Project report: Advancing Established and Integrated Marine Microalgae Biofuel to Commercialisation

Lead organisation: Muradel Pty Ltd

Project commencement and completion date: 1 January 2013 to 28 February 2015

Project summary

For biofuels to be both commercially and environmentally sustainable there are three criteria that must be met. Firstly, the biofuels must be energy positive where the energy produced from combustion of the biofuel must be greater than the energy used to produce the biofuel. Secondly, the use of the biofuel from creation to disposal (life-cycle) must have a smaller carbon footprint than a fossil crude oil derived equivalent fuel. And, thirdly the cost of the biofuel to the consumer must be parity or less than a fossil crude oil derived equivalent fuel. This project addressed the technical and economic challenges of producing renewable biofuels from marine microalgal biomass (Tetraselmis spp) and obtained the technical, economic and environmental data required to elucidate the commercialisation pathway for microalgal biofuels. The major outcome from the project was the development of the Green2Black™ technology platform, which transforms organic feedstocks to oils for biofuels and specialty chemicals.

The project was funded through the Advanced Biofuels Investment Readiness Program administered by the Australian Renewable Energy Agency, funding agreement number Q00150, and industry partner SQC Pty Ltd a subsidiary of Aban Australia Pty Ltd.

Project scope

The scope of the project was to design, build, commission and operate a fully integrated marine microalgae to biofuel demonstration plant in Whyalla, South Australia. The project was based around 5 key objectives:

1. Optimise the recycle of growth media substrate into growth ponds; including water and nutrients, for sustainable and continuous growth of marine microalgal biomass.
2. Integrate Muradel’s proprietary harvesting technologies into the growth ponds to dramatically reduce energy usage (with improvement providing a positive return on energy) and dramatically reduce the carbon footprint of these unit operations.
3. Design and build the Muradel Demonstration Plant (MDP) for scale-up from 200m² to 4000m² ponds with integrated harvesting and incorporation of static mixing technologies for improving biomass productivities.
4. Incorporate whole biomass conversion and extraction technology into the MDP to produce green crude.
5. Finalise the design of Muradel’s Integrated Production Module, which would provide a sustainable commercially viable marine microalgae to green crude process that can be replicated to meet production requirements.

Public consultation

Whyalla Community Consultation Plan

A comprehensive consultation plan was prepared and documented in March 2013. This was independently endorsed by the Chairman of the Whyalla Chamber of Commerce. The purpose of this initiative was to provide the local community with transparent information
about the project, to provide an opportunity for the community to raise questions or concerns which the Company would then endeavour to answer.

Promotion of the Whyalla Showcase and Community Consultation event included:

- Publicly advertised, open invitations placed in the Whyalla News during the week leading up to the event.
- Direct invitation by email to Muradel known contacts.
- Invitations forwarded by the Whyalla Chamber of Commerce to its members.

The first public consultation event was held in Whyalla on 18 June 2013 as part of a wider promotion of the Company, its project and potential that included the following:

- Redevelopment of the Company web site and creation of a comprehensive Company information brochure.
- Publicity via the Whyalla Council, following Council’s formal agreement to support the project and leasing of a 2 hectare site to Muradel through to March 2015.
- A launch event held at this Whyalla site on 14 June 2013, involving the hosting of the previous Commonwealth Government’s Minister of Energy, Hon Gary Gray AO, MP who officially revealed Muradel’s green crude product derived from its microalgae.
- Muradel Showcase event on 14 June 2013 held at the Science Exchange Centre at the Royal Institute of Australia, with the Minister of Energy launching the project in South Australia, and unveiling a sample of “Green Crude”.

Outcome of the consultation

There were no adverse reactions or concerns. There was clearly strong support for the project. Many who attended described Muradel’s event as being the most successful event at that time.

The event attracted 33 pre-registered attendees and 30 additional attendees. Six Muradel representatives attended.

Attendees were representatives of local or Adelaide based businesses, local government, educators, and members of the general public with an interest in the new technology. Some were potential candidates for contract work i.e. employment firms; potential employees, and building contractors and suppliers.

The event was facilitated by the Chairman of the Whyalla Chamber of Commerce & Industry, Mr Allan Kane. Allan introduced Muradel, described the format of the meeting, and encouraged people to actively ask questions following each presentation.

Muradel provided background on the world’s growing need for renewable liquid fuels, background on the Company, and plans for Whyalla. The technology was described in detail, its pathway from the research lab to a Pilot Plant, and scale-up plans for Whyalla. Other topics included the environmental impact, and the objectives and timeline for the project.

Muradel also announced that as a gesture of commitment to the community and to provide further opportunity for community engagement, the Company would provide sponsorship funds for the inaugural “Whyalla Science and Engineering Challenge for Secondary Schools”, that was held August 2013.

