

Bioresources & Bioenergy: About hypes & mavericks

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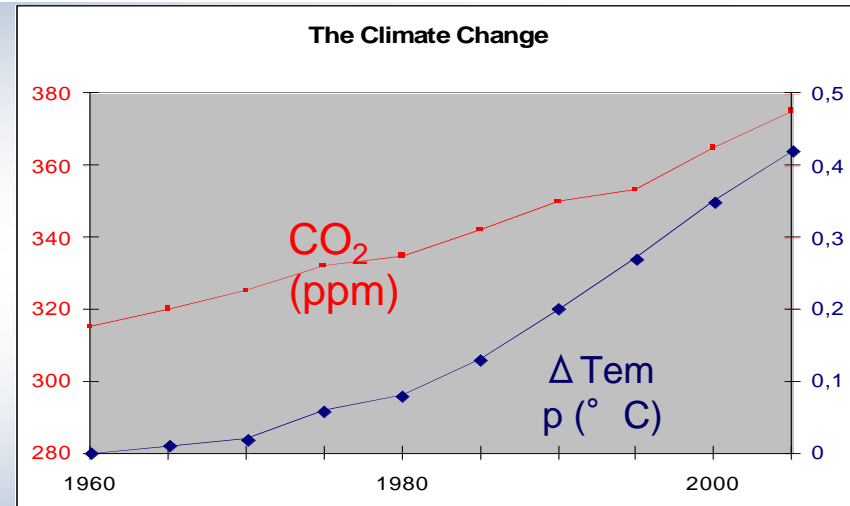
Frebr 2012

LabMET

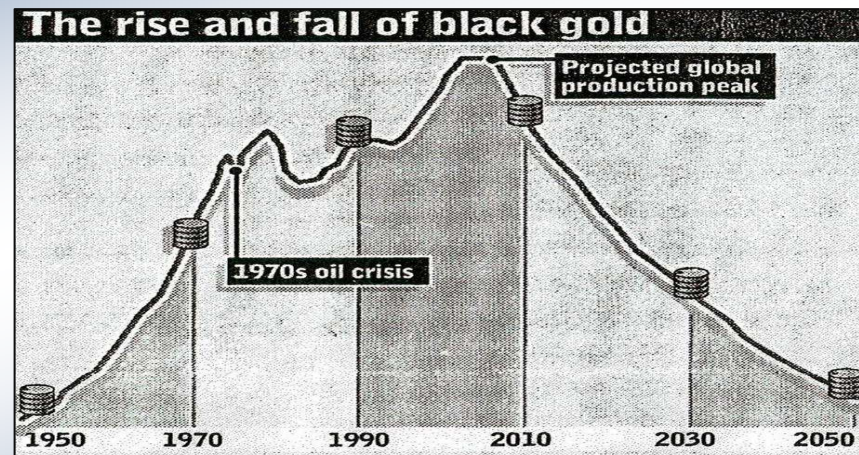


THE SUPERCHALLENGES OF THE 21st CENTURY

- ❖ Climate change:
 - ➔ Dramatic ecological changes



- ❖ Energy supply
 - ➔ The depletion of fossil fuel



Cambell and Laherre, 1999: *The coming oil crisis*

THE SUPERCHALLENGES OF THE 21st CENTURY

- ❖ Health & Diseases : Bird flu, Asian flu, ...
 - ↳ Pandemics, MAR/ESBL, ...
- ❖ Sustainable environment
 - ↳ Major wars for drinking water to be expected about 2020
(Pentagon report 2004)



Question: What has microbial biotechnology to offer in these domains?



Outline

□ **Hypes :**

- *The algae

- *Synthetic biology

- *Bio electrochemical systems

□ **Mavericks :**

- *The biorefinery

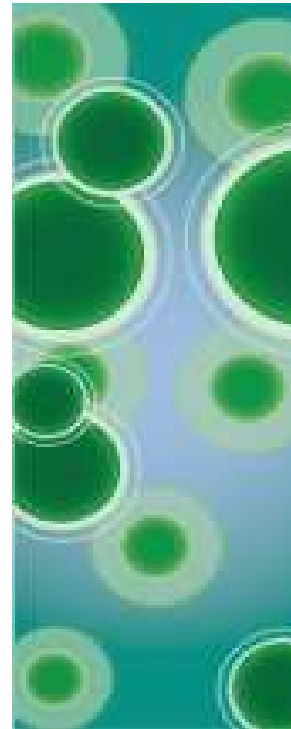
- *Bio(nano) catalysts/materials

- *Microbial upgraders

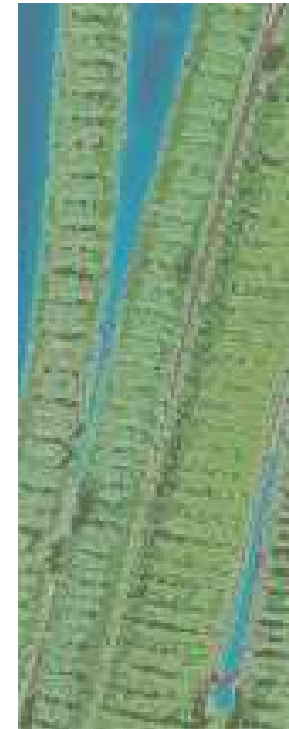


Hype 1: Algae feedstock

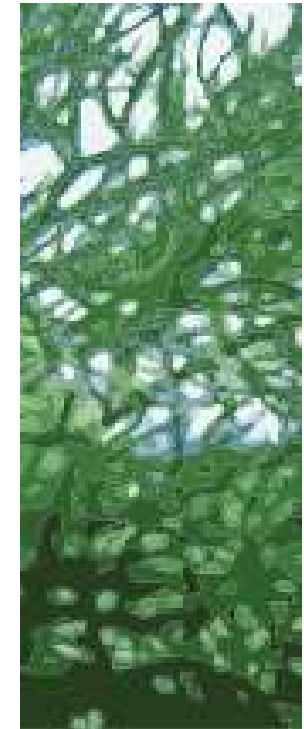
- Photosynthetic organisms
- No competition for food crops
- No need for freshwater
- No pesticides and herbicides
- Varying concentrations of carbohydrates, lipids, proteins...
- Biomass free of lignin



Microalgae
(5 – 50 μm)



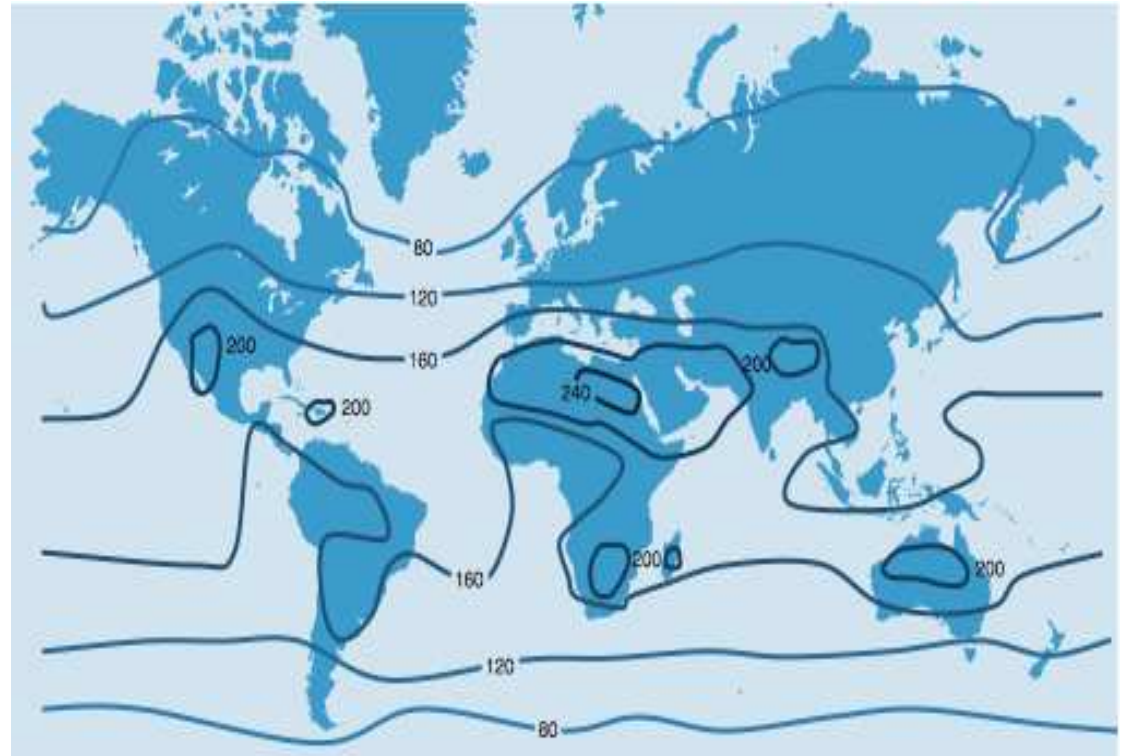
Cyanobacteria
(5 – 50 μm)



Macroalgae
(multi cellular
+ thallus)

Productivity

- Algae photosynthetic efficiencies in practice close to 4-5% vs 3% for terrestrial crops
- Outdoor productivities achieved between 40-80 ton DM ha⁻¹ a⁻¹
(*Richmond, 2004, ISBN: 0632059532;*
Sheehan et al., 1998; US NREL)
- **Unreasonable** targets:
100-227 ton DM ha⁻¹ a⁻¹
(*Schenk et al., 2008; Bioenergy Res. 1, 20-43; Stephens et al. 2010; Nat. Biotechnol. 28, 126-128*)



World map of estimated algae productivity (ton DM ha⁻¹ a⁻¹) at 5% photosynthetic efficiency

(*Tredici, 2010; Biofuels 1, 143-162*)

Cultivation systems

- Currently, there are two main cultivation systems
 - Open ponds (raceways) *Photobioreactors (PBR)



(Cyanotech; Kona, Hawaii;
www.cyanotech.com)



(Bioprodukte Prof. Steinbery;
Germany, www.algomed.de)

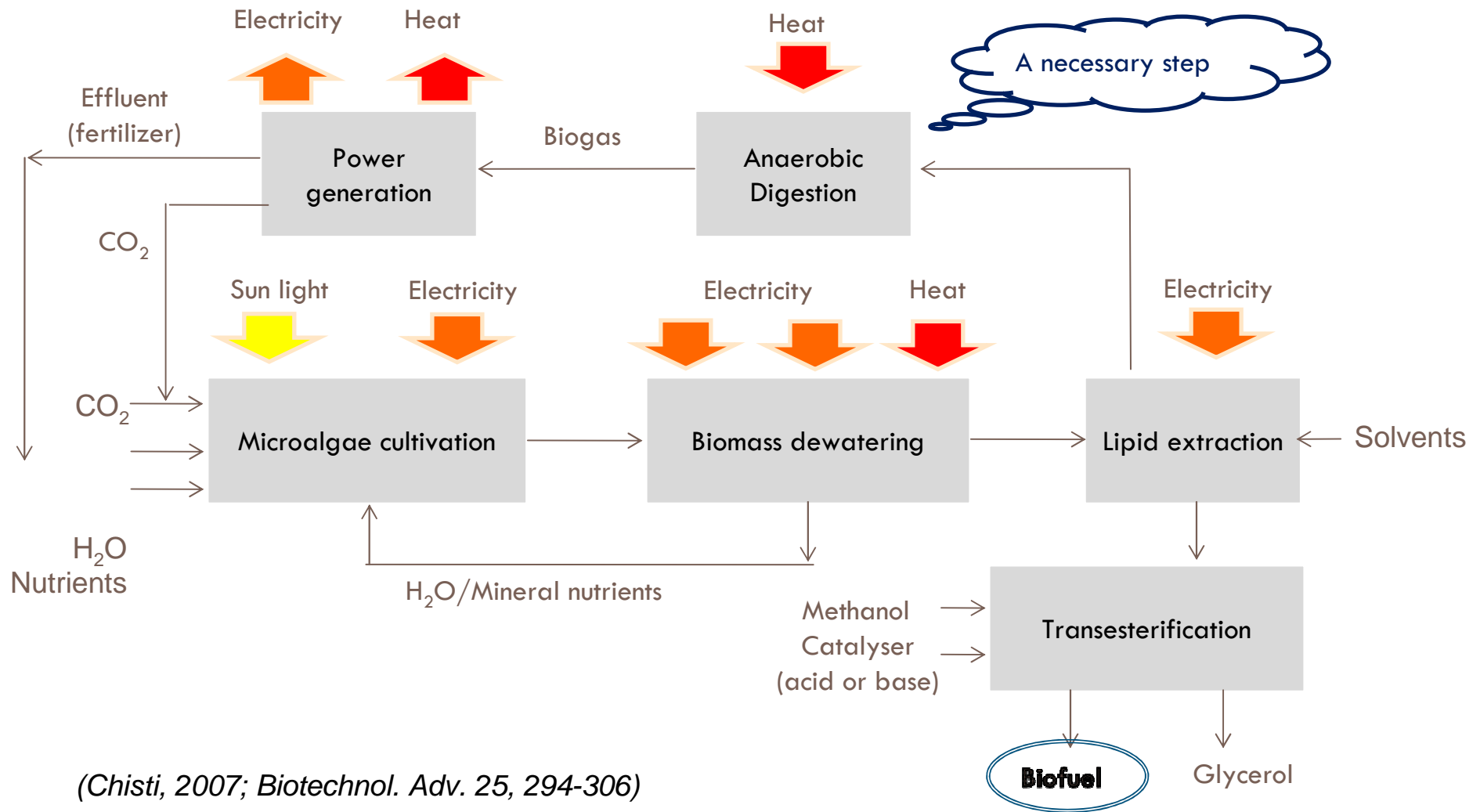
Players & Products (C&EN 2011; nr. 29)

