

Current Trends in Anaerobic Digestion

**Diversifying from waste(water) treatment to
re-source oriented energetic conversion
techniques**

Jules B. van Lier & Grietje Zeeman

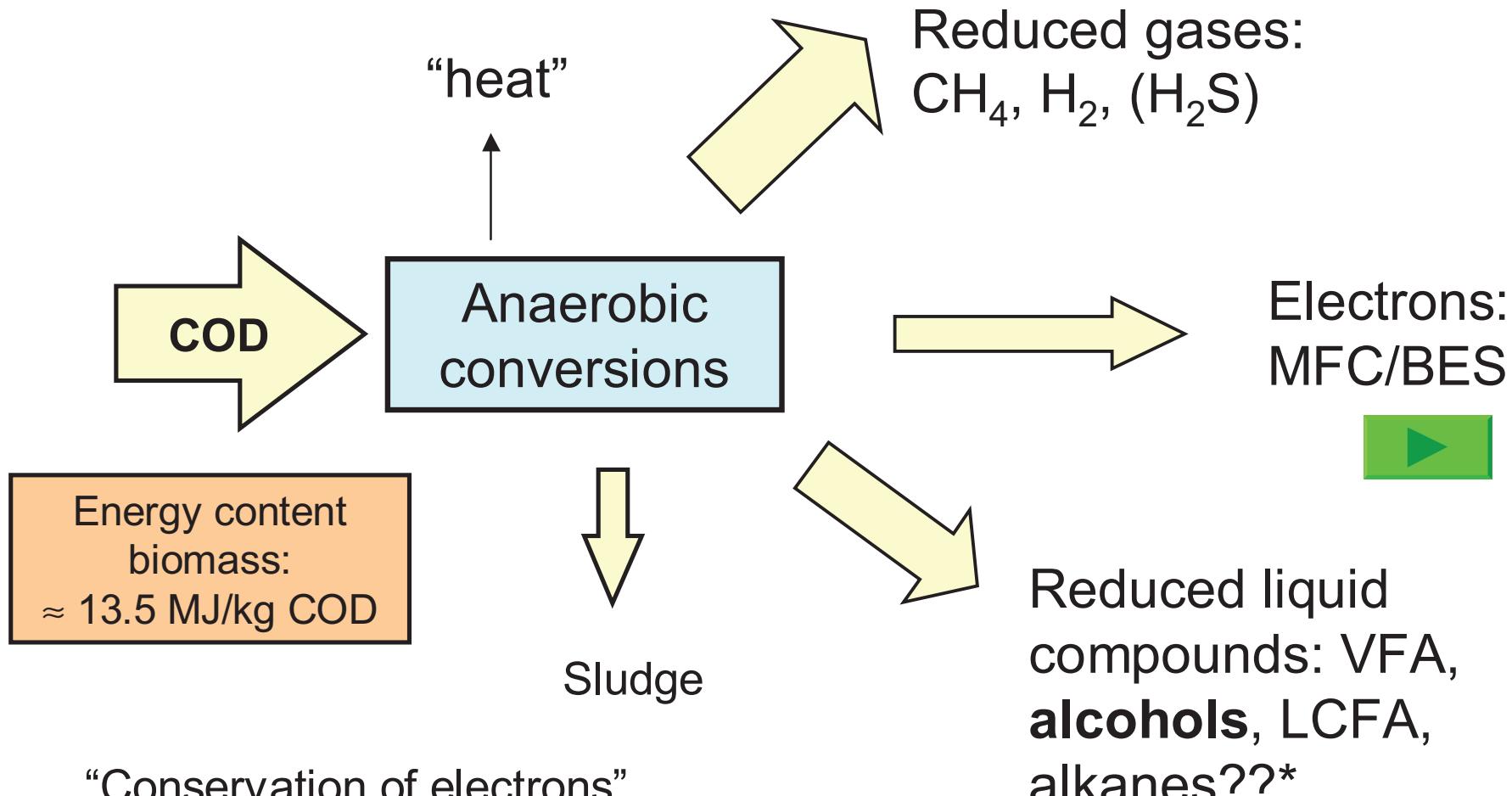
Lettinga Associates Foundation (LeAF)
Wageningen University, The Netherlands



