AquaFUELs Project FINAL CONFERENCE

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The Sustainability of Algae Biofuels: LCA ,Environmental and Economic Impacts

Imperial College

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Outline

- Introductions & Objectives
- Life cycle assessment (energy and CO_2 balance)
- Environmental assessment
- Economic assessment
- Conclusions

Partners involved:

Imperial College London

Imperial Centre for Energy Policy & Technology

- Key facts:
  - An inter-disciplinary team of experienced researchers
  - >20 staff and 30 PhD students
- Main activities/competencies:
  - Techno-economic, environmental and policy analysis
  - Biomass energy for transport, electricity and heat applications

Major contributions from:

NUI Galway OÉ Gaillimh

Irish Seaweed Research Group (ISRG)

University of Firenze

University of Almeria

University of Wageningen

The Imperial College team

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Objectives

The project addressed three main questions about **micro-** and **macro-** algae :

- Is the energy and carbon balance favourable?
  - What are the strengths and weaknesses of LCA estimates
- What are the environmental impacts from cultivation?
- Under what circumstance would algal biofuel production be economic?

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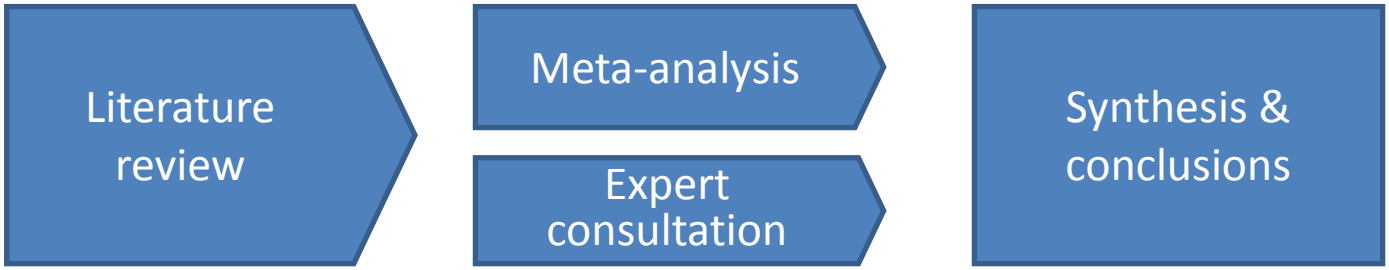
Approach



Studies included in the review

- **Kadam (2002):** co-firing for power generation;
- **Lardon et al. (2009):** biodiesel
- **Clarens et al. (2010):** Algae cf. other bio-feedstocks;
- **Jorquera *et al.* *(2010):*** energy life cycle of algae biomass.
- **Sander & Murthy (2010):** biodiesel;
- **Stephenson *et al.* (2010):** raceways vs PBRs in the UK
- **Campbell *et al.* (2010):** cultivation in ponds.

Problems identified with micro-algae LCA

- **Little primary data upon which process assumptions can be based.**
  - a wide range of conceptual designs, but only partial descriptions of algal biofuel production systems.
  - Systems are assembled from component parts, rather than designed as integrated systems.
- **Comparison is hindered by the use of inconsistent boundaries and functional units.**
  - The studies use a range of allocation methods, some of which are overcomplicated.
- **The validity of results called into question by experts:**
  - hypothetical nature of the LCA
  - Insufficient detail about the system, the strain used, the productivity and the possible amount of oil that can be extracted
- **Inferences that may be drawn from the existing LCAs are tenuous at best.**

Meta-modelling approach

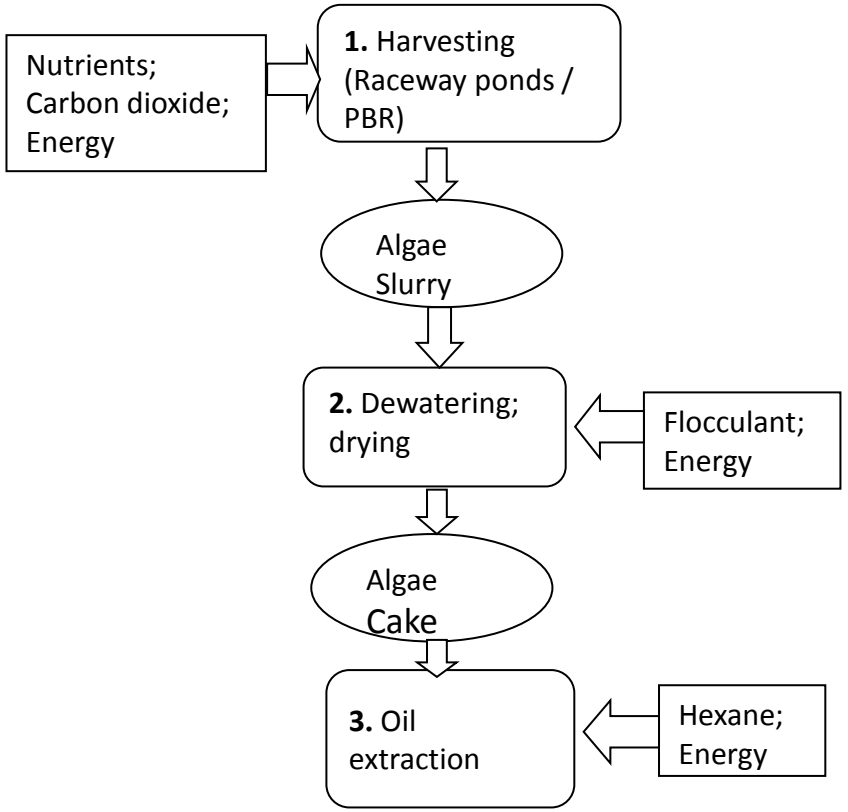
Modelling steps

Stage 1
- Identify original data, assumptions and system boundaries

Stage 2
- Normalize units
- Additional assumptions include:
  - The calorific value of the Dry Algal Biomass
  - Conversion of productivity per M^3 to productivity per M^2

