Pall Corporation

Membrane Harvesting Technology
Algae Separation & Concentration

Enabling Industry Solutions

BIO – Pacific Rim

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Content

- **Pall Algae BioMass Program**
  - **Dewatering using Membranes**
- **Research and Modeling Scale System (RAMs)**
- **Algae Separation & Concentration Filter (ASCF)**
- **Commercialization**

Pall Algal BioMass Program

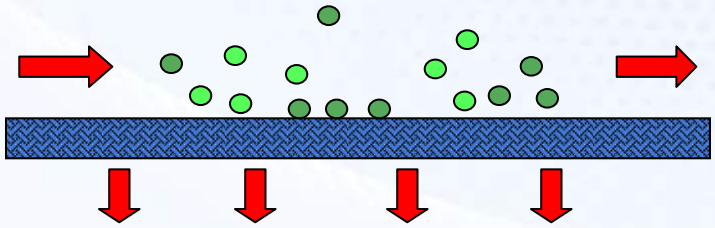
- **Pall's Algal BioMass Process Development Program has been finding solutions for technology developers for over 6 years**
  - **Industry Need**
    - **Low energy means of DeWatering harvested algae**
    - **Ability to manage water resources (scarcity)**
    - **Ability to manage nutrients**
    - ⇨ **Technology must be scalable**
  - **For some applications**
    - **Undamaged cells (viability)**
    - **DeWatering without chemicals**
    - **Control over the algae slurry concentration**
- **Pall's membrane based Algae Separation & Concentration approach meets these industry requirements**

Algal BioMass Membrane Applications

- **Water mining for make-up water with MF**
- **Algae BioMass concentration with membrane systems**
  - **Research, Pilot & demonstration scale commercial systems**
  - **Water & Nutrient management**
  - **100% BioMass harvest yield**
  - **Preconcentration step before high solids device**
  - **Recover BioMass from secondary DeWatering equipment**
    - **water & nutrient recycle**
  - **Maintain optimal concentration in Waste Water remediation**
  - **Microfiltered growth medium for inoculation use**