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AD ↔ Energy: heat, energy carriers, electricity

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"Conservation of electrons"

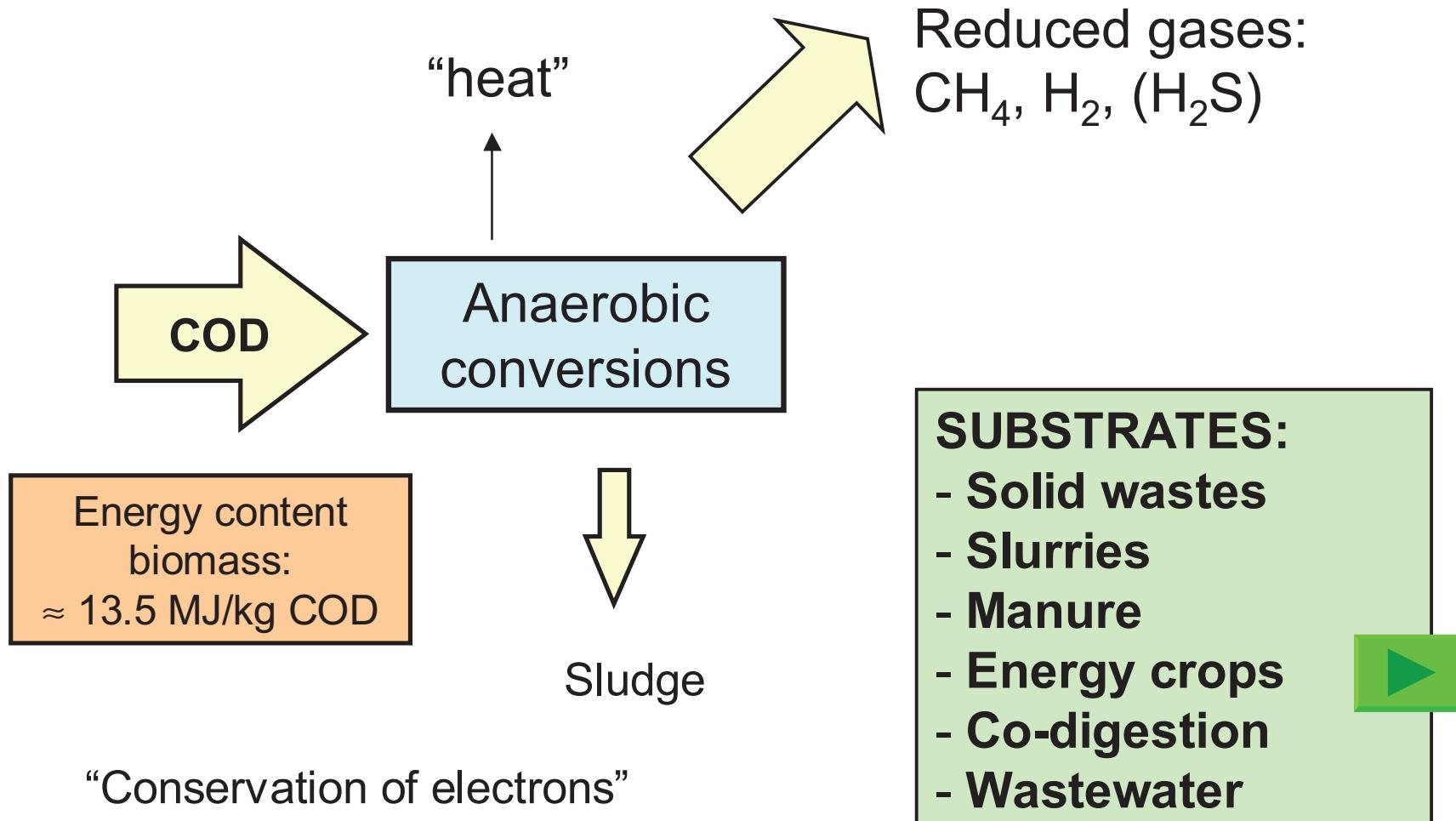
*Zengler et al., '99, *Nature* 401, 266-269: alkanes → CH_4



