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Title: Developments of five selected microalgae companies developing “closed” bioreactor biofuel production systems.

Abstract: This work reviews the current status of five selected companies at the forefront of production of liquid fuels from microalgae produced in “closed” photobioreactors and fermenters: Algae.Tec, Algenol Biofuel, Heliae, Solazyme, and Solix. The five companies in the review all have developed novel closed production systems, each with unique technology partners, capabilities, and commercial strategies. Advantages of reactors include higher volumetric productivity and reduced contamination risks. Conversely, the largest challenges for reactors are minimizing capital and production costs, in addition to attracting initial investment capital for non-conventional complex technical systems. This review provides a concise summary of each company’s technology, background, and where available, a qualified assessment of the productivity and economics of their systems. This review demonstrates that commercially viable production systems will need to achieve sustained volumetric productivity to reduce per unit costs, and industry cross-collaboration will be essential for closed system technology developments to successfully produce cost-competitive fuels.

Keywords: Microalgae; biofuel; closed photobioreactor, reactor, renewable energy.

1 Introduction
Temporal and geographic supply insecurity of fuels sources, particularly liquid fuels, has been a major stimulus for alternative energy sources since the early 20th century (Hubbert, 1956; Hubbert, 1962). Human use of bioenergy resources has existed for millennia, yet modern commercial liquid biofuels such as bioethanol and biodiesel are in the main derived from short-rotation crops on arable agricultural lands (Gomez et al., 2008; Vasudevan and Briggs, 2008). In contrast, microalgal biofuel production enables the reduction of arable land and water competition between conventional biofuel feedstocks and agricultural food production due to higher productivities and potential in non-agricultural areas (Cantrell et al., 2008; Chisti, 2007; Clarens et al., 2010; Gross, 2007; Hankamer et al., 2007; Huntley and Redalje, 2006; Sheehan et al., 1998). Whilst microalgal biomass can be
anaerobically digested, gasified, fermented, pyrolysed, chemically altered (etc.) to derive combustible
gases, oils, or solid fuels (Amin, 2009; Chisti, 2007), modern commercial microalgal production
requires focus on the complete total system productivity and cost (Borowitzka, 1999; Kunjapur and
Eldridge, 2010). Like any biologically-based commercial primary industry, improving microalgal
productivity requires contraction of per unit costs (such as land, labour, energy, fertiliser,
environmental service consumption, etc.) (Borowitzka, 1999; Clarens et al., 2010; Jamers et al., 2009;
Kunjapur and Eldridge, 2010; Moheimani et al., 2013c), and in parallel maximising the commercial
output of the culture over time.

At present, two basic microalgae biomass production system technologies aim to supply the
enormous demand for sustainable, renewable algal biofuels: “open” or “closed” systems (Borowitzka,
1999; McHenry, 2010; Ugwu et al., 2008; Vasudevan and Briggs, 2008). Many microalgae species
require highly controlled culture conditions, and species that exhibit a selective advantage in
particularly extreme environments can be grown in “open” systems, such as outdoor ponds and dams
(Borowitzka, 1999). In contrast, the term “closed” in reference to closed algal production systems,
generally means limiting culture exposure to contamination by water and airborne organisms. Fully
commercial microalgae production has been generally limited to relatively small-scale volumetric
production of high-value products in open pond systems (Pulz and Gross, 2004). Open system
cultivation exhibits relatively lower capital (CAPEX) and operational costs (OPEX) compared to the
existing generations of quasi-commercial closed systems, and have a historically proven record of
production (Borowitzka, 1999; Chisti, 2007; Huntley and Redalje, 2006; Spolaore et al., 2006).

Common open systems include natural water bodies, constructed dams/ponds, and also tanks, with
each system design and location balancing a number of algal culture advantages, disadvantages, and
trade-offs, such as higher or lower yields, production stability, and associated costs (Borowitzka,
1992; Kunjapur and Eldridge, 2010; Ugwu et al., 2008). However, open systems commonly exhibit
low yields due to poor water mixing, biological contamination, microalgal predation, low solar
resource utilisation, poor CO\textsubscript{2} diffusion, minimal temperature control, and require large land areas and
water volumes (Amin, 2009; Borines et al., 2011b; Borowitzka and Moheimani, 2010; Chisti, 2007;
Clarens et al., 2010; Gross, 2007; Hankamer et al., 2007; Huntley and Redalje, 2006; McHenry, 2010;
Open system microalgae production closely resembles aqua/agricultural production systems, and exhibit comparable dependencies on complex biological interactions (Borowitzka, 1999; Kunjapur and Eldridge, 2010; Moheimani et al., 2013c). However, due to their technical complexity closed systems generally have relatively high CAPEX and OPEX (Borowitzka, 1999; Lee, 2001; Vasudevan and Briggs, 2008), and commercial algal producers aim to maximise total factor productivity to reduce commercial fuel production costs per unit of output (Kunjapur and Eldridge, 2010; Lee, 2001; Ugwu et al., 2008). These basic technical and economic fundamentals underpin the development of entirely new and innovative methods of industrial biomass production for biofuels.

