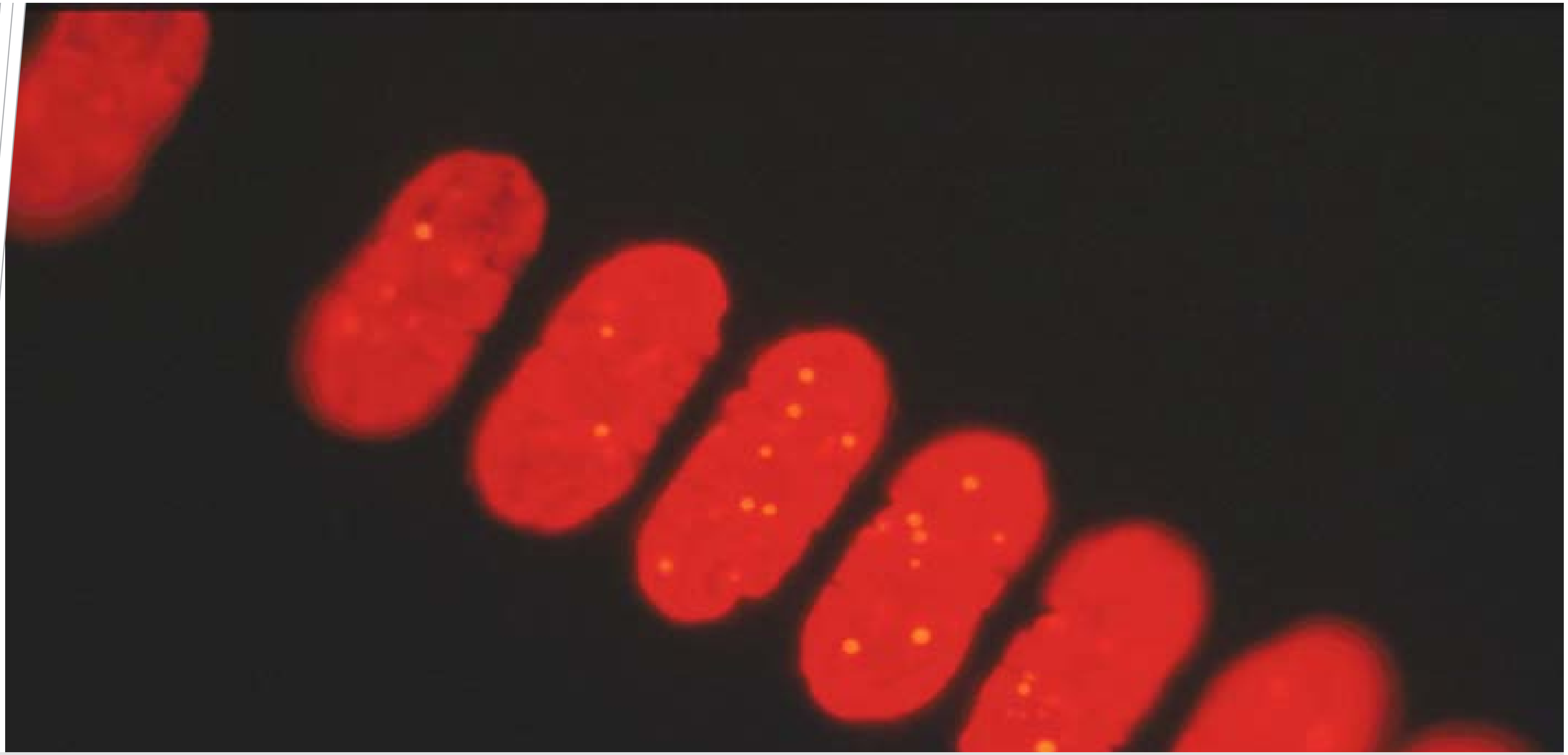


www.csiro.au

Challenges and opportunities for biodiesel from algae: approaches by CSIRO, Australia

Energy Transformed National Research Flagship

Susan I. Blackburn, Tom Beer and Kurt Liffman

National Research FLAGSHIPS Energy Transformed

CSIRO

Biofuels Symposium, Tsukuba, Japan, August 2009

CSIRO Energy Transformed Flagship Team

- Tom Beer – Biofuels Stream Leader; Prefeasibility study
- Susan Blackburn – Strain selection and optimisation
- Kurt Liffman – Thermal and fluids engineering

- David Batten
- Peter K. Campbell
- Chong Wong
- Ben Aldham
- Greg Griffin
- Greg Threlfall
- John Volkman
- Graeme Dunstan
- Dion Frampton
- Lesley Clementson
- Nicolas Labriere
- Ian Jameson
- Lisa Albinsson

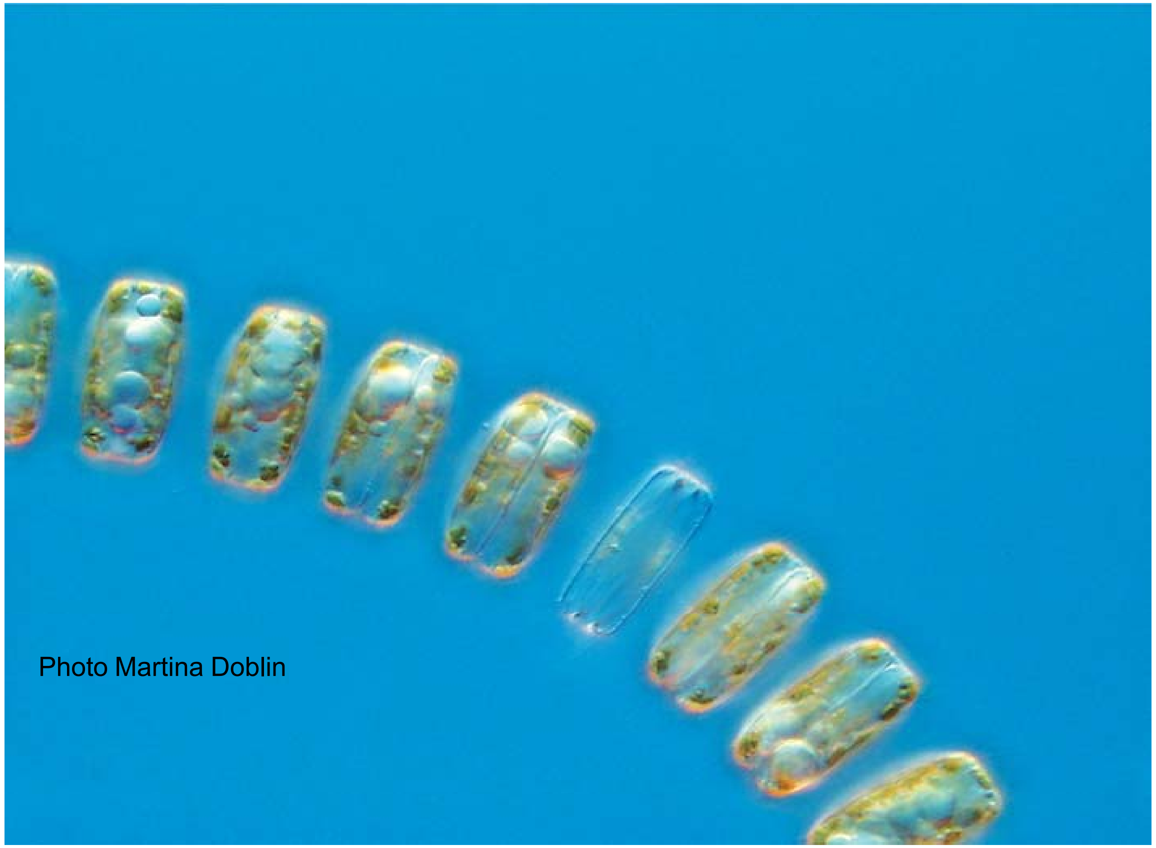
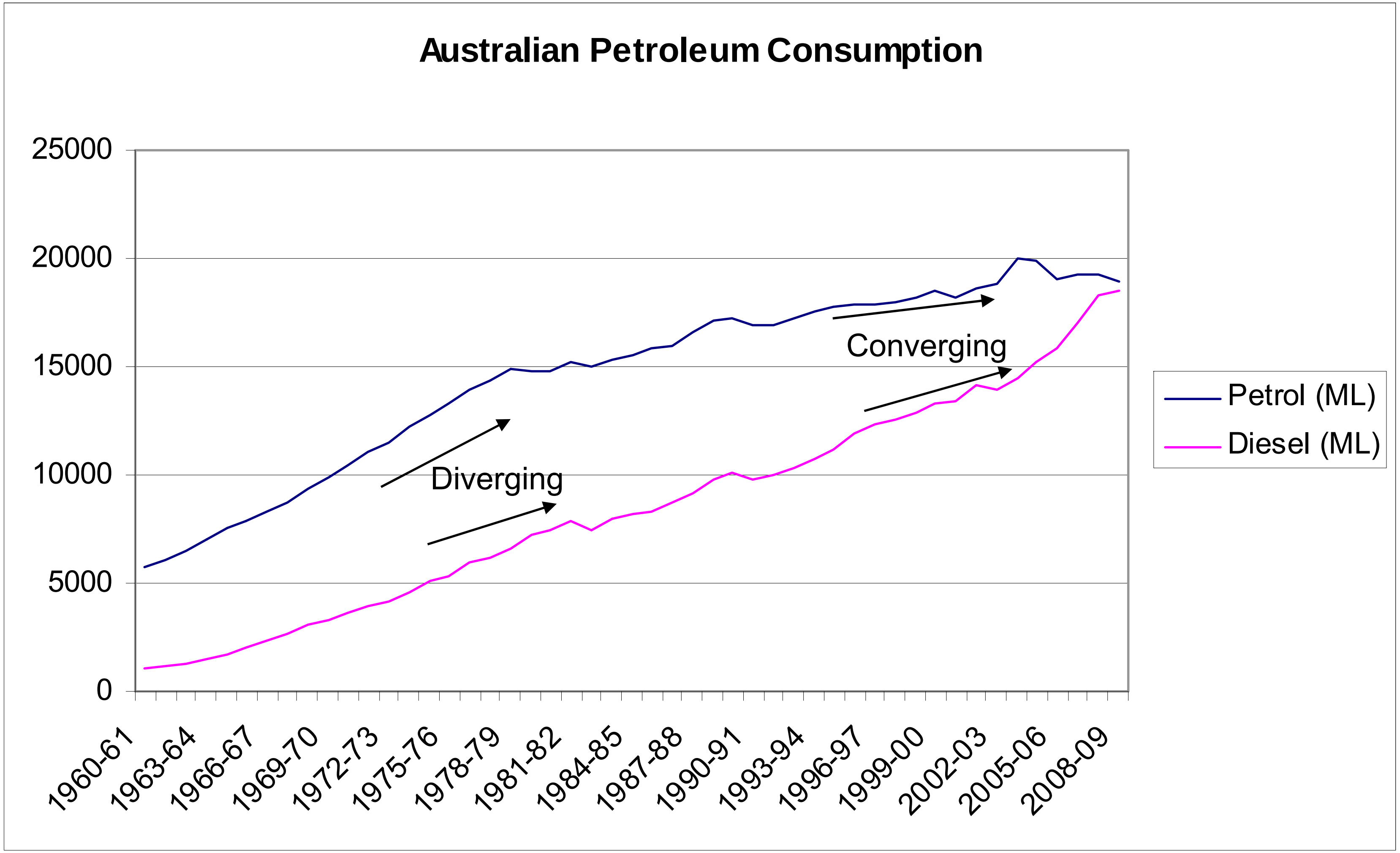


Photo Martina Doblin

Diesel use growing more rapidly than petrol



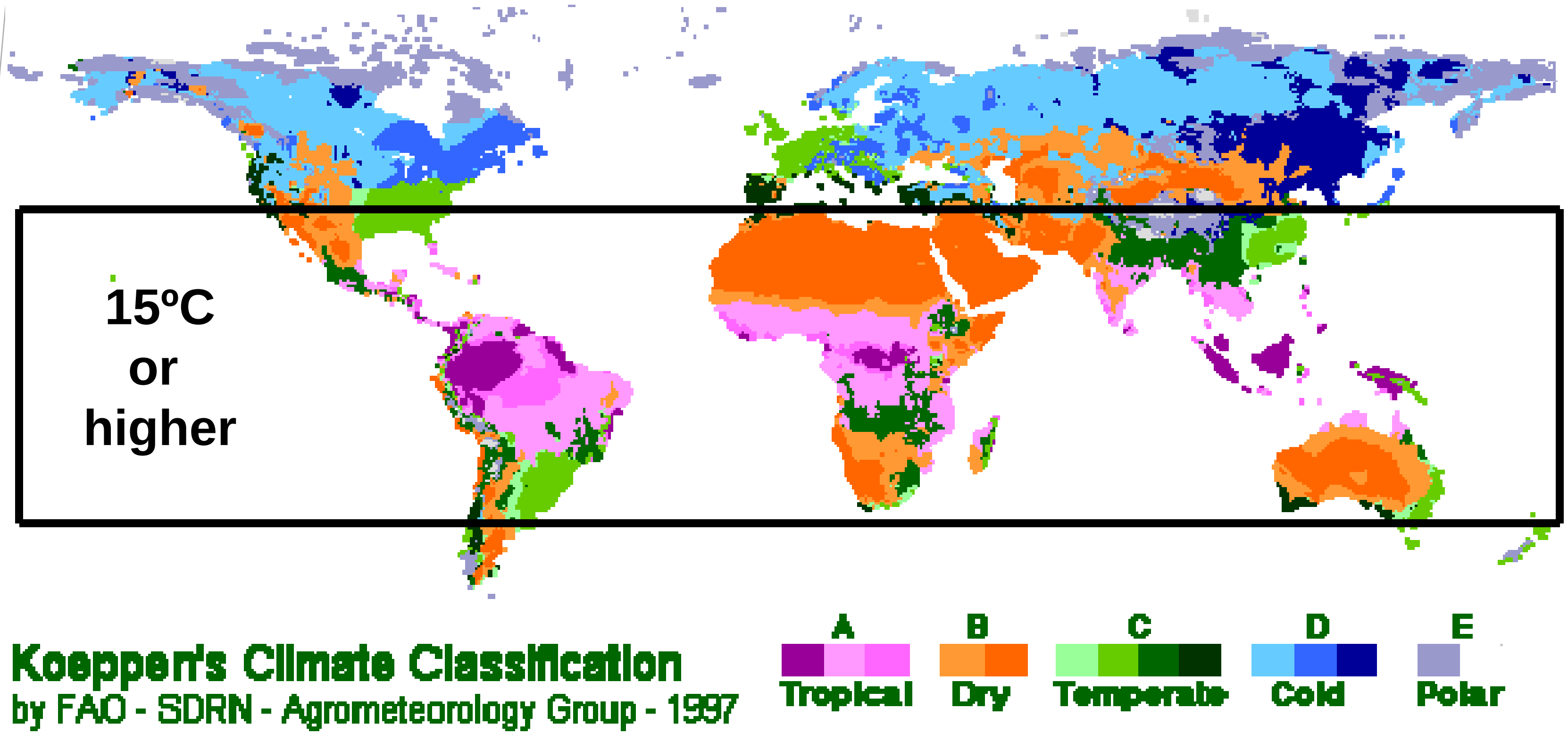
Why Algae?

- Worldwide interest in making biofuels from biomass is high:
  - global warming associated with higher levels of GHG emissions
  - onset of peak oil in a global economy
  - national energy security concerns, and
  - perceived opportunities for more sustainable, regional development.

- Algae produced most fossil fuels in the first place.
  - Microalgae are diverse, grow rapidly, yield more biofuel than oil plants, can sequester CO_2, contain no sulphur, are highly biodegradable & are less competitive with other plants as a source of human food, fibre or other products.

- Already they are aqua-cultured to produce various high-value foods, nutraceuticals and chemicals
  - Methods adopted have not yet proved to be economically and ecologically viable for the production of biodiesel or other biofuels in quantities large enough to replace fossil fuels.