<u>Firm</u>	<u>Technology</u>	<u>Product</u>
Solazyme	Heterotrophic dark algal production on sugarcane feedstock	*Biodiesel *Skin cream (alguronic acid) *Algal flour with Roquette *Fine chemicals with Bange (Br)
Cellena	Photobioreactors & ponds	*Neutraceuticals *Oleo chemicals
Algenol (Dow)	Photobioreactors	*Ethanol and propylene in headspace
Sapphire Exxon Mobile- Synthetic Genomics; BP-Energy Bioscience	Open ponds with synthetic biology	*Fuel oil

The only money makers thus far are the “dark algal” producers



Conventional biofuel chain:



(Chisti, 2007; *Biotechnol. Adv.* 25, 294-306)

(Wiley et al. 2011; *Wat. Env. Res.* 83; 326-338)

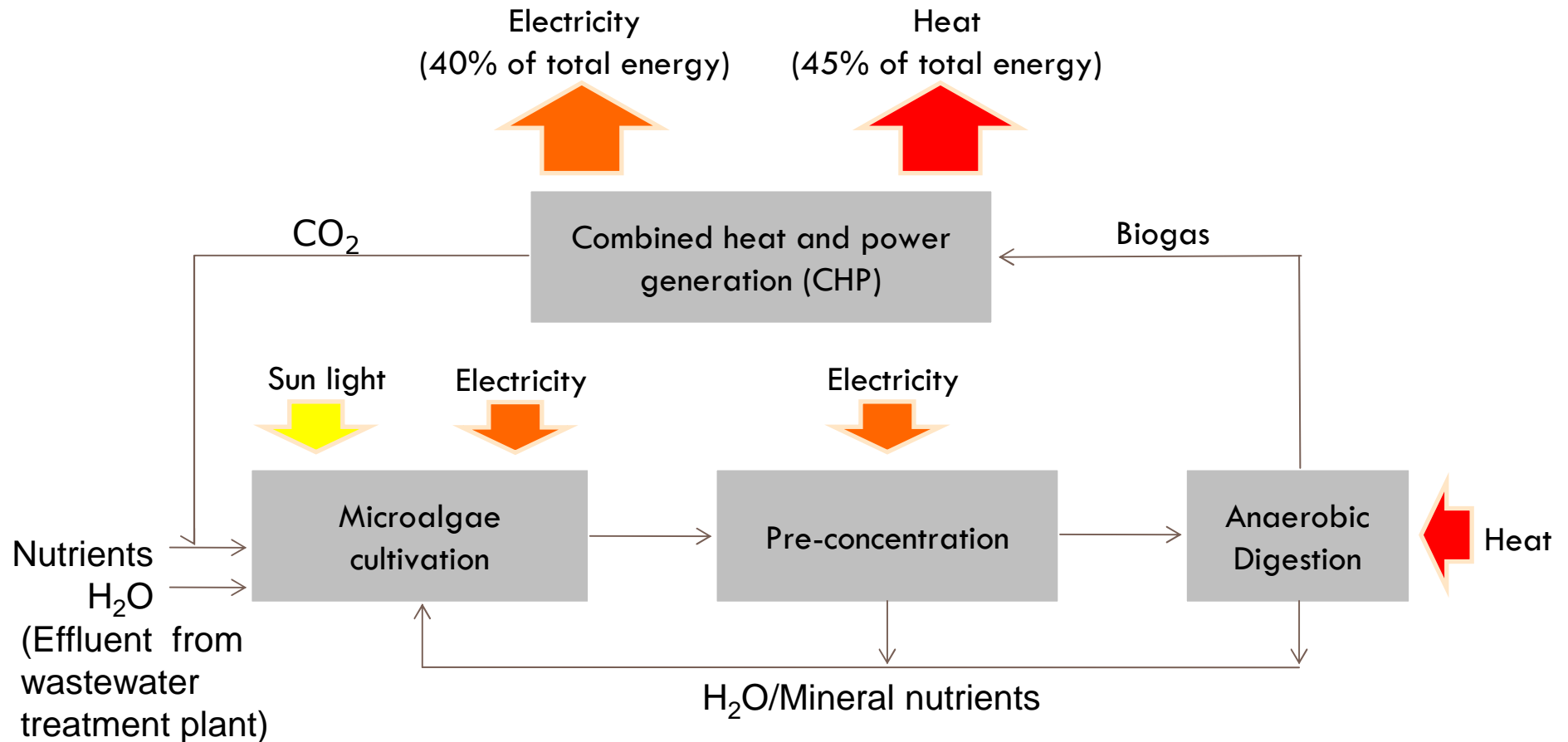
The scum solution (Savage, 2011, Nature 474: 15-16)
(Murphy & Allen 2011, EST 45: 5861-
5868)



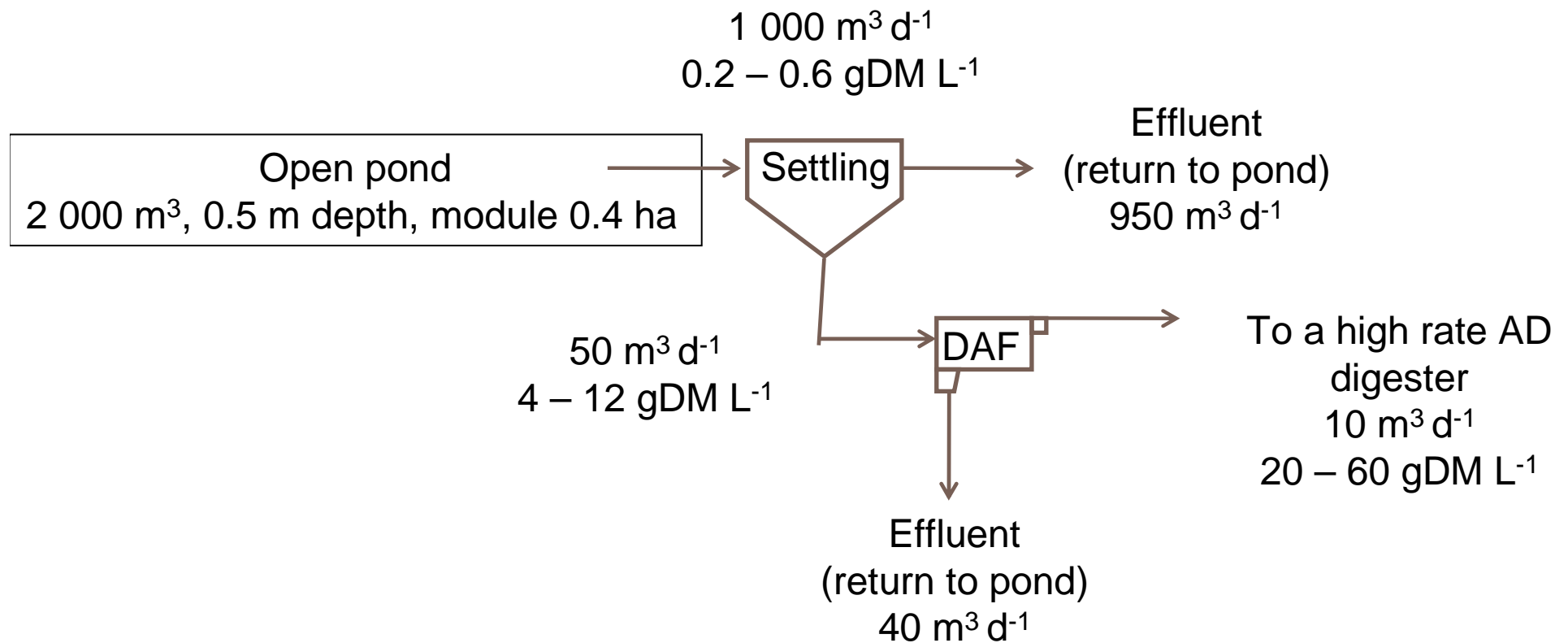
Take home: Biomass equivalent energy demand
to pump water 1 ton DM/ha.yr
harvest 4 ton DM/ha.yr
process as 40 ton DM/ha.yr (!)
liquid fuel

Note : Total max. 80 ton DM/ha.yr !

LabMET algae to biogas concept



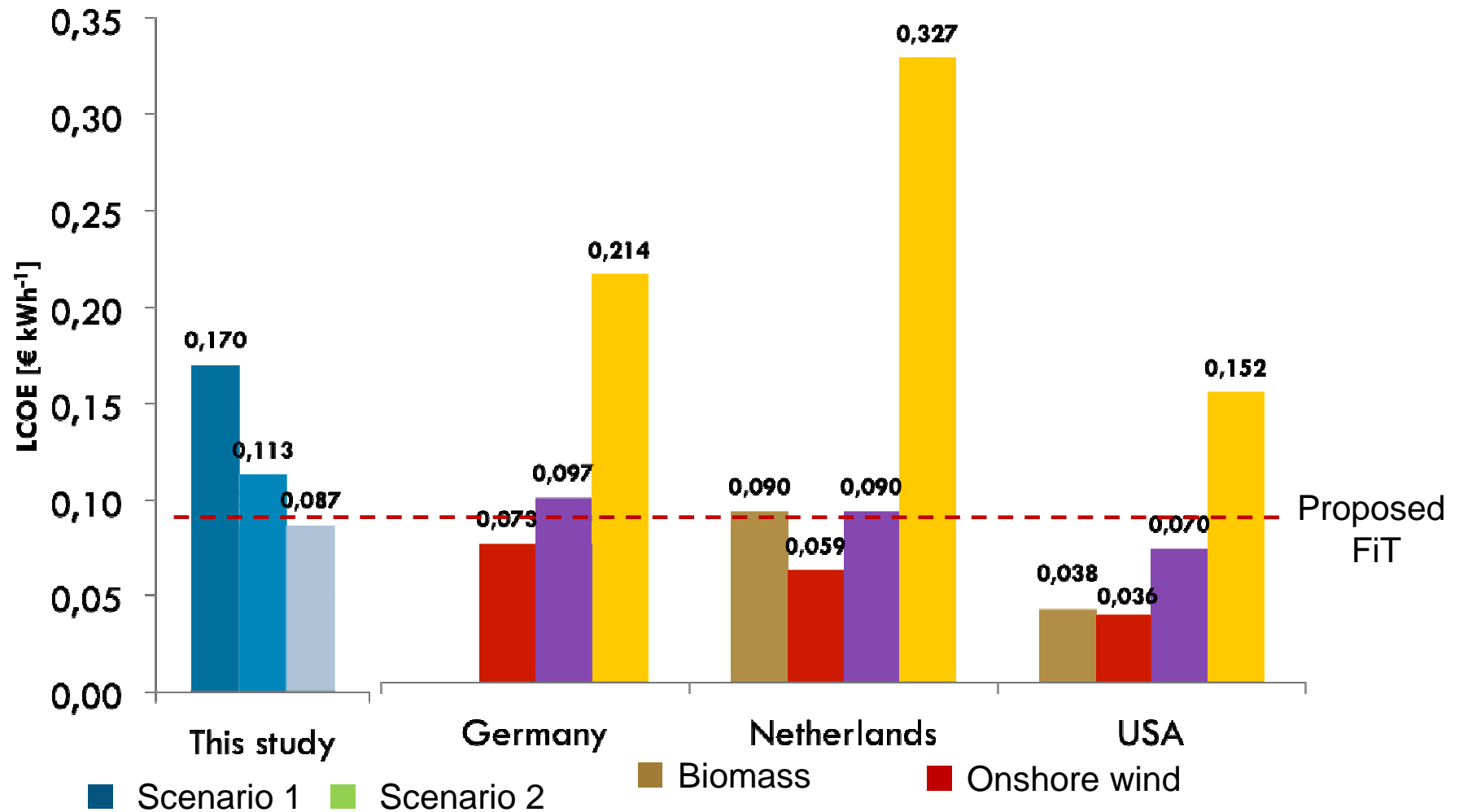
LabMET algae to biogas concept



(Adapted from Benemann and Oswald ,1996; *US DOE*)