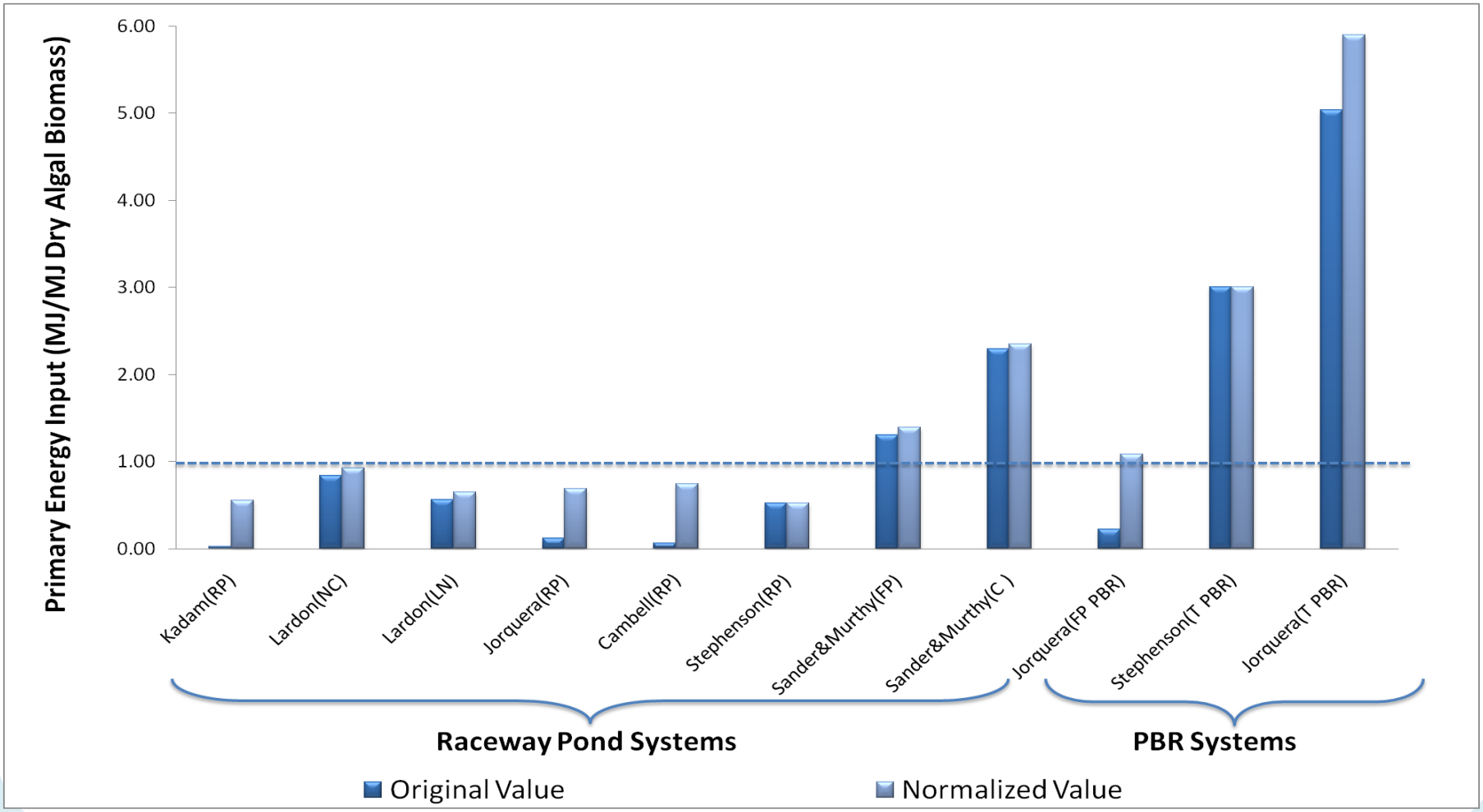
Stage 3
- Normalize system boundaries
  - Add / remove system components to give consistent boundary
  - Modify process assumptions only where necessary
- Normalize functional unit