Project Outcomes

The Muradel Demonstration Plant (MDP) at Whyalla, South Australia, was constructed in the first half of 2014, with commissioning completed by July 2014. The MDP was officially opened on the 31 October 2014 by the Honourable Geoff Brock, Member for Frome, Minister for Regional Development and Minister for Local Government; and the Whyalla City Council Mayor Jim Pollock.

The MDP comprises 700 ML salt water storage supplied by 2 bores; evaporation pond; 6 x 2 m², 2 x 20 m², 2 x 200 m² and 1 x 4000 m² paddlewheel mixed raceway ponds; proprietary electro-flocculation channel, clarification tank, continuous centrifuge; proprietary continuous sub-critical water reactor; laboratories, workshop, offices and utilities (Figure 1).
Figure 1: The Muradel Demonstration Plant, showing the plant office, 4000 m² microalgal production pond, continuous sub-critical water reactor and the inoculation ponds.

The design, construction and commissioning of the MDP created significant direct and indirect employment opportunities with over 118 companies being involved with construction and equipment supplies. An aerial photograph of the ~2 hectare site is shown in Figure 2. A video of the MDP can be viewed at https://www.youtube.com/watch?v=OC1KjpadJH4.

Figure 2: Muradel Demonstration Plant, Whyalla South Australia.

Muradel has developed an integrated process incorporating microalgal biomass production, harvesting, dewatering, concentration, conversion and extraction to green crude, then fractionation and refining to drop-in biofuels. This process is known as Green2Black™. The main unit operations are shown in Figure 3.
Figure 3: Integrated Green2Black™ technology produces the whole barrel and is protected by a suite of provisional, PCT and national phase patent applications.

Key findings

Technical feasibility

The MDP reached full production after the commissioning of all unit operations in July 2014. The initial growth data is shown in Figure 4 and the steady-state mass and energy data is qualified in Figure 5, and quantified in a Life Cycle Analysis (LCA) described on Page 6. The targeted annual average productivity of >25 g·m⁻²·d⁻¹ was not achieved in the 4000 m² pond, which was not surprising as these productivities have not been consistently achieved in any other system at commercial scale. Muradel considers that the target productivities are achievable in the long-term, and continuous improvement will be attainable as the pond is continuously operated over different seasons. The target productivities have been demonstrated previously by Muradel (Fon Sing et al 2014).

Figure 4: Biomass productivity at the MDP in Whyalla (black bars representing monthly average and grey bars representing maximum values).
Figure 5: Operational Energy Expenditure for the MDP illustrated by the relative contribution of each process to the total operational energy expenditure for the MDP component of the entire process.

The mass and energy data indicate that the MDP can produce ~50 kg Green Crude d⁻¹ (potentially ~41-46 T ha⁻¹ yr⁻¹ of Green Crude) at an energy returned/energy invested (ERoEI) of 2.67. As a co-product ~16 kg of CH₄ (methane) can also be produced if anaerobic digestion of the carbonaceous residual from hydrothermal liquefaction was employed.

The Green Crude produced by Muradel from Tetraselmis spp. was found to have a similar boiling point profile to West Texas Intermediate, shown in Figure 6. The Green Crude was analysed for C, H, N, S and O and the following results were obtained: Carbon 75.6%, Hydrogen 9.9%, Nitrogen 3.7%, Sulphur 1.6% and Oxygen 9.2%. Nitrogen and oxygen are the heteroatoms that need to be eliminated; they are distributed throughout the whole boiling range of the product. There are 2 options for production of biofuel from Green Crude, namely hydrotreatment or blending with fossil crude oil. During the ARENA funded project Muradel did not have access to hydrotreating technology, however a blending trial was carried out with Chennai Petroleum Corporation Limited, an Indian state-owned oil and gas corporation headquartered in Chennai, India. The blended crude oil (10% Green Crude & 90% Narimanam petrocrude) was distilled as per ASTM Standard D2892 with each fraction quantified and compared with 100% Narimanam petrocrude. The true boiling point distillation qualitative data is shown in Figure 7.

Figure 6: Non-blended and blended fraction distributions.

The target biofuel for Muradel is renewable diesel. The majority of diesel fuels contain hydrocarbons with boiling points between ~150°C and 380°C. The diesel fraction (170-370°C) obtained from the blend constituted ~39% of the total volume, which was similar
to the non-blended diesel fraction. Therefore blending appeared to have no affect on yield. The compositional data for the blended diesel fraction was similar as the non-blended except for the sulphur content, which has risen from 982 ppm to 1054 ppm.