Comparison of levelised cost of electricity



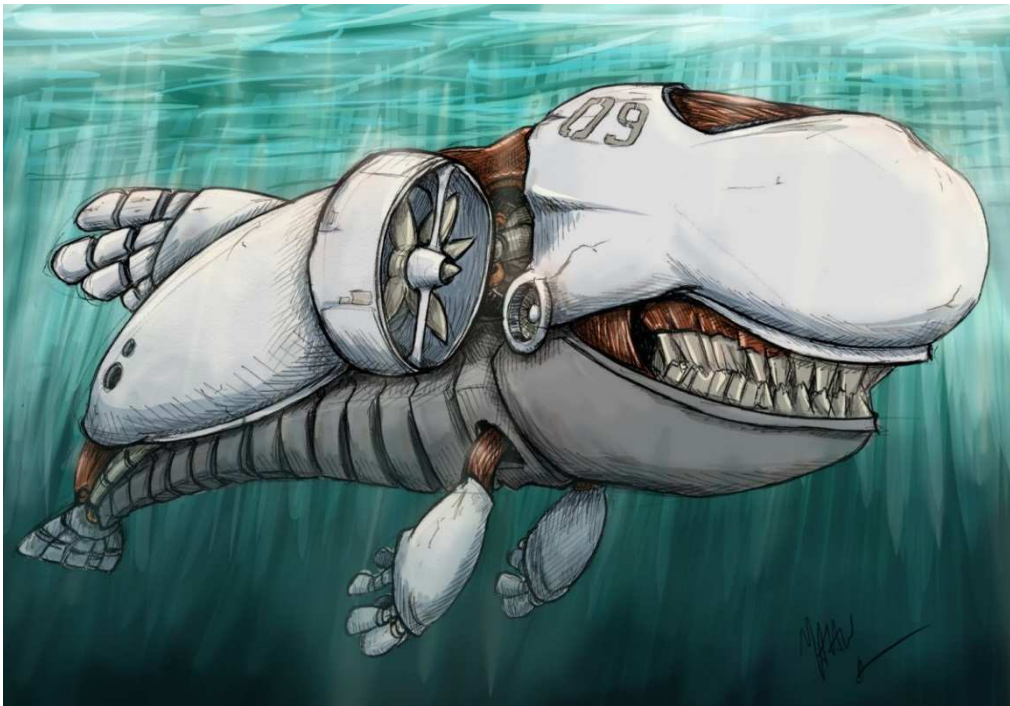
Take home: Energy from algae is not so bad relative to other green sources.

(IEA, 2010; ISBN: 9264084304)



Conclusion hype 1: The algae

- We need to search for:
 - Algae which float better
 - Algae which harvest and process easily
- Serendipity is key!!



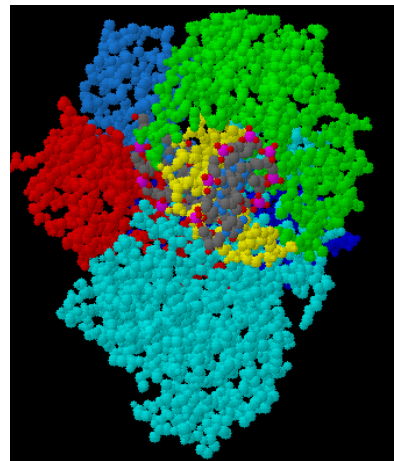
Hype 2: Synthetic biology

- Today, we can create new-to-nature synthetic genes, enzymes, microorganisms and plants
- Metabolically engineered plants and microorganisms can be better suited for our needs

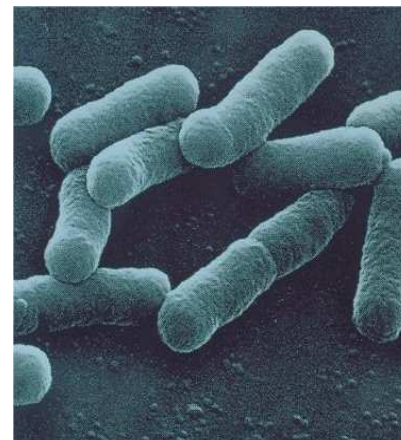
Synthetic genes



Synthetic enzymes

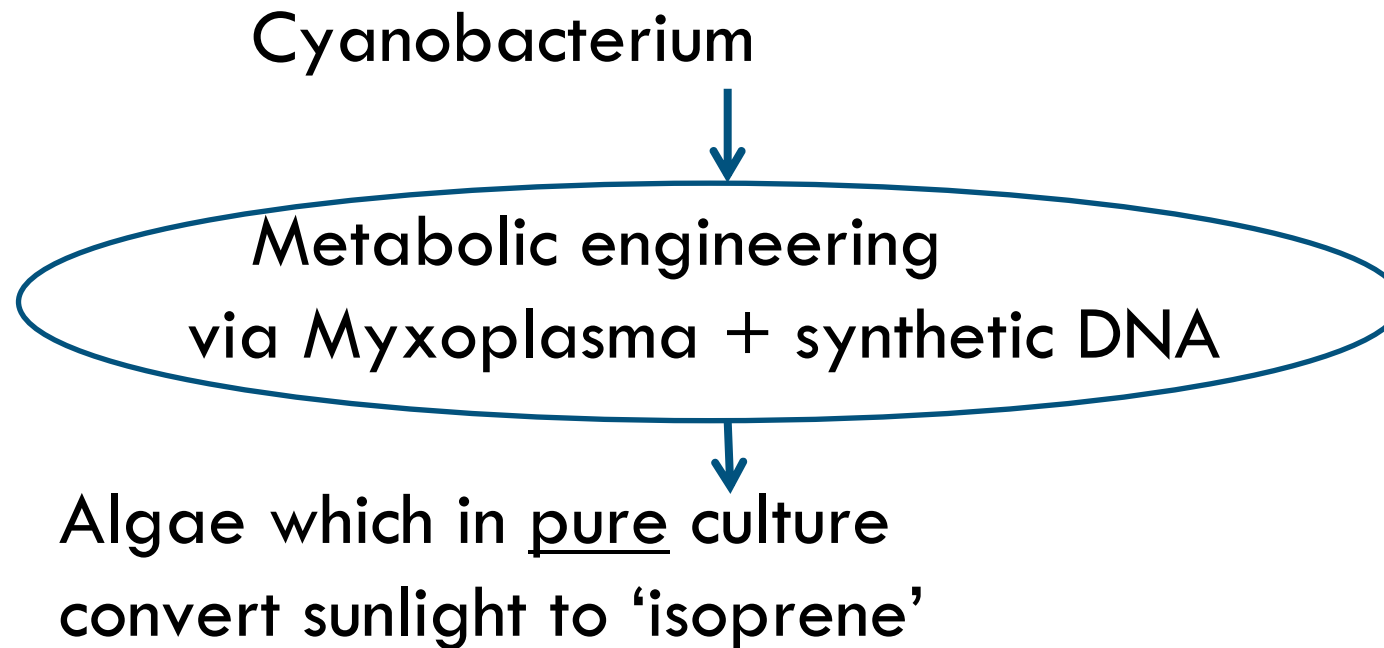


Metabolically engineered
microorganisms and plants



Hype 2: The synthetic biology

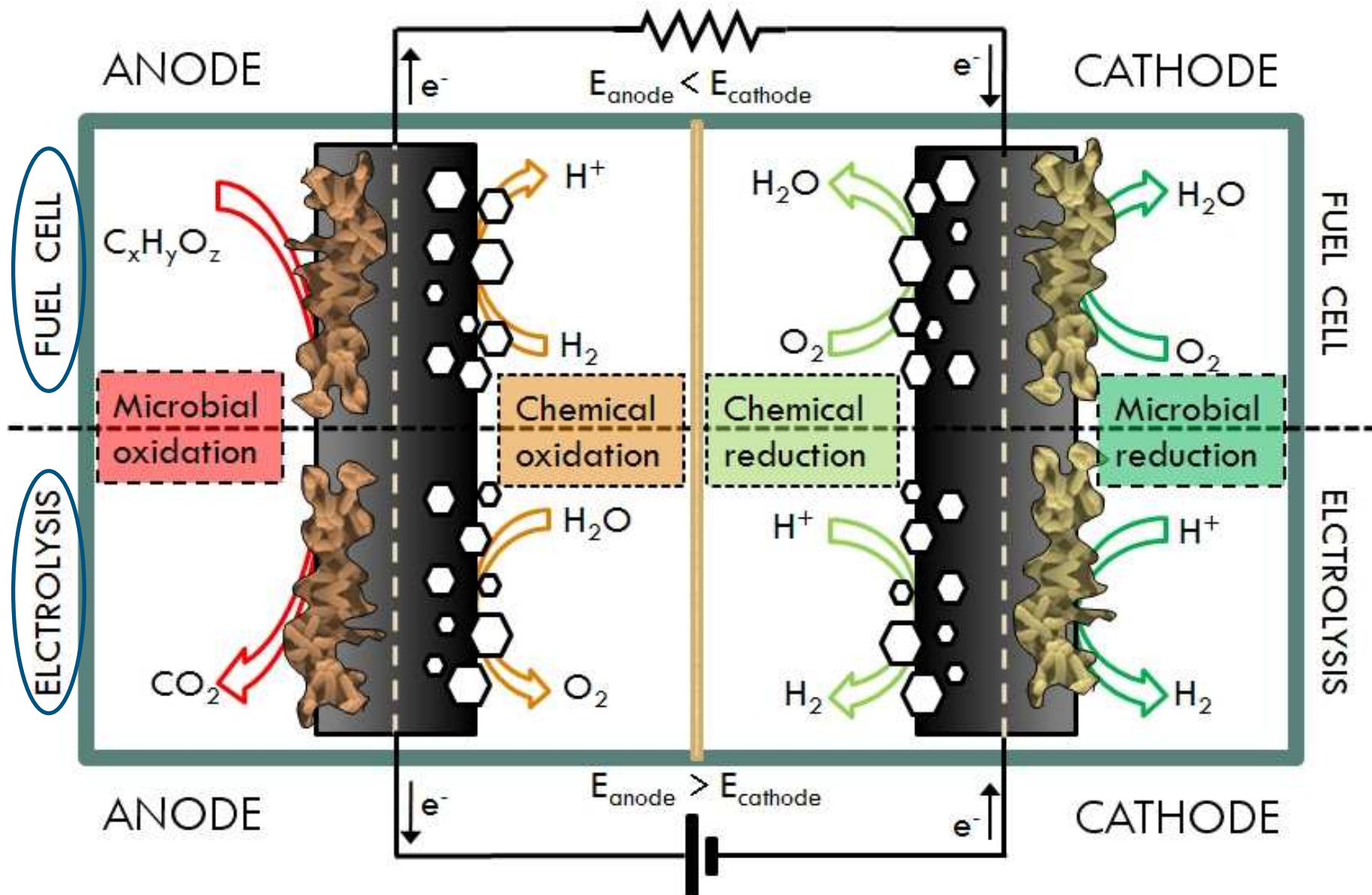
- The Craig Venture approach



Take home : Nice as science, but very high technical barriers



Hype 3: Bio Electrochemical Systems (BES)



At present: 3 concepts of BES

1. Energy concept i.e. organic matter to kWhel
2. Product concept i.e. COD to added value items
3. Sustainability concept i.e. BES for a better environment

Energy concept

- Conventional thinking

- ▣ 'Gratuit' energy from wastewater
- ▣ 'Gratuit' energy from plant root exudates

{	BES from waste	0.1	$\text{kW}_{\text{el}}\text{m}^{-3}$
	BES from root exudates	0.001	$\text{kW}_{\text{el}}\text{m}^{-3}$

Benchmarks:

{	Batteries	30-90	$\text{kW}_{\text{el}}\text{m}^{-3}$
	Chemical fuel cells	140	$\text{kW}_{\text{el}}\text{m}^{-3}$
	Anaerobic digestion	4	$\text{kW}_{\text{el}}\text{m}^{-3}$

Take home: Plenty of energy-dense competitor systems exist

Product concept

- Extra energy is supplied to the anodic harvested electrons
- Products such as caustic, peroxide, fresh water, organic acids & alcohols
- Biological current is the limiting factor !
- Conventional technologies must be faced

Take home: Production is about
-Rates ($> 100 \text{ kg m}^{-3} \text{ d}^{-1}$)
-Quality (specification is essential)

Sustainability concept

- Make SMART use of electrochemical properties
- Examples:
 - * Pollutant removal
 - * CH₄ (GHG) release mitigation
 - * Electro-assisted anaerobic digestion