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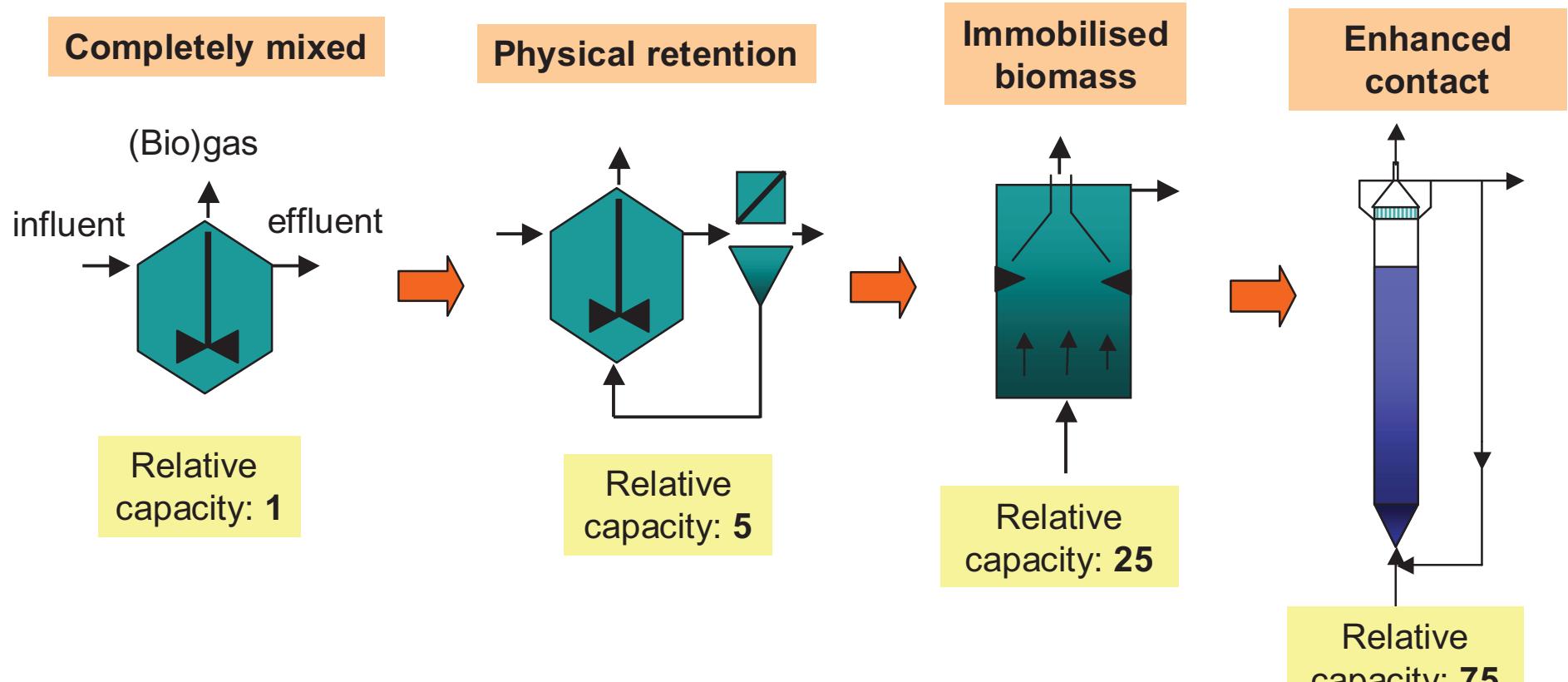
AD ↔ Energy: heat, energy carriers, electricity

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Energy recovery in anaerobic wastewater treatment