Normalised system boundary

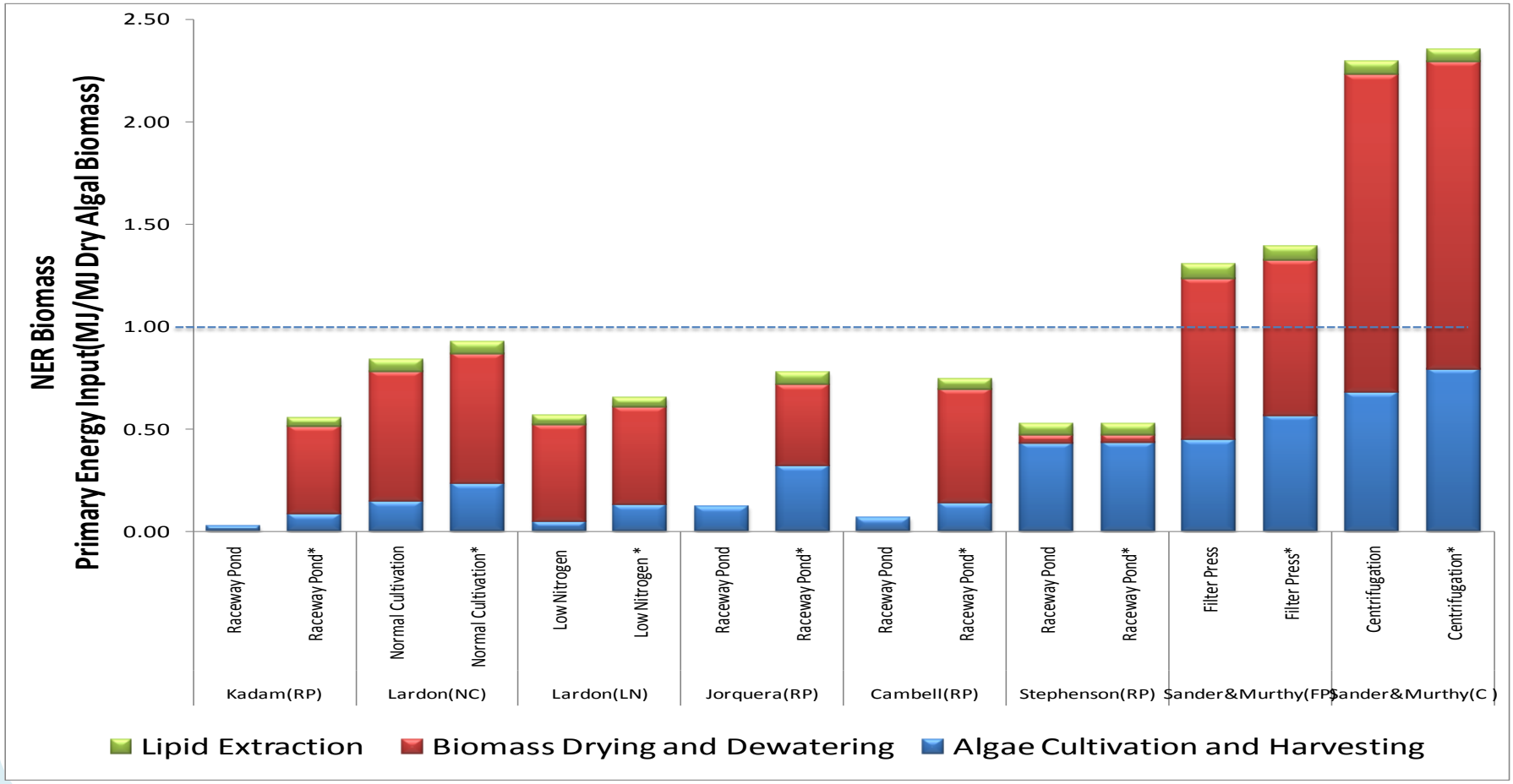


$$NER\ biomass = \frac{\sum Primary\ energy\ inputs(\mathbf{cultivation,\ drying,\ oil\ extraction})}{\sum Energy\ content\ of\ dry\ biomass}$$

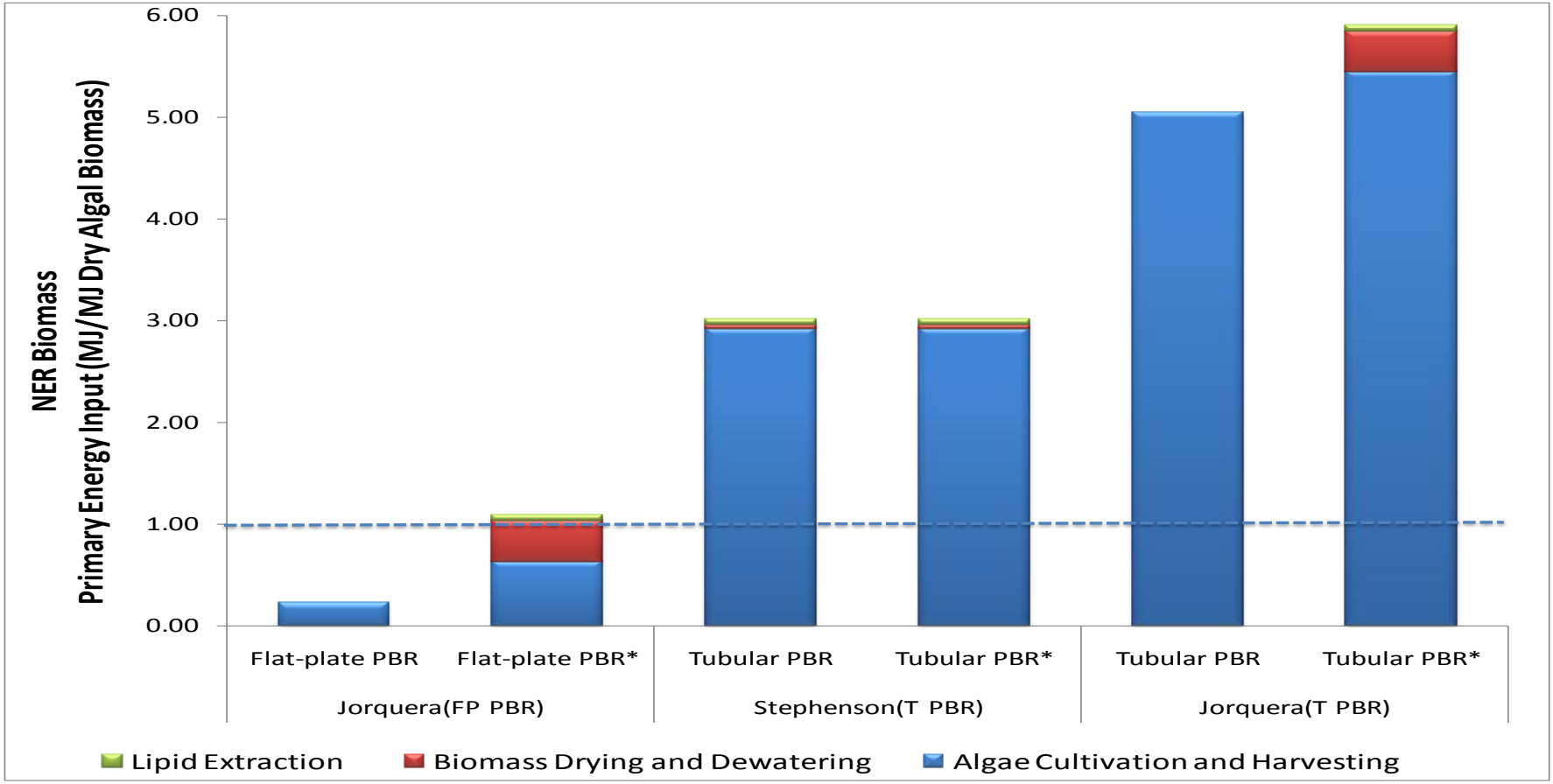
Results: Net energy ratio - Raceway ponds vs. PBRs