**Sustainable
Mechanisms
for
Alternative
Remediation
Technologies**

Take home: Apply BES where no alternative strategies are available

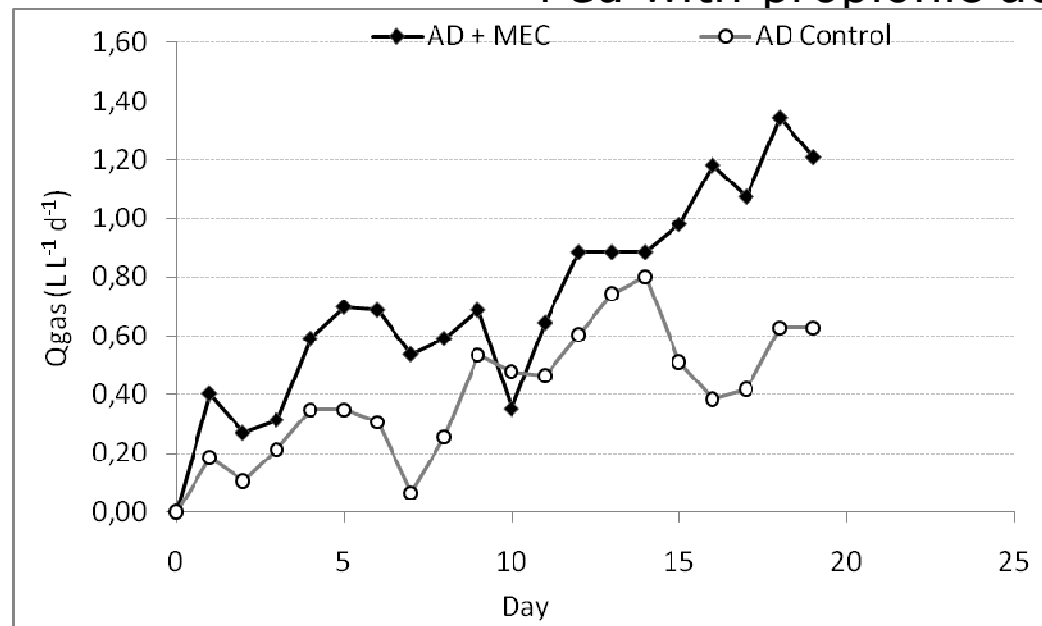


SMART - AD & BES

Example nr. 1

MEC in AD

- **Cathode inside** reactor producing H₂ in situ
- ➔ Experimental set up: - 5 mA, 2.5 V per 1.5 L reactor or 10 W/m³ reactor
- Fed with propionic acid



Electricity consumed only **7 %** of extra electrical energy gained

(Eggermont et al. 2011; unpublished; LabMET)

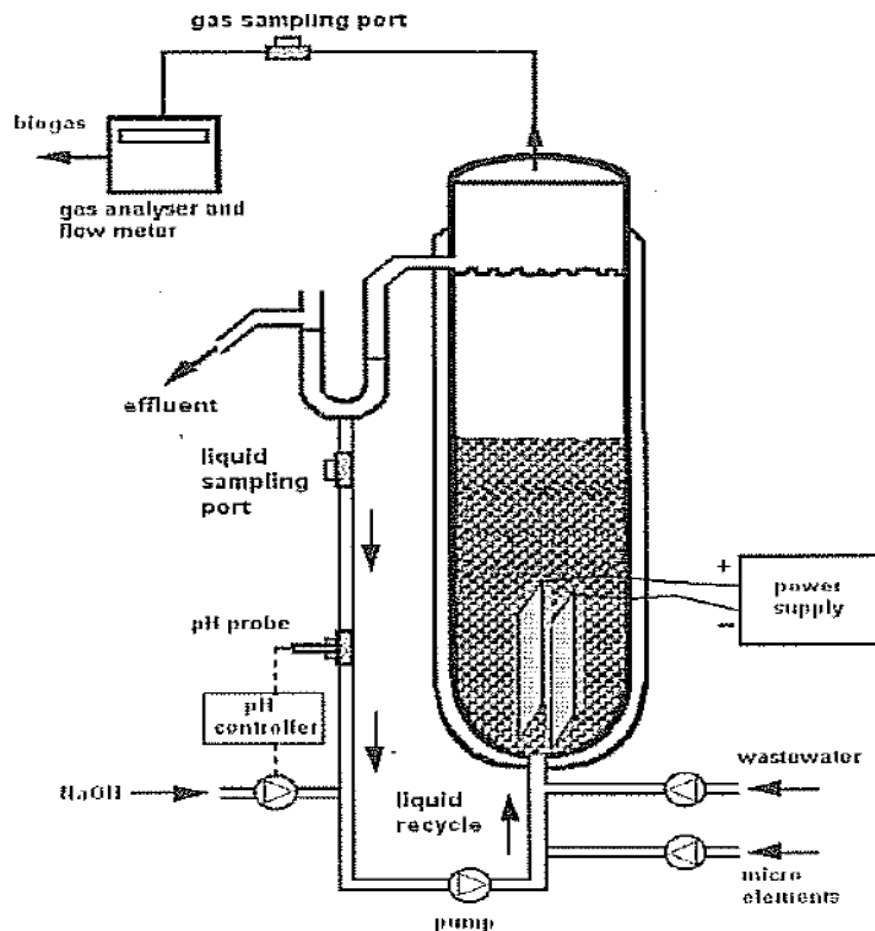


SMART - AD & BES

Example nr. 2

MEC in AD

- **Cathode and anode inside** reactor



Electrolysis in the AD reactor
200-300 W installed/m³
reactor provided 25% higher
biogas production



Electricity consumed only
25% of extra electrical
energy gained

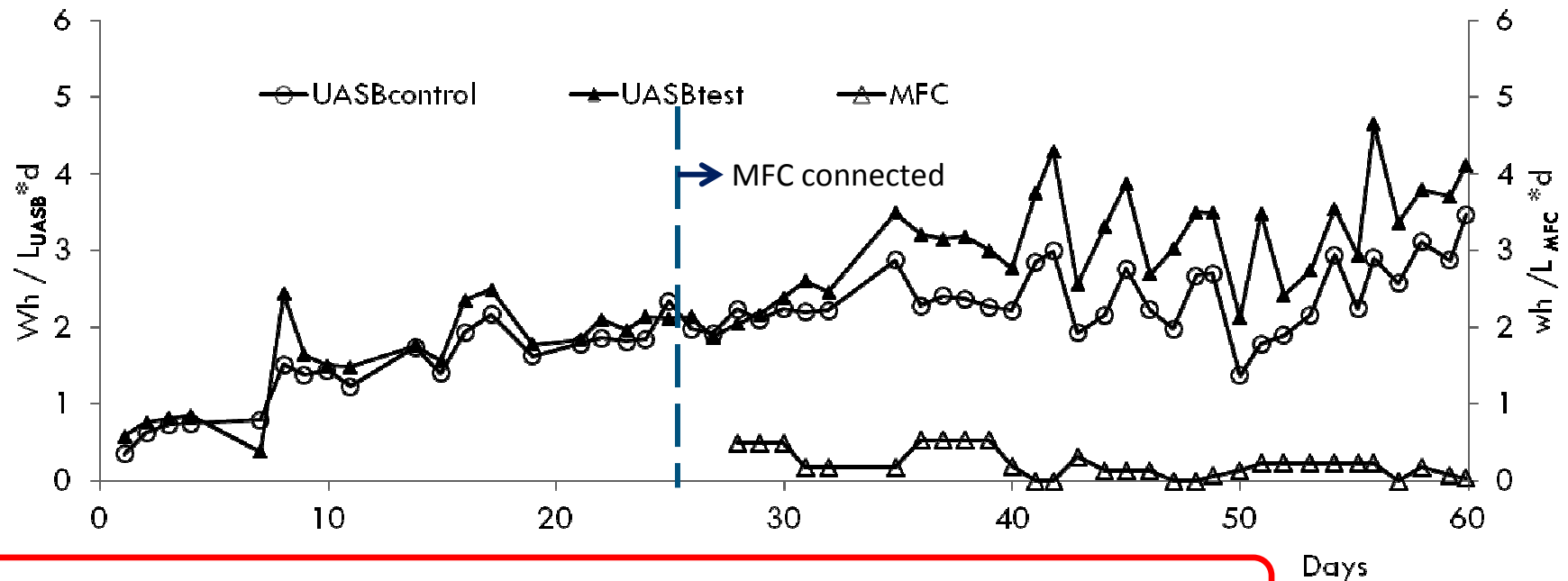
(Tartakovsky et al., 2011; *Bioresource Technology* 102: 5685-5691)

AD & BES

Example 3

MFC in AD **Anode inside**, air cathode outside:

Energetic performance during stable loading and HPr shock



Take home: The MFC, although at low power output, strongly

empowers the UASB. $(Wh/L_{UASB}) / (Wh/L_{MFC}) = 20$
(Arends et al. 2011; unpublished LabMET)

Conclusion : BES in general are still in search of a proper niche

RECAP :

**BIORESOURCES & BIOENERGY:
ABOUT HYPES & MAVERICKS**

*** THE CHALLENGES**

*** THE HYPES ↔** | **CLIMATE CHANGE**
ENERGY SUPPLY
SUSTAINABLE ENV.

**YET → HOW WELL FOUNDED
ARE OUR ASSUMPTIONS ?**

Example 1 : Fossil fuel shortage

(Furfari 2001; www.leonardo-energy.org)

Geopolitics of Energy with Samuele Furfari

<http://www.leonardo-energy.org/drupal/node/2038>



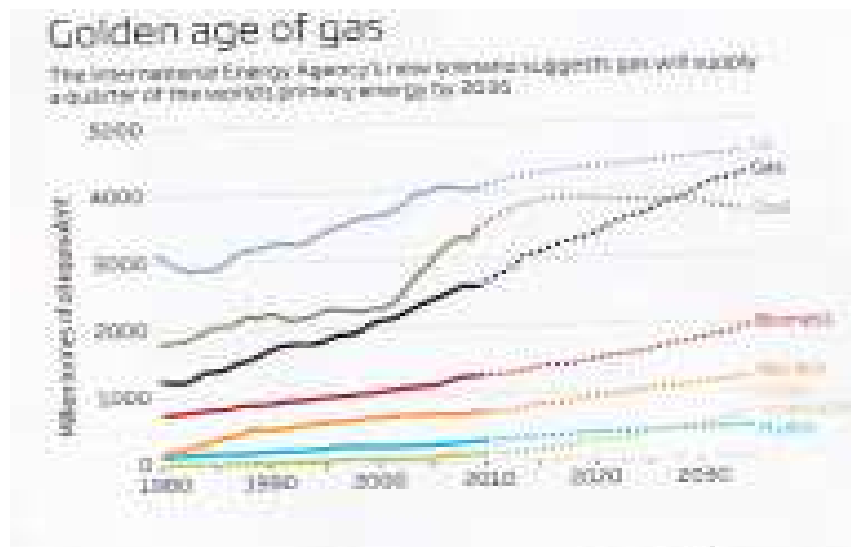
Samuele Furfari has been an official of the European Commission for over 25 years. He has built his entire career on the energy sector, working in the Directorate General for Energy and Transport. There, he participated in the development of the European energy policy and its application at community level, particularly through the creation of local and regional energy agencies and a number of initiatives like the Intelligent Energy Executive Agency and the ManagEnergy Program.

Furfari also teaches Geopolitics of Energy at the Free University of Brussels, where he graduated as a Chemical Engineer and subsequently obtained a PhD in coal gasification. He was born in 1953, has Italian nationality, and is married and the father of two children.

Example 1: Fossil fuel shortage

Facts

- The oil production reserves are still huge !
 - ↳ New equipment will open massive reserves
e.g. in Iraq
Brazil
- Gas reserves are even larger (New Sci Jan 2012)



Example 1 : Fossil fuel shortage

Consequences

- The EU has set the 20 – 20 – 20 policy
 - i.e. by 2020
 - minus 20% greenhouse gas levels
 - minus 20% energy consumption
 - plus 20% renewables in energy mix

BUT there is so much fossil fuel that
the market will not at all soon be in need of
Renewable Energy Sources (RES)

Example 2: Fossil fuel dominance

Bitumes sand in Canada → 300.000 m³ tailings per day
which contain per m³

5 kg of residual solvent
50 kg of residual tar

Now 40 km² at 10 m height, this produces 0.1 L biogas/m³.d
or 40.000 m³ biogas/d!