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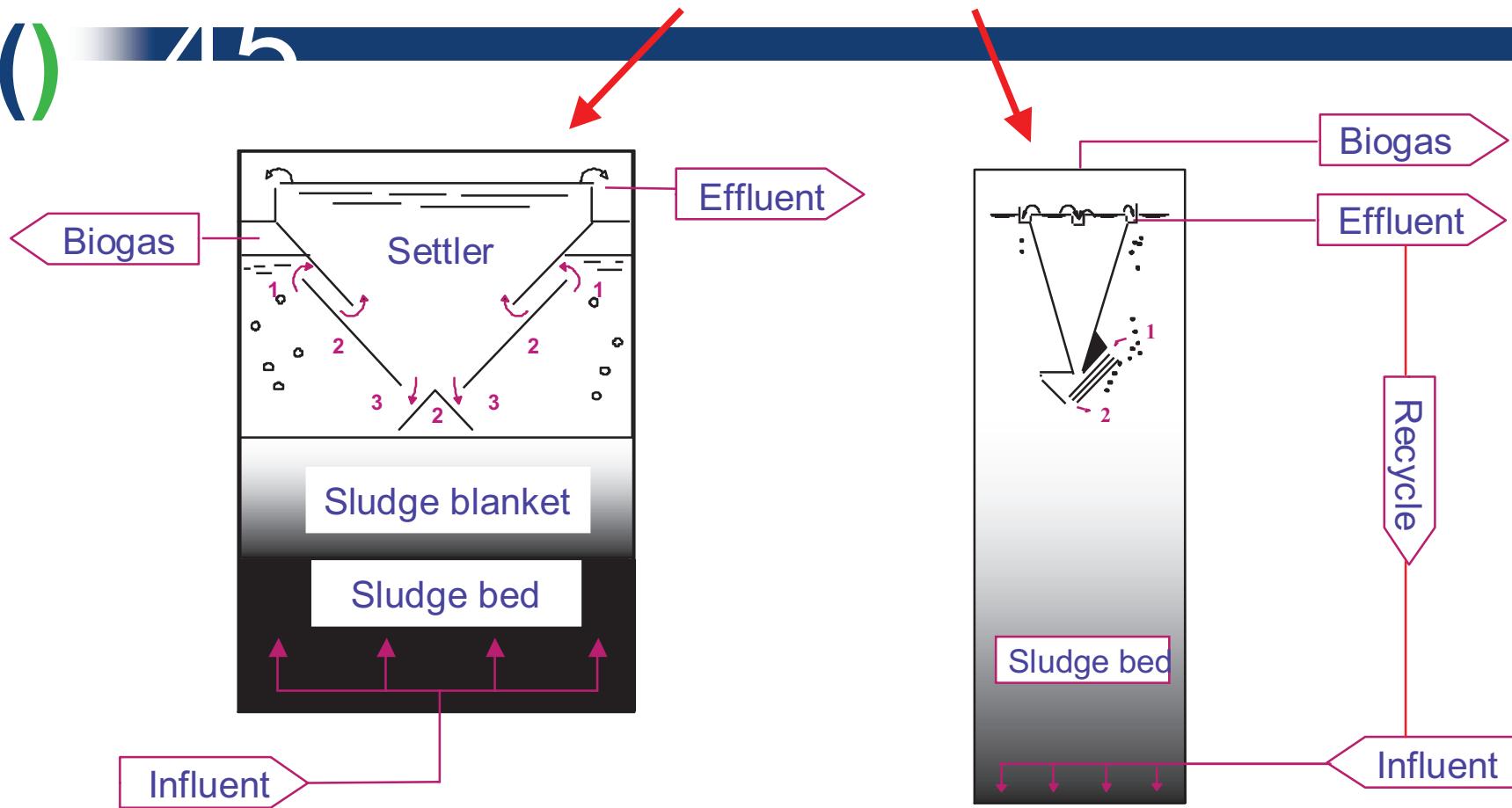
**Development of “high-rate”
anaerobic treatment systems**



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From UASB to EGSB

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1. Sludge/biomass inlet
2. Gas baffle plates
3. Return settled sludge