•**Crossflow Filtration -** Flow is parallel to membrane

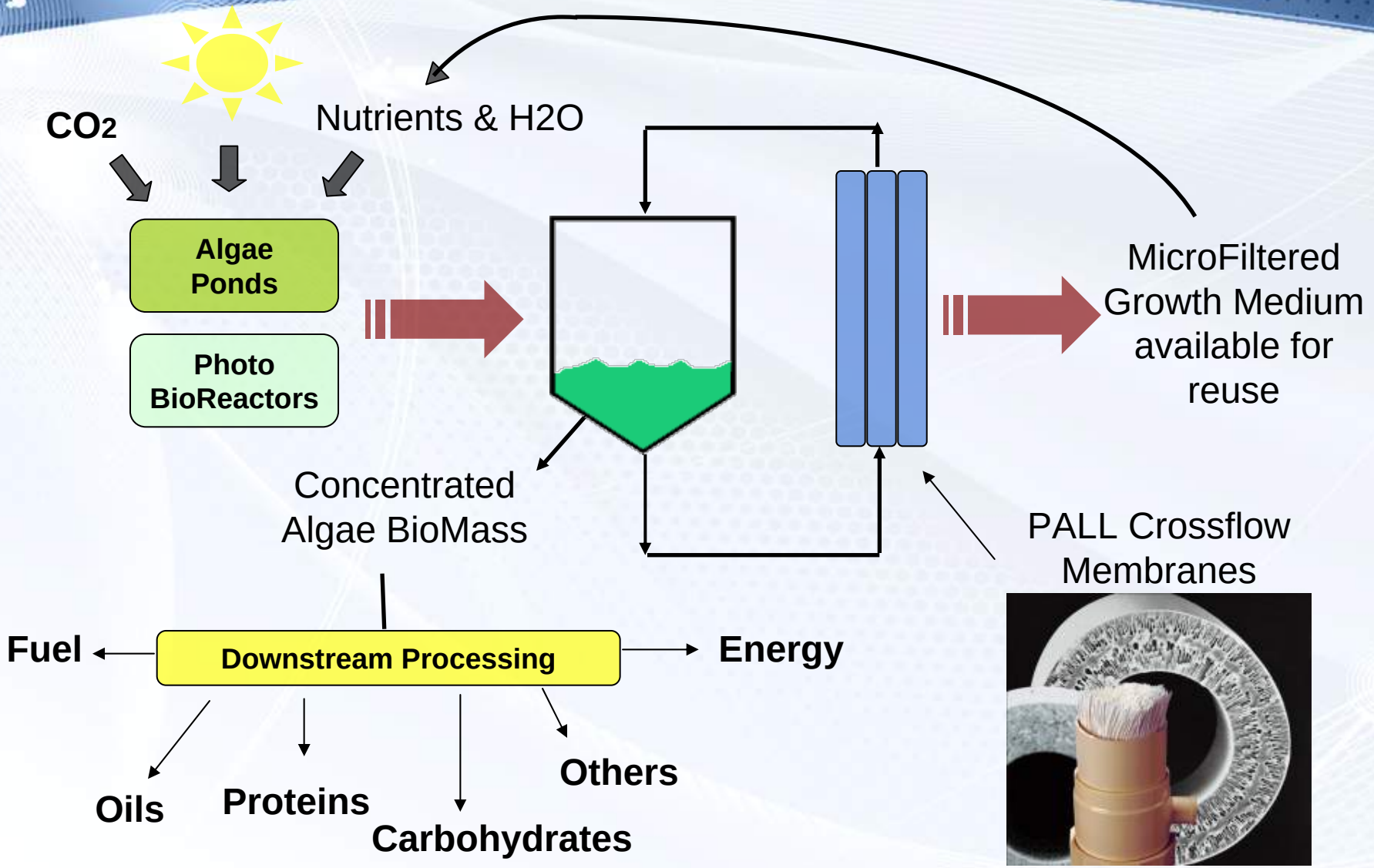
Dilute Algae From Growth System



Concentrated Algae

Filtered Growth Medium

Algal BioMass Concentration Application



Algal Membrane Processes – Where to Start

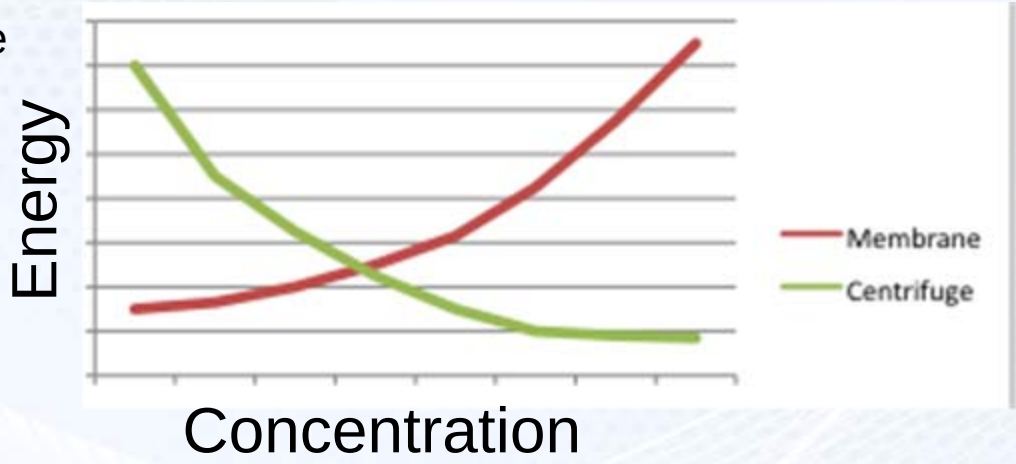
BioMass End Use Determination :

- **Concentration & Consistency**
  - Final Concentration of BioMass Slurry
  - Degree of DeWatering Required
- **Downstream Processes**
  - Aqueous Extraction
  - Hydro Thermal Liquefaction
  - Fermentation
- **Consistency**
  - Slurry
  - Paste
  - Dry

Process Design

- **The degree of DeWatering required will be determined by the downstream processing of the BioMass**
- **Combination of technologies may be needed to optimally achieve the final desired concentration**
- **Goal: Thickened paste or dry products**
  - Membranes used as a pre-concentration step
  - Additional unit to perform the final concentration
    - Centrifuge for thickened paste
    - Belt filter for dry flake
    - Spray drier for dry powder

  ⇨Energy Efficient Approach



- **Goal: Thickened slurry**

  Membranes can be used to provide a slurry with a consistent concentration for downstream processing

Pall Experience – Specific Energy Consumption

Concentration at Harvest 0.5 g/l dry weight	Concentration at Harvest 10 g/l dry weight
Concentrated to 60 g/l Specific Energy < 0.5 kW-hr Per M3 of Harvest < 1.0 kW-hr Per Kg of BioMass	Concentrated to 60 g/l Specific Energy < 0.7 kW-hr Per M3 of Harvest < 0.07 kW-hr Per Kg of BioMass
Concentrated to 100 g/l Specific Energy < 0.6 kW-hr Per M3 of Harvest < 1.2 kW-hr Per Kg of BioMass	Concentrated to 100 g/l Specific Energy < 1.4 kW-hr Per M3 of Harvest < 0.14 kW-hr Per Kg of BioMass
Concentrated to 200 g/l Specific Energy < 0.7 kW-hr Per M3 of Harvest < 1.4 kW-hr Per Kg of BioMass	Concentrated to 200 g/l Specific Energy < 1.7 kW-hr Per M3 of Harvest < 0.17 kW-hr Per Kg of BioMass