(Siddique et al. 2011, EST 45: 5892-5899)

**Take home: The coal tar mining industry operates in total
environmental disrespect !**

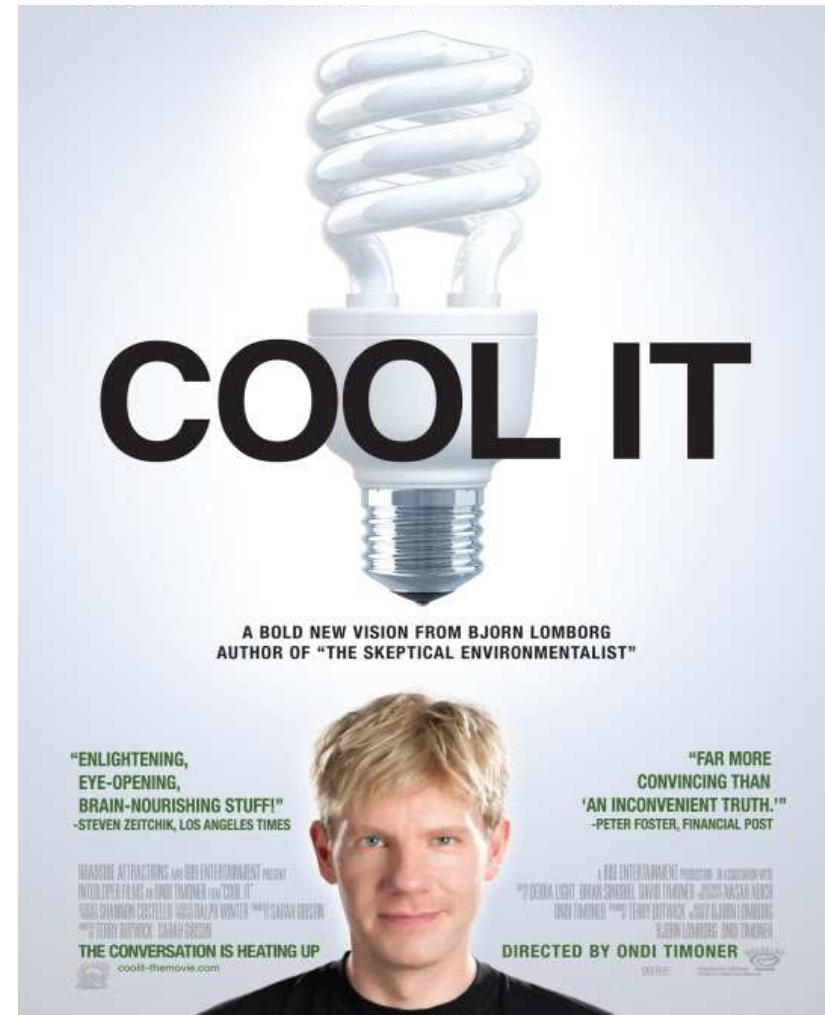


Example 3: CO₂ storage technology

- Bjorn Lomborg 2010:
Cool it!
- “We must wisely invest for climate changes”











Put money where it has effect !



Repositioning of fuel versus the environment

1. Biogas for mobility

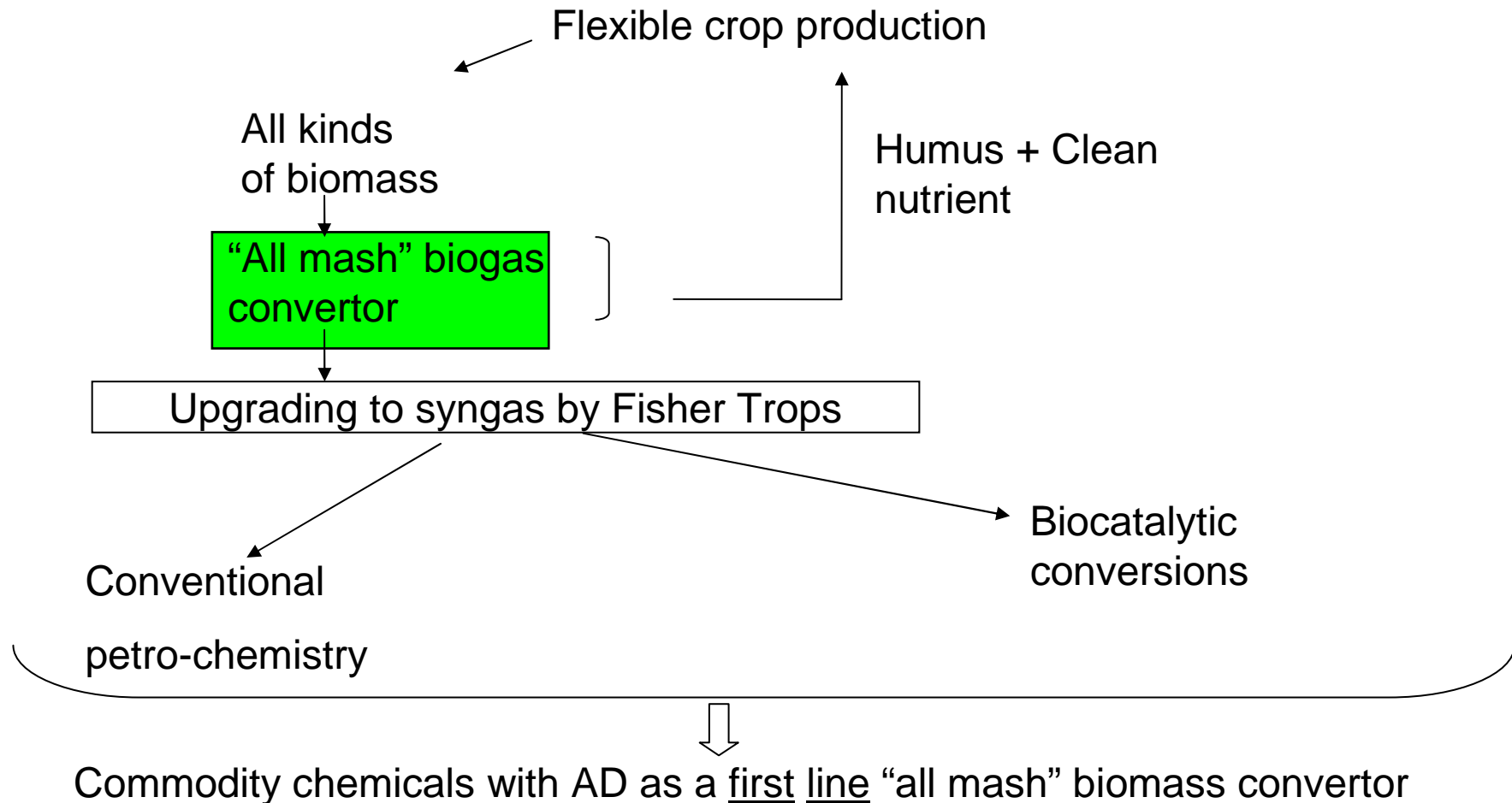
Biodiesel			20.000 km/ha
Bio-ethanol			33.000 km/ha
BTL (biomass to liquid)			
by			
° FT-conversion			63.000 km/ha
° AD conversion			66.000 km/ha

↳ Can cover 50% of the “EU 2020 Biofuel for mobility” without change in landuse (AD 2007)

(Weiland, 2006; Eng. Life Sci.6, 302-309)

Repositioning of the fossil fuel and the environment

2. AD Biogas based sustainable organic chemistry



(Yeuneshi et al., 2005; *Biochem. Eng. J.* 27: 110-119)

(Datar et al., 2004; *Biot. Bioeng. J.* 86: 587-594)



Repositioning of the fuel and the environment

3. What is needed to make 20% RES have an effect

- First: Full internalization of external costs of conventional energy e.g. | GHG by fossil fuel
| Radioactive waste by nuclear
- Second: Financial policies to support | - energy efficiency
| - new energy sources
- Third: Education to change behaviour of consumer
→ Learn to use less energy so that the renewables can be of significance
Example: | * Much less travel
| * Much less meat

Take home : * Oil dominance is here to stay for another 50 years
* RES and Biorefinery Biotech depend entirely on political foresight !

RECAP :

**BIORESOURCES & BIOENERGY:
ABOUT HYPES & MAVERICKS**

*** THE CHALLENGES / THE HYPES**

*** THE MAVERICKS**

→ THE BIOREFINERY

→ THE BIO(NANO)CATALYSTS/MATERIALS

→ MICROBIAL UPGRADES

Maverick 1: The Biorefinery

Agriculture:

Primary production
of biomass



**Plant (green)
biotechnology**

Biorefineries:

biomass
conversion



**Industrial (white)
biotechnology**

**Bioproducts
Biomaterials
Biofuels**



Products of the biobased economy

- Bioplastics
- Biofuels
- Biodetergents
- Bulk chemicals
- Fine chemicals
- Cosmetics
- Farmaceutical ingredients
- Vitamins
- Food ingrediënts
- Flavours and fragrances
- ...



The biobased economy



The biobased economy can combine economical, societal and ecological progress

- More sustainable production processes
- Biocompatible or biodegradable products
- Decrease of CO₂ emissions
- Use of renewable resources
- Decrease of our dependence on fossil resources
- New market creation for agricultural products
- Better distribution of wealth over the world population

Biofuel Production Processes

Fuel	Unit processes	Wastestream	Reliability
Pure Plant Oil	Pressing, chemical extraction, extra refinery	Pressed cake	High
Biodiesel	Esterification	Glycerol residue	High
Bio-ethanol	Fermentation, distillation,...	Distillery slops direct Evaporation condensates	High
Fisher-Tropsch Diesel	Gasification, FT synthesis	Light oils	High
Biogas → kWh- <i>electric</i> + kWh- <i>thermal</i>	Anaerobic digestion + MFC after treatment	None!!!	<u>Thus far: poor</u> <u>Now: OK</u>

Take home : To be sustainable, take care of the wastestreams

BIOREFINERY Example 1

- The maxifuels concept

(Ahring et al., 2007; unpublished) (<http://www.biocentrum.dtu.dk>)

Lignocellulose → 1 Steam explosion → 2 Enzymes
→ 3 C6 fermentations → 4 C5 fermentation → 5
Lignin separation → 6 Distillation → 7 Biogas
fermentation (used on site)

Endpoints: - Ethanol
- Lignin



BIOREFINERY Example 1

State of the Art:

Cellulosic ethanol is :

- ❑ Modestly more sustainable than grain ethanol (*Schaidle et al . 2011: Env Progr Sust En. 30:743-753*)
- ❑ Under development by: Iogen Corp , Mascoma Corp , Lignon Eng Corp, Abengoa Bioeng. Corp based on enzymes of Genencore Inc, Diversa Corp , Novozymes Inc , Diadic Corp . (*Chandel & Sing 2011, AMB 89: 1289-1309*)

BIOREFINERY Example 1

State of the Art (Cont.)

- Yet, second generation ethanol is still too expensive (ie of the order of some 0.4 USD per L ethanol) to be competitive with grain ethanol .

Main EtOH G2 running demos

(> 1000t/y) in the EU

Plant Owner	Location	Input capacity (t/year)	Output capacity (t/year)
Abengoa Bioenergy, Biocarburantes Castilla y Leon, Ebro Puleva	Babilafuente, Salamanca, Spain	25 000 t/year (lignocellulosics, steam explosion, wheat / wheat straw, corn stover)	4000
Inbicon (Dong Energy)	Kalundborg, Denmark	30 000 t/year (lignocellulosics, wheat straw)	4300
<i>Chempolis Oy</i>	Oulu (Chempolis Oy R&D Center), Northern Finland	25 000 t/year (nonwood, non-food raw material formic acid pathway)	Running?
SEKAB Industrial Development AB (IDU Project)	Örnsköldsvik, Sweden	lignocellulosics, flexible for wood chips and sugarcane bagasse	4500 Running?



BIOREFINERY Example 2

AD of energy crops

Energy crop

Lignocellulose → Chopper to < 1 cm → Digester → Residue to
land

Endpoints:

- kWhel / 40 % netto output
- Clean nutrients + Humus

Example :

Nuhrenberg 100 000 t DM /year ; 10 MW !!