Controlling microalgal production to a high degree in closed systems offers significant biofuel precursor biomass productivity advantages, and closed systems enable efficient production in an environment that resists biological contamination (Chisti, 2007; Huntley and Redalje, 2006; Vasudevan and Briggs, 2008). As the volumetric algal biomass productivity needs to be much higher to offset high production costs in controlled biomass growing environments, there is a requirement to circulate cultures efficiently, and limitations from mass transfer issues are a common issue in closed system cultivation designs for large scale production (Borowitzka, 1999; Hankamer et al., 2007; Lee, 2001; Ugwu et al., 2008). Significant optimisation of initial closed system prototype designs, must continue into commercial system design scaling into larger systems. At each stage of development the algae biofuel industry has endured recurring issues associated with production stability, variable photosynthetic efficiencies, and numerous technical challenges, including poor CO₂ addition, high energy inputs, and fundamental difficulties in microalgae harvesting and extraction (Borines et al., 2011a; Brennan and Owende, 2010; Clarens et al., 2010). Species-specific characteristics (high precursor productivities, efficient cultivation and harvesting, etc.) are fundamental to reducing the total production costs of algal biofuel production as they can represent around half total OPEX (Borowitzka, 1992; Chisti, 2007; Griffiths and Harrison, 2009). Experience to date has shown great difficulty in closed system scale up, and extrapolations from small laboratory operations are often unreliable (Borowitzka, 1992). However, overcoming fundamental technical and economic algal biofuel post biomass production are also a major challenge to the industry.
Outside of conventional selective breeding, or genetic enhancement to optimise specific biofuel precursor outputs or for extreme environmental tolerance, there are enormous technical gains to be made in downstream of production that can reduce CAPEX and OPEX for algal-derived fuel production. Algal biomass extraction and refining techniques are generally species-specific and dependent on the final application (Borowitzka, 1992). Integrated post-harvest systems such as new generation biorefineries may enable cost-effective production to reduce total production costs in aggregate across the range of final products, effectively cross-subsidising biofuels (Arundel and Sawaya, 2009; Chisti, 2007; McHenry, 2013; Wyman and Goodman, 1993).

Within this context, this work reviews the partnerships/investments, technology, economics and developments of five microalgae biofuels companies, (in alphabetical order): Algae.Tec; Algenol; Heliae; Solazyme, and; Solix Biofuel/BioSystems. The review focuses on the research and development technical challenge and the interesting partnerships and downstream processing capabilities of each company, and relates their development needs to the industry as whole. The work aims to clarify the often simplistic publically available microalgae biofuel industry information, and aims to facilitate progress in the microalgae investment in research and development. The authors have attempted to present technical developments and qualifying commentary, without a focus on the specifics of any commercialisation strategy. However, due to the limited availability of peer-reviewed literature concerning closed microalgae production, particularly in relation to commercially sensitive elements and data, the authors have compiled publically available information and have attempted to provide the reader with an illuminating comparative analysis of the industry to date.

2 Algae.Tec Ltd www.algaetec.com.au

Algae.Tec, with operations in Atlanta, Georgia, USA, and Nowra in New South Wales, Australia, and offices in Perth, Australia completed a USD5 million capital raising on the Australian Stock Exchange in 2010 (AlgaeIndustryMagazine.com, 2012a). Algae.Tec's technology and processes have been successfully trialled in the research and development stage. The company is now progressing from fundamental R&D to medium-scale demonstration, leading to large modular commercial developments. Algae.Tec (formerly Teco.Bio) was established for the commercial development
technology created by the founding shareholder companies, Teco Pty Ltd and Dot-Bio Inc, which are owned by Teco.Bio LLC. The company is developing the enclosed “McConchie-Stroud” modular photo-bioreactor design, in New South Wales in Australia. On 2nd August 2012 Algae.Tec's demonstration facility located at Shoalhaven, Nowra in NSW opened, comprising a single photobioreactor module. Algae.Tec's Nowra facility known as 'Shoalhaven One' is sited next to the Manildra Group’s industrial ethanol facility, south of Sydney. Manildra Group is Australia's largest ethanol producer, and Algae.Tec's algae photoreactors utilise CO$_2$ gas produced from the ethanol fermenters as inputs into the “McConchie-Stroud” algae growth system (Algae Tec Ltd, 2012). The “McConchie-Stroud” system incorporates parabolic light collectors, or light emitting diodes as a secondary artificial light system for overnight growth, including light intensity and an indirect light distribution system inside the reactor using transparent tubing. Algae.Tec estimate a total collector area of around half a ha per module, based on a winter solstice solar insolation of 5.8 kWh m$^{-2}$ d$^{-1}$, a summer solstice insolation of 7.0 kWh m$^{-2}$ d$^{-1}$, and an annual average of 6.5 kWh m$^{-2}$ d$^{-1}$ (Algae Tec Ltd, 2010). The reactor design exhibits a relatively small land footprint, with a 400 module facility estimated to require 150 ha for the total facility, including solar collector area, process area, and ancillary infrastructure.

2.1 Algae. Tec’s technology and production developments

Algae.Tec’s substantial Algae Development Program (ADP) Report (ver.10/03/2010) shows that the company has constructed more than 60 bench-scale photobioreactor configurations designed to continuously operate with a 10-13% CO$_2$ source concentration, species-optimised pH and nutrient packages, inlet algae concentrations between 200 to 500 ppm (wt), and light wavelengths between 380 and 730 nm at below 600 W m$^{-2}$. Configuration tests have been in operation for over 30 days, all feeding data into an in-house simulation model. The configuration test productivities generally range from 0.02 to 0.175 g L$^{-1}$ h$^{-1}$, with a rough average of 0.1 g L$^{-1}$ h$^{-1}$, and lipid content in the range between 9% and 70%, with around one third producing greater than 50% lipid yield. Corresponding carbohydrate concentrations ranged from 8% to 63%, with around one third producing greater than 40% carbohydrate yield. Similarly, protein compositions ranged from 7% to 70%, with up to 50% of
species producing less than one third protein yield under optimal conditions (Algae Tec Ltd, 2010).