1. Sludge/water mixture
2. Settled sludge

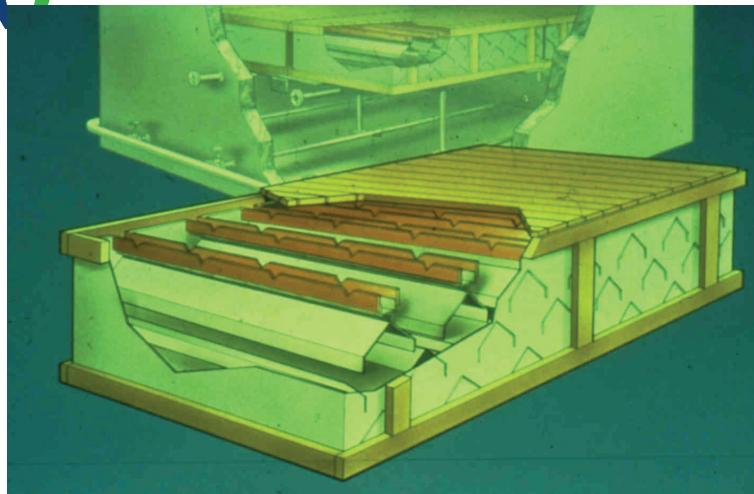


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 **BIOTHANE SYSTEMS
INTERNATIONAL**

Application of Multi-layer settling system

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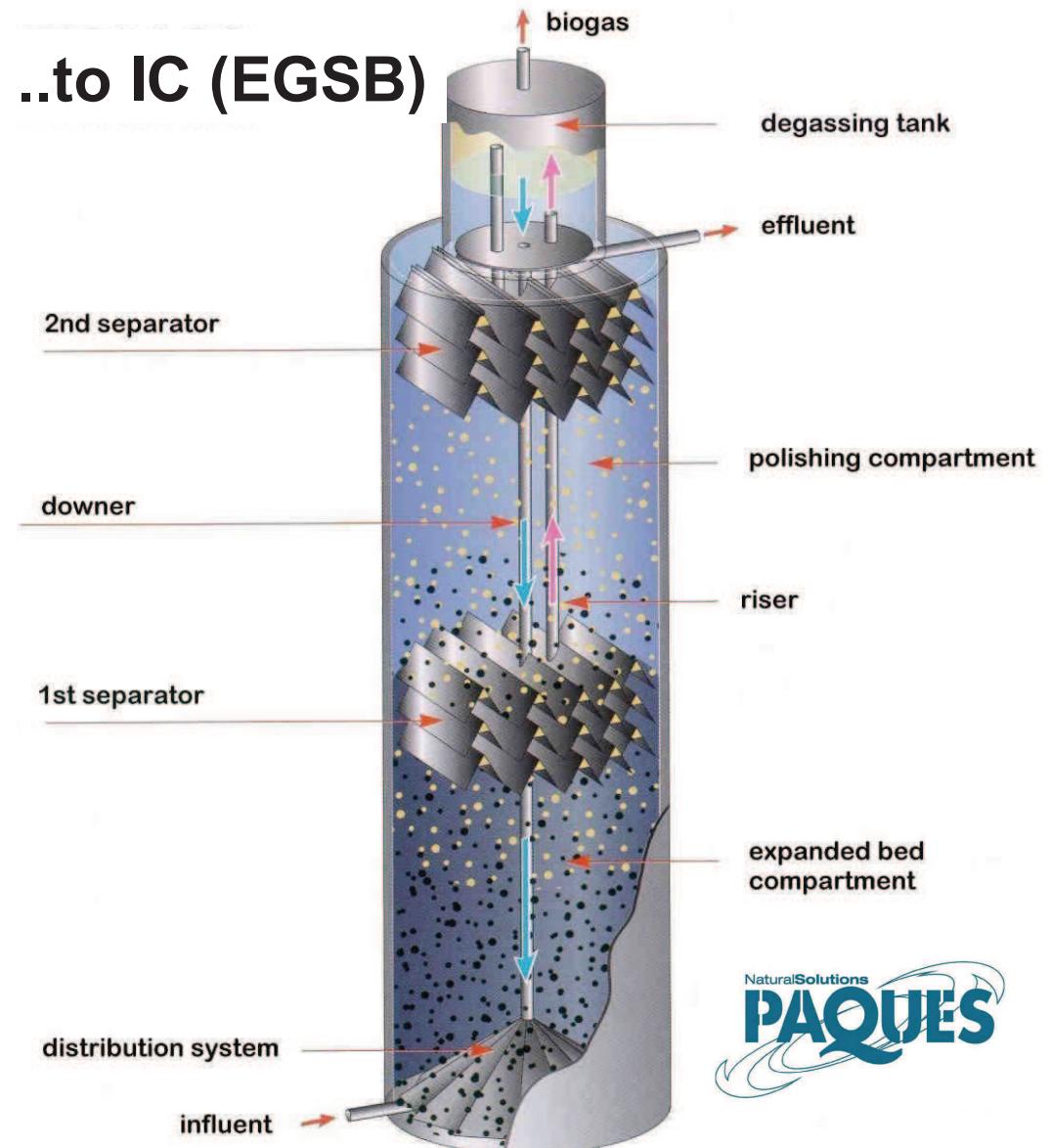