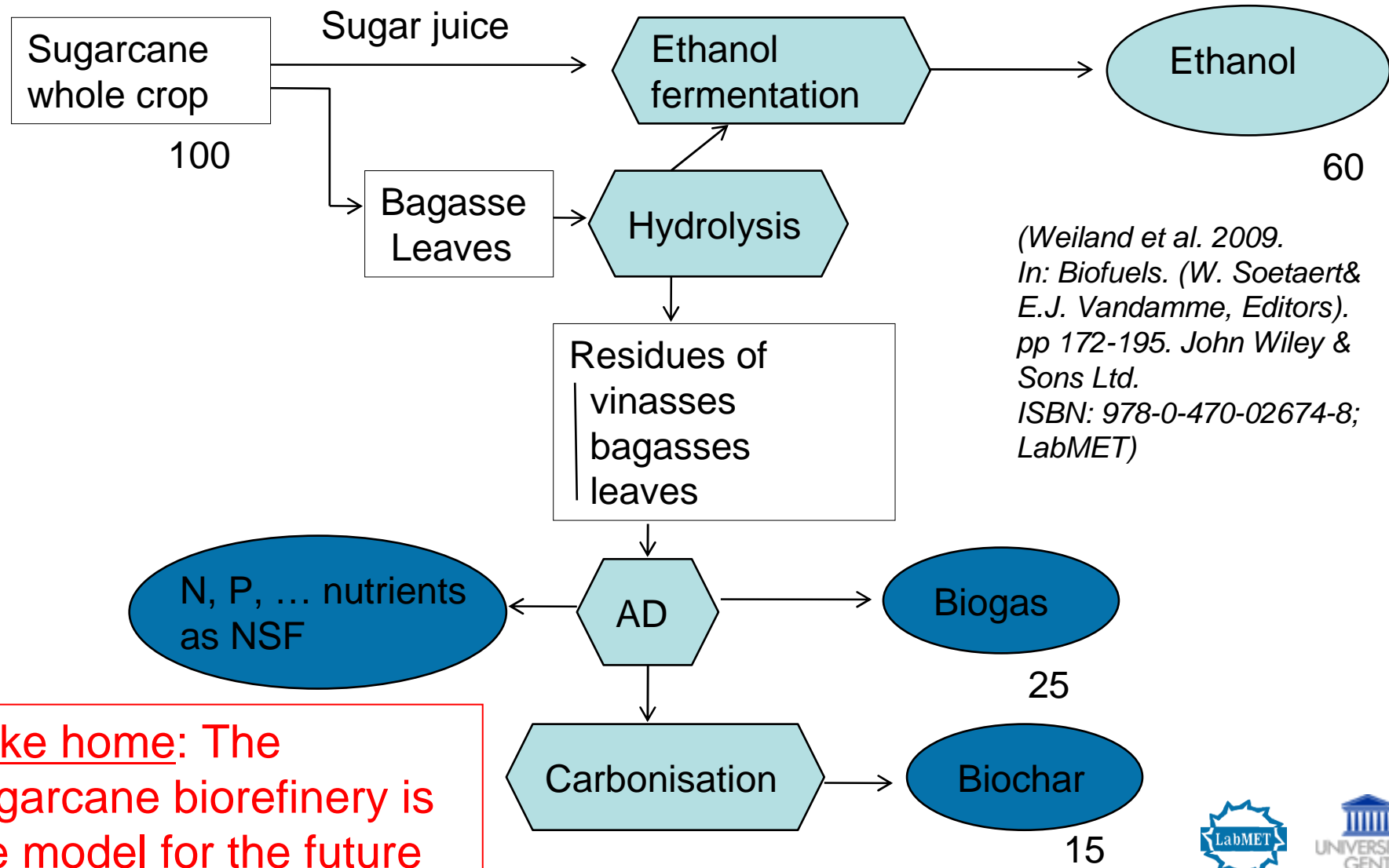


BIOREFINERY Example 2



BIOREFINERY Example 3

The sustainable sugarcane system



Take home: The sugarcane biorefinery is the model for the future

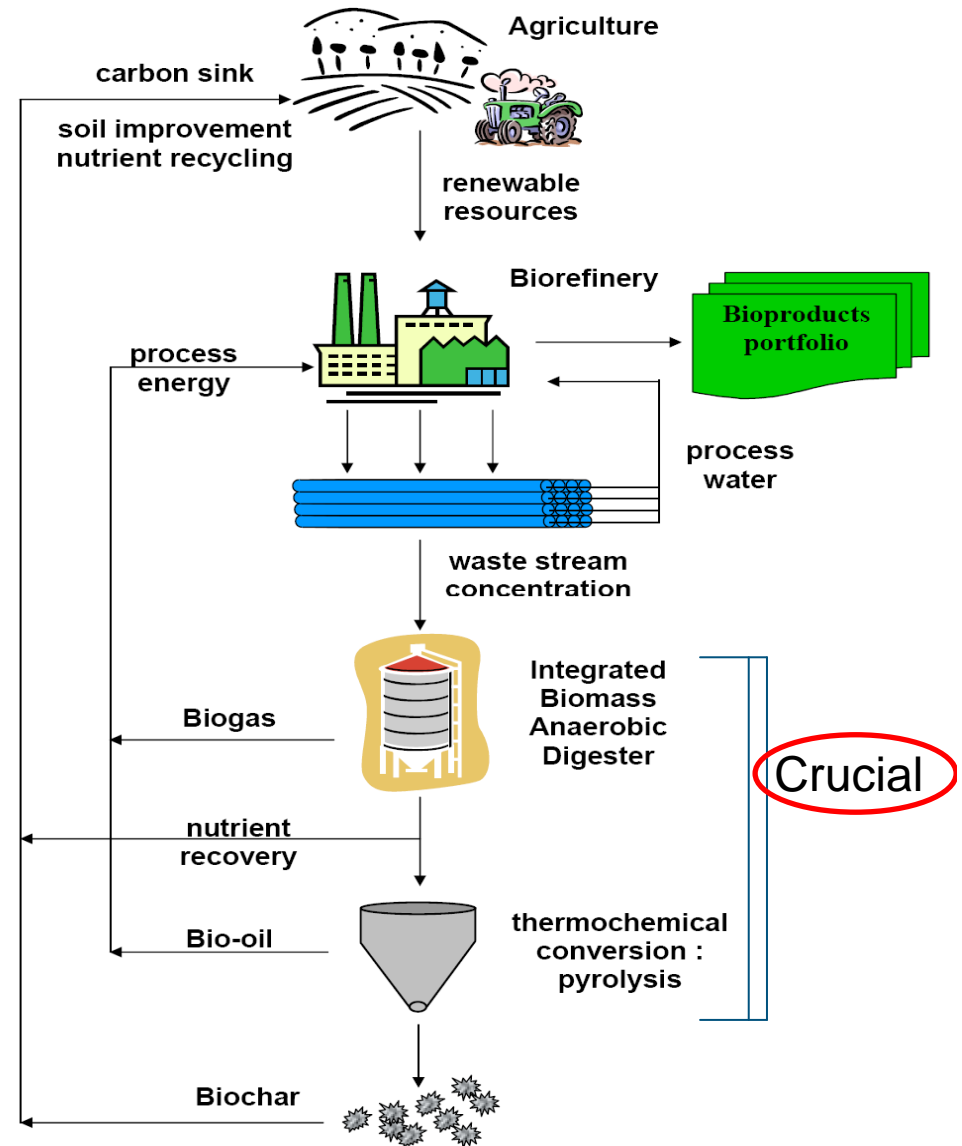
Bio-economy integrated

Plant biotechnology

Industrial biotechnology

Environmental biotechnology

Thermochemical conversion



The soil as factor

- Biochar

(Lehmann et al., 2007; Nature 447: 143-144)

- Improves soil structure



- Enhances the Microbial Resource Management of the soil ecosystem



- 1 ton C = 3 ton CO₂
→ Represents 69 euro GHG equivalent

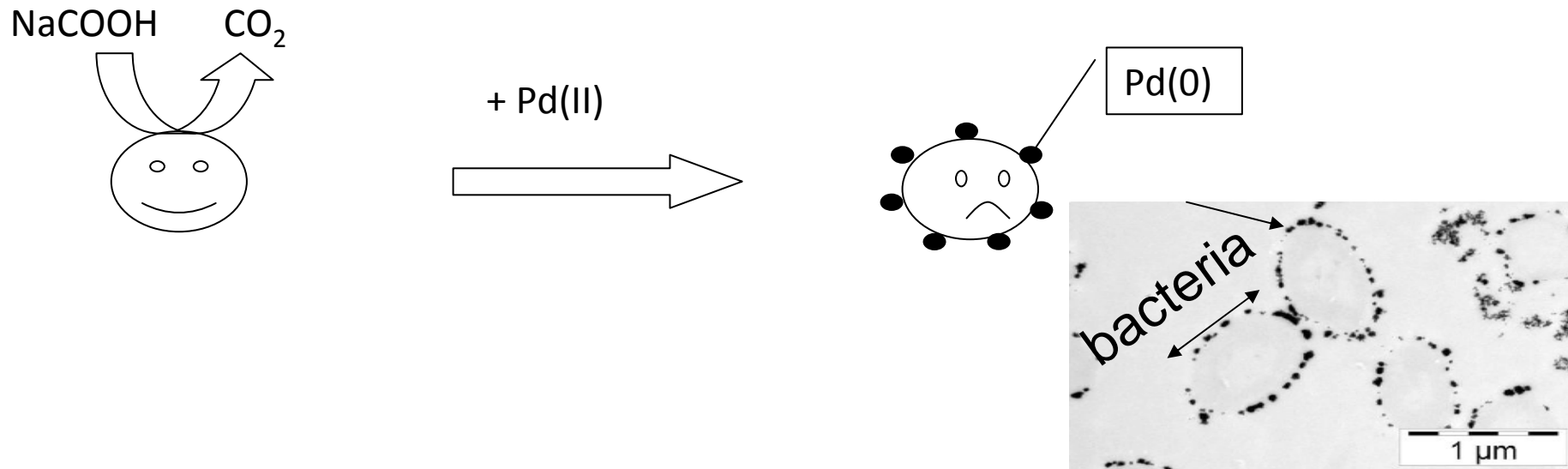


Conclusion maverick 1: Biorefinery

- Only sustainable provided adequate integration of
 - AD
 - Nutrient recovery
 - Maintenance of full “soil ecological services”
- Depends heavily on the “scarcity of the fossil fuel reserves”

Maverick 2: Bio Nano Particles

Production of Pd nanoparticles by bacteria

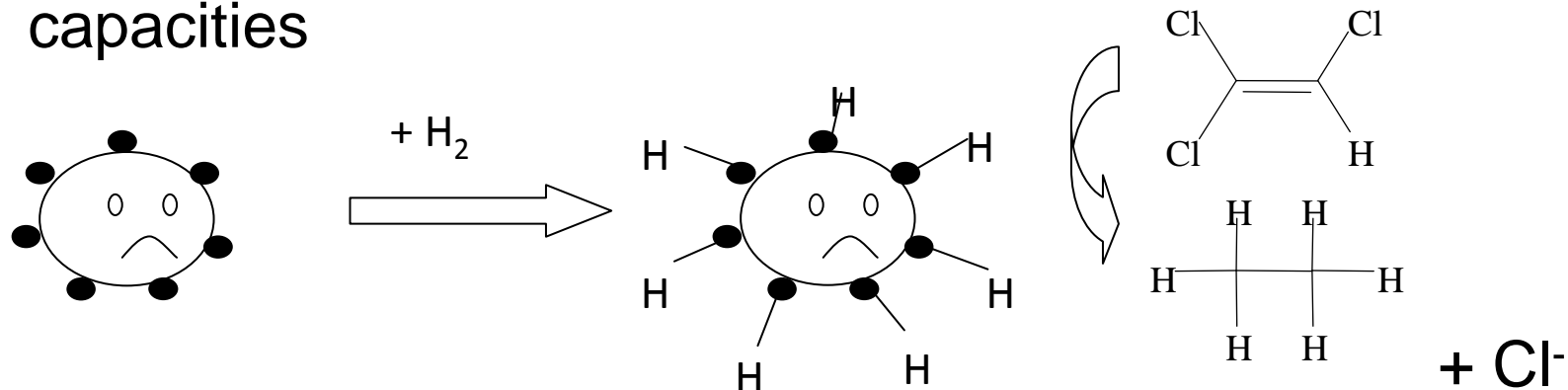


- *Shewanella oneidensis* cells couple the reduction of soluble Pd(II) to the oxidation of an electron donor
- Deposition of this biogenic Pd as nanoparticles on the cell wall and periplasmic space

(De Windt et al., 2005; *Environ Biotechnol*, 90:377-389; LabMET)

Application of BioPAD as catalyst

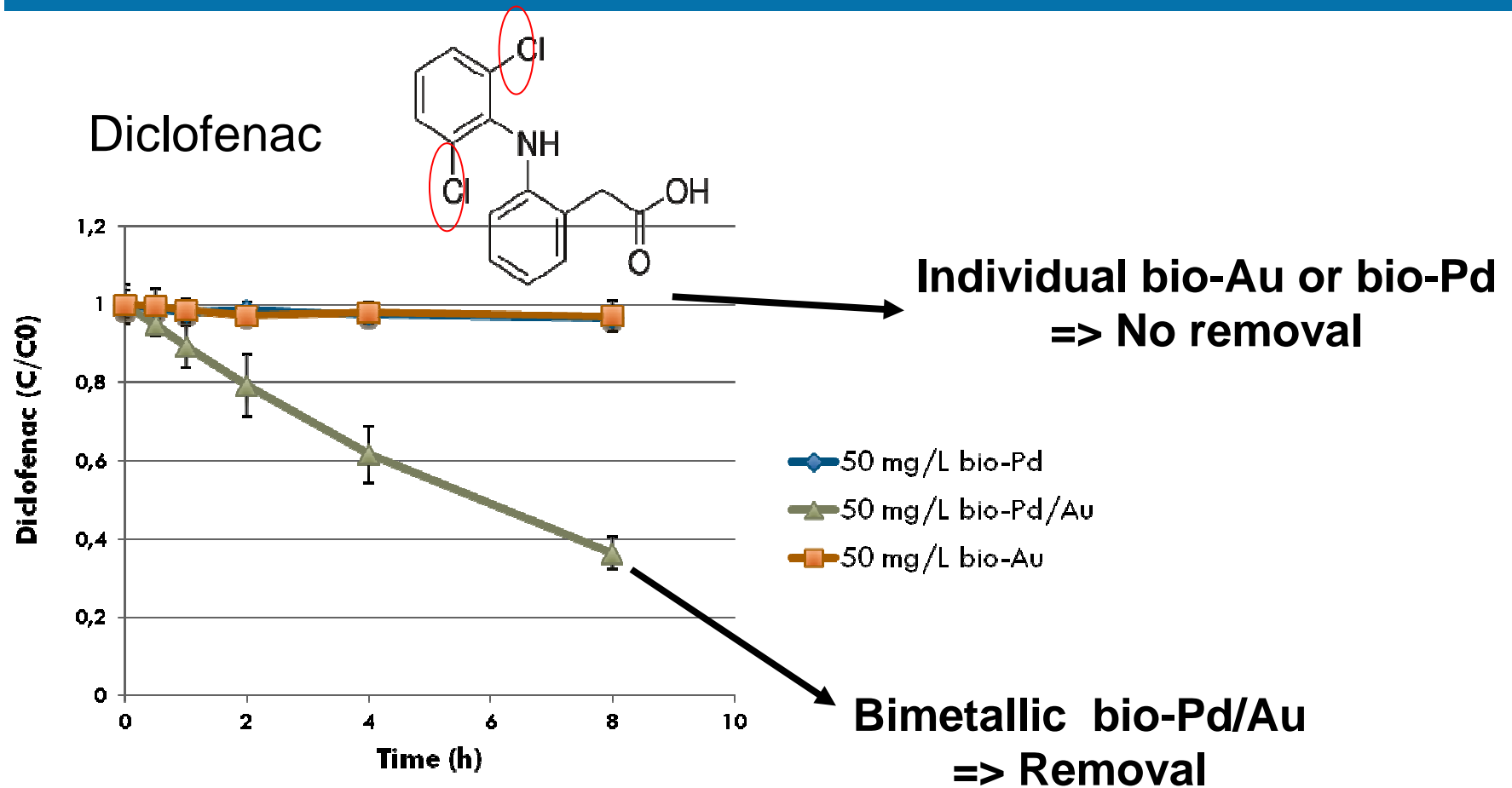
- Loading the bio-Pd with H₂/formate=> strong reductive capacities