Australia's competitive advantage



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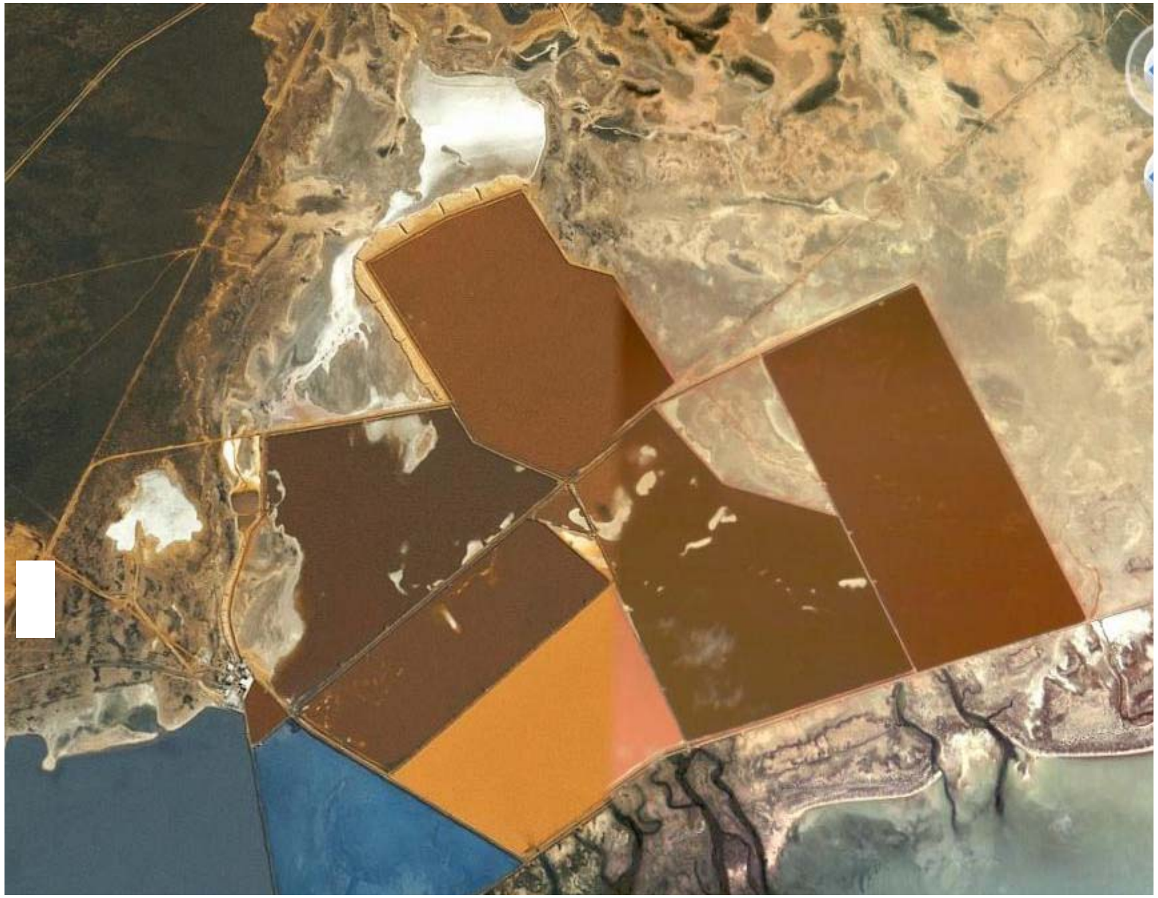
Australian algae industry

Cognis algae lakes, Whyalla, South Australia (also Western Australia)



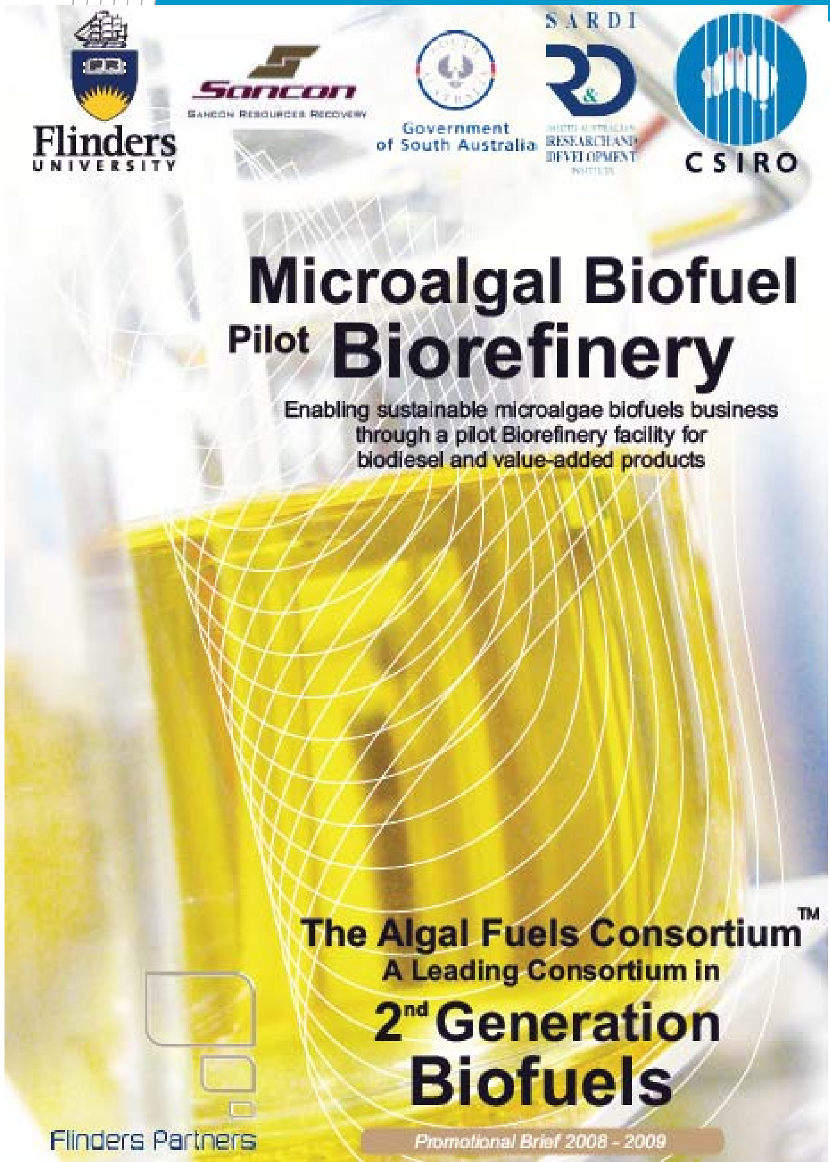
Nutraceuticals –
largest global producer
natural β-carotene;
food / feed colourants

Without further research:

Most dedicated algae-to-biodiesel projects will face uneconomically high costs for:

- Algal selection and optimization
- Site acquisition and preparation
- Bioreactor construction materials
- Construction, deployment and reconstruction
- Chemical and energy inputs
- Algal harvesting, dewatering and concentration
- Lipid extraction
- Biodiesel and by-product processing
- Surveillance, process control and maintenance
- Transport

Australian Government, 5th August 2009



"Minister for Resources and Energy, Minister for Tourism

SECOND GENERATION BIOFUELS FUNDING ANNOUNCED

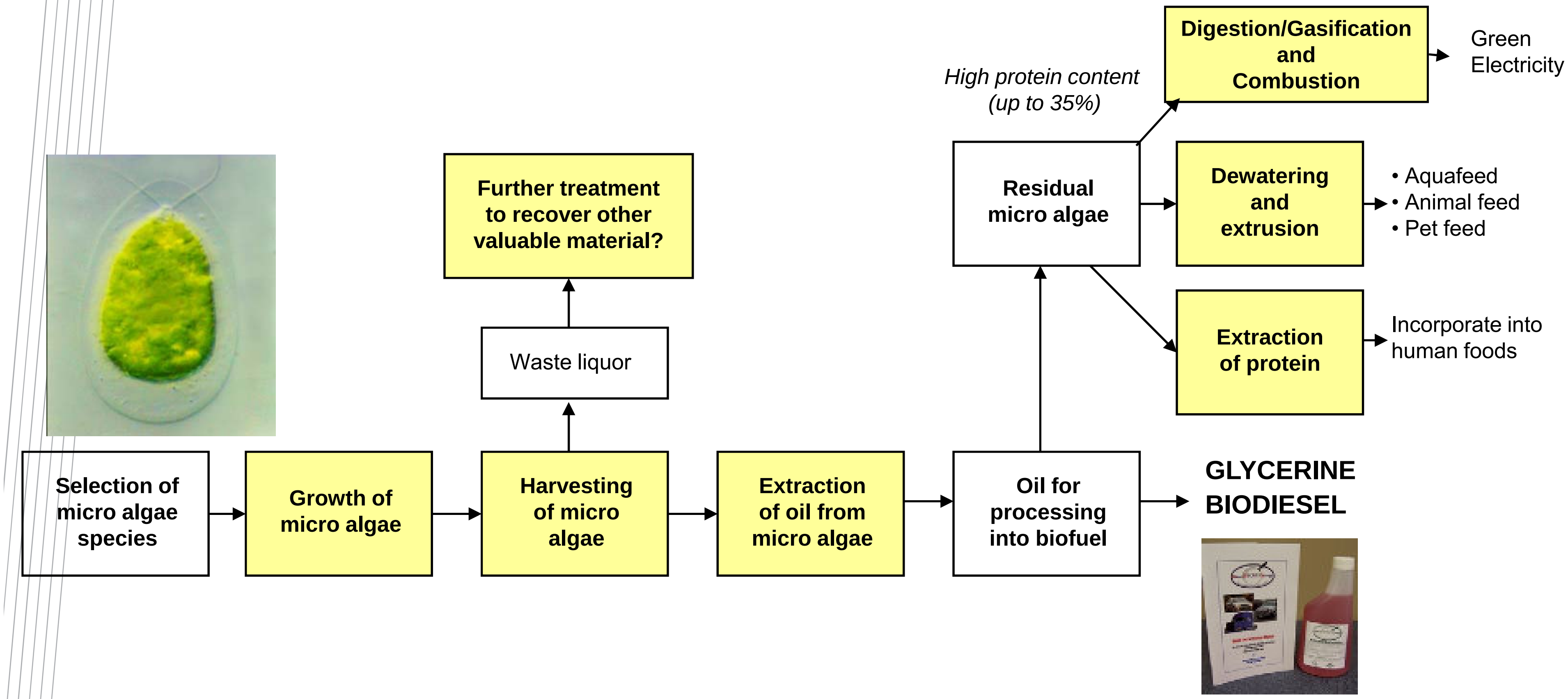
The Minister for Resources and Energy, Martin Ferguson AM MP, today announced the successful applicants for funding under the Australian Government's $15 million *Second Generation Biofuels Research and Development Program*.

The *Second Generation Biofuels Research and Development Program* supports the research, development and demonstration of new biofuel technologies which address the sustainable development of the biofuels industry in Australia."

CSIRO Energy Transformed National Research Flagship: Innovative second-generation biofuel technologies

- Three major challenges are identified:
  - **Develop and apply (in consultation with stakeholders) a sustainability framework to assess the triple-bottom line status of biofuels.**
  - **Discover, develop and use innovative Australian algal strains and enzymes to improve efficiencies of biofuel production.**
  - **Scale up operations to a) continuous and b) commercially viable operations.**

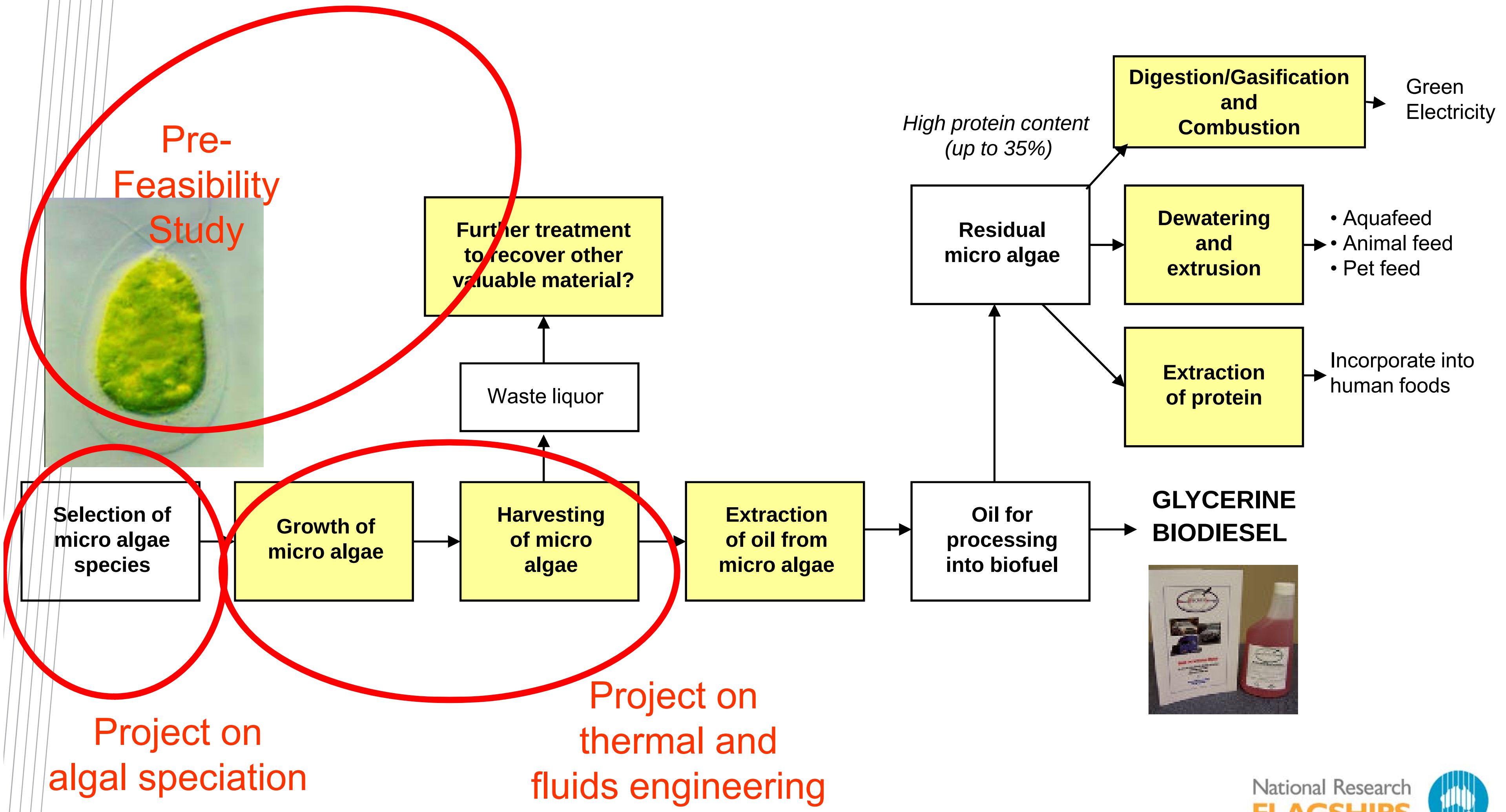
Algae to Biodiesel Pathway



S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

National Research FLAGSHIPS Energy Transformed CSIRO

Algae to Biodiesel Pathway



S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

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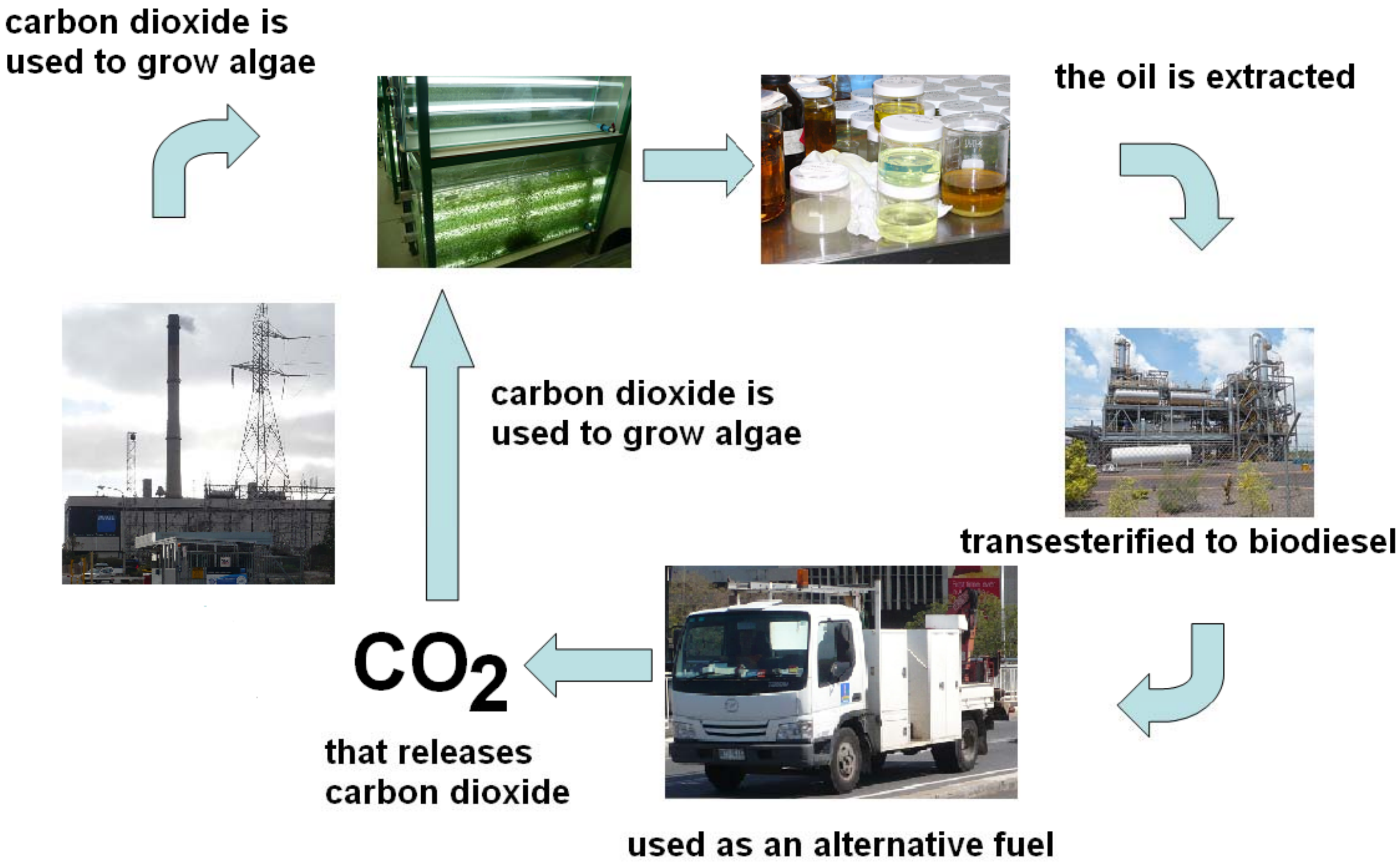
Pre-feasibility study

- Objectives:
  - To estimate the realistic potential size of microalgae's contribution to supplement Australia's conventional fossil fuels;
  - To place bounds on Australian microbial biomass production under different land-use scenarios and process technologies;
  - To quantify the greenhouse gas benefits that could emerge as a result of producing biodiesel from algae;
  - To examine the possible co-product implications; and
  - To provide an indicative evaluation of the triple bottom line benefits associated with the use of algae (and especially microalgae) as a biofuel.
- Project leader:
  - Tom Beer