From UASB....



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..to IC (EGSB)



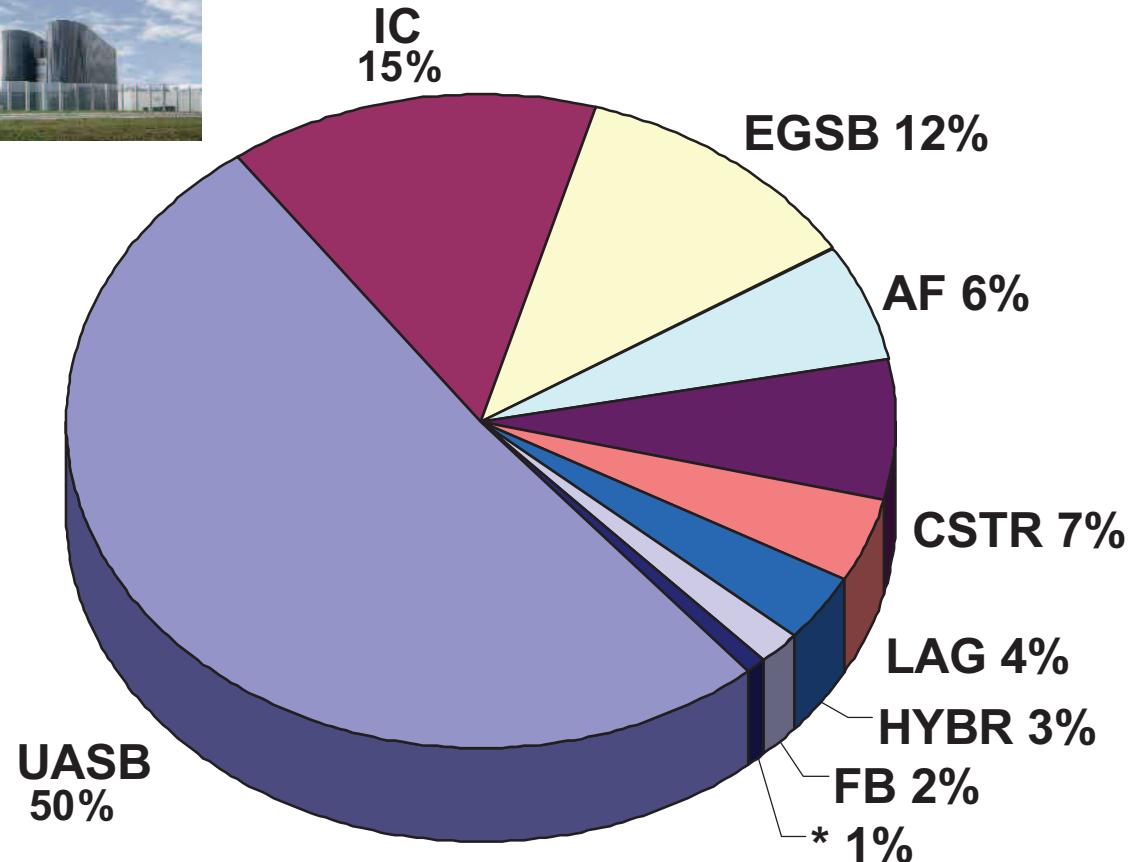
NaturalSolutions
PAQUES

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Historically applied anaerobic processes

(1981 – 2007 (Jan.) N= 2266)



(Granular) sludge bed based: 77%

* References with incomplete data (1%)