The ADP Report also shows evidence of several optimised nutrient packages for a broad range of species, which experimental data shows influences both the aggregate and relative productivity characteristics, such as lipid concentration. The report included work on harvesting to separate several alga species from water, including flocculation, filtration, flotation, and frothing, some with and without additives, with some harvesting efficiencies of around 80%. The ADP report also described proprietary harvesting techniques with efficiencies of around 90%, although the report noted harvesting energy and cost trade-offs and is aiming for somewhat lower separation efficiencies. The ADP report estimated the energy conversion ratios of approximately 0.75 MWh of electricity, 5.6 MWh of light, 2.7 kL of water to produce one tonne of algae, an efficient closed production system.

In late 2011 Algae.Tec signed a collaboration contract to undertake a feasibility study and initiate its first algae biofuels production facility in Asia with the Sri Lankan subsidiary of global cement giant Holcim. If it proceeds, the staged facility is expected to be fully operational by 2015. “The Algae.Tec facility is designed to reduce the cement manufacturing carbon dioxide emissions with an off take into the algae growth system,” said Holcim Lanka CEO Stefan Huber. “Algae.Tec has a truly innovative technology backed by an expert international engineering team” (Algae Tec Ltd, 2011).

2.2 Current economic projections

In private discussions with the company, the authors discussed the commercial-scale module installed at the Nowra facility. The facility aims to produce around 150 t of biomass per module, and an annually extrapolated production for a single module is projected to be around 70,000 kg of oil, 70,000 kg of high protein feed, with the ability to sequester around 400 tCO$_2$-e. The oil produced from high lipid strains are suitable for hydroprocessing$^1$ into primarily jet fuel, with lower fractions of biodiesel and bioethanol.

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$^1$The term hydroprocessing describes several common techniques used to refine precursor substances into quality fuels, and forms the basis of large-scale oil refineries and is now more commonly used in biorefineries. Hydroprocessing includes hydrogenation (chemically reacting hydrogen with the substance), hydrocracking
Based on the costs and production assumptions in the ADP report (producing 63,210 t y\(^{-1}\) of biomass with a ~40% lipid content), the authors estimate production costs of 1 kg of algal oil would be around USD0.86, which is one of the lowest reported costs for algae oil production known to the authors. This calculation was based on a 500 module plants operating and capital expenditures, amortised over ten years. Refining the algae oil into liquid fuel by using hydroprocessing will also cost an additional 0.05-0.12 USD L\(^{-1}\). However, the actual total cost of production will hinge on the optimisation between OPEX and maintaining high productivities, and the market values of the expected 500 module facility output of around 8,000 t y\(^{-1}\) of fatty acids and 60,000 t y\(^{-1}\) of biomass (Algae Tec Ltd, 2010). At this time, attracting partnered funding to assist commissioning of larger systems is a significant development requirement for the company.

**2.3 Algae.Tec summary**

Algae.Tec Ltd’s ADP Report describes the company’s considerable capabilities in production, evaluation, and optimisation of various species production characteristics (colour, type, shape, size, productivity, product yields, temperature preferences, nutrient requirements, energy needs, harvesting, component analysis, etc.). The detailed in-house research, development, and production activities demonstrate the company exhibits the technical capabilities to achieve design and process innovation towards commercialisation. However, the challenge of large-scale commissioning remains, particularly in relation to demonstration-scale algae culture with high productivities, and the module design refinements. In terms of closed system operation and optimisation, this will likely require further development of the solar collection and light distribution system, identification of suitable microalgae, optimising of the modular photobioreactor internal mass transfers, quality control of the refined algae fuels, and the total value of the ancillary final products selected. The continuing demonstration and expansion of the number of inter-connected modules at Algae Tec's facility at Nowra in NSW, Australia will determine to a high degree the productivity of the technology. This (thermal decomposition of a substance into smaller carbon chain fuels by hydrogenation), and hydrotreating (the removal of impurities such as S, N, O, and metals from the using hydrogen reactions).
will play a dominant role in the commercial success of the system at scale, and to the impact the
technology may have on the microalgal biofuel industry.

3 Algenol Biofuel [www.algenolbiofuels.com](http://www.algenolbiofuels.com)

Algenol is an owner-operated biotechnology company, based in Bonita Springs, Florida, USA, which
reportedly use a “hybrid algae” to synthesise biofuels and high-value organic green-chemicals.

Algenol has entered into several collaborative agreements with universities and corporations to assist
the company in accelerating the development of its proprietary DIRECT TO ETHANOL®
technology. Paul Woods invented the DIRECT TO ETHANOL® technology in 1984, and patents
were granted in 1998 (Australia), 2001 (USA), 2004 (USA), and 2007 (EEC). The company operates
at least five research, production, and biorefinery facilities (small-scale) in Puerta Libertadad, Sonora
in Mexico, Fort Myers in Florida, Freeport in Texas, Berlin in Germany, and Zug, Switzerland.

The “hybrid algae” is described by the company as a “metabolically enhanced” blue-green
algae strain that initiates fermentation of the cellular carbohydrates into ethanol vapour via specialised
enzymes. The company claims the alga is non-GMO, and that no actual genetic material is being
reengineered or introduced. The company Biofields has an exclusive license for the Algenol
technology until 2013, and has purchased 22,000 ha in Sonora, Mexico aiming to produce 940 ML y⁻¹
by 2013. However, this has been delayed due to permitting issues. Planned demonstration facilities
were expected to produce 380,000 kL y⁻¹ of bioethanol by 2012, and other partnerships aim to
produce 7.5 GL y⁻¹ by 2020. Algenol has also signed joint development agreements with an
impressive list of companies such as the Dow Chemical Company, The Linde Group, and Membrane
Technology Research, among others.