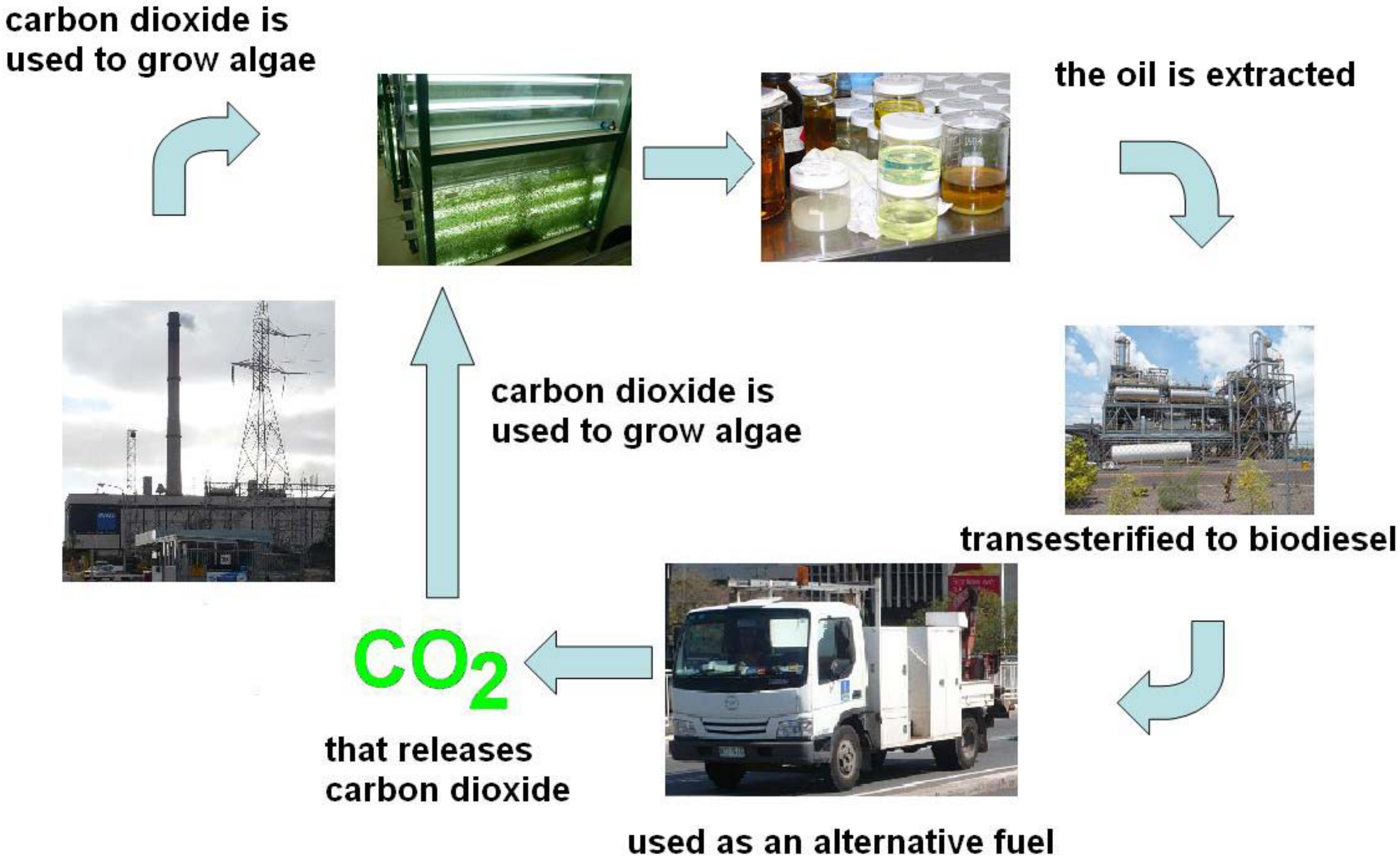
Life Cycle Analysis
(Full Fuel Cycle or Well-To-Wheel analysis)

The Carbon Cycle

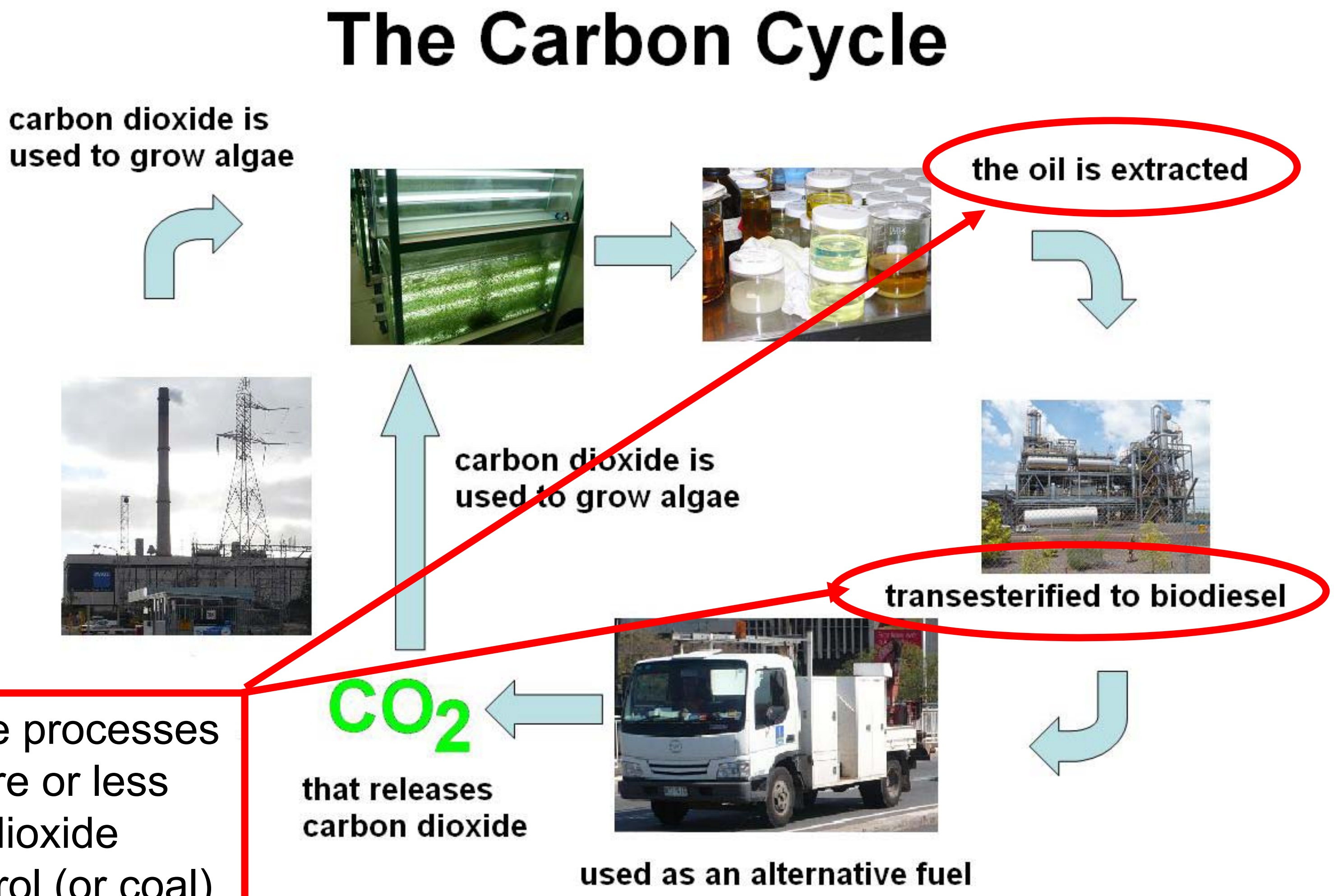


Life Cycle Analysis
(Full Fuel Cycle or Well-To-Wheel analysis)

The Carbon Cycle



Life Cycle Analysis
(Full Fuel Cycle or Well-To-Wheel analysis)

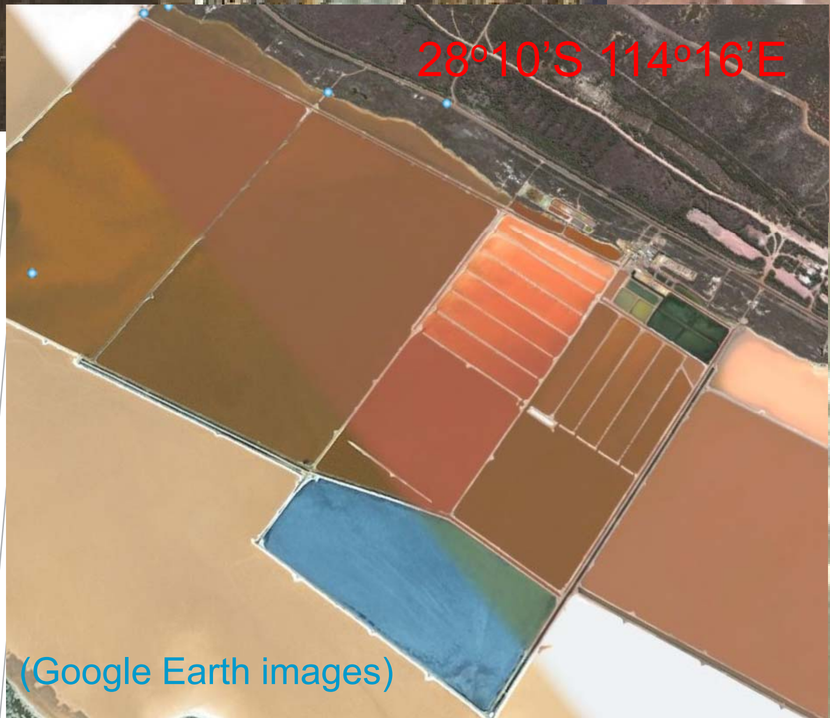


Do these processes emit more or less carbon dioxide than petrol (or coal) and its manufacture

Scenarios – Ponds only

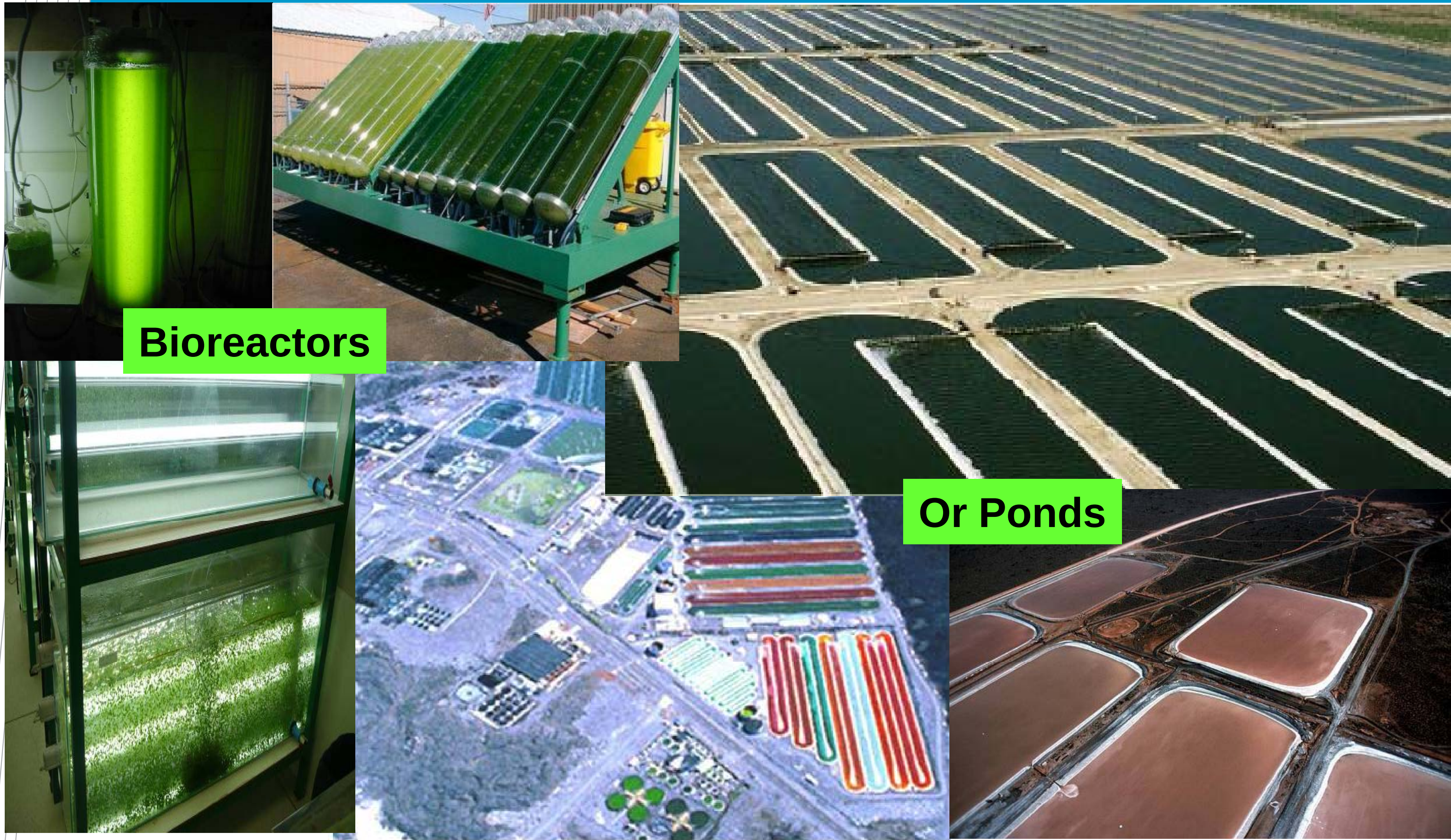
Cognis, AquaCarotene, Beta Nutrition

Saline Ponds. *Dunaliella* species. Tidal mixing.



(Google Earth images)

Bioreactors or ponds?



Spirulina and *Haematococcus* Cultivation at Cyanotech Corp., Hawaii.
Spirulina: blue-green ponds; *Haematococcus*: orange-red ponds)

Life Cycle Analysis – Design variables

LIQUID FUELS FROM MICRO-ALGAE IN AUSTRALI/

by

D.L. Regan and G. Gartside
CSIRO Division of Chemical Technology
South Melbourne, Victoria

National Library of Australia Cataloguing-in-Publication Entry

Regan, D. L.

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ISBN 0 643 03503 6.

1. Liquid fuels. 2. Algae products–Australia.
I. Gartside, G. II. Commonwealth Scientific and
Industrial Organization (Australia). *III. Title.*

662'.669

FINAL REPORT

to the
Department of Energy
Pittsburgh Energy Technology Center
under
Grant No. DE-FG22-93PC93204

SYSTEMS AND ECONOMIC ANALYSIS

OF MICROALGAE PONDS

FOR CONVERSION OF CO_2 TO BIOMASS

Submitted by
John R. Benemann
and
William J. Oswald, P.I.
Dept. of Civil Engineering
University of California Berkeley
Berkeley, CA 94720

Attention: Dr. Perry Bergman
U.S. Dept. of Energy
Pittsburgh Energy Technology Center
Pittsburgh, PA 15234
Phone 412 – 892 4890 / Fax 412 892 5917

March 21, 1996

Assume raceway ponds instead of tidal mixing

Assume 30 g/(m2-day) [110 t/(ha-yr)] and 15 g/(m2-day) [55 t/(ha-yr)]