Source: Worldref. 04-2007



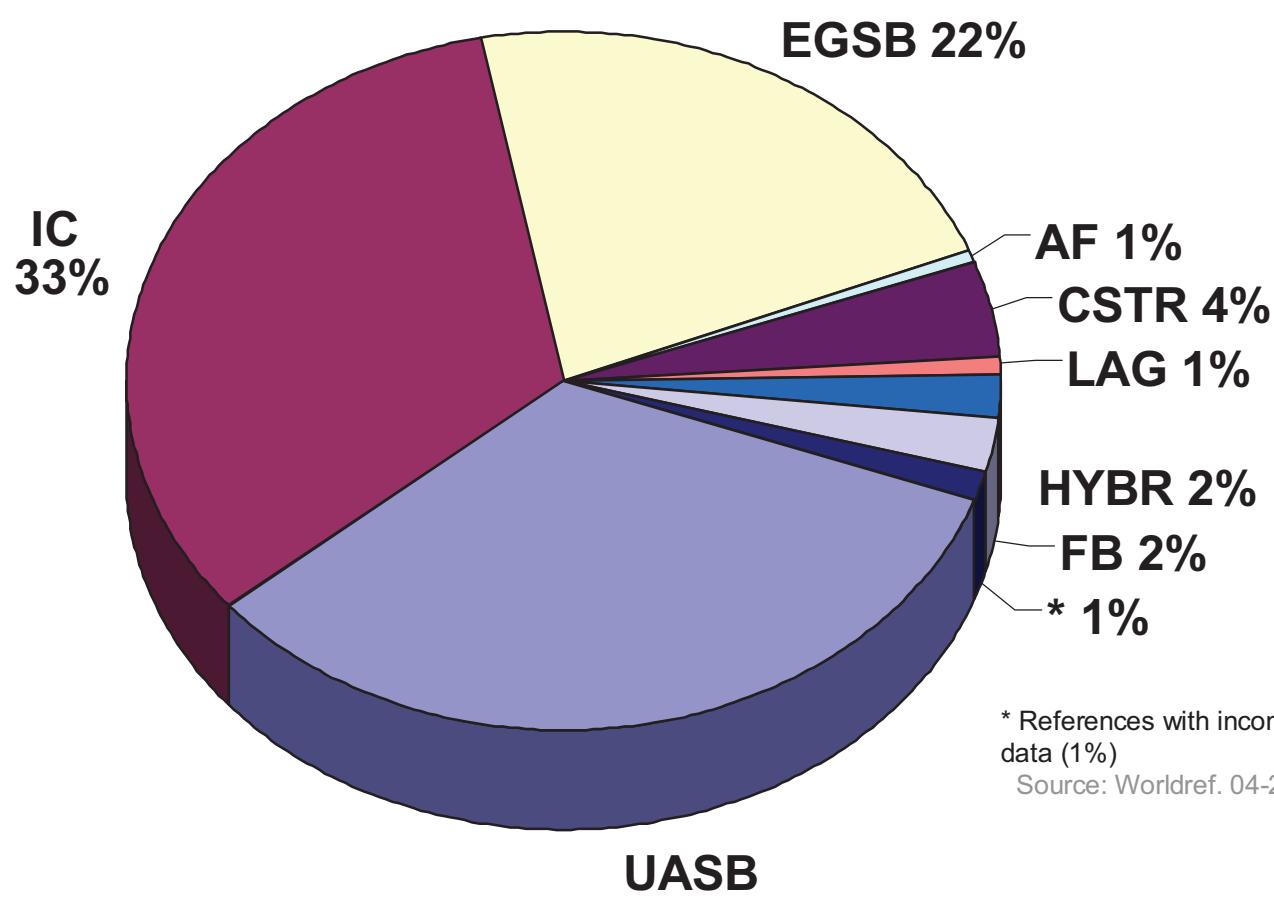
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Currently Applied Anaerobic Processes

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(2002 – 2007 (Jan.), N= 610)

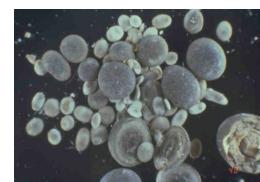
Expanded Bed Reactors: 55%



* References with incomplete data (1%)