Approximately USD200 million of equity has been raised, with more than USD40 million
invested in R&D facilities, and employing more than 150 scientists and engineers. Algenol has
received USD25 million for the US Department of Energy’s (DoE) American Recovery and
Reinvestment Act to build a pilot-scale biorefinery. A USD50 million partnership between The Dow

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² The authors were able to find the following patents the company hold: WO2009098089, WO2010068801, and
WO2008055190.
Chemical Company (the world’s largest producer of polyethylene and a major ethanol user), National Renewable Energy Laboratories (NREL), and Algenol was announced in 2010. Algenol also received a USD10 million grant from Lee County, Florida to build a 0.2 ha research facility to house Algenol’s laboratories (Ahlm, 2012).

3.1 Algenol’s technology and production developments

Algenol operates a zero discharge aquaculture facility for R&D and maintains a large collection of blue-green microalgae strains. The central component of the DIRECT TO ETHANOL® process is a 15 m long and 1.5 m wide polyethylene film outdoor photobioreactor constructed with semi-transparent plastic. The photobioreactor uses treated seawater with added nutrients, and includes a volume of air above the water. After algae inoculation, CO$_2$ is introduced into the outdoor photobioreactor and the hybrid algae reportedly produce sugars that are converted into ethanol intracellularly. The ethanol diffuses through the cell wall into the culture medium and evaporates along with water, into the air volume then condensing on the inner surface of the photobioreactor to be collected by internal “gutters”. Therefore, the photobioreactor will be required to be axenic to control bacterial contamination that will consume ethanol. The ethanol from the ethanol-freshwater solution produced is concentrated, and distilled. The DIRECT TO ETHANOL® process produces around 1 L of fresh water per L of ethanol, and Algenol estimate the energy output of the process will be approximately eight-times the energy input, although the authors are unaware of any results to confirm this. In terms of ethanol-water separation, Algenol collaborators, Membrane Technology Research’s (MTR) BioSep™ technology using membrane distillation technology will be the basis of the separation system. The Dow Chemical Company and Algenol will construct a USD50 million pilot algae biofuel plant at Dow’s existing chemicals complex in Freeport, Texas. If successful, Algenol’s technology will likely be used to produce ethylene to displace natural gas chemical feedstock. Dow and Algenol will also jointly undertake R&D on advanced materials for the film photobioreactors and test refined reactor designs for the DIRECT TO ETHANOL® process.

Georgia Institute of Technology, NREL and MTR are partnering with Algenol for a USD25 million DoE loan guarantee to target pilot production volumes of up to 190,000 L ha$^{-1}$ y$^{-1}$, with an
initially estimated yield of 20,000 L ha\(^{-1}\) y\(^{-1}\). At present the company has demonstrated production of around 85,000 L ha\(^{-1}\) y\(^{-1}\) of algal bioethanol (Algenol Biofuels, 2013). The pilot plant includes construction of 3,100 Algenol photobioreactors on 9.5 ha adjacent to Dow’s Freeport operations, which provide the 2 t of CO\(_2\) d\(^{-1}\) (dry) for the pilot project. Dow will develop advanced materials for the photobioreactor system, while NREL will undertake laboratory and on-site analysis of simulated power plant flue gas, as well as industrial sources of CO\(_2\), and their impact on Algenol’s algae. Georgia Institute of Technology in collaboration with the University of Colorado and MTR will design and test ethanol separation, and CO\(_2\) delivery technologies. Georgia Institute of Technology will also undertake CO\(_2\) life cycle of Algenol’s process. Algenol and The Linde Group have agreed to collaborate to optimise management of CO\(_2\) and O\(_2\) for Algenol’s photobioreactors. Further downstream, Valero Services Inc. (a subsidiary of Valero Energy Corporation) and Algenol have agreed to explore combining Algenol’s technology with Valero’s fuel and chemical production, distribution, and transportation capabilities.

### 3.2 Current economic projections

Algenol claims that the cost of their algal ethanol process can be driven below USD0.4 L\(^{-1}\) at scale, including capital costs, and the target price of between USD0.25 and USD0.33 L\(^{-1}\) is projected for the pilot scale biorefinery at Freeport. The company expects its flexible film photobioreactors to last at least 5 years, and possibly 10 years. However, the authors do not sufficient information to assess these claims due to a lack of information regarding the basic biology of the algal strains, the productivity of the culture systems, or the efficiency of MTR’s BioSep™ membrane distillation technology, and economics of the total production chain.

### 3.3 Algenol summary

The company has stated that its algal strains have been cultivated continuously for several years, and the pilot facility and biorefinery in Freeport will enable Algenol and their partners to assess the strain performance with the pilot system, which is a large number of ~22.5 m\(^2\) photobioreactors. The pilot R&D will enable a yield and productivity assessment of scaling up the bioreactor, and was completed
in late 2012. Further downstream research in the membrane distillation area will also be fundamental steps for Algenol to overcome. However, the large capital available the considerable capabilities of the partnerships are a major advantage.