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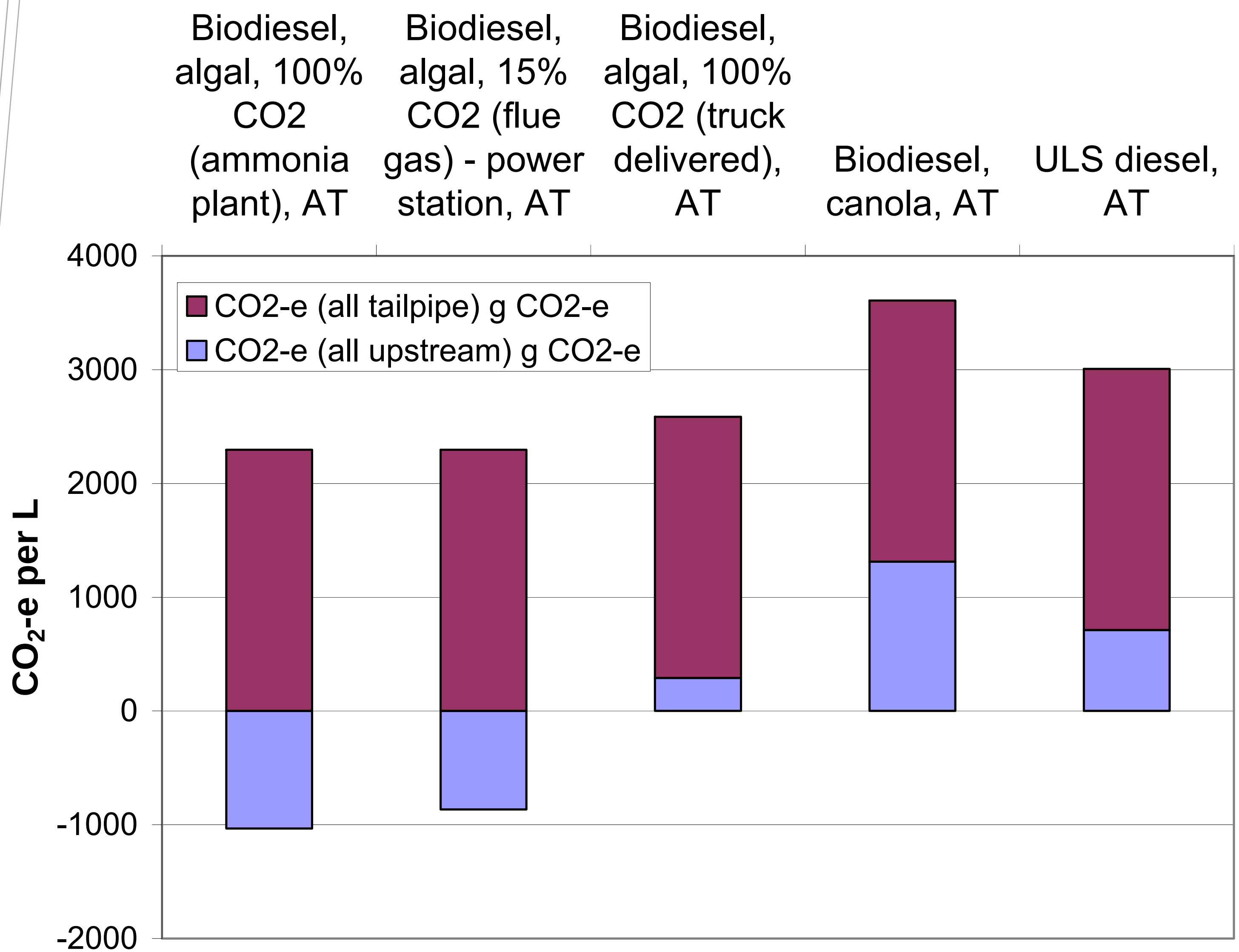
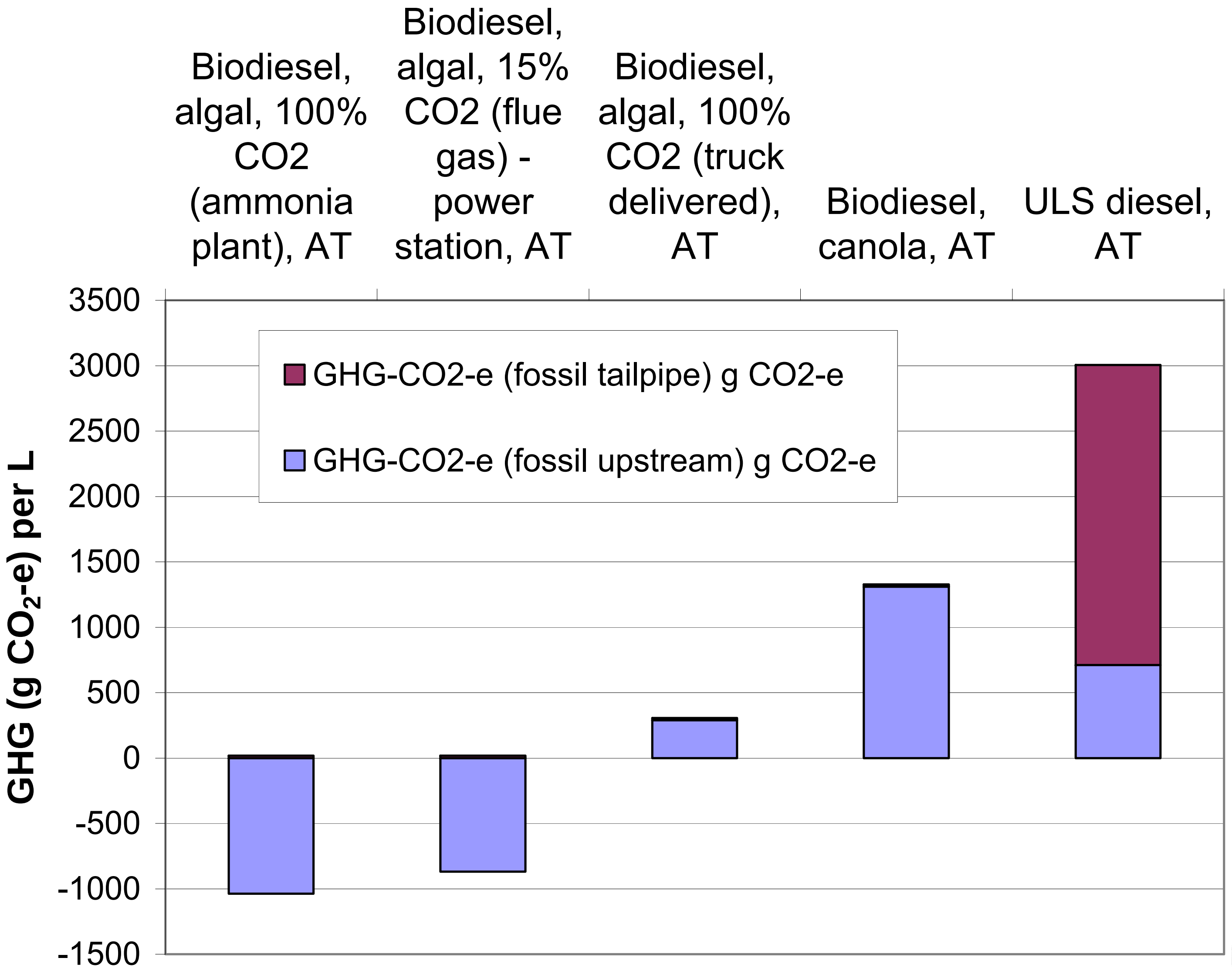
Carbon Dioxide Emissions per Litre

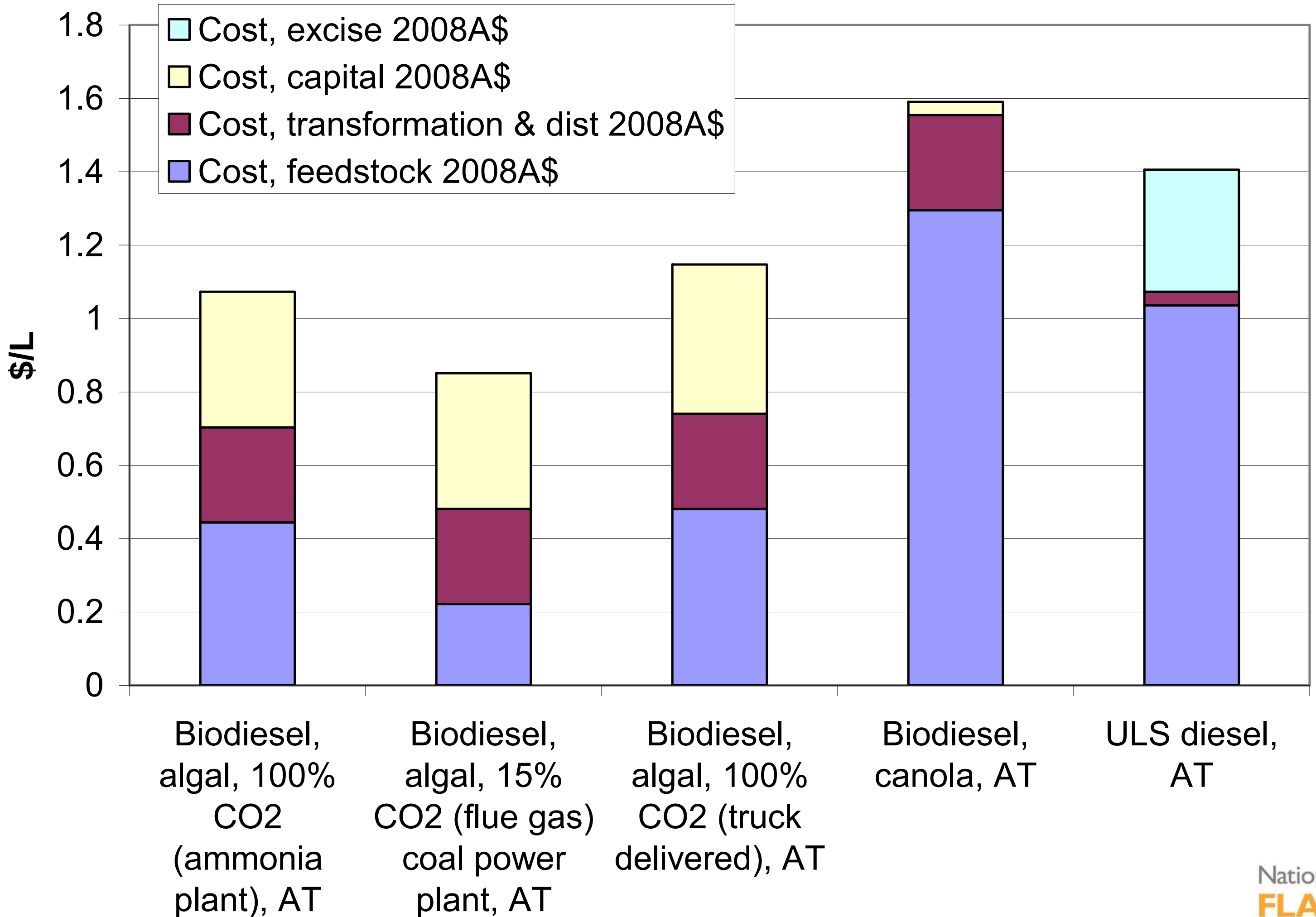


Greenhouse Gas Emissions per Litre

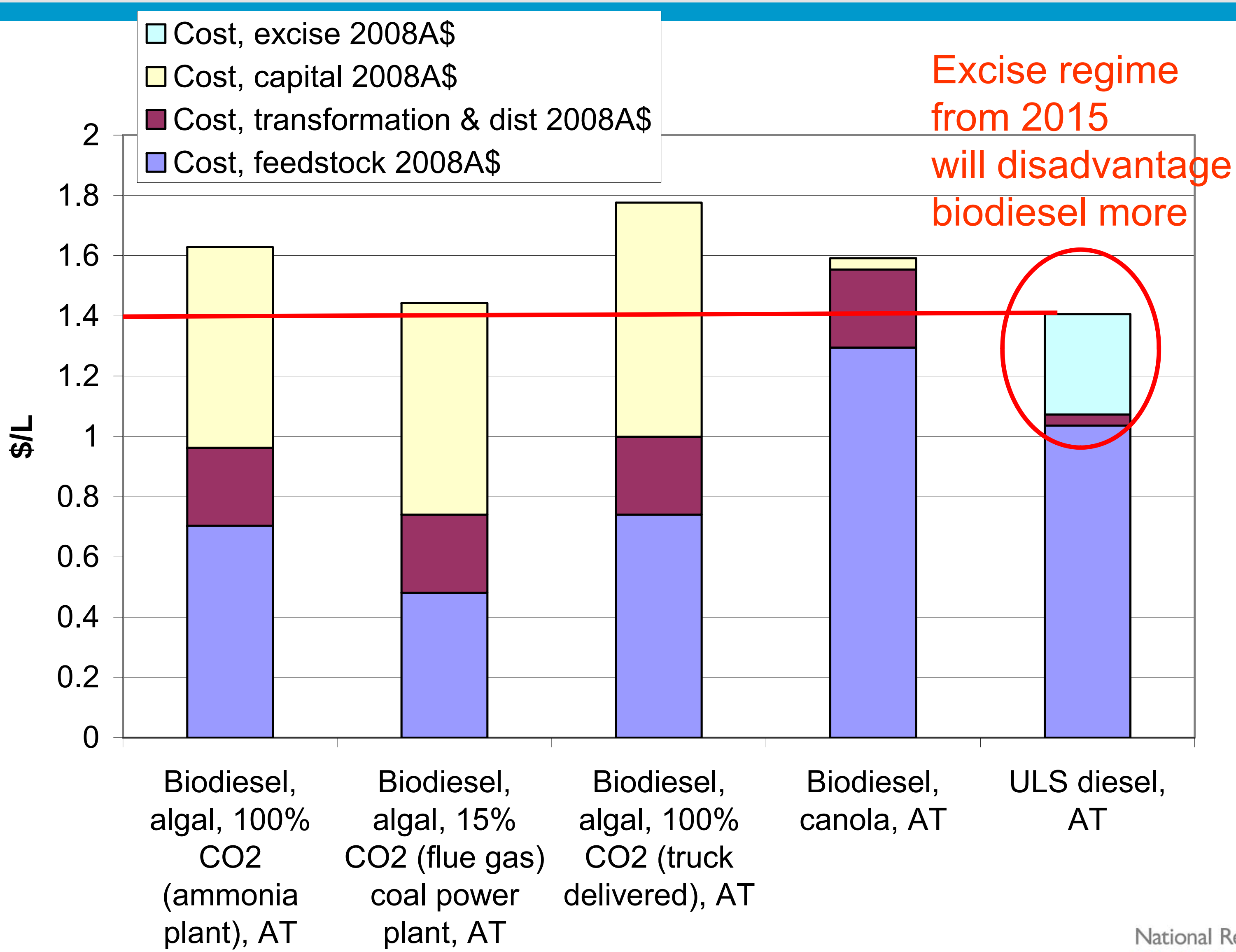


S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

Costs per Litre 30 g/(m^2-day) [110 t/(ha-yr)]



Costs/L (if only 50% yield) 15 g/(m^{2}-day) [55 t/(ha-yr)]



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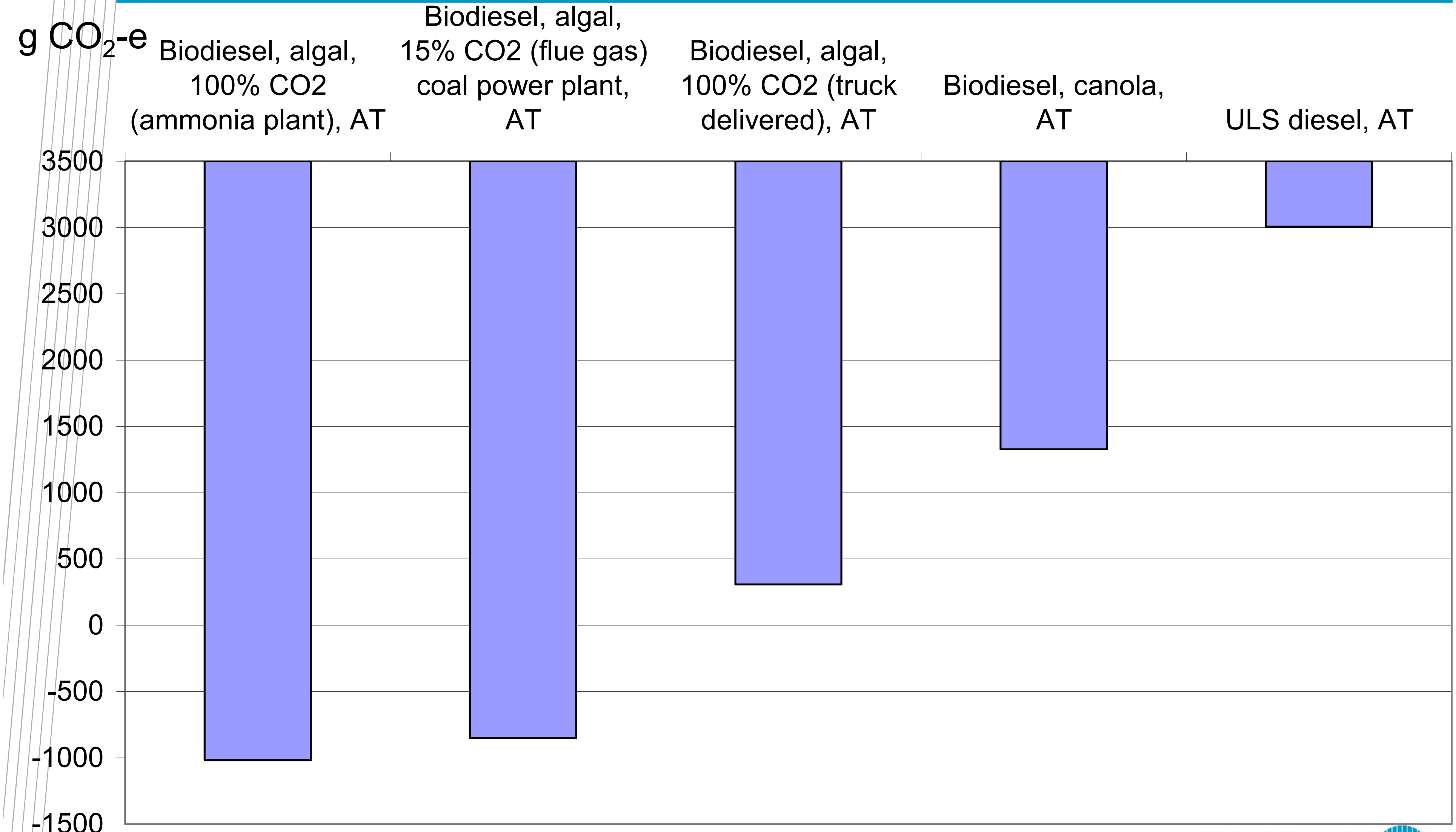
Greenhouse gas emissions per litre