Crossflow system design and operation can be optimized for low energy consumption

Harvest concentration impacts CAPEX & OPEX

Algae Concentration Membrane Systems

- **Membrane approach has been compared directly with:**

Dissolved Air Flotation (DAF):

Higher BioMass concentration than DAF
No need for flocculation chemicals
Lower overall energy
100% algae harvest yield
Water & nutrient recycle

Centrifuges:

Much more energy efficient than Centrifuges
Considerably less maintenance required
100% algae harvest yield
Water & nutrient recycle

Evaporation:

Significantly lower energy than evaporation (unless waste heat)

ASCF is Competitive & Robust:

Cost competitive (CAPEX)
Lower OPEX (Energy)
Small footprint
Less stringent civil infrastructure requirement
Lower labor requirement with lower skill level
Scalable (Perfect for preconcentration)
Control over slurry concentration
Cell viability & higher quality BioMass

Energy consumption with membranes <0.5 – 1.0 kW-hr per cu meter harvest processed

Algal BioMass Concentration Landscape

		Pall Algae Separation & Concentration Filter (ASCF)	DAF	Centrifugation	Settling	Belt / Press Filtration
CAPEX	Equipment Scope	Medium/High	Low/medium	High	Low	Medium
	Infrastructure	Low	High	Very High	Low	Low
	Footprint	Medium	High	Medium	Very High	Low
OPEX	Energy	Low	Low/medium	Very High	Low	Low/medium
	Chemicals	Low	Very High	Low	Low	Low
	Labor	Low Skill	High Skill	High Skill	Low Skill	Low Skill
	Maintenance	Low	Medium	High	Low	Low
Harvest	Harvest Yield	100%	90%	95%	90%	90%
	BioMass [ ]	20% - 25%	4% - 6%	30%+	2% - 5%	25%
	Degree of DeWatering	High	Low	Very High	Low	High
	Control of Slurry [ ]	Very High	Low	Low	Low	Low
Quality	Water & Nutrient Recycle	Very High	Low	Low	Low	Low
	Solids & BioMass in Growth Medium	No	Yes	Yes	Yes	Yes
	Microfiltered Growth Medium	Yes	No	No	No	No
	BioMass	Very High	Medium	Low	Medium	Medium
	Cell Viability	Very High	Medium	Low	High	Low
Scalability		Very High	High	Medium	Low	Low

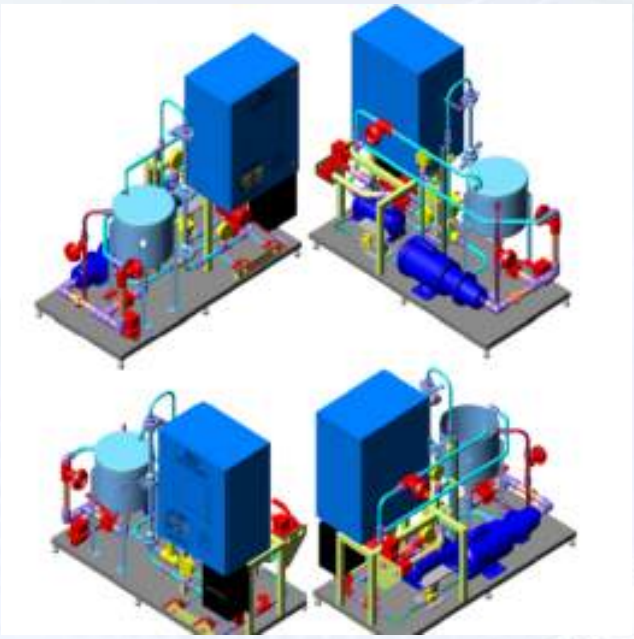
Collaborative & Paid Development Programs

- **Development Program phases**
  - **Research & Modeling**
  - Field Evaluation
  - Pre-commercial
  - Commercial