4 Heliae Development, LLC [www.heliae.com/](http://www.heliae.com/)

Heliae is a private company from Mesa, Arizona, with equity held by Arizona State University (ASU). Heliae primarily use technology and knowledge licenced from researchers Qiang Hu and Milton Sommerfeld, both from ASU, who have significant research experience in photobioreactor system design and mass culture. Boeing has invested USD225,000 in the algal research at ASU, and the US DoE have invested up to USD6 million over 3 years. In terms of fuels, Heliae aims to produce aviation jet fuel from algae using selected microalgae strains cultivated to produce oils, which when deoxygenated are identical to kerosene. ASU, as one of the leading team in a Sustainable Algal Biofuel Consortium, will test the biochemical conversion of microalgae to fuels and products, and also the physical chemistry of algal fuels and fuel intermediaries. Heliae were also awarded a USD3 million Strategic Research Group award from Science Foundation Arizona for further development of algal strains for commercial production of jet fuel. The commercial direction of Heliae has broadened somewhat over the past few years, with less of a focus on fuels, and more commercial focus on whatever component of the algal biomass achieves a commercial returns, and have recently expanded their portfolio of patents to around 30 issued patents (Schwartz, 2012). Areas of focus now include nutrition, therapeutics, agri-feed, health, and specialty chemicals and fuels (Heliae, 2013). The company has also hired new executives with demonstrated commercialisation and technical experience in bioenergy, agribusiness, and algal biofuel experience, including Adrian Galvez, the former Senior Vice President of Engineering at Solazyme, and Mike Rohlfsen, the former Vice President of Business Development at PetroAlgae (AlgaeIndustryMagazine.com, 2012b).

4.1 Heliae’s technology and production developments

Hu and Sommerfeld have inactivated ADP-glucose pyrophosphorylase in a *Chlamydomonas reinhardii* starchless mutant, which increased triacylglycerol production by an order of magnitude.
This and other work suggested that shunting of photosynthetic carbon partitioning from starch to triacylglycerol synthesis may be more effective than directly manipulating the lipid synthesis pathway for increased triacylglycerol production (Anandarajah et al., 2012; Li et al., 2010). The final lipid concentrations achieved were almost 50%, and a slight reduction in overall growth rates were observed. Furthermore, Hu and Sommerfeld are known to the authors to have identified several strains with high concentrations of triacylglycerols, which, post deoxygenation treatment, closely mirror the length of the hydrocarbon chains found in aviation fuel. A competitive advantage of triacylglycerol production is the elimination of chemical or thermal cracking processes, and when fuel additives are introduced, the output fuel is suitable for aviation engines. As Heliae use a specific mutant alga, the culture system technology is based on a unique plate-type of photobioreactor to produce sufficient algae to inoculate their mass culture facilities to provide a buffer to assist contamination control. At present Heliae are using a single commercial-scale trough and raceway production technology with the option of being an open system in addition to a closed system, depending on the target market and contamination requirements. The single commercial-scale production module is a 30 m by 3.5 m with a trough and raceway section, covered by a greenhouse, and CAPEX per ha is around USD2 million (Schwartz, 2012). The company is developing a small-scale (20 ha) pilot demonstration facility next to the headquarters, and is expected to be completed in late 2013. Heliae have signed long-term off-take agreements which underpin the existing expansion plans.

Post-production, Heliae have significant experience with membrane filtration systems and associated maintenance protocols. Membrane fouling by the algae cake and adsorption of proteins and polysaccharides were found to be effectively removed by periodic air-assisted backwashes, and a one hour soaking of the membrane in 400 mg L$^{-1}$ NaClO (Zhang et al., 2010). These downstream advances have the potential to significantly lower production costs and energy consumption. However, the company also uses conventional solvent extraction techniques. Post-harvest, the authors expect that Heliae will likely use hydroprocessing techniques to refine the subsequent product streams, as this will enable greater output flexibility at scale.
4.2 Heliae summary

Heliae are primarily focussed on fundamental research and incremental developments, rather than implementing production systems at this time. It is likely that the strains, technology, and capability of Heliae will be incorporated into larger algal entities in the future. Much of Hu and Sommerfield’s research is published in peer-reviewed journals, and thus these researchers’ claims and production experience is highly regarded. However, as a future major producer of algal aviation fuel, Heliae seem to be specialising in the enabling sphere of numerous products, rather than concentrating on mass production of biofuels. The authors also lack details of long-term algal productivity from Heliae group, in addition to production costs, or future development plans to inform a more detailed assessment of Heliae in this review.

5 Solazyme www.solazyme.com

Solazyme, an owner-operated company from South San Francisco, California, USA, is the only microbial biofuel company that is currently producing algal-based fuels in the many tens of thousands of litres annually. One of Solazyme’s fuels, known as Soladiesel$_{BD}^\text{®}$ (FAME) meets ASTM D6751, EN 14214, and military specifications, and has a low temperature performance superior to any currently available biodiesel. Another Solazyme fuel, Soladiesel$_{RD}^\text{®}$ (Renewable #2 Diesel) meets ASTM D975 and military specification, with a cetane rating of over 78, higher than standard US diesel fuels indicating a quality fuel production (Solazyme, 2012b; Solazyme, 2013a). Soladiesel$_{BD}^\text{®}$ and Soladiesel$_{RD}^\text{®}$ are the first successful algae fuel road test trials (up to B100) for thousands of miles in unmodified vehicles and delivery infrastructure, and can be blended with conventional fuels. Solazyme has also produced a liquid fuel replacement for the F-76 distillate for ships tested with the US Navy, known as Soladiesel$_{HRF-76}^\text{®}$. Solazyme’s jet fuel, known as Solajet™, is the first algae fuel to pass all specifications required to meet the ASTM D7566 standard, equivalent to the ASTM D1655 (Jet-A1) standard (Solazyme, 2013b). Solazyme is also involved in the industrial chemical, nutrition,
cosmaceutical and pharmaceutical production (Solazyme, 2013a), which is clear from the large number of patents filed focussing on pharmaceuticals/cosmaceuticals, unrelated to algal fuels.\(^3\)