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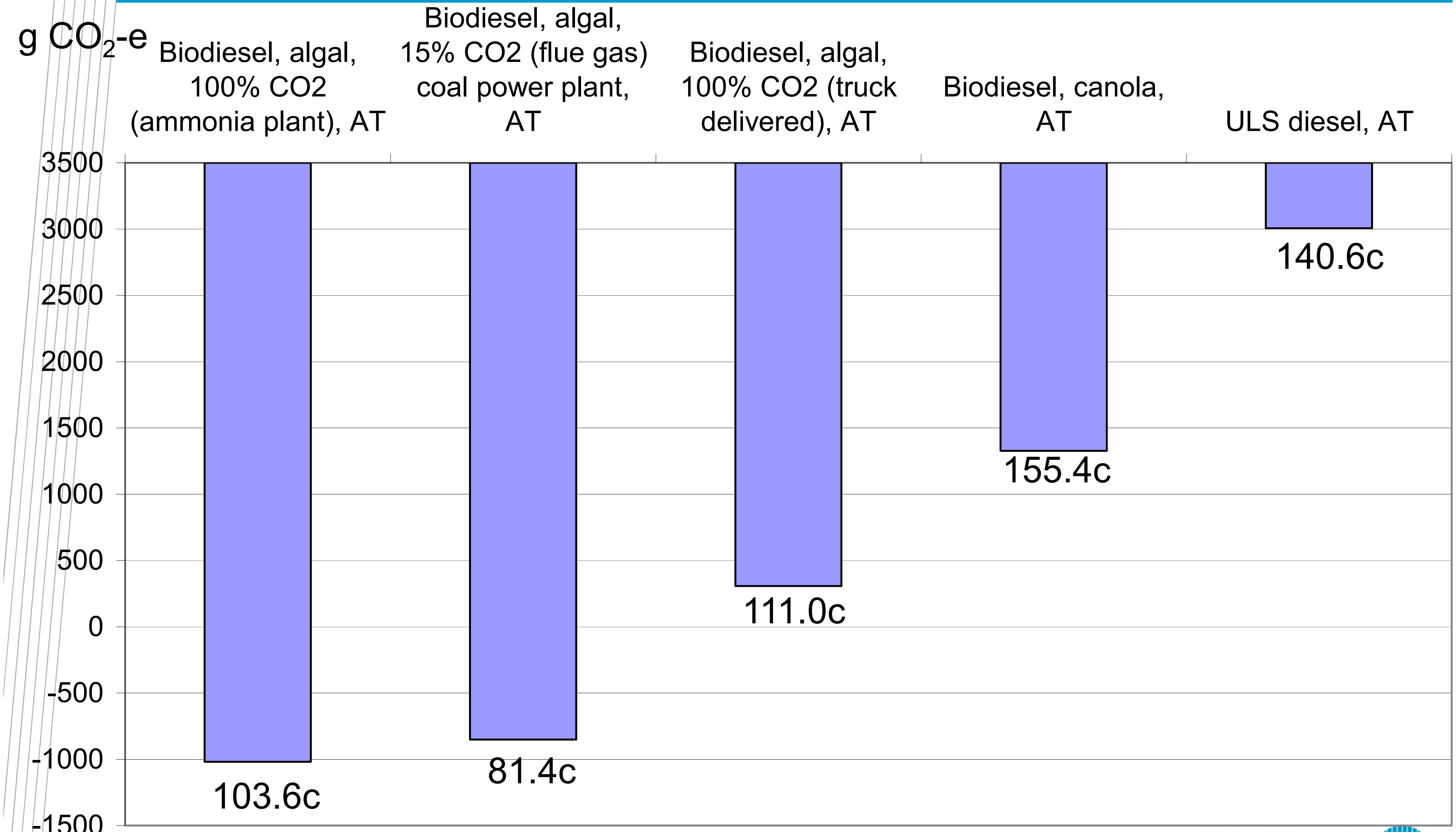
Greenhouse gas emissions per litre



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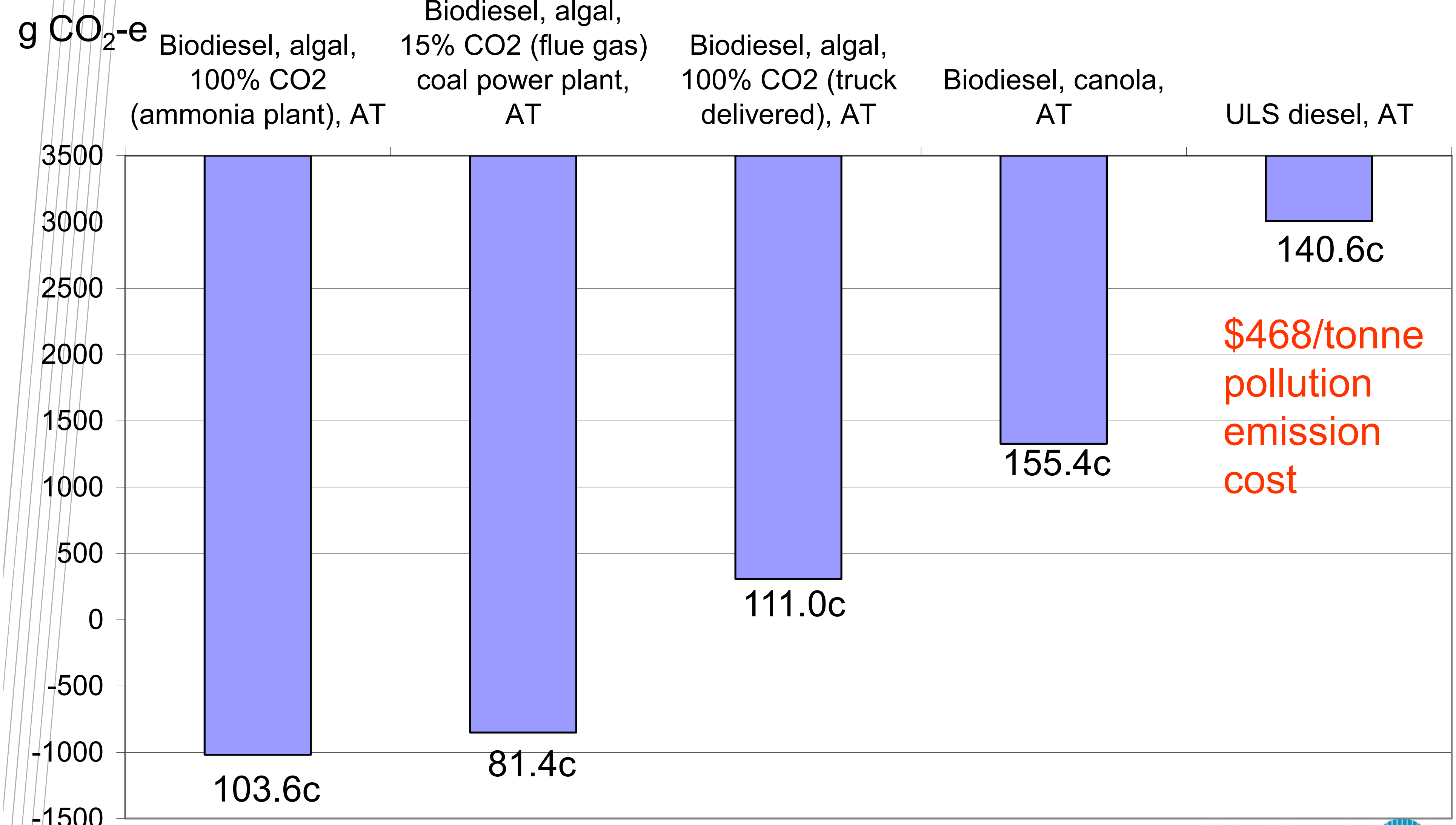
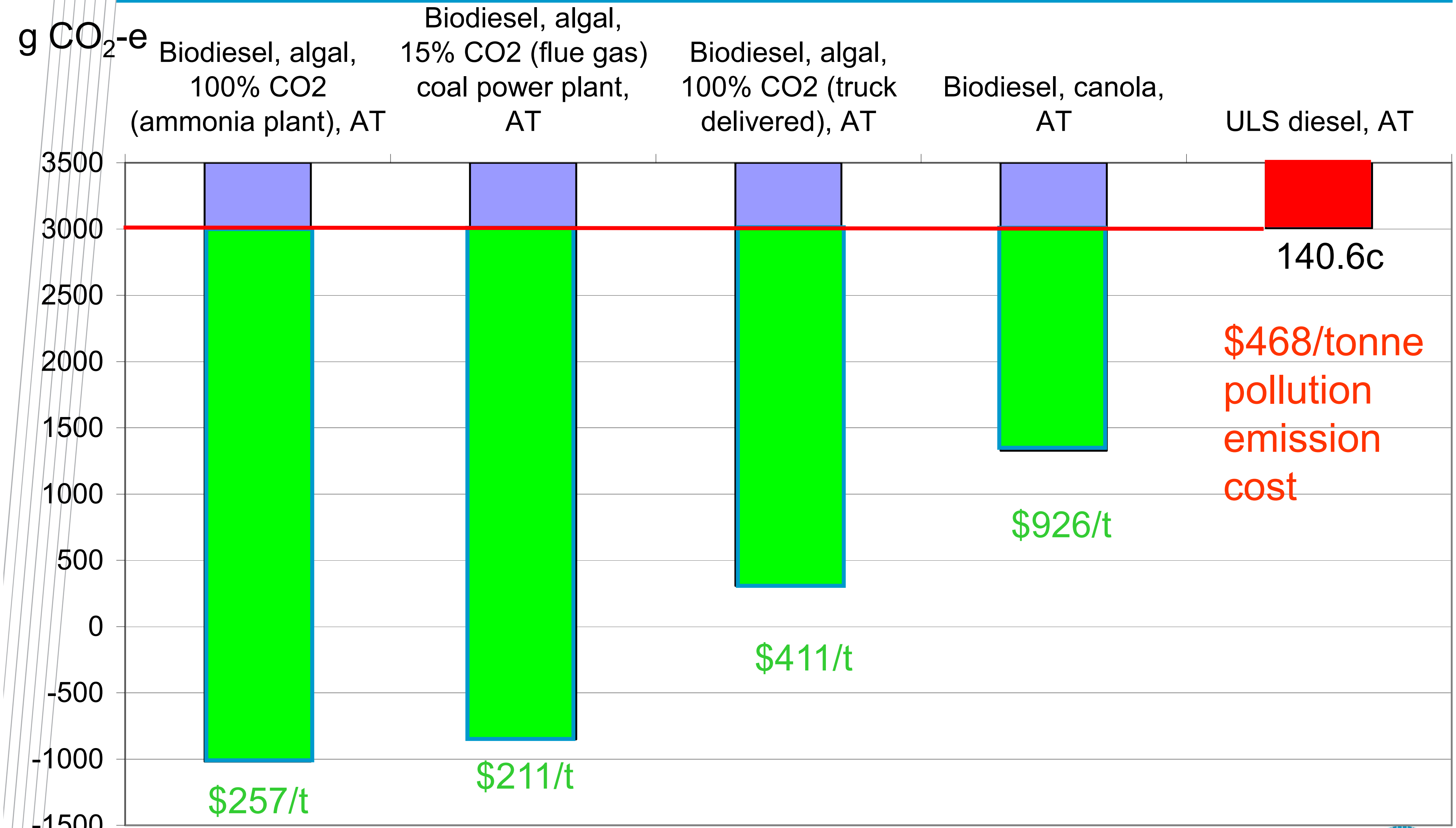
Greenhouse gas pollution cost ($/tonne)



Greenhouse gas abatement costs ($/tonne)



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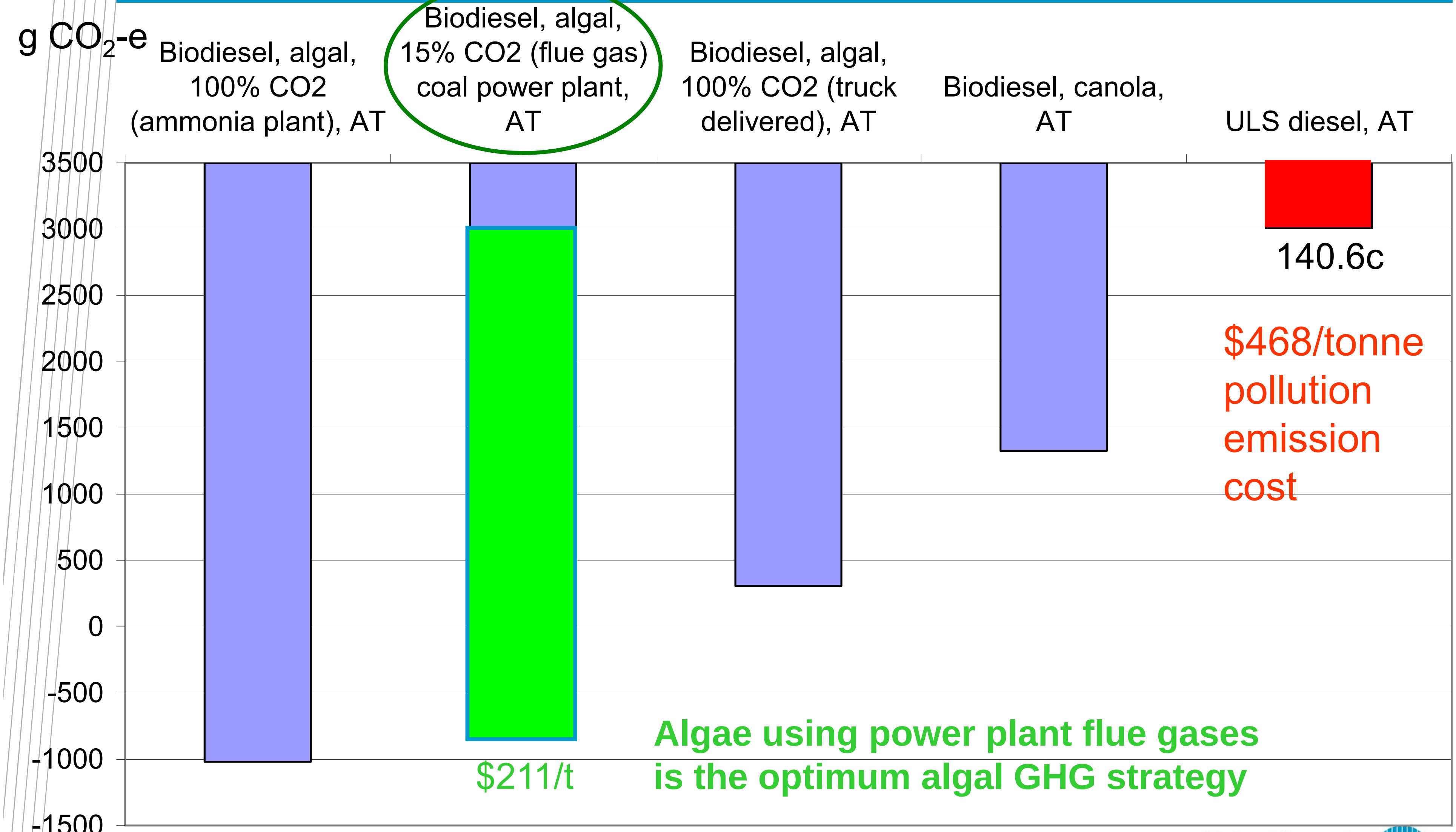
Greenhouse gas abatement costs ($/tonne)



Algae using power plant flue gases is the optimum algal GHG strategy

S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

Life Cycle Analysis

- Campbell, P.K., Beer, T., and Batten, D. (2009) Greenhouse Gas Sequestration by Algae – energy and greenhouse gas life cycle studies, in Proc. 6th Australian Life-Cycle Assessment Conference. http://www.csiro.au/resources/Greenhouse-Sequestration-Algae.html

Algal strain selection and optimisation

Objective:

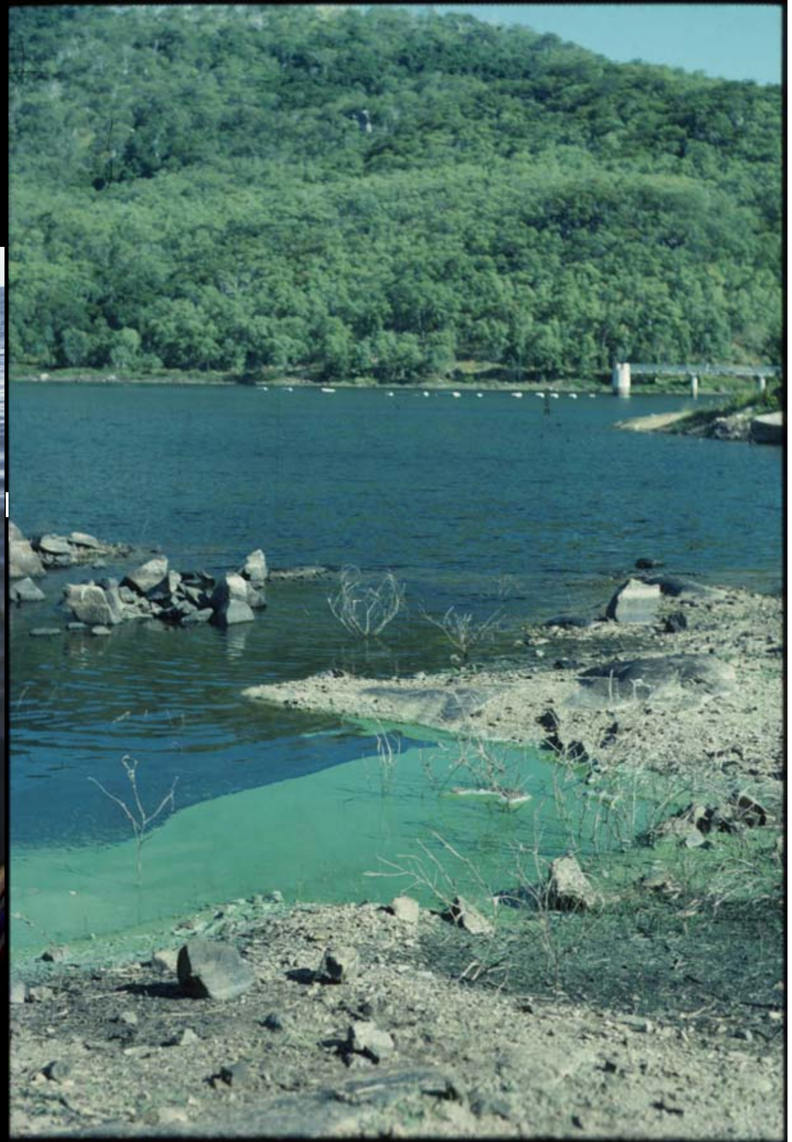
To identify and characterise, develop, enhance and trial Australian endemic microalgae with the best growth rates, oil profiles and productivity for production technologies selected and developed by CSIRO and / or industry partners, for biodiesel and co-product applications, including GHG abatement, and suitable for Australian conditions and environments.