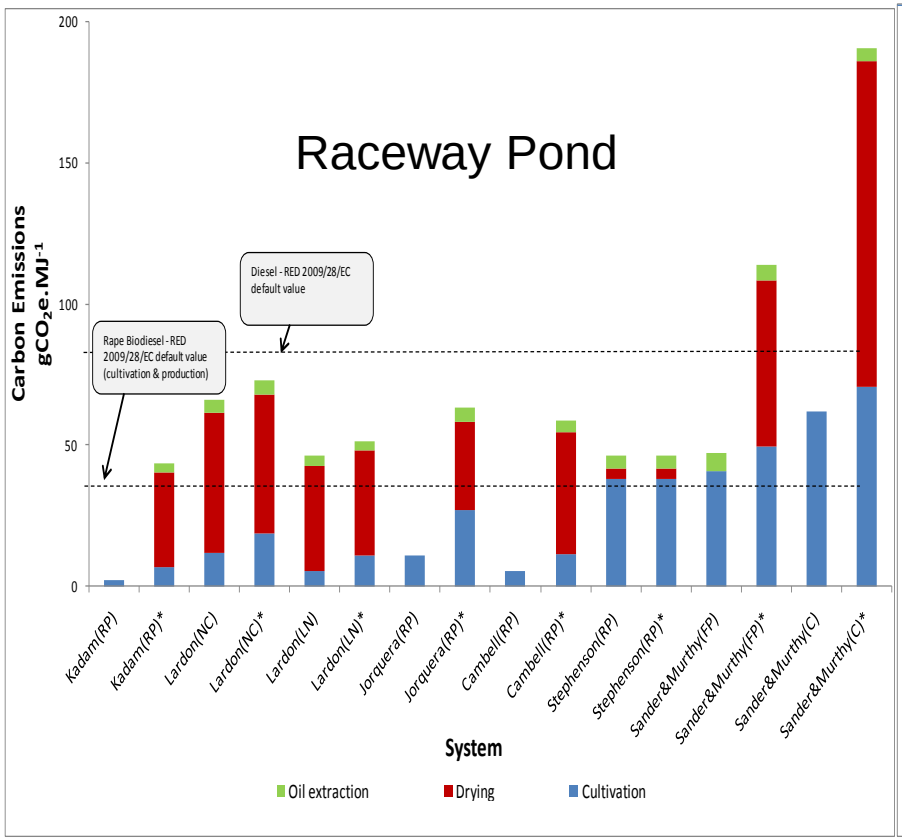
Energy balance: raceway ponds

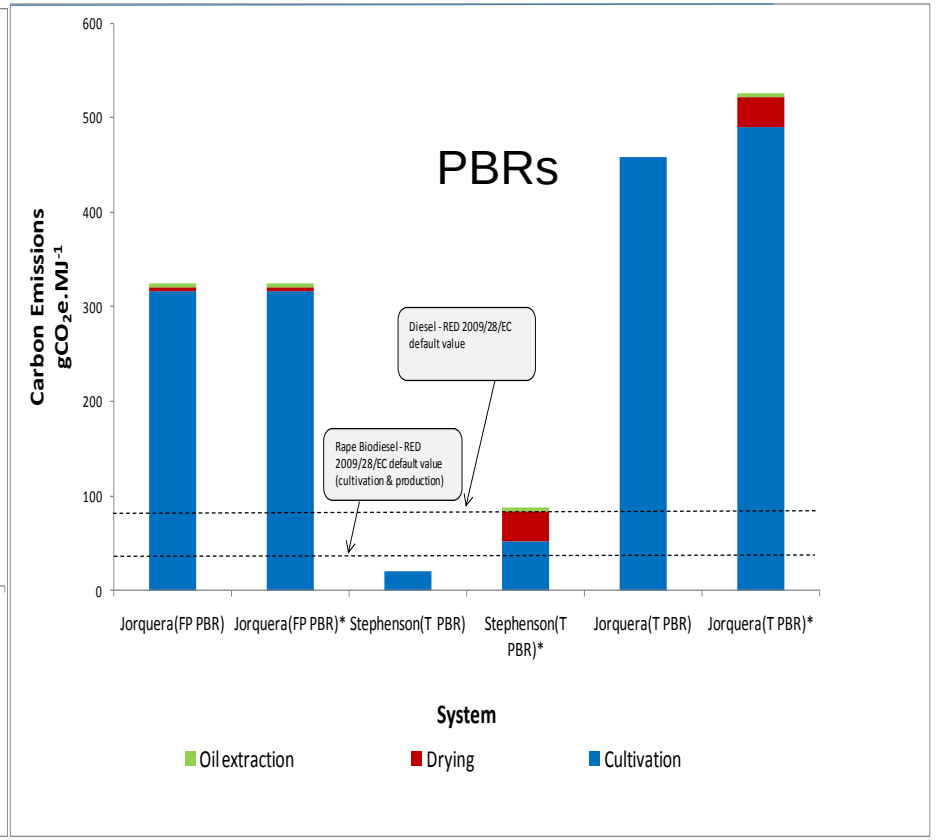


Energy balance: PBRs



Carbon Emissions





Conclusions for micro-algae LCA

- The net energy ratio for biomass production is unattractive, or at best, marginal
  - Production most attractive where energy is not the main product.
  - Raceway Pond Systems have a more desirable NER than PBR Systems
  - Carbon emissions are comparable to conventional biodiesel or worse (main factor = electricity consumption)
- The most optimistic values come from the systems that are the least complete.
  - Process steps not included here, but that might reasonably be added include: embodied energy in flocculant, and hexane loss during lipid extraction.
- Large variation in energy consumed during cultivation and harvesting phase
  - Key factors are: the productivity of the algae, its calorific value and oil content
- Assumptions in the original studies are often obscure, or open to interpretation. E.g. Kadam's nitrogen output is greater than input
- A viable commercial system would need to tackle energy required for pumping,drying and de-watering, embodied energy for construction, and in nutrient supply.