Solazyme capital raising has procured around USD100 million, and has partnerships with Unilever, Chevron, and the US Department of Defense (DoD). The DoD selected Solazyme to research, develop, and demonstrate commercial-scale manufacture of algae-derived F-76 naval distillate for testing to military specifications. The contract included delivery of around 80 kL of SoladieselHRF-76® (reportedly worth USD8.5 million) to the US Navy, and a subsequent contract for an additional 550 kL. Solazyme’s contract with the US Navy was to provide around 5,700 L of their Solajet™ fuel. Solazyme has also received USD2 million from the US National Institute of Standards and Technology to demonstrate light sweet crude production from domestic US resources, while the California Energy Commission awarded a USD789,697 to Solazyme for SoladieselRD® production from cellulosics. However, recent capital raising by the company increased the cash available by an additional USD115 million on top of the approximately USD160 million cash already held. The company also recently obtained USD120 million in finance from the Brazilian Development Bank (BNDES) for a joint venture commercial-scale facility in Brazil adjacent to Bunge’s Moema’s sugarmill in São Paulo (Lane, 2013).

5.1 Solazyme’s technology and economic developments

Solazyme’s production technology is based on fermentation of plant cellulosics, which supply nutrients to the GM heterotrophic algae without sunlight in metal vats. The GM algae are reportedly more than 80% lipid, and recently installed and tested fermentation vats in their Iowa facility are now up to 500 kL, a notably successful scaling of production. The Iowa facility is expected to produce 20,000 tonnes of oil by early 2014 (Solazyme, 2012c). The wide range of potential feedstocks for the system include agricultural products and waste, grasses, forestry residue, (etc.) The current fermenters are maintained between 30 to 40°C, which produce approximately 75 kL of algal biomass within a

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few days. Fermentation enables to production of high volume in short timeframes, with controllable production and outputs of fuels and other biomaterials. Solazyme’s stated technology fermentation efficiencies are generally above 75% (with best conversions of over 90%), with resultant algal biomass oil contents greater than 75%. Concerns regarding the sustainability of the practice were in part alleviated by independent full life-cycle greenhouse gas assessments of Soladiesel, which found 85 to 93% mitigation relative to mineral-based ultra-low sulphur diesel. Separate assessments by NREL found Soladiesel produced 30% less particulates and almost 20% less CO relative to conventional fuels post-combustion (Solazyme, 2009). In 2012 Solazyme completed the commissioning of their integrated algal biorefinery with a nameplate annual output of 2 million L in Peoria, Illinois (Solazyme, 2012a). Solazyme has not disclosed their fuel extraction technology from algal biomass, only indicating they use standard equipment used for soy or canola oil (i.e. solvent extraction). The authors believe they are using hydroprocessing techniques in contrast to transesterification to produce Soladiesel and Solajet fuels due to the volumes and fuel quality to date.

5.2 Solazyme summary

Solazymes’ fermentation technology is a relatively simple, modular, reliable and proven means of producing algae biomass. Therefore, the fuel production efficiencies and associated costs will be determined by a large part by the GM algae, of which the specific modifications remains confidential, and to some extent the downstream extraction and refining process. A large potential barrier to industrial-scale production may be the regular supply of the large quantities of sustainable plant feedstock. The authors expect sugarcane will become the primary feedstock, and expect both the sustainability and cost of the resultant fuels will be highly dependent on the means of production and price of the cane, or equivalent feedstock. The 2013 joint venture in Brazil supports this assessment. Nonetheless, the existing partners, the impressive production history, and the independent assessments to date are very promising in terms of the net life-cycle greenhouse gas mitigation, the direct combustion emission reductions, and production technology scale-up. The essential question now remains the eventual price of the produced fuels, and if they can compete with conventional fuels on a cost basis.
Solix Biofuel (since renamed to Solix BioSystems) is descended from the US DoE’s Aquatic Species Program (ASP), which commenced in 1978 to explore biodiesel production from macro and microalgae without competing with food. Solix was founded as a private company in 2006 with the support of Colorado State University (CSU) to enable scaled biofuel production as a technology provider, and not primarily a fuel producer. Solix Biofuel is the supplier of the AGS™ (an acronym for Algae Growth System) technology, a photobioreactor used to culture microalgae. Solix operate a demonstration facility on the Southern Ute Indian Reservation in Colorado, an expansion from the pilot facility which was in operation in Fort Collins. Solix is currently culturing native Colorado microalgae strains selected for oil production at around 40% by dry weight.

Solix has extensive partnerships and investors, including The Babcock & Wilcox Company, Bechtel National, Bohemian Asset Management, Cemex, Colorado State University, Hazen, I2BF, Infield Capital, Los Alamos National Laboratory, National Instruments, Shanghai Alliance Investment Ltd., Southern Ute Alternative Energy, Targeted Growth Inc., University of California, US DoE, and Valero. Solix has raised around USD40 million in funding. Funding from existing partners (USD16 million) enabled Solix to complete a production facility in Durango, and establish their commercial operations in China (Bloomberg; Solix Biofuels, 2011d).