Project leader:

Susan Blackburn

Algal Production:
algae produce high biomass in nature (algal blooms)

Dinoflagellate bloom, eastern Tasmania



Cyanobacterial bloom, Queensland

Fatty acid composition

Fatty acid	BDF from			Lipids from			
	Crude palm oil	Crude coconut oil		*Dunaliella maritima*	*Dunaliella salina*	*Chlorella vulgaris*	*Polytoma oviforme*
Caproic acid, C8:0	-	7.4		-	-	-	-
Capric acid, C10:0	-	5.8		-	-	-	-
Lauric acid, C12:0	0.35	49.8		-	-		-
Myristic acid, C14:0	0.92	18.8		0.4	0.5	2.0	-
Palmitic acid, C16:0	44.1	8.6		11.8	17.8	19.6	39
Stearic acid, C18:0	4.4	2.7		0.4	1.5	3.3	3
Arachidic acid, C20:0	0.09	0.18		0	0	0	0
	49.8	**93.1**		**12.6**	**19.7**	**25.7**	**42.0**
Palmitoleic acid, C16:1	-	-		4.2	2.5	8.8	2
Oleic acid, C18:1	39.0	5.5		2.5	3.4	7.3	31
Linoleic acid, C18:2	11.2	1.3		4.1	6.1	11.8	5
Linolenic acid, C18:3	-	0.07		45.8	39.4	22.6	8
Sum of Unsaturated FA	**50.2**	**6.9**		**87.4**	**80.3**	**74.3**	**58**

Oil content as % dry weight for some microalgae grown under nutrient-sufficient conditions

Species	Lipid %	Reference
Chlorella emersonii	29	1
Chlorella minutissima	31	1
Chlorella sorokiniana	20	1
Chlorella vulgaris	18	1
Dunaliella salina	14.4	2
Dunaliella primolecta	23.1	3
Isochrysis galbana	21.9-38.5	4
Nannochloropsis sp.	33.3-37.8	5
Nitzschia closterium	27.7	2
Phaeodactylum tricornutum	19.8	3
Tetraselmis suecica	20-30	6

1: Illman et al. (2000), 2: Zhu and Lee (1997), 3: Thomas et al. (1984b), 4 : Fidalgo et al. (1998), 5: Fábregas et al. (2004), 6: Otero and Fábregas (1997).

Choice of species is critical

Australian National Algae Culture Collection

•CSIRO National Biological Collections: Algae – a living collection

•1000 strains of more than 300 microalgae species

•unique Australian biodiversity, sourced from the tropics to Antarctica, marine and freshwater microalgal classes

•isolation of new strains from Australia's biodiversity

Formerly
CSIRO Collection of Living Microalgae
http://www.cmar.csiro.au/microalgae

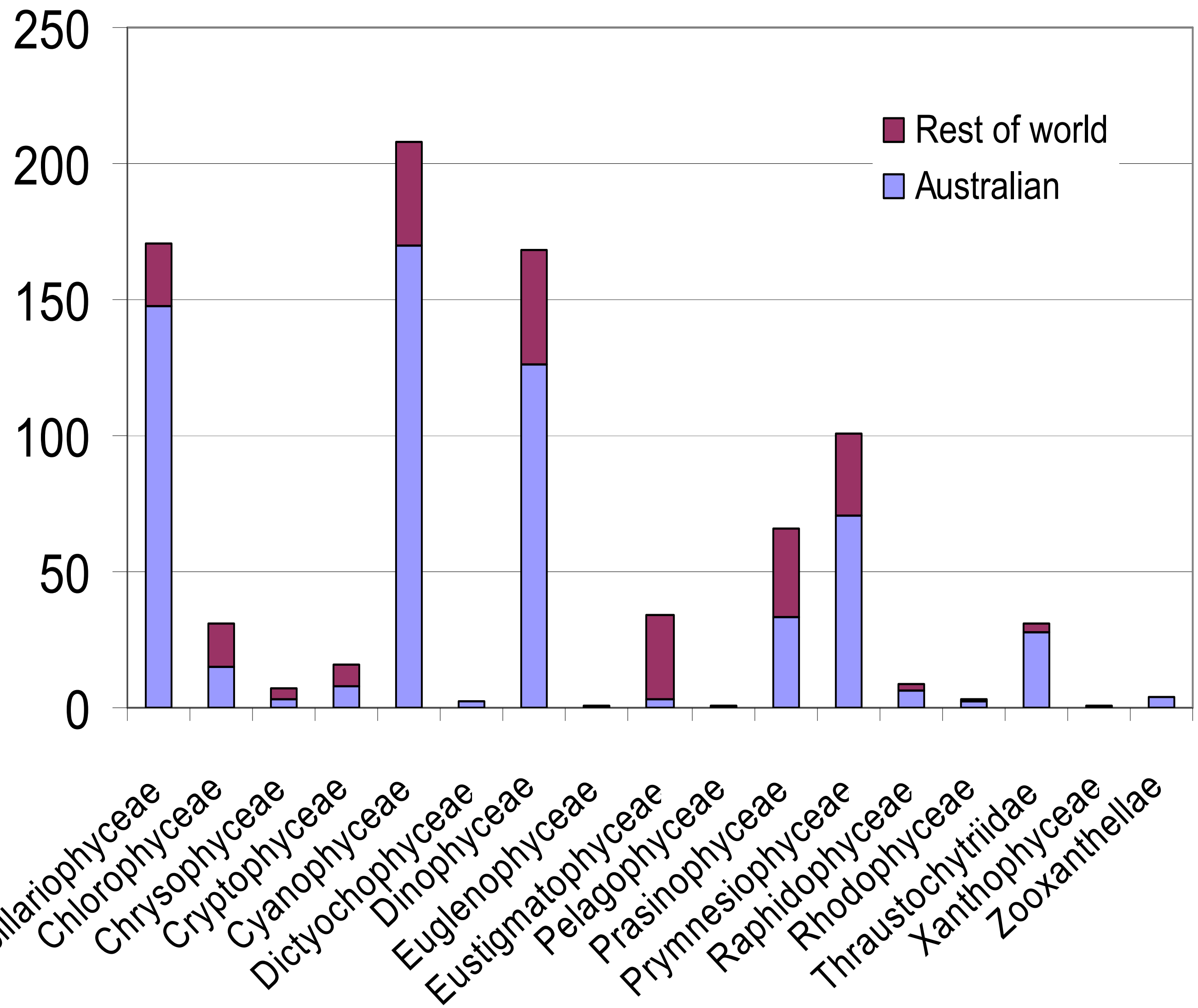
•strain characterisation: taxonomic identification, chemical & molecular characteristics, growth parameters

Algal Culture Facility

•Controlled environment rooms and cabinets

•Secure facility - AQIS

Number of Strains in the Collection, October 2008



Screening of the Australian National Algae Culture Collection (ANACC)

Characterise selected strains for:

'Biodiesel' Analysis

- Fatty acid methyl esters (FAME or biodiesel)

As well as 'Co-product' Analysis:

- Pigments
- Phytosterols
- Diacylglyceryl ethers
- Hydroxy fatty acids
- Long chain ketones and fatty acids
- Other novel lipids

New Australian strain isolation: Biorational discovery

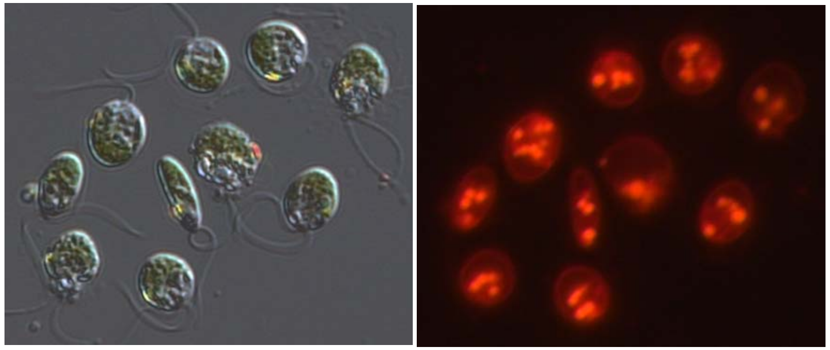
- Biomass production / oils and other products
  - growth rate; productivity; biomass production
  - lipid profile; oil content
  - co-products e.g. protein, carbohydrates, pigments / antioxidants, omega-3 oils, etc.

- Biogeography / environment
  - Australian – endemic: AQIS issues
  - climatic zones: temperate, sub-tropical, tropical
  - water supply / quality
    - extremophiles e.g. hypersaline
    - wastewater: algae for bioremediation

200 new strains isolated

- Technologies
  - open ponds or photobioreactors or a combination of both
  - flue gas / CO_2 sources (high CO_2 assimilation)

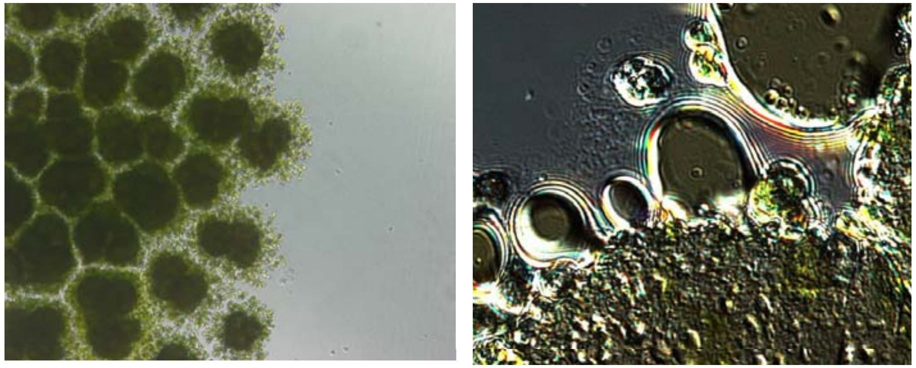
New Strains isolated 2009



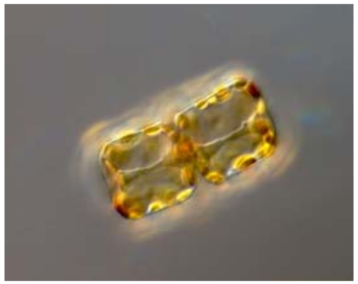
Hypersaline 13_ *cf Dunaliella*

Hypersaline 40_ cyanobacteria

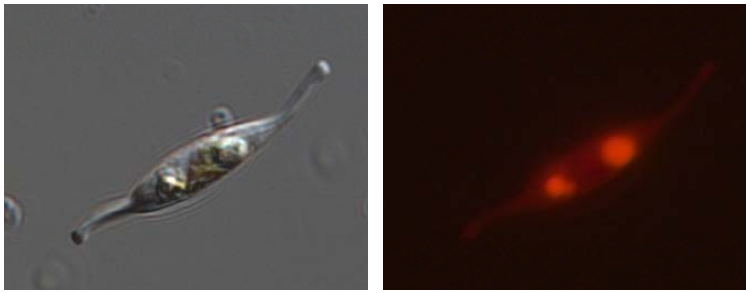
KTPL3-19 *Closterium sp.*



BBUL04 *Botryococcus*

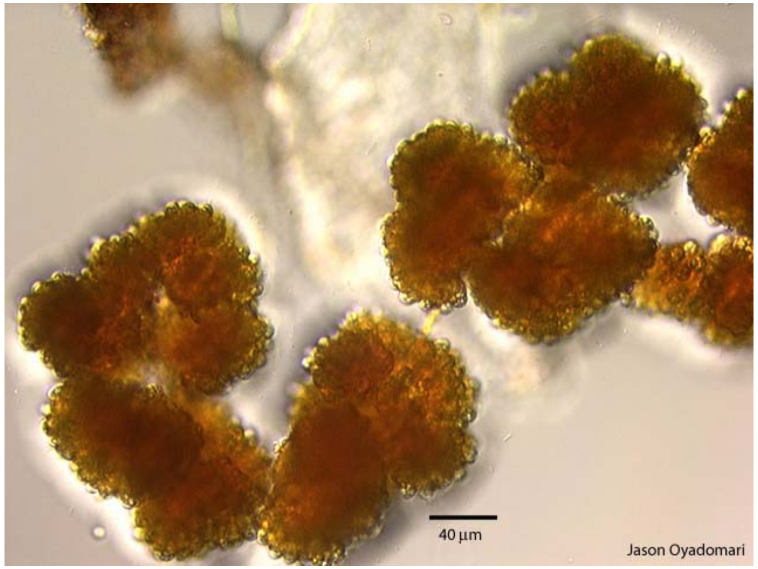


Lauderia annulata



DF_Hypersaline_ *Nitzschia closterium*

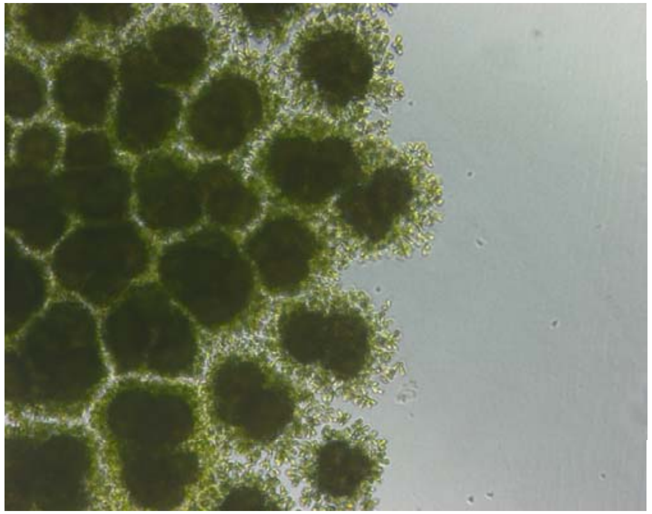
Botryococcus braunii: source of long-chain hydrocarbons



Up to 86% of the dry weight of the green alga *Botryococcus braunii* can be long-chain hydrocarbons. The composition depends on the particular “race” of *Botryococcus*. The classic hydrocarbons are called botryococcenes. These are C_{30}-C_{37} isoprenoid triterpenes having the formula C_nH_{2n-10}

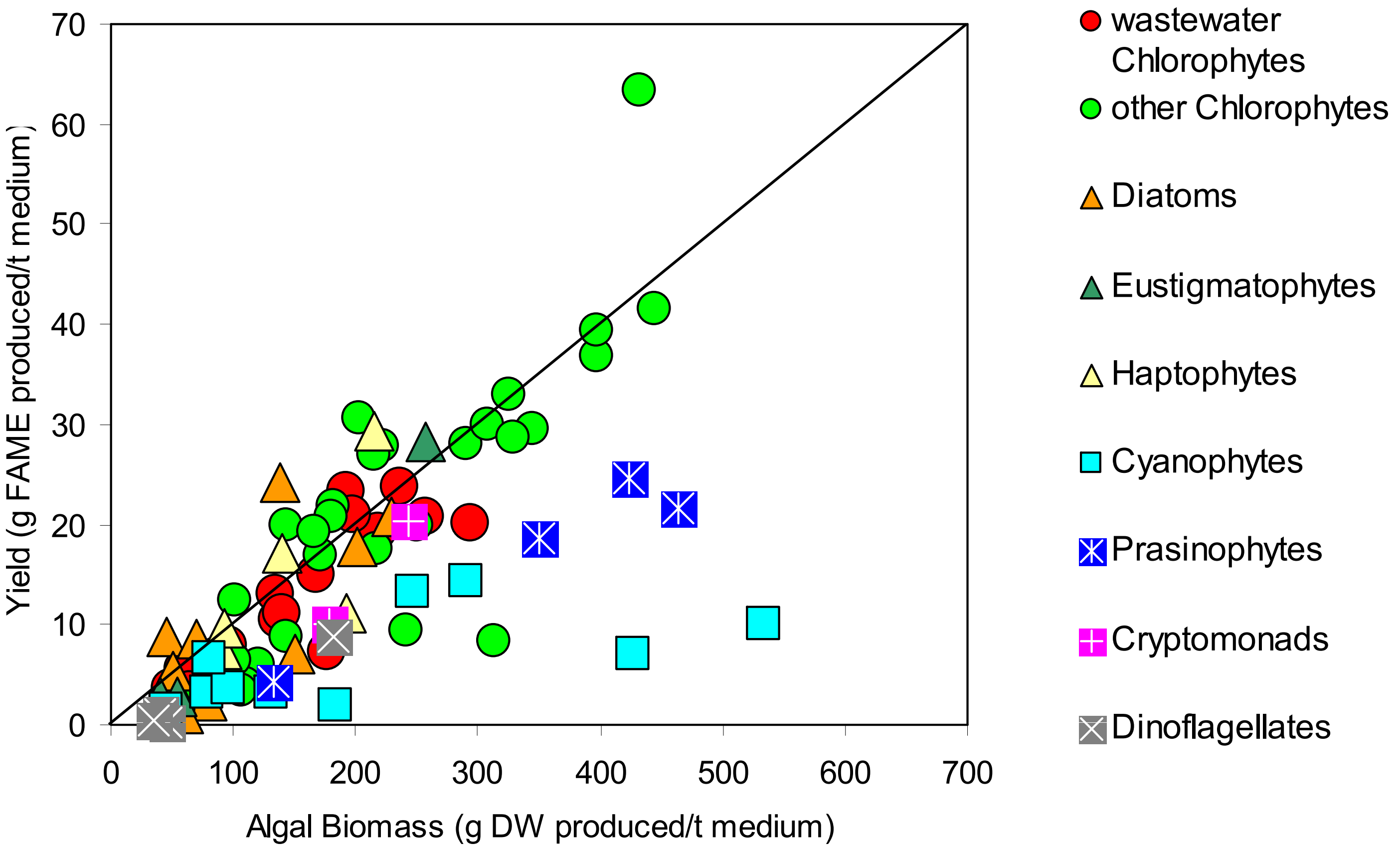
Botryococcus can bloom in Australian waters; however it grows slowly.

