, with an estimated cost of AUD$4 - $5 per kg of H_2. This is to be compared with the $1-$2 per kg cost using the current preferred hydrogen production method by “reforming natural gas”, a non-sustainable and greenhouse-gas emitting process (ACIL Tasman Pty Ltd, 2003).

Yumurtaci and Bilgen (2004) considered electrolysis using excess capacity of hydroelectric power stations, and with electricity costs of 4c/kWh obtained a hydrogen cost of $2.80 / kg. However if the goal is large scale production, the capacity ultimately required would exceed that which could be considered surplus, and the building of large new hydroelectric power stations would be highly controversial as a means of moving to a "hydrogen economy".

It is not yet possible to provide a detailed costing for the biohydrogen system, as many important areas (such as the hydrogen collection system) remain to be investigated. However one significant input which is known reasonably well is the cost of the plastic film tubes, which have been priced at approximately $4/m^2 in 200 mm diameter. The tube material has a lifespan of 4 years, and the contribution of the material cost alone to the hydrogen production can be calculated using a levelised cost analysis (Blakers, 2000):

$$c_u = \frac{C\alpha}{E(1-e^{-\alpha t})} + \frac{M}{E} + c_o \tag{2}$$

Setting C = $4 x 10^6 (i.e. the materials cost alone for a 1km^2 plant), E = 10^6, t = 4, and α = 0.07 the result is c_u = $1.20 / kg. Although installation and maintenance costs for the tubes, and for all the other required infrastructure, have not been included this is an encouraging figure, suggesting that the net cost of production could be of the order of $5 / kg.

5. CONCLUSION

Bio hydrogen production using *C. reinhardtii* algae, is a possible approach to large scale renewable hydrogen generation. It is an inherently energy inefficient process that will rely on large scale low cost bioreactor systems. A technically plausible system based on long flexible translucent plastic tubes has

been identified. If the biological research proceeds as hoped and produces a tenfold conversion efficiency increase, as well as the improvement of the duty cycle from 30% to 70%, photosynthetic biohydrogen could have a net cost comparable to that produced by wind power driven electrolysis. Many issues remain to be investigated in more detail in order to obtain a better estimate for the cost of the system. The main areas of research in the near future are hydrogen diffusion and collection, and the thermal behaviour of the system.

6. ACKNOWLEDGMENTS

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