![Boiling Curve Comparison](image_url)

**Figure 7:** Boiling curve comparison between Muradel Green Crude and West Texas Intermediate.

Muradel subcontracted The University of Queensland to complete a LCA of the MDP. Muradel has demonstrated that Green Crude at an EROEI of 2.67 which is comparable to unconventional petroleum extraction like tar sands or oil shale which have EROEI values of ~3 and ~1.5 respectively. It was important for Muradel to model the entire process from solar energy capture via microalgae growth through Green Crude to actual fuel production of renewable diesel. The Green2Black™ process from marine microalgae to renewable diesel was shown to have a GHG (Green House Gas) output of 66.78 g CO₂-e MJ⁻¹ for Muradel renewable diesel compared with 95.88 CO₂-e MJ⁻¹ for conventional diesel and similarly, EROEI values of 1.02 for Muradel renewable diesel versus 0.81 for conventional diesel.

**Economic feasibility**

Detailed economic modelling and sensitivity analyses were carried out in Nov 2014 for microalgal biomass production and conversion of microalgae to green crude. Cost of production was estimated based on extrapolation from data at demonstration scale, including assumptions for reducing costs based on completing process development and forecast efficiencies of scale.

The microalgae biomass to biofuel financial model key assumptions were:

- Annual average bioamss productivity > 25g.m⁻².d⁻¹ ash free dry weight with 60% conversion to green crude
- The MDP in Whyalla can be expanded to 600 hectares (not the optimal 1,000 due to topographic data limitations available at the existing Whyalla site)
- The cost of biomass production can be reduced by 44% over what is currently estimated and forecast based on integration efficiencies, efficiencies of scale and reduction in input energy costs (based on required cost reductions for economic viability)
- The cost of conversion can be reduced by 44% over what is currently estimated and forecast based on integration efficiencies, efficiencies of scale and reduction in input energy costs
- Internal/external estimates of capital costs
- Project funded by equity
- Price of crude oil of > A$100/barrel by 2020
Financial metrics for this scenario were as follows:

- 30 year NPV at 15% discount rate = A$11 million on a pre-tax basis
- IRR = 16.4%

Sensitivity analysis in Figure 8 demonstrates that microalgae-derived green crude is highly sensitive to achieving forecast production yield and cost of production as well as CapEx. A 10% decrease in forecast yield or 10% increase in CapEx makes the project even more marginal at this scale.

![Impact of biomass yield on NPV](image1)
![Impact of Capital cost on NPV](image2)

**Figure 8: Economic model for 600 hectare microalgae to green crude facility. (*Indicates current best estimate based on MDP performance)**

The 2014 fall in the price of oil and the uncertain medium term outlook on pricing, raises the risks for financing a microalgal green crude production project in the short term.

It is evident that the Green2Black™ process can provide green crude for renewable diesel with a positive energy balance and a smaller carbon footprint than conventional diesel, but the economic forecast for commercial production are unfavourable. The price of oil is likely to remain less than A$680/barrel for the short to medium term and we are unlikely to see the price of oil exceed A$100/barrel for some time. Commercial viability could occur at greater than $120/barrel if the previously stated assumptions could be achieved. Currently Muradel can produce a dry weight tonne of biomass for $400 (pond to 20% solids ash free dry weight).

Muradel has also investigated a range of alternative biomass sources to complement the microalgae development. It was concluded that zero to negative feedstocks using Green2Black™ would be economically viable at a sale price of fossil crude above USD55/bbl ($67/bbl, Fx 0.825).

New opportunities

The development of the MDP has created direct and indirect employment. Local companies in the Whyalla region were engaged to build the MDP and are engaged in ongoing repairs and maintenance. In 2015, Muradel has 8 full-time employees and plans to employ up to 8 more full-time staff through its next plant expansion planned to commence at the end of 2015. During 2016 Muradel will expand its operations at the MDP to incorporate additional unit operations and production ponds to pursue new commercial opportunities.

In brief Muradel developed a unique technology to produce green crude oil from saline microalgae, resulting in a carbon neutral fuel, as a viable alternative to fossil fuel. From there, the Company further evolved its Green2Black™ technology to take other organic feedstocks for biofuels, and for growing and processing alternative algal strains specific to the needs of incoming major international chemical, nutraceutical and cosmetic manufacturers.

Muradel is currently pursuing three commercial opportunities with Green2Black™:

1. Commercial production of microalgae for lipids
2. Conversion of tyre’s to renewable oils
3. Conversion of biosolids to renewable oils

With regard to Muradel’s microalgae production and processing capabilities, in August 2015 Muradel secured a service agreement to scale-up and optimise the production a proprietary marine microalga for the production of lipids for oleochemical feedstocks. It is envisaged that the microalgae production facilities at Whyalla will be gradually scaled up to commercial production over the next 2-3 years. The residual microalgae biomass (40-50% w/w) after lipid extraction will be converted to green crude via the Green2Black™ technology platform. The microalgae commercialisation pathway is independent but complimentary to new organic feedstock, namely...
tyres and biosolids to green crude commercialisation pathways, providing vertical integration of Green2Black™ and a suite of sustainable oil products.