Macro-algae LCA

- No detailed LCA for the energy and carbon balance of macro-algae are available in the literature.
- In contrast to micro-algae, there is extensive experience of macro-algae cultivation in South-East Asia – data collection possible!
- A number of research projects are expected to publish on this subject in the near future (Biomara, Supergen, Energetic Algae).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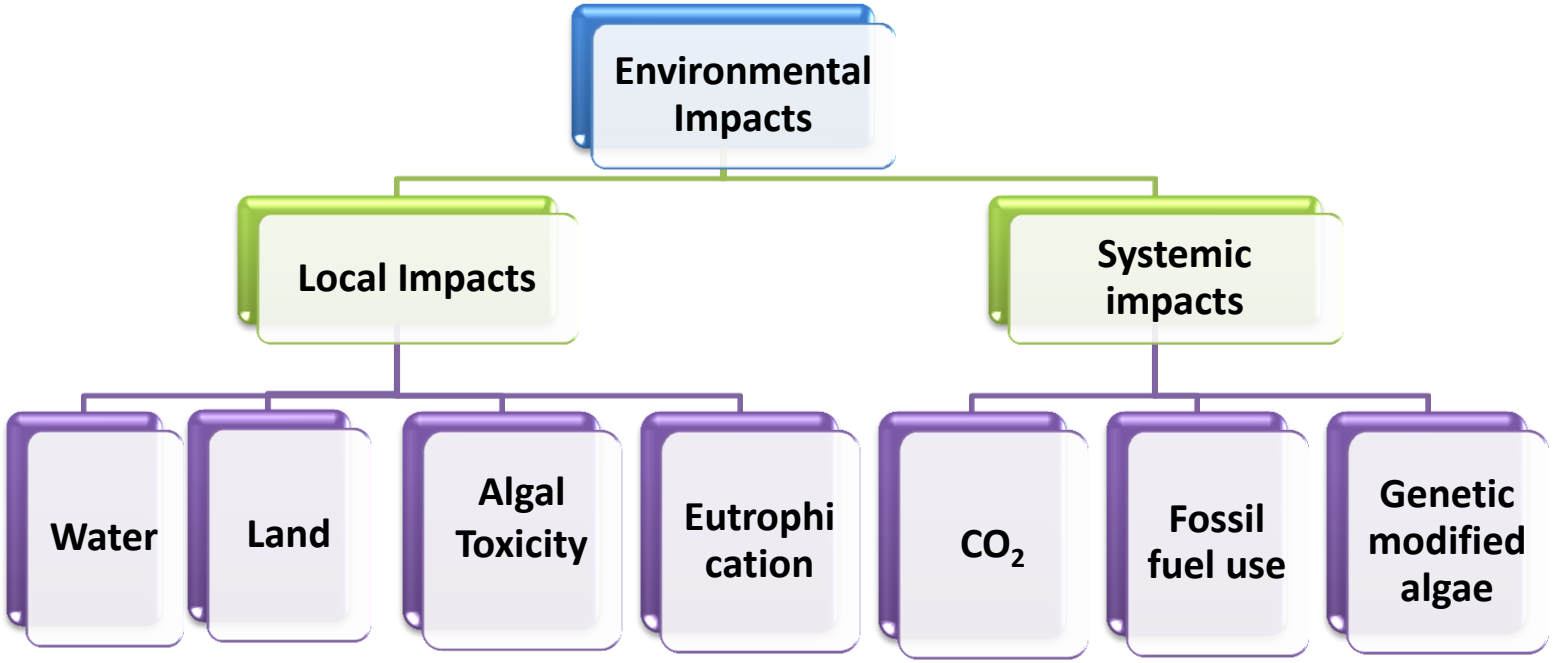
Environmental Impacts

- Environmental impact were identified through literature review and discussion with partners.



Environmental impacts:

Water and land

	Micro algae	Macro algae
Water 	• Evaporation must be compensated • Pumping costs limit height above sea level in seawater systems • Nutrient leakage may cause eutrophication • Use of waste water may limit use of co-products	• Not thought to be a major issue.
Land 	• Possible use of marginal land • Use of impervious soils to prevent pond lining?	• Competition for near-shore sea area

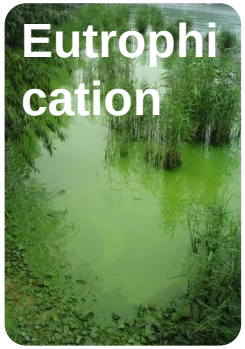
Environmental impacts:

Nutrients and CO_2 fertilisation

	Micro algae	Macro algae
Nutrients 	• Use will be essential • Some scope to use waste water • Some scope to re-cycle	• Fertilisation not practical • Opportunity to mitigate pollution from known sources – e.g. Fish farms
	• CO_2 efficiency a major issue. (many studies assume stochiometric use, but this is unlikely) • Handling large quantities of CO_2 or flue gas at ground level presents an environmental hazard,	• Fertilisation not practical

Environmental impacts:

Eutrophication & toxicity

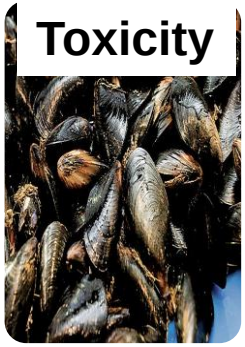


Micro algae

- Release of spent growth media into the environment may be a hazard.