6.1 Solix’s technology and developments

Solix’s photobioreactor design aims at high-yield cultivation leading to low-cost production, harvesting, and extraction, irrespective of specific microalgal biological requirements. As such, Solix’s strategy is likely to be a technology supplier to fuel producers, and the AGS™ technology is supposedly designed to enable continuous production from any algal strains or climate. Solix’s Lumian™ AGS™ system is essentially a series of 36 m water-filled metal tanks that support transparent plastic bags full of culture medium circulated by weighted rollers. The design of semi-submerged photobioreactors aim at reducing support infrastructure and photobioreactor material requirements. The AGS™ system independently controls air and CO₂ in twenty 200 L bags summing
to a total culture capacity of 4000 L, with an ‘inoculum expansion lane’ comprising of two 14 L bags and six 28 L bags. (Solix Biofuels, 2011c). Solix’s Coyote demonstration facility has a maximum production capacity of 28 kL ha$^{-1}$ year$^{-1}$ of algal oil, while Solix’s approximate culture peak yield rates are equivalent to around 19 kL of oil ha$^{-1}$ y$^{-1}$, or around 5 g of oil per m$^2$ d$^{-1}$ total facility area. The facility incorporates propagation and extraction, with water and CO$_2$ supplied by co-location with coal-bed methane production dewatering and amine scrubbing, respectively (Solix Biofuels, 2011a). Solix expects net production costs to contract to under USD0.50 L$^{-1}$ at larger scales, although at present production costs are around USD9 L$^{-1}$. The microalgae are harvested by centrifuge, and refined into biodiesel using transesterification (Solix Biofuels, 2011b). The centrifugal method of harvesting in combination with the Los Alamos National Laboratory’s patented acoustic concentrating and extraction the oil from algal cells enables Solix to eliminate chemical solvents (such as hexane), and also reduce energy inputs.

6.2 Solix summary

While Solix has many partnerships and a long history of knowledge and technology transfer from the AFP, the company has provided little publically information on the detailed costs, input requirements, reliability of production, all for the range of species/strain productivities for which the AGS$^\text{TM}$ is purportedly designed to accommodate. A key ambiguity in the available literature is the published peak production rate of around 5 g of oil m$^2$ d$^{-1}$, which is relatively low for the current closed system technologies, and also to the length of time this was maintained as production stability is crucial. As this is not a particularly high productivity for a closed system, the authors would require additional productivity and cost detail to assess the competitive position as a technology supplier for industrial microalgae production companies. However, the intellectual property held by the company in relation to their technology is strong relative to other closed system competitors$^4$.

7 Discussion

Annually there is about 20,000 t of algae produced worldwide and only a small portion of this is
produced in closed photobioreactors. In general there is only one main advantage when growing
microalgae in open ponds and that is the lower cost of production. While to date, open ponds seems to
be the most reliable method for large scale algae cultivation for producing bioenergy, the potential of
closed photobioreactors should not be ignored. For instance, the eventual productivity of the
Algae.Tec’s commercial-scale interconnected demonstration system and the subsequent module
design refinement over the next few years in Australia will be a crucial indication to the algal biofuel
market of the ability of the company and the technology to effectively compete on a commercial
basis. Whilst the downstream fuel production is an important element for their commercial success,
the eventual long-term productivity and the total costs will underpin the current economic model of
offsetting emissions for large industrial CO$_2$ polluters. Similarly, Algenol’s assessments at their
Freeport facility will remain in train for the next few years, and maintaining the efficacy of membrane
distillation will be an interesting advance in the field. The large amount of funding and technical
capacity from their partners will enable Algenol to progress quickly through numerous production
system elements in a relatively swift interval. In contrast, Heliae’s algal strains, technology, and
capability will likely advance the field through partnerships with larger algal entities, and Hu and
Sommerfield’s algae production experience will be a crucial element in maintaining the raw materials
to expand into new markets outside of biofuels. From the group of five companies reviewed,
Solazyme has some of the most advanced commercial systems, primarily based on their selection of a
relatively simple, modular and reliable fermentation technology. However, the eventual industry
acceptance of the proprietary GM algae, and the eventual cost of their industrial-scale biofuel
production from a sustainable and cost-effective supply of plant feedstock will be of great interest to
the industry. Solazyme’s impressive list of existing partners, fuel production history, and successful
public demonstrations in a range of vehicles to date are a major step forward in the establishment of a
commercial microalgae production technology. However the Solazyme technology will not be able to
commercially rely on large emitters to expand production, as the process does not require CO$_2$ inputs,
and will require co-location with large waste biomass producers. Finally, despite the long history of
Solix from the AFP, their AGS™ technology, the relatively low peak production for a closed system
and the unknown system stability for a range of species suggest they may be behind the forefront as a
technology supplier for other industrial microalgae production, including the large number of
companies focussing on open pond production. However, the technology may provide a low-cost,
flexible, and reliable closed system that a number of niche companies can purchase to produce
specialty high value algal products. Table 1 provides a microalgae biofuel industry-wide snapshot of
selected major players using both closed and open systems, and also hybrid mass production systems.
Table 1 demonstrates the number and capacity of major commercial entities competing in with closed
and open systems, noting the relatively strong focus on downstream processing, suggesting a
maturation of the industry of the past few years.

Table 1: Comparisons of major production elements of the five closed system companies, with
comparisons to selected open system companies below.