- Applicable for chlorinated solvents, PCB's, micropollutants, pesticides (lindane), nitrate, perchlorate, Cr(VI)

(Mertens et al., 2007; Chemosph, 66: 99-105; LabMET, Hennebel et al., 2009; Chemosph 76(9): 1221-1225; LabMET, Hennebel et al., 2010; Wat. Res.44(5): 1498-1506; LabMET Chidambaram et al., 2010, ES&T:44: 7635-7640; LabMET; Hennebel et al., 2009; Biotechnol and Bioeng, 102: 995-1002; LabMET)

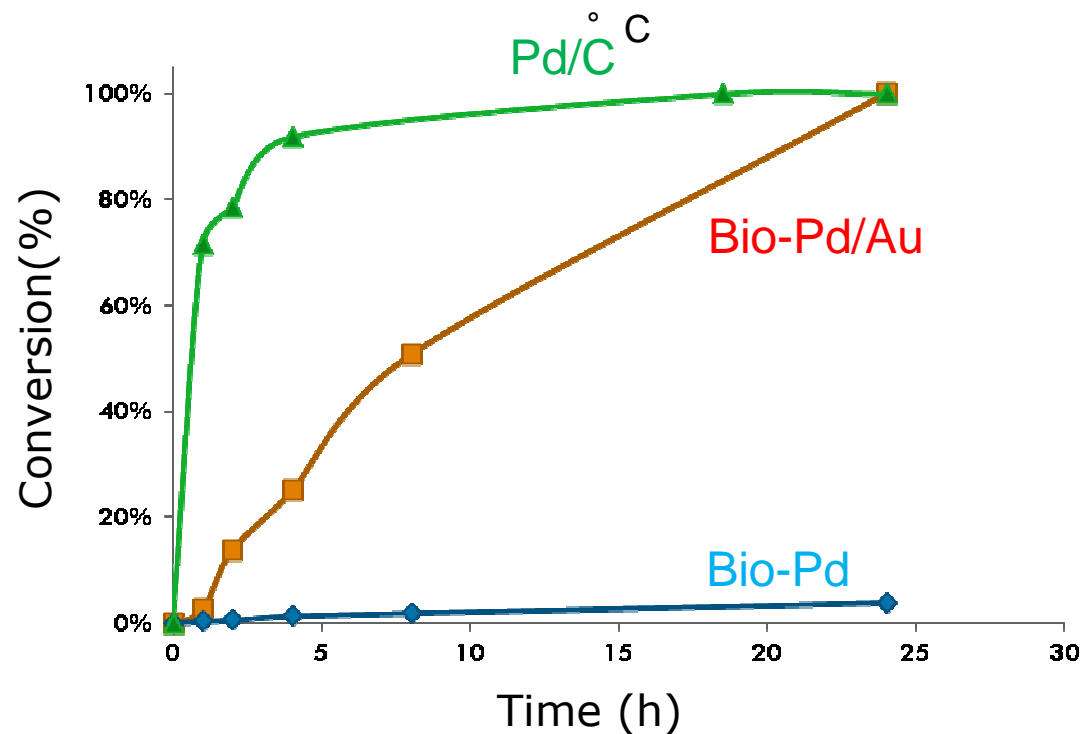
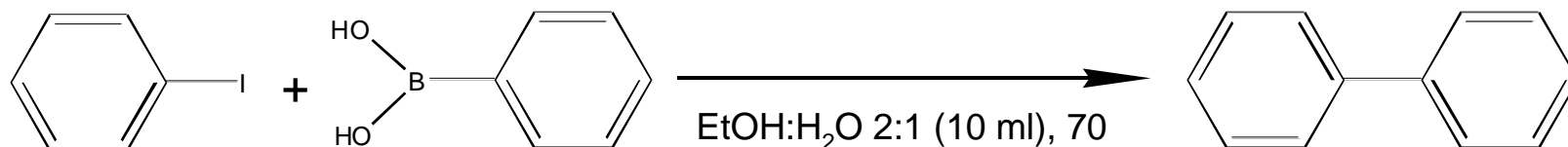
Bio-bimetals: improved dehalogenation



Take home: Bimetallic structures can increase activity and selectivity

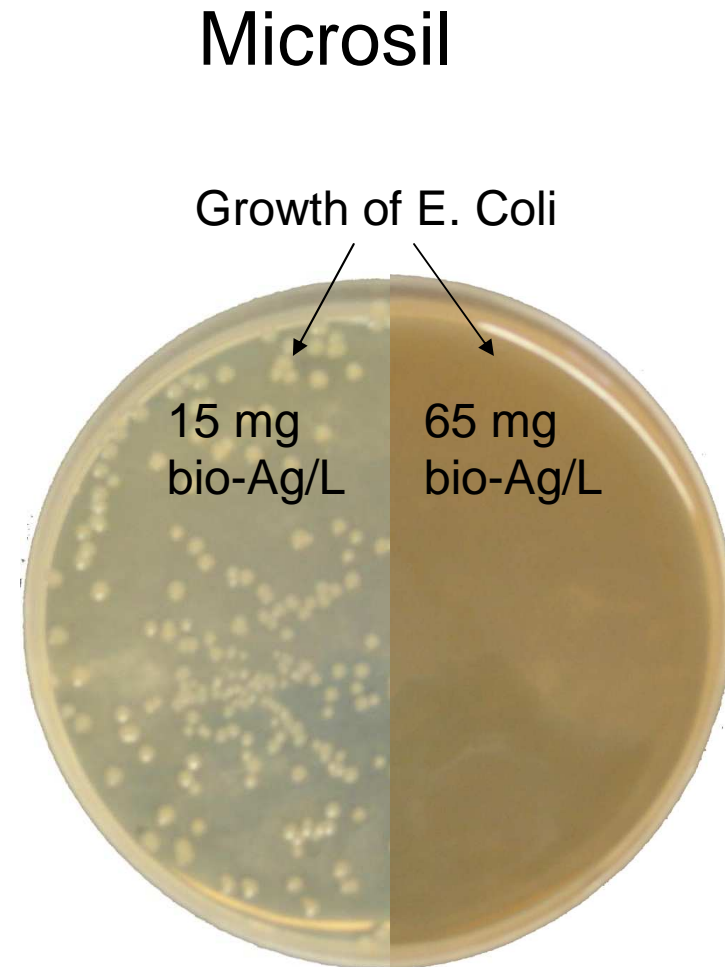
Bio-bimetals: catalyst in organic synthesis

Suzuki coupling reactions (*De Corte et al., 2011, submitted, LabMET*)



Ag-nanoparticles

- With **biocidal effect** against
 - Bacteria (MIC \pm 25 mg/L)
 - Fungi (MIC \pm 100 mg/L)
 - Algae (MIC \pm 0,10 mg/L)
 - Viruses (*De Gusseme et al., 2010, AEM 76(4): 1082-1087, LabMET*)
- **Cost effective** method
 - No expensive infrastructure required
 - Easy to grow bacteria
 - Rapid and cheap processing method
 - Tested on pilot-scale

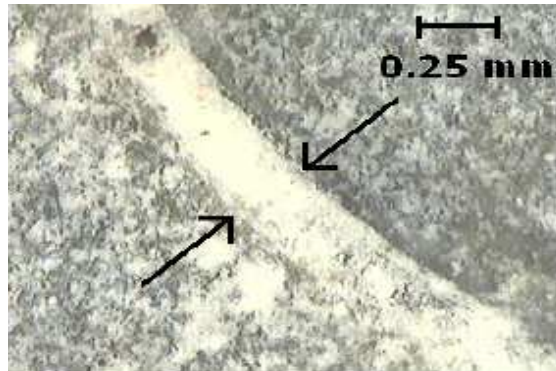


(*Sintubin et al., 2009, Appl. Microbiol. Biotechnol .84: 741-749; LabMET*)

Other perspectives

- CaCO_3 : biomortars for microbiologically enhanced crack remediation

(*De Muynck et al., 2008; Cem Concr Res, 38: 1005-1014; LabMET*)



- ➔ Self-healing concrete

(*Van Tittleboom et al., 2010; Cem Concr Res, 40: 157-166;*
Wang et al., 2011; Constr and Building Mat,
DOI:10.1016/j.conbuildmat.2011.06.054; In Press, LabMET)

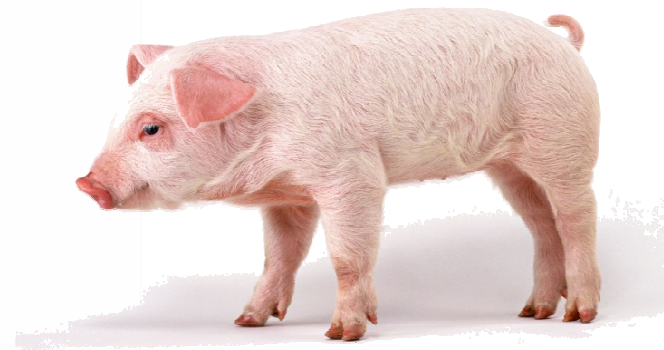
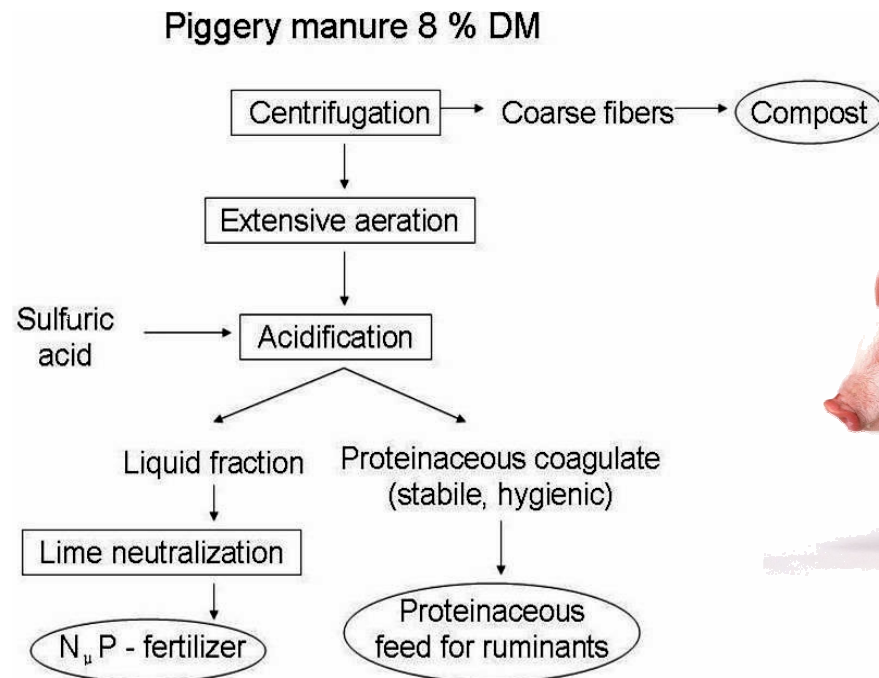
Conclusions : Plenty of room for novel bio-catalysts

Maverick 3: Microbes as upgraders

Example 1: Fecal cycles in short loop can work

Production of SCP in intensive husbandry
aquaculture

Piggery manure to single cell protein (SCP) to feed
(Beernem (1974) IWA/R&D prize; LabMET)