Macro algae

- Possible use in remediation



- Depends on species and cultivation conditions.
- Contamination may be a problem if any products enter the food chain

- Few toxic species
- Potential for contamination of wild harvests

Environmental impacts:

GMOs and wild harvest

	Micro algae	Macro algae
Genetic modification 	• Legal status not clear • Containment not possible in ponds or PBRs	• May be used for strain selection • Containment impossible
Wild Harvest 	• Wild harvest unlikely to be practical	• Kelp is at the bottom trophic level: overharvest could have far-reaching consequences. • Bloom harvest could mitigate environmental damage

Environmental impacts:

Conclusions:

Micro-algae

- Diverse range of impacts. Water, energy and nutrient use are key
- Many impacts are location specific, e.g. water and land use.
- Some impacts are uncertain or may affect what systems are viable in particular legislatures – e.g. some co-products may not be permitted to enter the food chain

Macro-algae

- Little or no use of freshwater
- Integrated cultivation presents an exciting opportunity
- Wild harvest is limited by impacts on ecosystem
- Bloom harvest can mitigate environmental damage

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Economic assessment – micro algae

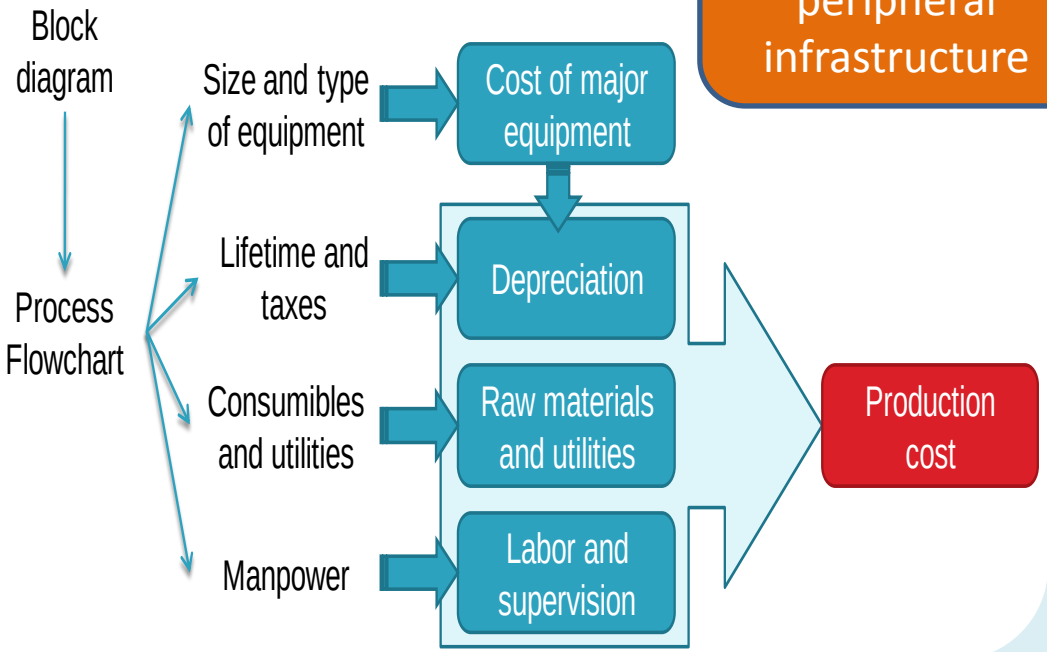
Approach

1. Review the existing economic assessments
2. Develop scenarios for current and future performance
3. Conduct a simple engineering cost model to compare

Studies included in the review

Author
Lundquist, et al., (2010)
Stephens, et al., (2010)
Darzins, et al., (2010)
Richardson, et al., 2010)
Zamalloa, et al., (2011)

Cost model



4 scenarios were developed for raceway ponds and PBRs

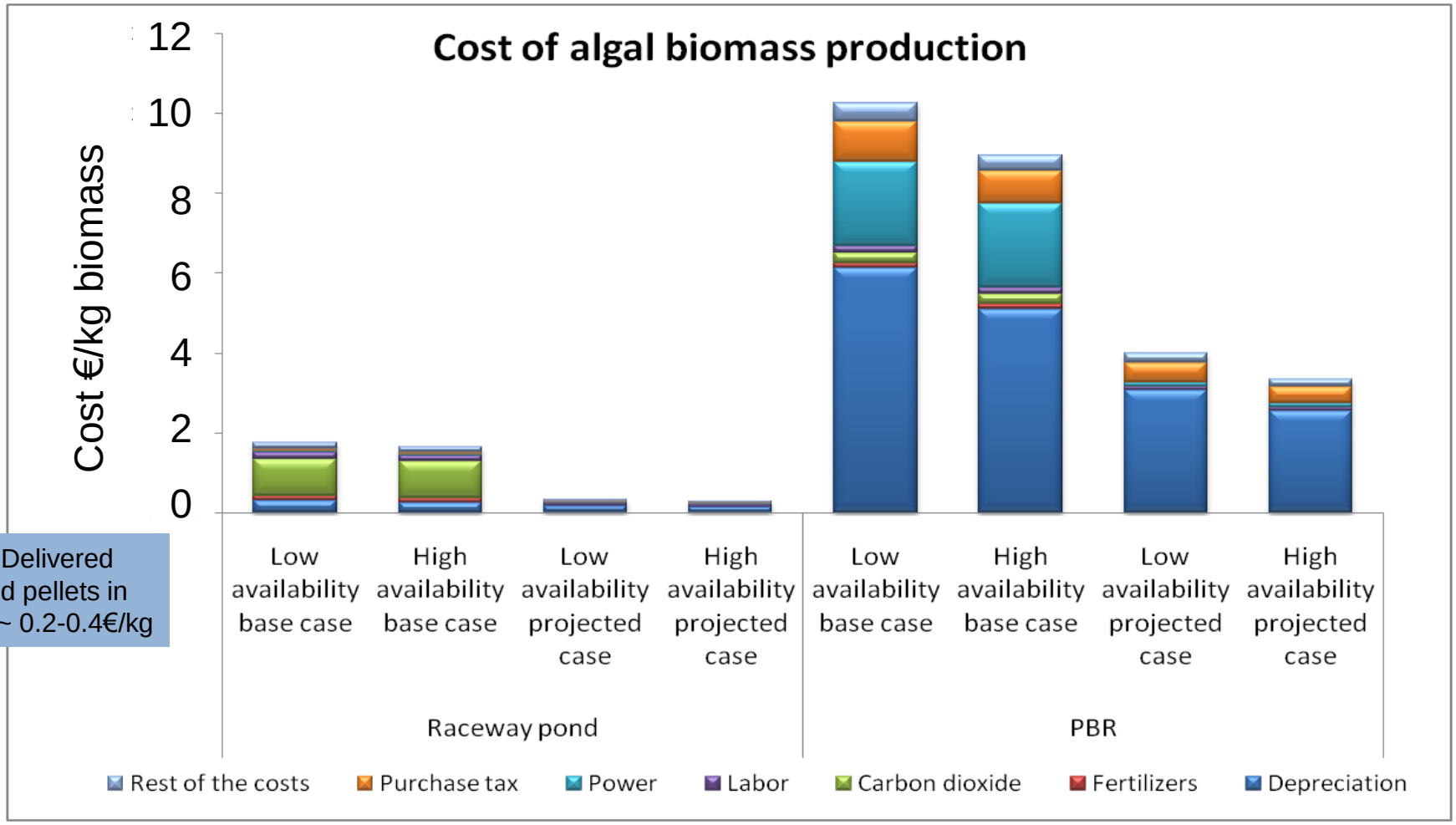
Raceway pond
- 400Ha
- Evaporation 10(L/m^2/day)