University of Western Sydney / CSIRO collaboration : Energy and Nanotechnology: nano-scale catalysts for production of biofuels



Screening of ANACC microalgae

Fatty acid yield versus biomass production



Diagonal line indicates 10% of dry weight is fatty acid

S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

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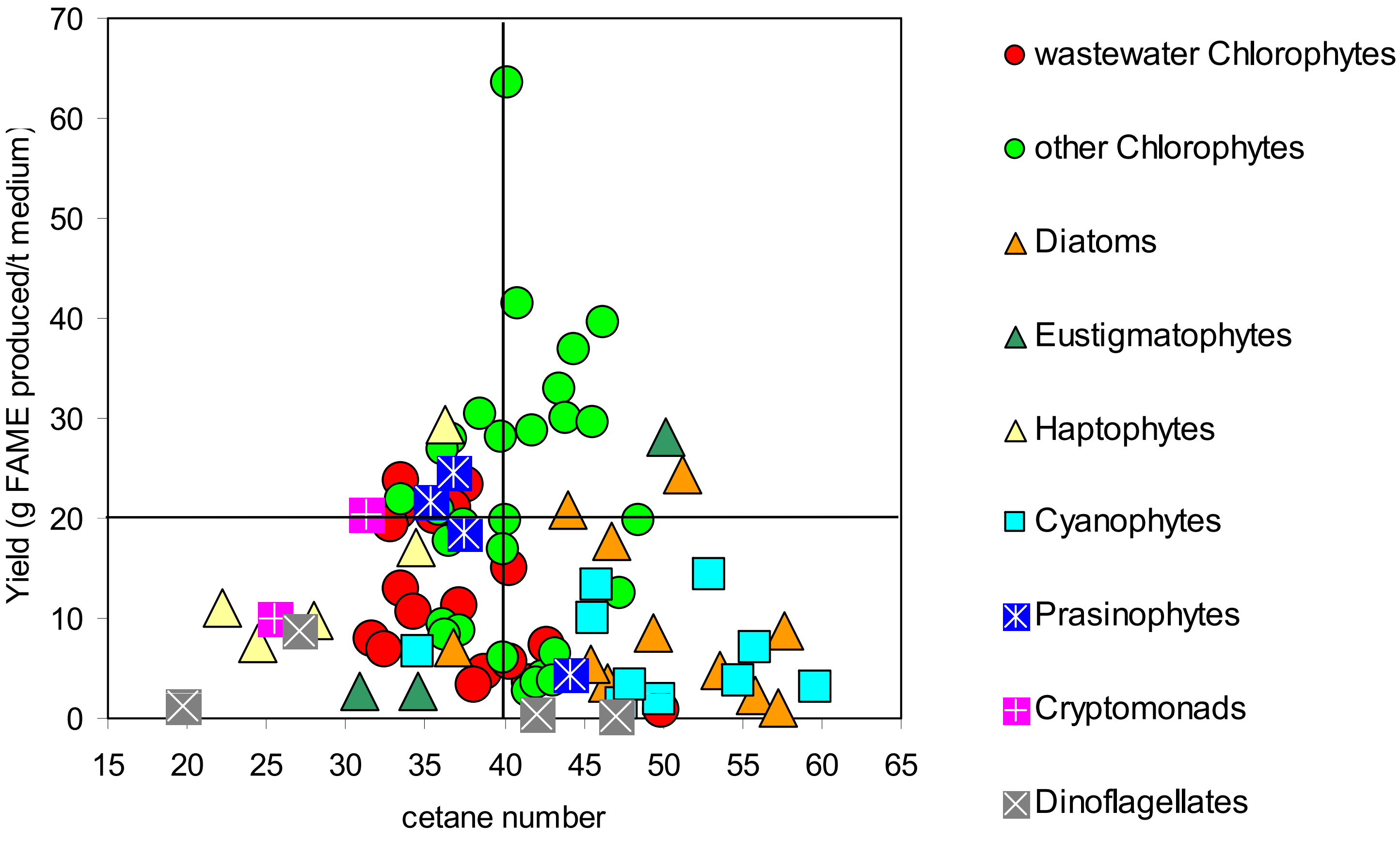
Screening of ANACC microalgae

Fatty acid yield and Cetane Number (90 strains)



S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

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Biodiscovery: hypersaline green microalgae

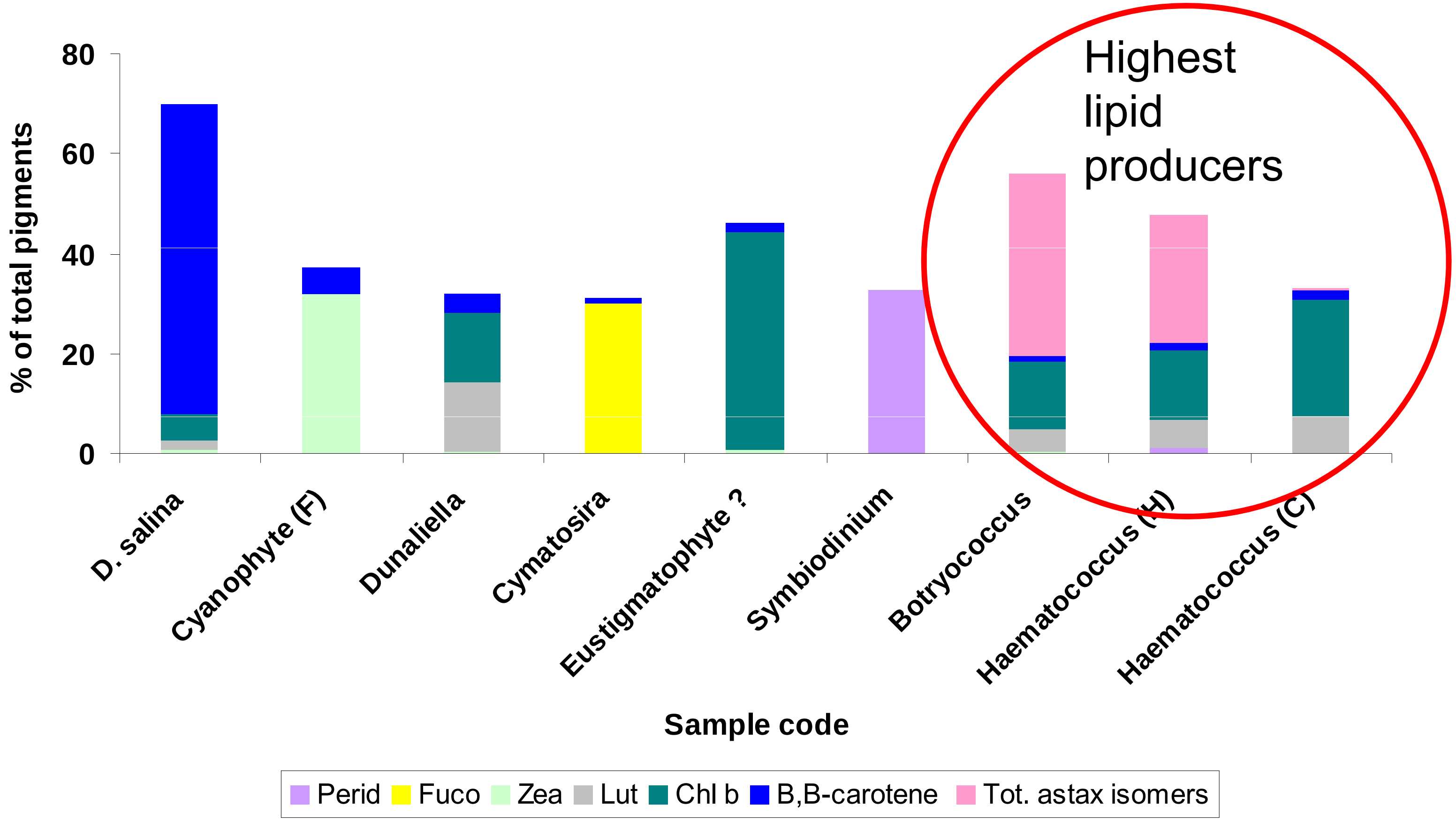
Typically *Dunaliella* spp. do not produce the long-chain C_{20} and C_{22} Omega 3 PUFA

strain	*Dunaliella tertiolecta*	*Dunaliella*-like				*Dunaliella*-like which produces long-chain PUFA						*Tetraselmis*-like			*Tetraselmis suecica*
fatty acid	CS-175*	BD3-13	BD3-12	BD3-09	BD3-06	BD3-01	BD3-03	BD3-05	BD3-07	BD3-17	BD3-04	BD3-08	BD3-16	BD3-15	CS-187*
16:4 w3	**21.0**	**8.7**	**10.7**	**10.8**	**19.1**	12.1	14.0	13.4	13.3	14.2	13.2	12.4	14.7	15.2	10.8
20:5 w3	-	-	-	-	-	0.1	0.2	0.2	0.2	0.2	0.2	**6.8**	**6.6**	**9.0**	4.8
22:6 w3	-	-	-	-	-	**0.2**	**0.8**	**0.9**	**1.0**	**1.0**	**1.5**	-	-	-	trace

*Volkman *et al.* 1989

Potential co-products: Pigments

High pigment producing strains



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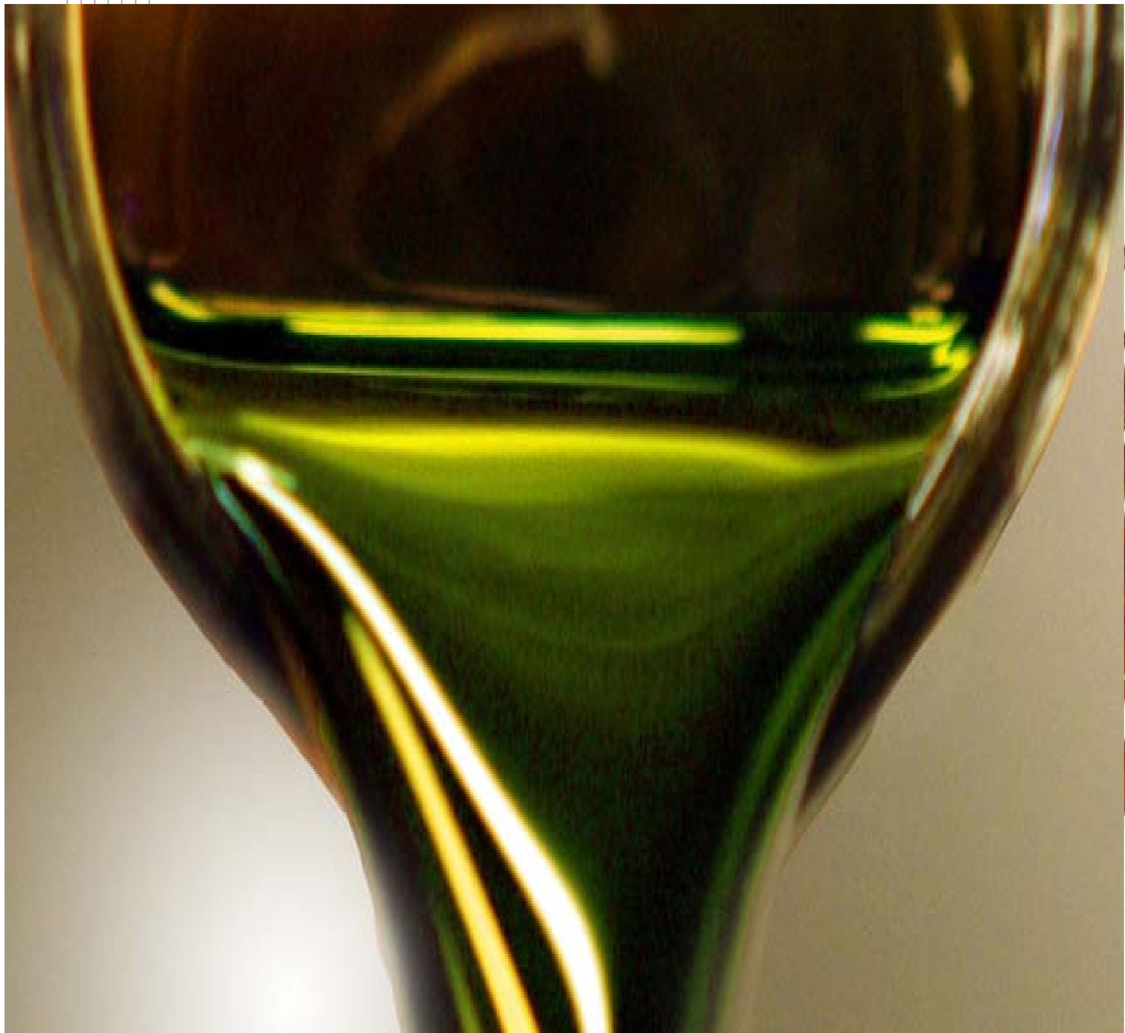
Co-product Development: Oil / Pigments



Thermal and fluids engineering project
(CSIRO Materials Sciences and Engineering)

- Task Objectives:
  - **To provide the following areas of expertise and equipment:**
    - **Optimising Flow Conditions**
    - **Flow Optimisation within Pipelines**
    - **Algae Separation**
    - **Heat Transfer**
    - **Impellor Design**
    - **Sparging Systems**
  - **To evaluate the cost-efficiency of Open Ponds versus Covered Ponds or Raceways versus Enclosed Photobioreactors**

- Project Leader:
  - Kurt Liffman

Project Background

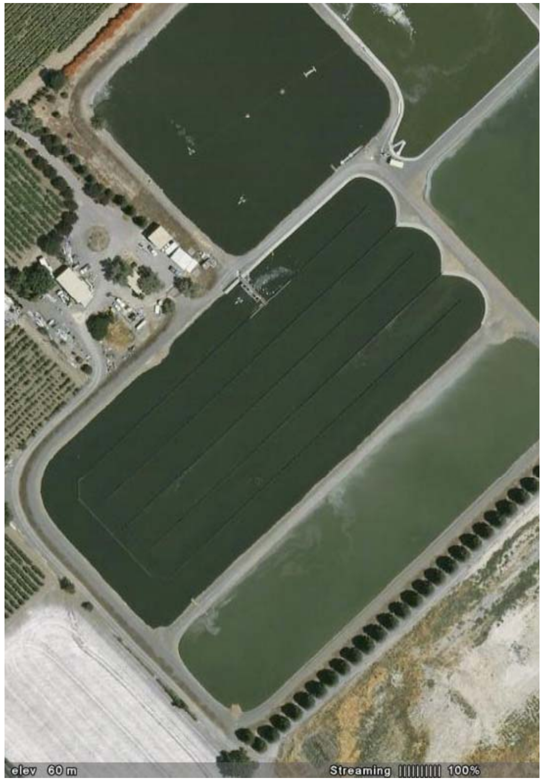
- Relatively straight forward to make fuel from micro-algae.
- Technologically viable process since the 1970s
- Lance Hillen (DSTO, Aust) produced jet A and petrol from *Botryococcus*

- Challenge: to produce algal fuel economically.
- Fundamental problem: Algal slurry is a dilute medium
- Ten tonnes of algal slurry/water processed to produce one litre of oil

- Potential solution: minimize capital costs and "free" energy input, i.e.,
  - Cheap land
  - Stirred, open ponds; not photo-bioreactors
  - Atmospheric CO_2 , for true biosequestration
  - Cheap, quick harvesting system

Improving Open Pond Productivity

We wish to understand the factors governing the productivity in race-way ponds and then apply these principles to basic open ponds



Raceway pond

Open pond

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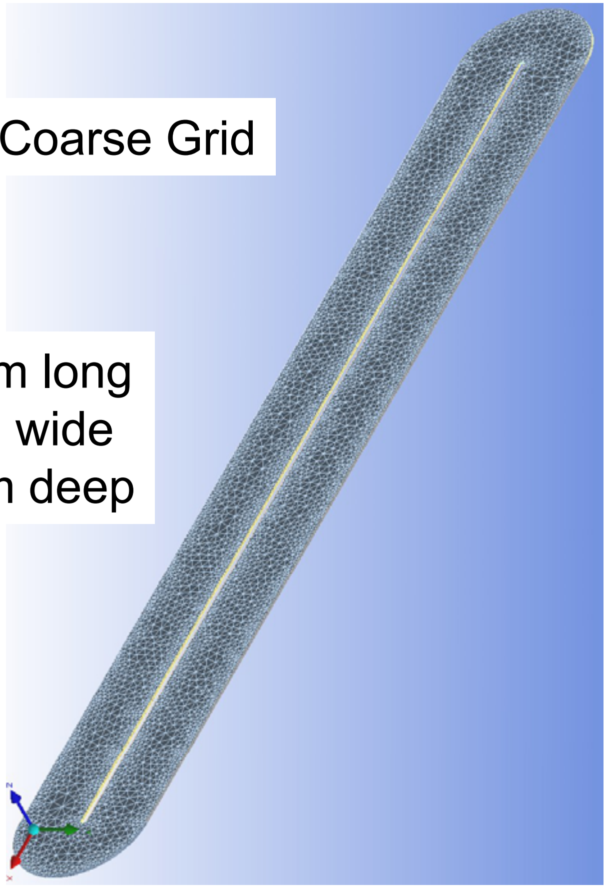
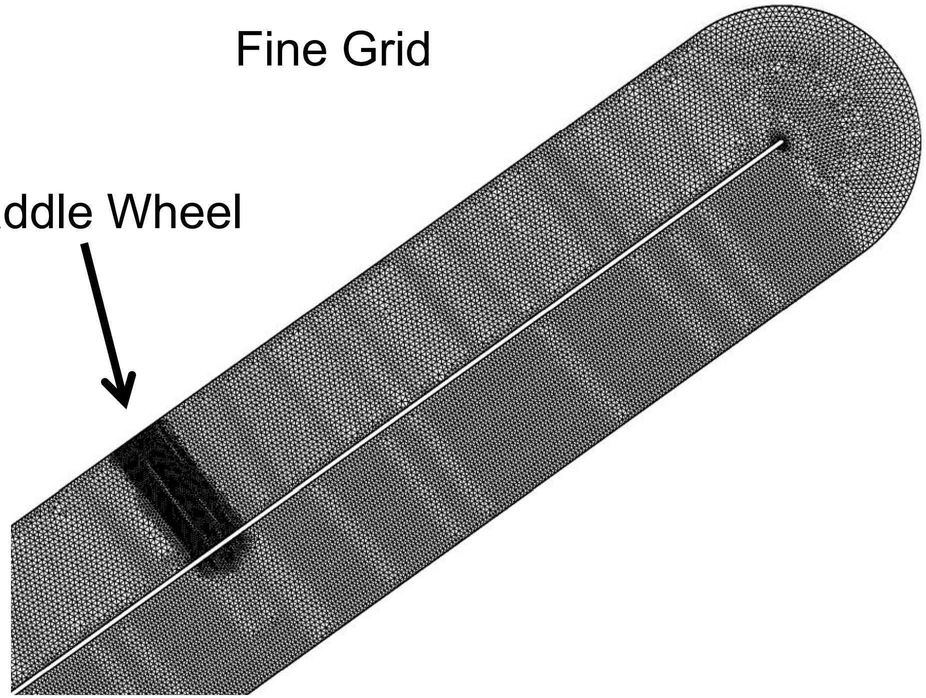
Computational Fluid Dynamics (CFD)

We have built a computational code to model the growth of algae in raceway and open ponds. Factors of interest are: intensity of sunlight, CO_2 absorption/diffusion, turbulence, pressure drop, velocity, algae growth.