Research & Modeling scale (RAMs) System

Research & Modeling scale (RAMs) System

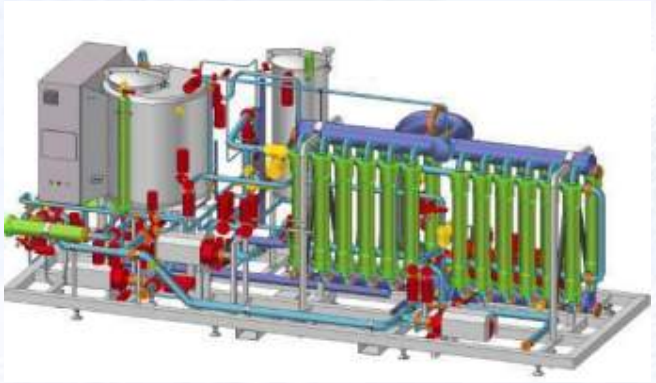
- Cost effective method for evaluating membrane Concentration of Algal BioMass
- Eliminates costly “Trial and Error” experiments with “Fit for Purpose” design
- Provides budgetary guidance for pilot & commercial scale systems
- Minimum amounts of fluids required
- Flexible to test various membrane types
- Enables early Algal DeWatering feasibility forecasting for the process or project



Process & Application Scale Up

RAMs → Field Evaluation → Commercial Scale

- Field Evaluation system designs and purchase specifications evolve from the data generated during Research & Modeling phase
- Process Optimization with Field Evaluation Systems
- Pall experts are available for process consultation and continuously refine the model for commercial economics
- Utility requirements can be predicted from the data generated
- All process development work is treated as “confidential”
- Evaluation reports are scientifically supported



Algal Separation & Concentration Filter (ASCF) Systems

Four customer programs have progressed to the Field Evaluation phase

Field Evaluation ASCF 2nd stage concentration & lower volume processing 1000 liters/shift

Combined Primary & Secondary Concentration on a single skid Field Evaluation ASCF 1 – 2.5 m^3/hr

Field Evaluation ASCF for Primary concentration & high volume processing 7.5 – 38 m^3/day

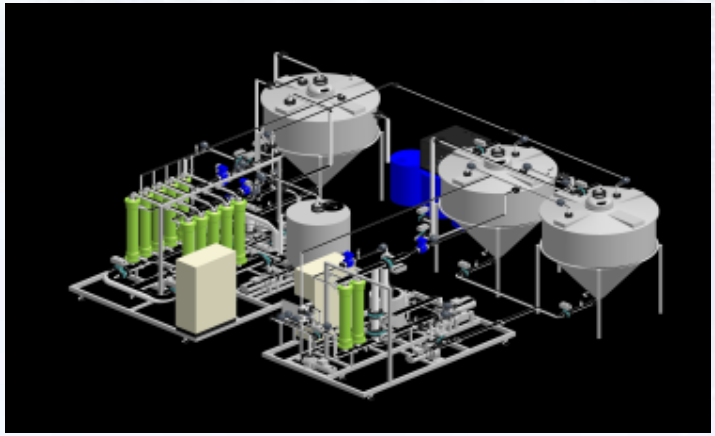
ASCF systems shown during FAT

Pall Development Program Experience

- **Research scale projects globally total 20 and counting**
- **Field Evaluation scale projects**
  - **Demonstration of concentration to customer requirements**
    - **Concentrate to 140 g/l for wet extraction**
      - Membrane approach evaluated against DAF + Centrifuge
      - No changes in membrane performance
    - **Preconcentration to 60 g/l prior to centrifuge DeWatering**
      - 60+ concentration cycles over 6 months
      - No changes in membrane performance
      - Recycling of growth medium into process
        - Water and nutrient management benefits
      - < 0.5 kWhr per cu meter harvested
    - **Multistage membrane concentration**
      - 200 g/l demonstrated with
      - Energy input < 0.7kWhr per cu meter harvested
    - **Maintenance of optimal Algae concentration for Waste Water**
- **Pall Aria™ pilot on waste water feeding algae growth systems**

Pall Commercial Algae Project Experience

Three technology developers have chosen Pall ASCF for their commercial projects



- 8 m^3 per hour of harvest
- 15 m^3 per hour of harvest
- 14 m^3 per hour of harvest

One technology developer has chosen Pall Aria™

- Commercial Aria™ system sold for Pond water make-up

Summary

- Pall Algal BioMass Concentration Program in 6th Year
- Program is Enabling Energy Efficient BioMass Harvest
- 100% Algae BioMass Harvest – Perfect for Preconcentration
- Enables Water & Nutrient Recycle
- Systems Optimized for Low Energy Consumption
- Systems Design Modeling and Project Economic Forecasting Capabilities
- Systems Scale to Large Commercial Sizes
- Process Developers are Deploying for their Commercial Projects

ENABLING A GREENER FUTURE

Questions?

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Pall Total Fluid Management
Process & Application Development Programs
Providing Solutions to Algal BioMass Technology Developers