PBR
- 10Ha
- Evaporation 0.5(L/m^2/day)

	High availability 300 days	Low availability 360days
Base case	**10 (g/m^2/day)**	**10 (g/m^2/day)**
Projected case*	**20 (g/m^2/day)**	**20 (g/m^2/day)**
Base case	**20 (g/m^2/day)**	**20 (g/m^2/day)**
Projected case † *	**40 (g/m^2/day)**	**40 (g/m^2/day)**

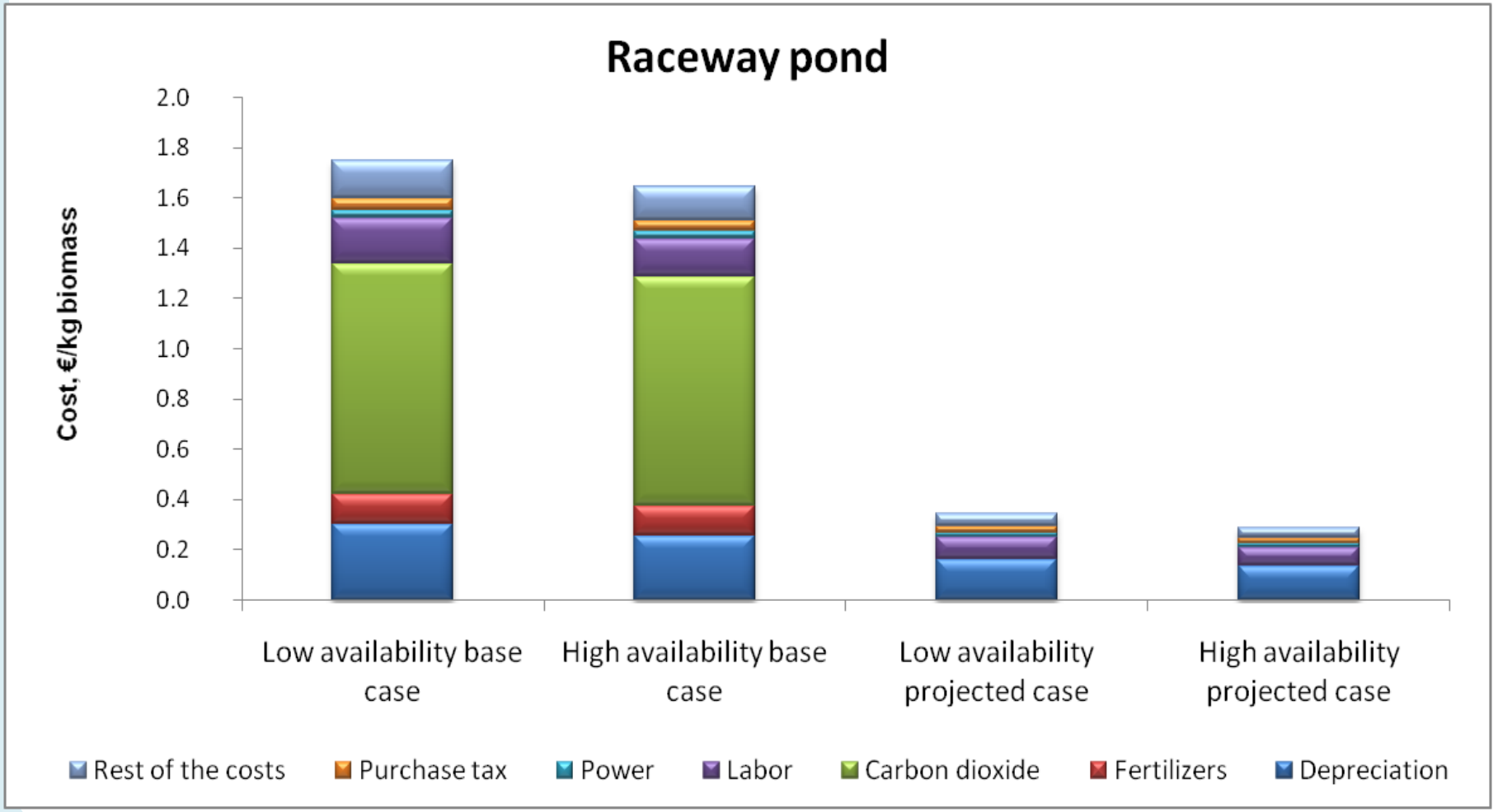
*Cost of water, CO_2, and nutrients not included in projected case.
†Power consumption reduced by 90%