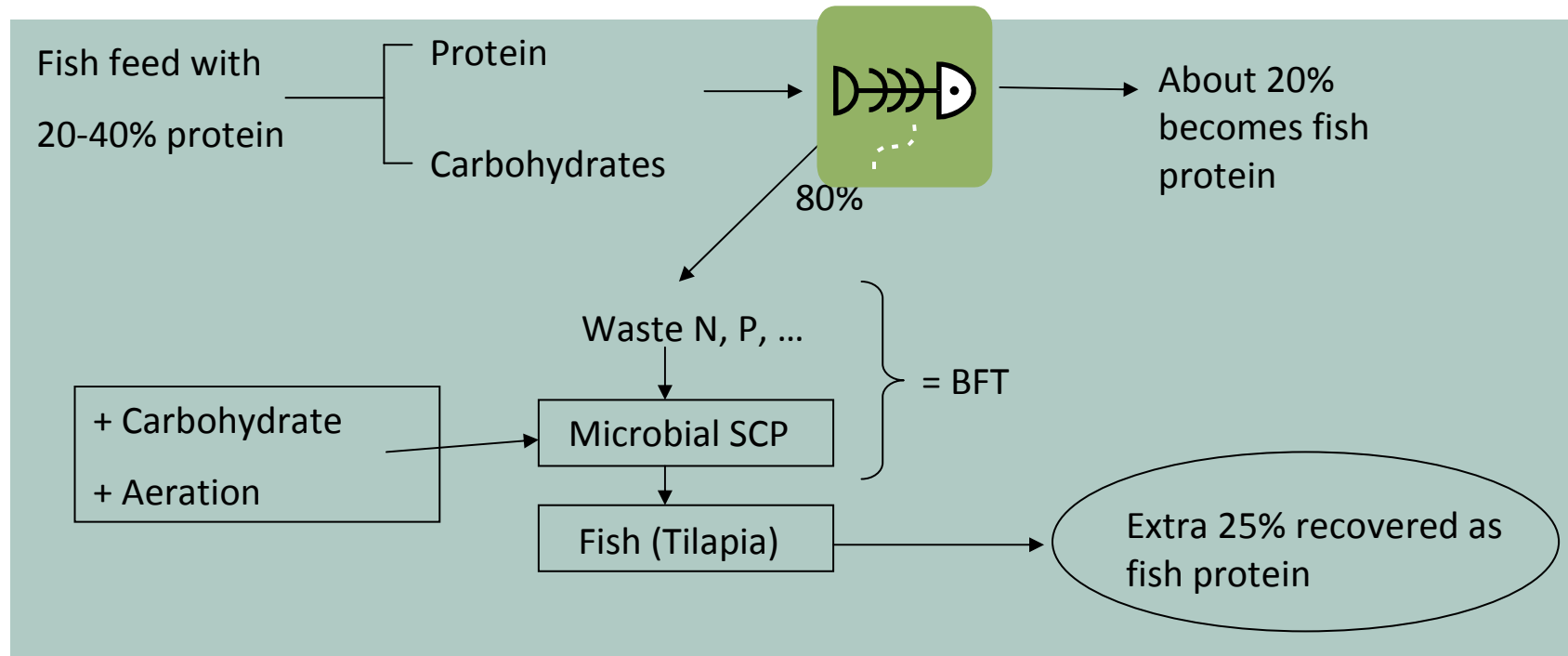


Maverick 3: Microbes as upgraders

Example 2: Fecal cycles in short loop can work

Production of SCP in intensive husbandry aquaculture

Direct recycling of fecal N as feed in aquaculture



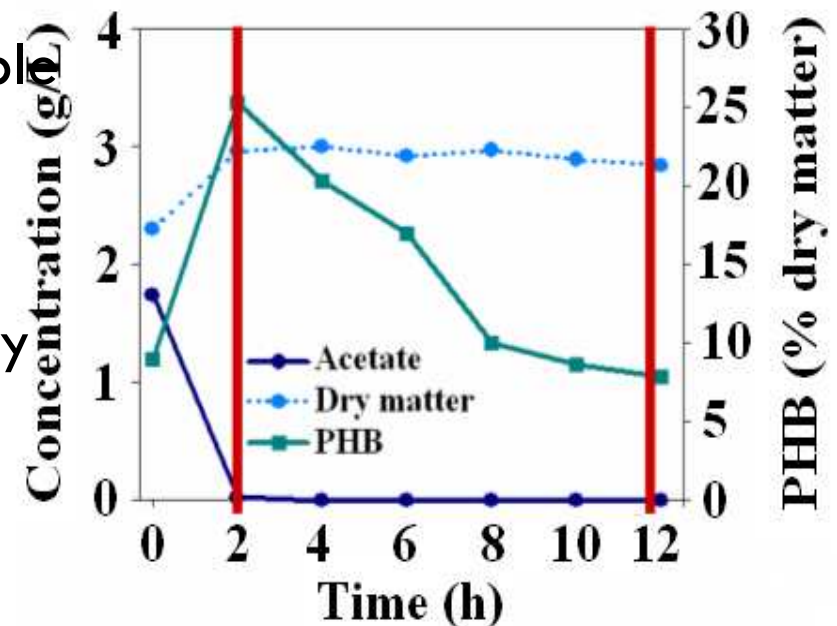
(Crab et al., 2007; *Aquaculture* 270: 1-14; LabMET)

(De Schryver et al., 2008; *Water Res.* 42: 1-12; LabMET)

Maverick 3: Microbes as upgraders

Example 3 : Production of poly- β -hydroxybutyrate (PHB) in wastewater treatment

- **PHB** = intracellular biodegradable polyhydroxyalkanoate (PHA) produced by a variety of microorganisms as carbon/energy storage material



(Reis et al., 2003. *Biop. Biosyst. Eng.* 25: 377-385)

Maverick 3: Microbes as upgraders

Activated sludge:

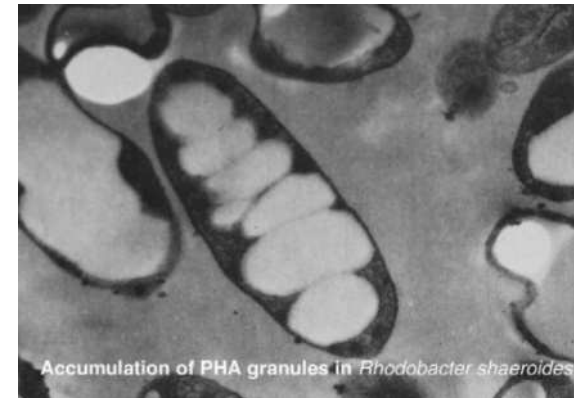
- Around 20% PHA on dry matter under anaerobic conditions
- Can be upgraded to 60% under micro-aerophilic conditions

(Salehizadeh & van Loosdrecht, 2004; Biotechnol. Adv. 22: 261-279)

PHB: - Use to produce polymers (Brussels North!?)

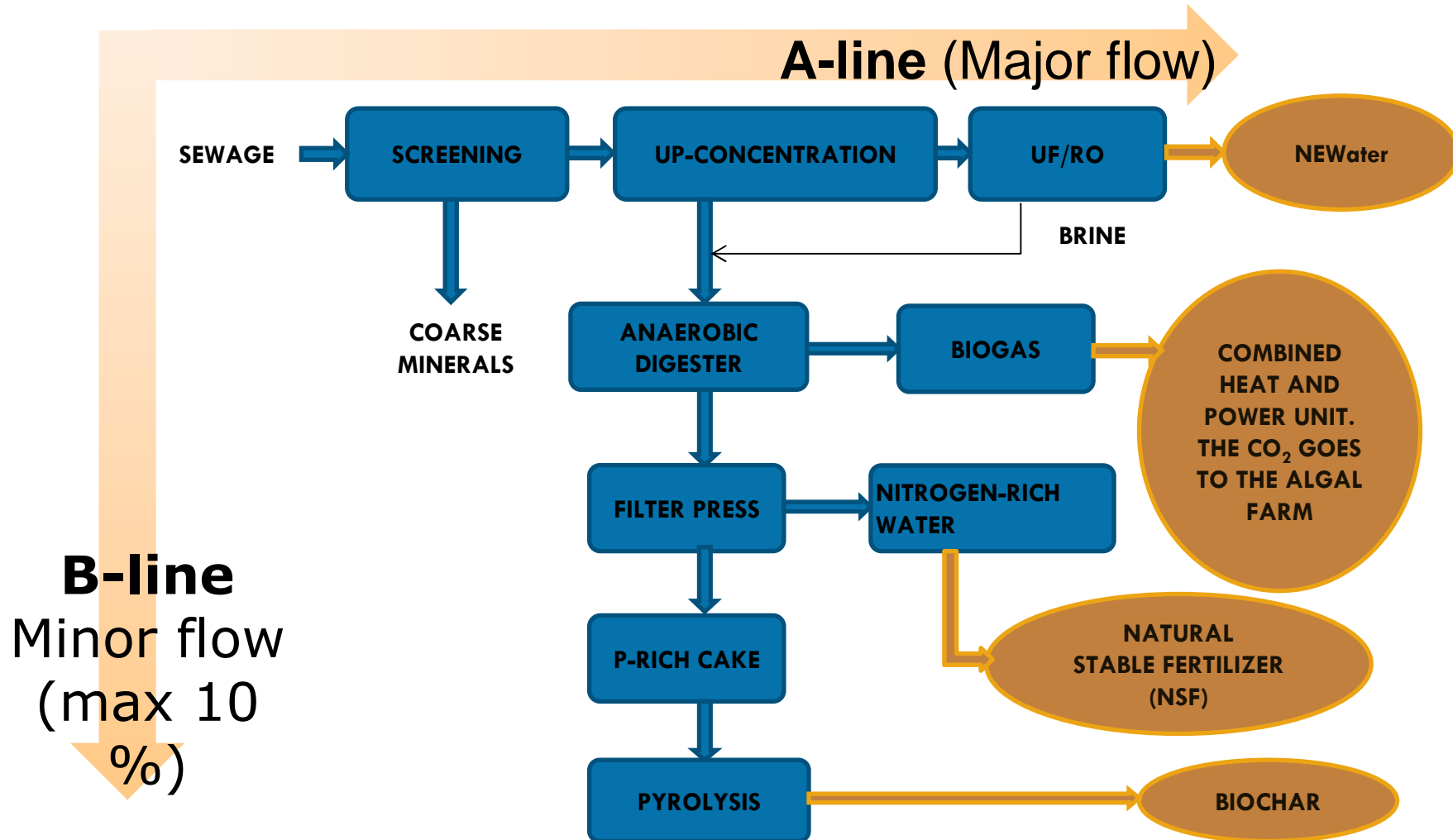
- Use as a prebiotic feed !!!

(Defoirdt et al. 2007; FEMS Microbiol Ecol 60: 363-369; LabMET)



Maverick 3: Microbes as upgraders

Example 4 : The “Zero Waste” Water Technology



(Verstraete et al. 2009; Bioresource Techn. 100, 5537-5545; LabMET)

Sewage as a multi-resource

Cost consideration for the proposed sewage recycling technology (according to C2C)

→ **the major flow**: directly to reuse

→ **the minor flow** (= a concentrate): produced at the entry of the plant, subjected to advanced recovery for energy and fertilizers

<u>Major flow</u>		
Dissolved air flotation	0.02-0.03 €/m ³	} 0.53-1.15 €/m ³
Dynamic sand filtration	0.05-0.06 €/m ³	
Ultra filtration and Reverse Osmosis	0.46-1.06 €/m ³	
<u>Minor flow</u>		
Anaerobic digestion	Break even	} 0.08-0.10 €/m ³
Mechanical separation	0.08-0.10 €/m ³	
Pyrolysis	Break-even	
	Total costs*:	0.61-1.25 €/m³

* this is the estimated total cost

(Verstraete et al. 2009; Bioresource Techn. 100, 5537-5545; LabMET)

Take home: Total bruto costs of about 1 €/m³ are comparable with CAS + UF + RO

Maverick 3: Microbes as upgraders

Winston Churchill in 1932: “Fifty years hence we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing by growing these parts separately under a suitable medium” The timing of this prediction proved ambitious, but the technology is becoming attainable



Maverick 3: Microbes as upgraders

Example 5: Microbes for a new food

- Bluegreen cyanobacteria



Lysate



Muscle cell growth by *in vitro* tissue engineering



Cultured meat

Decrease relative
to conventional meat

On energy use

Factor 2

On greenhouse gas emission

20

On water use

20

On land use

100 !

(Tuomisto and Teixeira, 2011, *Envir. Sci. Technol.* 45:6117-6123)



Concluding remarks about Bioresources & Bioenergy

- “Nature has used millions of years to perfect biological systems. Synthetic biology now will spend millions of dollars to mimick such perfection → *We must be pragmatic* about the prospects” (Tom Curtis, 1st MRM symposium, June 2011, Ghent, Belgium)
- Science must dare to explore. Yet scientific projects are currently compelled to promise miracles → *We should be honest* in what we propose in order not to end up in terms of credibility with the politicians,...



Concluding remarks about Bioresources & Bioenergy

- The “bio-maverick” technologies of the future probably will be:
 - ▣ Based on improved conventional cropping systems
 - ▣ Based on novel biocatalysts/materials
 - ▣ Based on direct coupling of plant biotech with microbial biotech e.g. to make PHB, cultured meat, ...



Concluding remarks about Bioresources & Bioenergy

The just driver for bio-economy is not

➤ Fear for fossil fuel shortage

BUT

➤ Foresight for a sustainable future