Raceway Pond Computational Domain



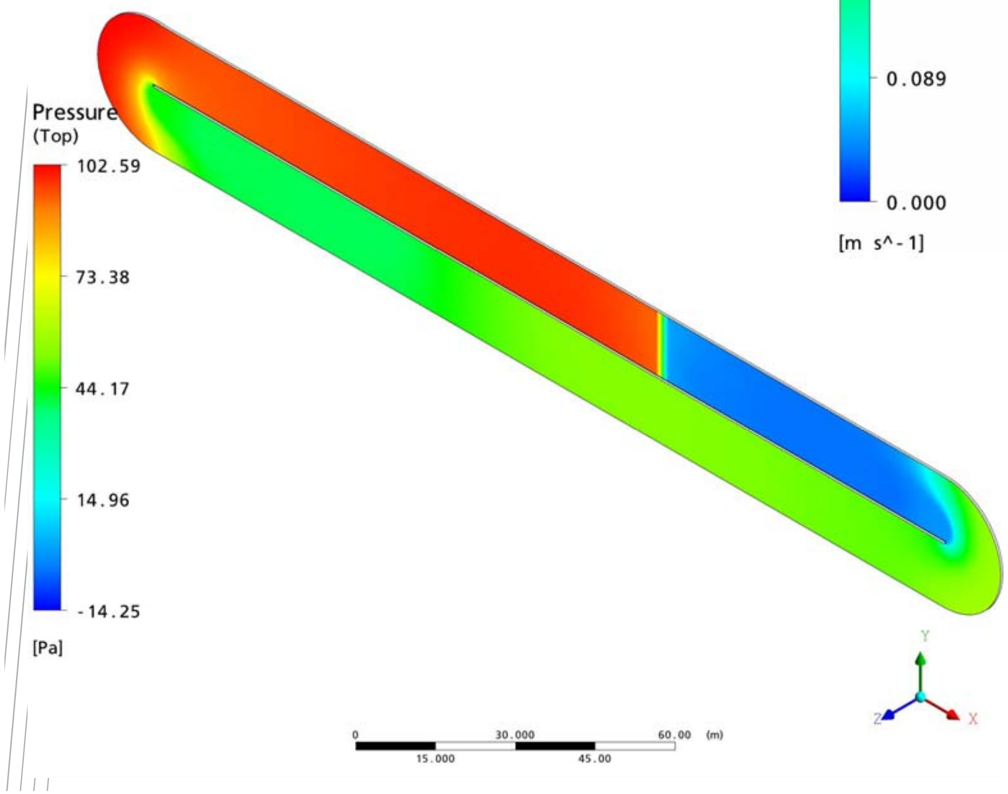


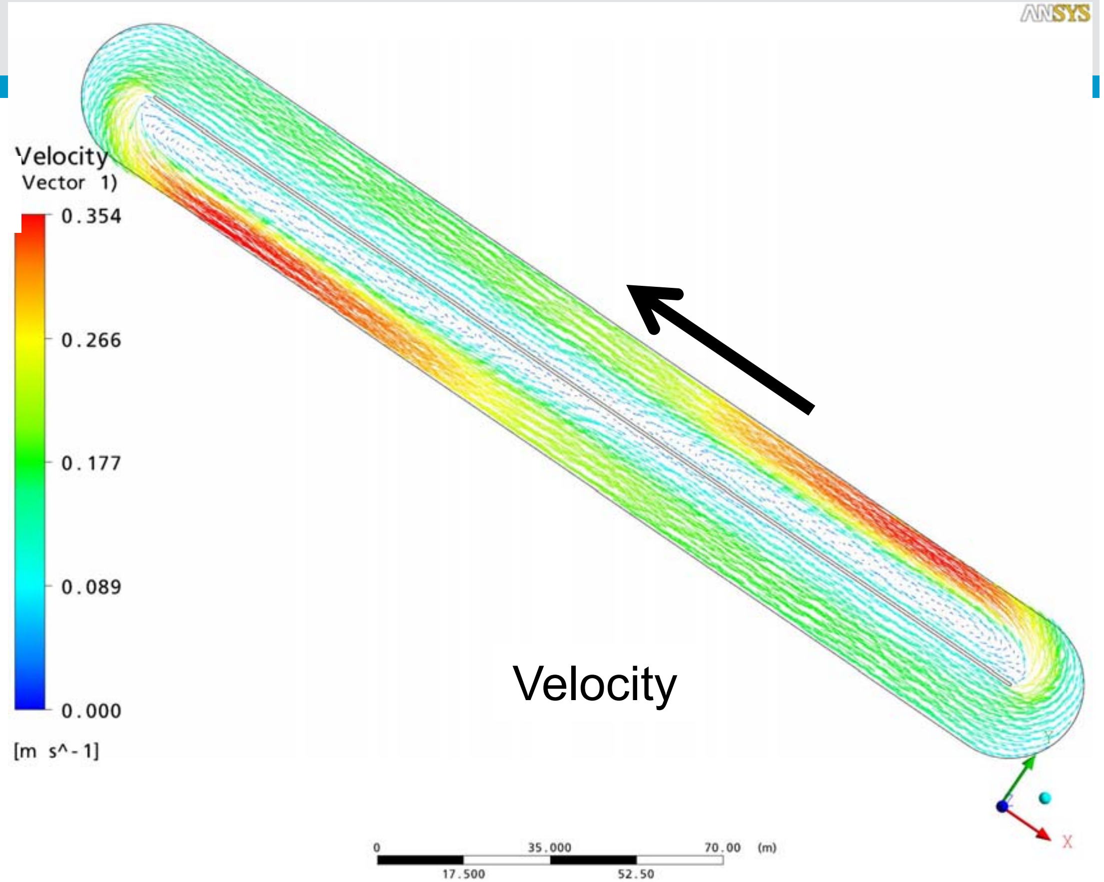
S.I. Blackburn, Biofuels Symposium, Tsukuba, Japan, August 2009

Computational Fluid Dynamics (CFD)

Raceway Pond Pressure and Velocity

Pressure



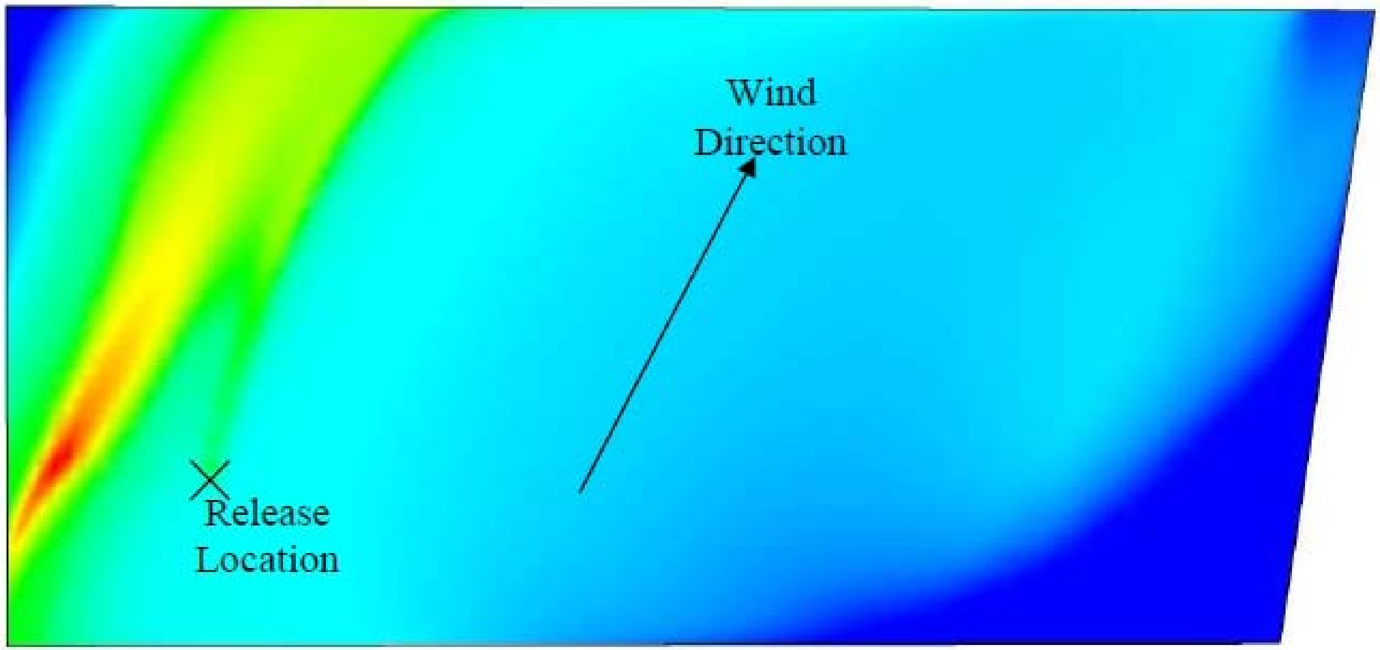


Velocity

Raceway Ponds tend to be expensive and energy intensive, as the water is always in motion.

Computational Fluid Dynamics – Mixing of algal ponds

Our initial (qualitative) results suggest that the degree of mixing is a fundamental driver of algae productivity. We are attempting to quantify this mathematically within our CFD code. Industrial scale mixing simulations of open ponds.



Computation of a plume of fertiliser – real pond scenario. Wind powered mixing.

Separation / harvesting technologies

Besides capital cost, harvesting algae is the major cost impediment (10-20%) in making algae a commercially competitive feed stock for biodiesel.

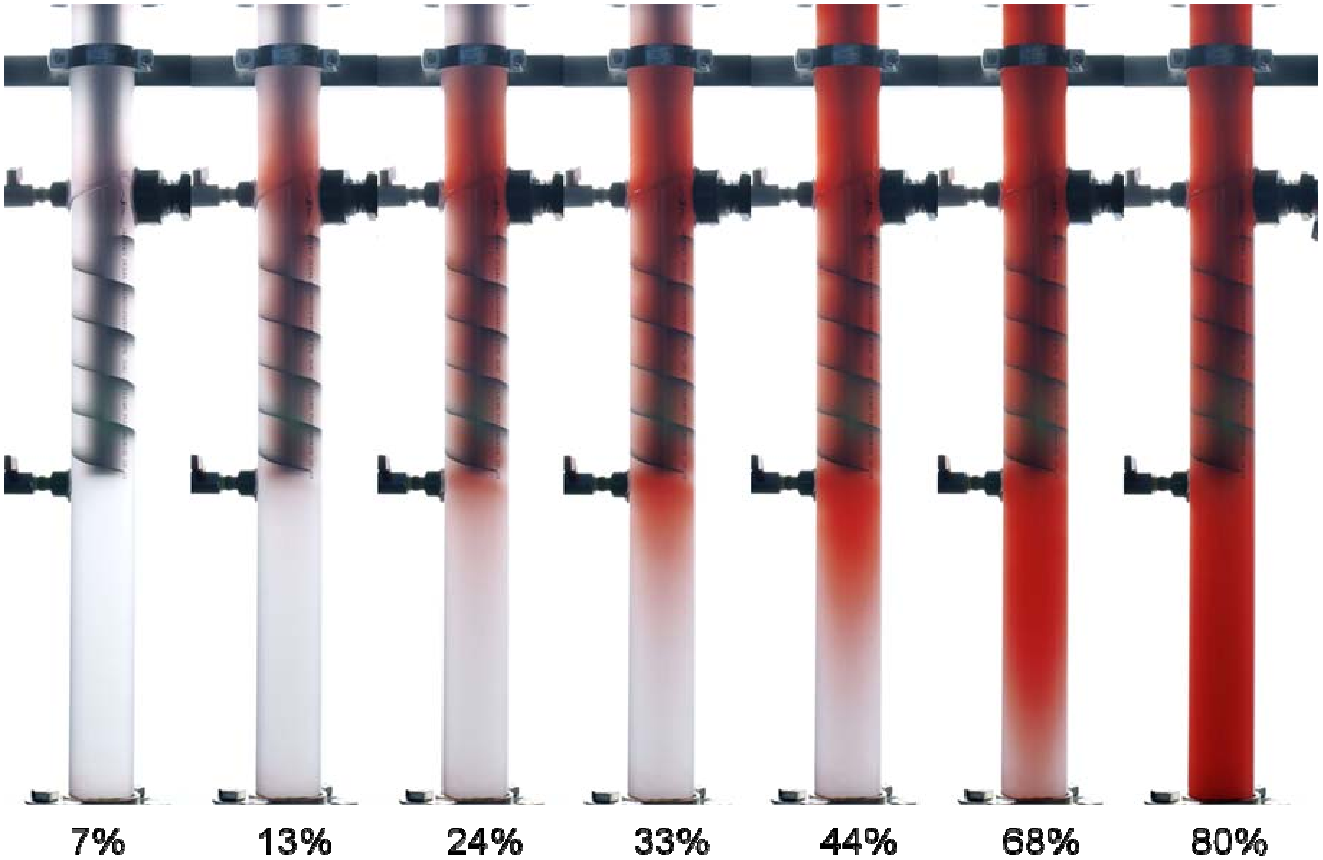
There are a number of algae harvesting technologies, e.g. sedimentation, floatation, filters and centrifuges. The separation system has to be designed for an individual alga / growth technology.

We have developed a potential in-line harvesting system called the CST, which uses centrifugal force, but without the expensive centrifuge (provisional patent).

In-line Algae Separation System (CSIRO SeparaTor or CST)

500L capacity

CST – experimental results



Percentage of oil in water

The future: Combined technologies / bioremediation / multiple bioproducts

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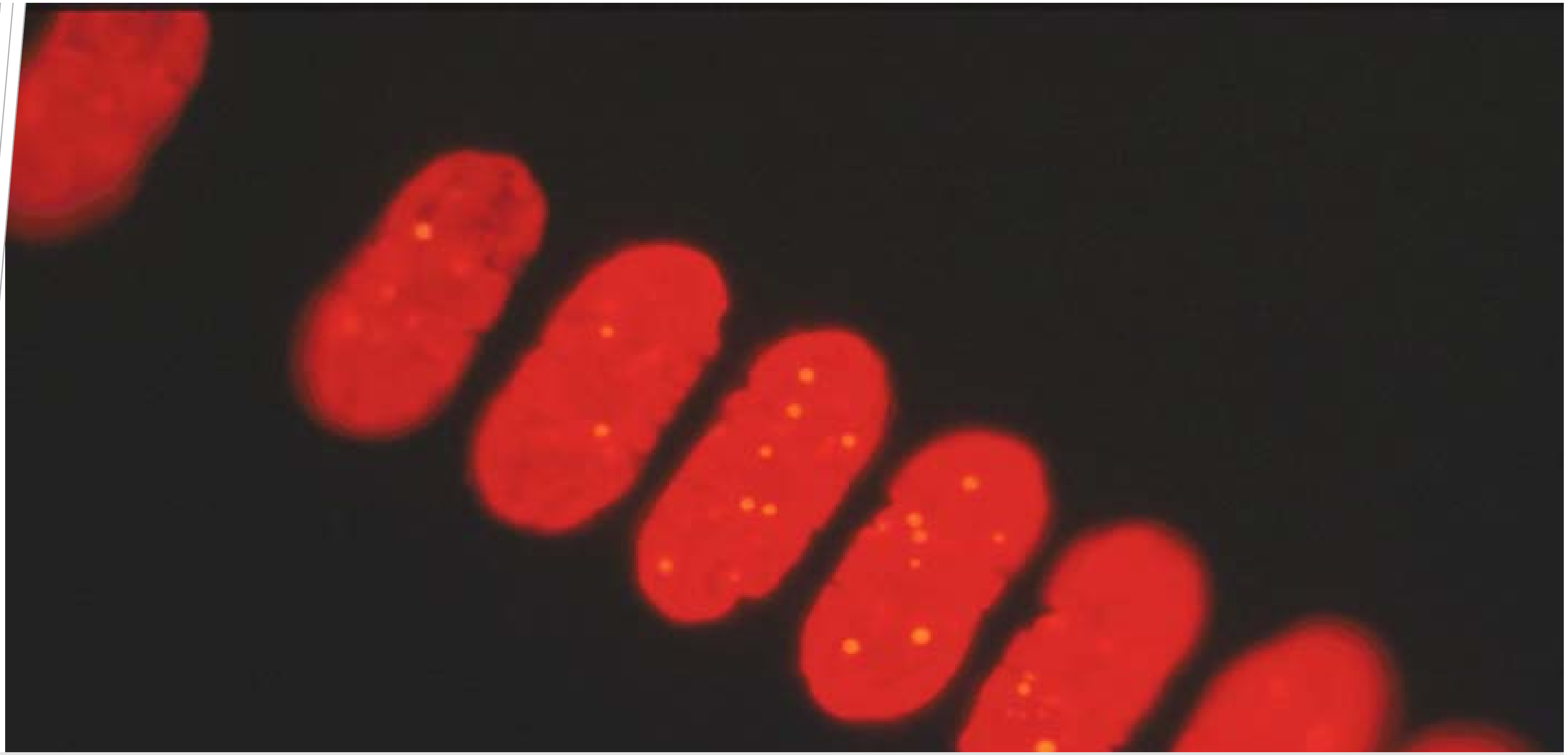
- Biodiesel
- Protein meal
- Fermentation to alcohols
- Speciality chemicals



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Thank you

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