Results:

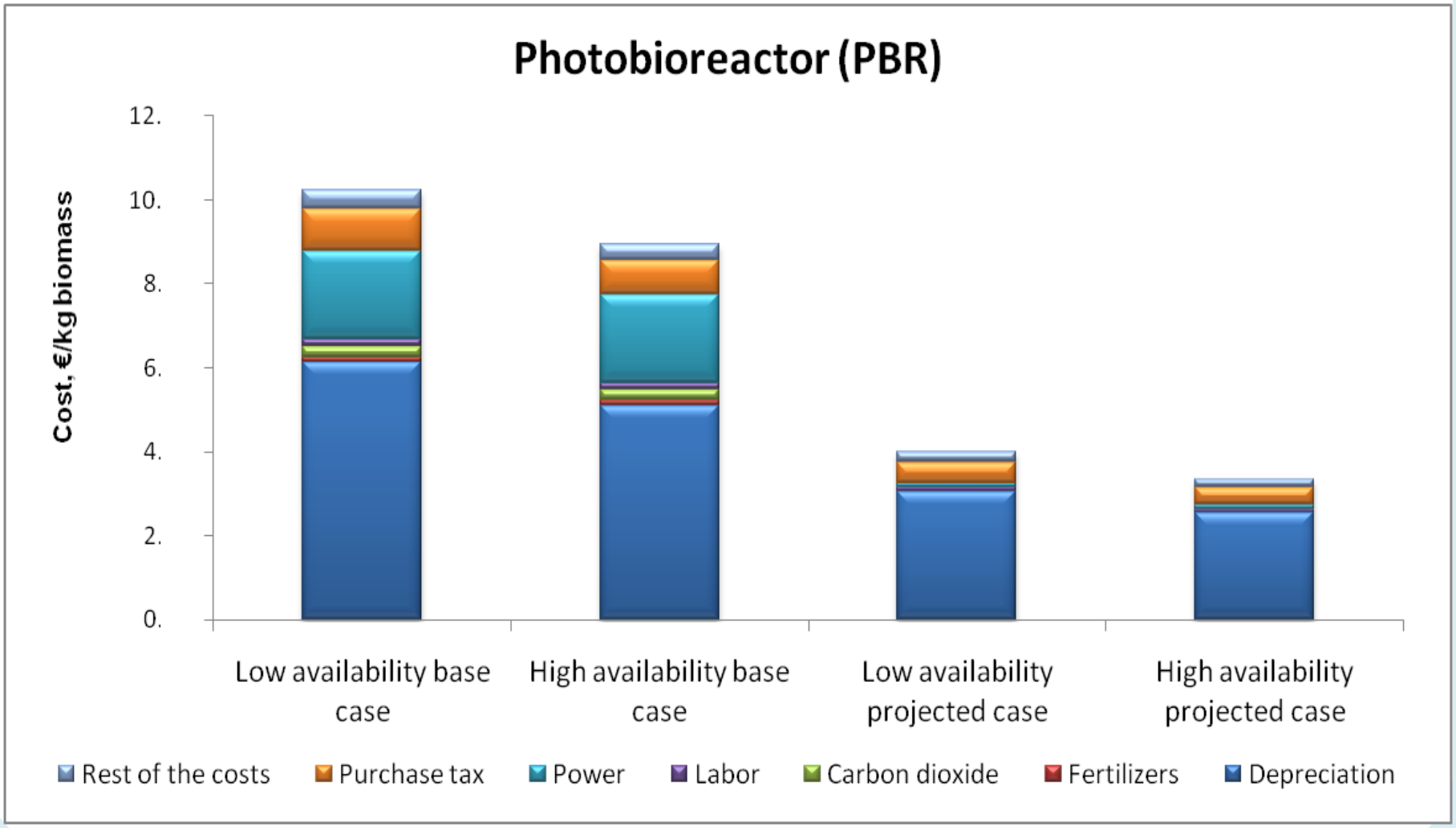


Cf. Delivered wood pellets in UK ~ 0.2-0.4€/kg

Results: Raceway pond



Results: PBR


Photobioreactor (PBR)
Cost, €/kg biomass
12.
10.
8.
6.
4.
2.
0.
Low availability base case
High availability base case
Low availability projected case
High availability projected case
Rest of the costs
Purchase tax
Power
Labor
Carbon dioxide
Fertilizers
Depreciation

Economic assessment

Conclusions

- Current cost analyses are appropriate to guide engineering development and test the sensitivity of design assumptions only. They cannot inform policy or investment decisions (better data needed)
- Raceway pond systems demonstrate lower cost production than PBRs
  - Raceway ponds: operating costs dominate
  - PBRs: capital costs dominate
- Dramatic improvements in *productivity* and *energy efficiency* required to reduce biomass production costs.
  - Significant (>50%) cost reductions may be achieved if CO_2, nutrients and water can be obtained at zero cost. But this is a very demanding assumption!
- Compared with other sources of biomass used for energy, algal biomass appears expensive (but the composition is more interesting)

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Overall conclusions

- Micro and Macro algae can produce a fascinating range of products – but biofuels are best viewed as a co-product.

- The viability of micro-algae for biofuels requires a leap of faith and imagination
  - The evidence in the public domain does not rule it out, but neither does it give a strong endorsement

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Thank you for your attention