<table>
<thead>
<tr>
<th>Company</th>
<th>Technology</th>
<th>Funding</th>
<th>Activities</th>
<th>Processing Claims</th>
<th>Fuel Quality</th>
<th>Production Reliability</th>
<th>Large-scale Production</th>
<th>IP Position</th>
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</thead>
<tbody>
<tr>
<td>Algae.Tec</td>
<td>PBR</td>
<td>~USD10M</td>
<td>Demonstration</td>
<td>Unknown</td>
<td>Uncertain</td>
<td>Too Early</td>
<td>2014-?</td>
<td>Unknown</td>
</tr>
<tr>
<td>Algenol Biofuel</td>
<td>PBR</td>
<td>~USD200 M</td>
<td>Demonstration</td>
<td>Unknown</td>
<td>Uncertain</td>
<td>Unknown</td>
<td>2013-2020</td>
<td>A few patents</td>
</tr>
<tr>
<td>Heliae</td>
<td>Plate PBR &amp; Raceway PBR</td>
<td>~USD4M</td>
<td>Research</td>
<td>Good</td>
<td>Uncertain</td>
<td>Unknown</td>
<td>?</td>
<td>Many patents</td>
</tr>
<tr>
<td>Solzyme</td>
<td>Closed Fermentation</td>
<td>~USD300 M</td>
<td>Demonstration</td>
<td>V. Good</td>
<td>ASTM</td>
<td>Good</td>
<td>2013-2015</td>
<td>Many patents</td>
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<tr>
<td>Solix</td>
<td>PBR</td>
<td>~USD36M</td>
<td>Demonstration</td>
<td>Unknown</td>
<td>Uncertain</td>
<td>Unknown</td>
<td>2015-?</td>
<td>Several patents</td>
</tr>
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<td>Algal Fuel Consortium</td>
<td>Open pond</td>
<td></td>
<td>Research</td>
<td>Unknown</td>
<td>Uncertain</td>
<td>Too Early</td>
<td>-</td>
<td>Unknown</td>
</tr>
<tr>
<td>Aquaflow Bionomic</td>
<td>Open pond</td>
<td></td>
<td>Demonstration</td>
<td>Good</td>
<td>High</td>
<td>Reasonable</td>
<td>-</td>
<td>Unknown</td>
</tr>
<tr>
<td>Aurora Biofuels</td>
<td>Open pond</td>
<td></td>
<td>Demonstration</td>
<td>V. Good</td>
<td>ASTM</td>
<td>Too Early</td>
<td>-</td>
<td>Several patents</td>
</tr>
<tr>
<td>General Atomics</td>
<td>Open Pond</td>
<td></td>
<td>Research</td>
<td>Good</td>
<td>Uncertain</td>
<td>Unknown</td>
<td>-</td>
<td>A few patents</td>
</tr>
<tr>
<td>Muradel</td>
<td>Open Pond</td>
<td></td>
<td>Demonstration</td>
<td>Good</td>
<td>Uncertain</td>
<td>Good</td>
<td>-</td>
<td>Pending</td>
</tr>
<tr>
<td>Sapphire Energy</td>
<td>Open Pond</td>
<td></td>
<td>Demonstration</td>
<td>V. Good</td>
<td>ASTM</td>
<td>Uncertain</td>
<td>-</td>
<td>Several patents</td>
</tr>
<tr>
<td>Seambiotic</td>
<td>Open Pond</td>
<td></td>
<td>Demonstration</td>
<td>Excellent</td>
<td>High</td>
<td>V. Good</td>
<td>-</td>
<td>One patent</td>
</tr>
<tr>
<td>Synthetic Genomics</td>
<td>Open Pond &amp; PBR</td>
<td></td>
<td>Research</td>
<td>Good</td>
<td>Uncertain</td>
<td>Unknown</td>
<td>-</td>
<td>Several patents</td>
</tr>
</tbody>
</table>

1 2 3 4 5 6 7 8 9 10 11 12 13 14
8 Conclusion

At its most fundamental, to be commercially viable in a selected application, closed microalgae production facilities will need to produce fuels at a lower cost than open microalgae systems, other biofuel systems, and conventional mineral fuel production (Kovacevic and Wesseler, 2010; Spolaore et al., 2006). As closed reactors have high CAPEX and OPEX (Borowitzka, 1999; Clarens et al., 2010; Lee, 2001; Vasudevan and Briggs, 2008), technology developers will need to focus on sustained volumetric productivity to reduce per unit costs to a commercially attractive level (Lee, 2001). Industrial-scale microalgae production of cost-competitive biofuels will require numerous parallel advances in system control, and efficiencies to decrease OPEX and CAPEX (Jamers et al., 2009; Kovacevic and Wesseler, 2010). The current embryonic status of bioindustrial development, and industry cross-collaboration and convergence will likely need to occur before a major expansion of algal production into new and large prospective markets (Jamers et al., 2009). The economic reviews suggests that biofuel production may become more of a co-product of closed microalgal production systems, rather than the primary commercial objective, as the higher production control achievable with such systems will require higher-value cost recovery. The flexibility offered to closed system developers to diversify from biofuels to other products may prove an essential commercial diversification option to buffer the relative volatility of conventional fuel markets that will influence specialist biofuel producers. Successfully competing commercially against conventional fossil fuels and biofuels will require enormous further technical and economic developments (Brennan and Owende, 2010; Kovacevic and Wesseler, 2010). For example the development of non-destructive microalgae oil extraction in closed photobioreactors, or the immobilisation of cultures to reduce fertiliser use, a major OPEX component with current systems at present (Moheimani et al., 2013a). Yet the authors believe that these developments are progressing at a rapid rate, and have large industrial backing and finance available. However, a greater level of partnering and collaboration between commercial entities and government agencies over a relatively long period of time will be necessary to develop a range of commercially viable and more sustainable algal biofuel production systems that can supply the growing demand for mass-produced liquid biofuels (Moheimani et al., 2013b; Moheimani et al., 2013c).
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