The expanded Green2Black™ technology has 5 integrated components:

**Figure 9:** The Green2Black™ integrated technologies.

Muradel has planned Whyalla to be the centre for advanced manufacturing for the assembly/manufacturing of their proprietary Green2Black™ technologies.

A major recent breakthrough for Muradel was configuring Green2Black™ to process both biosolids and used tyres for the production of renewable oil. This aspect of Green2Black™ is a ‘world-first’, where a sustainable solution has been identified for the management of organic feedstocks such as sustainably produced biosolids and used tyres.

**Regional Benefits**

There are significant employment benefits both directly and indirectly. We anticipate that for every one direct employee there will be two indirect employee opportunities.

Based on each currently identified commercialisation pathway being fully operational we believe that Muradel has the capability of creating >75 FTE within the Whyalla region.

With sufficient funding Muradel will be well positioned to roll out its planned expansion in the following ways:

- Microalgae lipid based products (chemicals, nutracueticals and cosmetics): >100 hectare microalgae biomass production facility in Whyalla
- Scale up of Green2Black™ for production of crude from tyre rubber: Australia’s first sustainable vehicle tyre management process facility in Whyalla
- Scale up of Green2Black™ for Bio-Solids: establishment of supplementary processing plants elsewhere in Australia and overseas
Conclusion and next steps

The completion of the ARENA Advanced Biofuels Investment Readiness Program project “Advancing Established and Integrated Marine Microalgal Biofuel to Commercialisation” was on the 28 February 2015. All project milestones listed in the ARENA Funding Agreement [Q00150] were met as evidenced in internal Milestone reports to ARENA.

Muradel has also investigated a range of alternative biomass sources to complement the microalgae development. To date, other low cost biomass for conversion to green crude using Muradel’s Green2Black™ technology have been identified. This alternative supply chain is more resilient to price parity with the price of fossil crude. This biomass provides a commercially viable project even at fossil crude prices of ~USD55 /bbl. A partnership is also developing with Southern Oil Refineries in Wagga Wagga who are prepared to work with Muradel to purchase and refine (hydrotreat) green crude for supply to end users. This allows Muradel to develop a complete supply chain for the Green2Black™ technology.

Muradel is also continuing with large scale production of marine microalgal biomass for the production of oleochemicals and use the residual biomass for green crude.

The journey to this point in Muradel's development has not been without many challenges. Scaling biological processes is difficult and the environment places continuous challenges on the biological processes that are being optimised in our open production ponds. There have been many administrative and technological challenges, which have been overcome by having a dedicated highly skilled and complimentary workforce. For Muradel to succeed thus far it has been completely reliant on the determination and commitment of all staff to be innovative and provide novel solutions. The list of challenges and solutions would be enormous but each day, advances in our development were achieved as we better understood the processes we are optimising to produce truly sustainable products.

The major lesson learnt is that without teamwork from the investors and ARENA to the directors to management and technical and administrative staff Muradel would be succeeding.

Communication

Journal Articles

Muradel places emphasis on dissemination of knowledge. During the project researchers at the University of Adelaide contributed to the development of IP resulting in high quality peer reviewed journal publications as follows:


18. S. Fon Sing, A. Isdepsky, M.A. Borowitcka and Lewis, D.M. (2014) *Pilot-scale continuous recycling of growth medium for the mass culture of a halotolerant Tetraselmis sp. in raceway ponds under increasing salinity: a novel protocol for commercial microalgal biomass production.* Bioresource Technology, 161, 47-54


**Patents**

Two provisional patents application were filed in 2014 (PCT filed July 2015):

1. Australian Provisional Patent Application 2014902412
   Title: Methods and systems for continuously separating particulates from a liquid medium.

2. Indian Provisional Patent Application 3064/CHE/2014
   Title: Process and methods for the conversion of algae, other carbonaceous feedstocks and mixtures of algae with carbonaceous feedstocks to crude oil and fuel products.

**Scientific Meetings**

CEO, David Lewis was invited to present at the following meetings:


5. 2014 Algae Biomass Summit San Diego 29 September – 2 October 2014, Plenary speaker *Crossroads for commercialisation*

6. 3rd Asia-Oceania Algae Innovation Summit, Daejeon, Korea 17-20 November 2014. *Hydrothermal liquefaction – the product*

   - Lewis, D.M., *Microalgae to biofuels – the product*
   - Isdepsky, A, *Saline microalgae for biofuels: from small scale to pilot scale*
   - Fon Sing, S, *Recycling of growth medium for the sustainable cultivation of microalgae in saline water for biofuels*
Media exposure

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