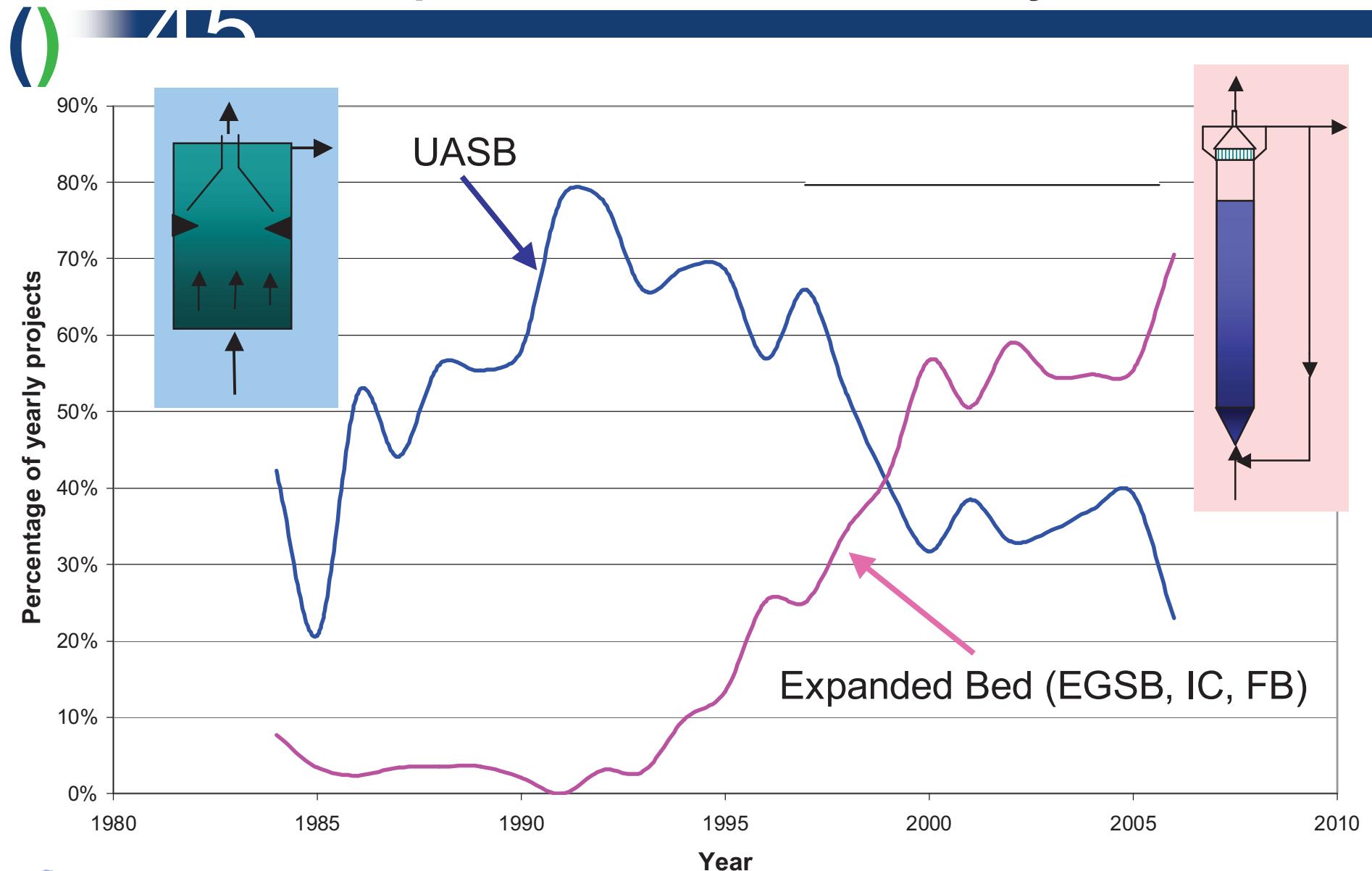
Source: Worldref. 04-2007

(Granular) sludge bed based: 89%



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Full Scale Expanded Bed versus UASB Systems



Full scale AWWT at beer brewery

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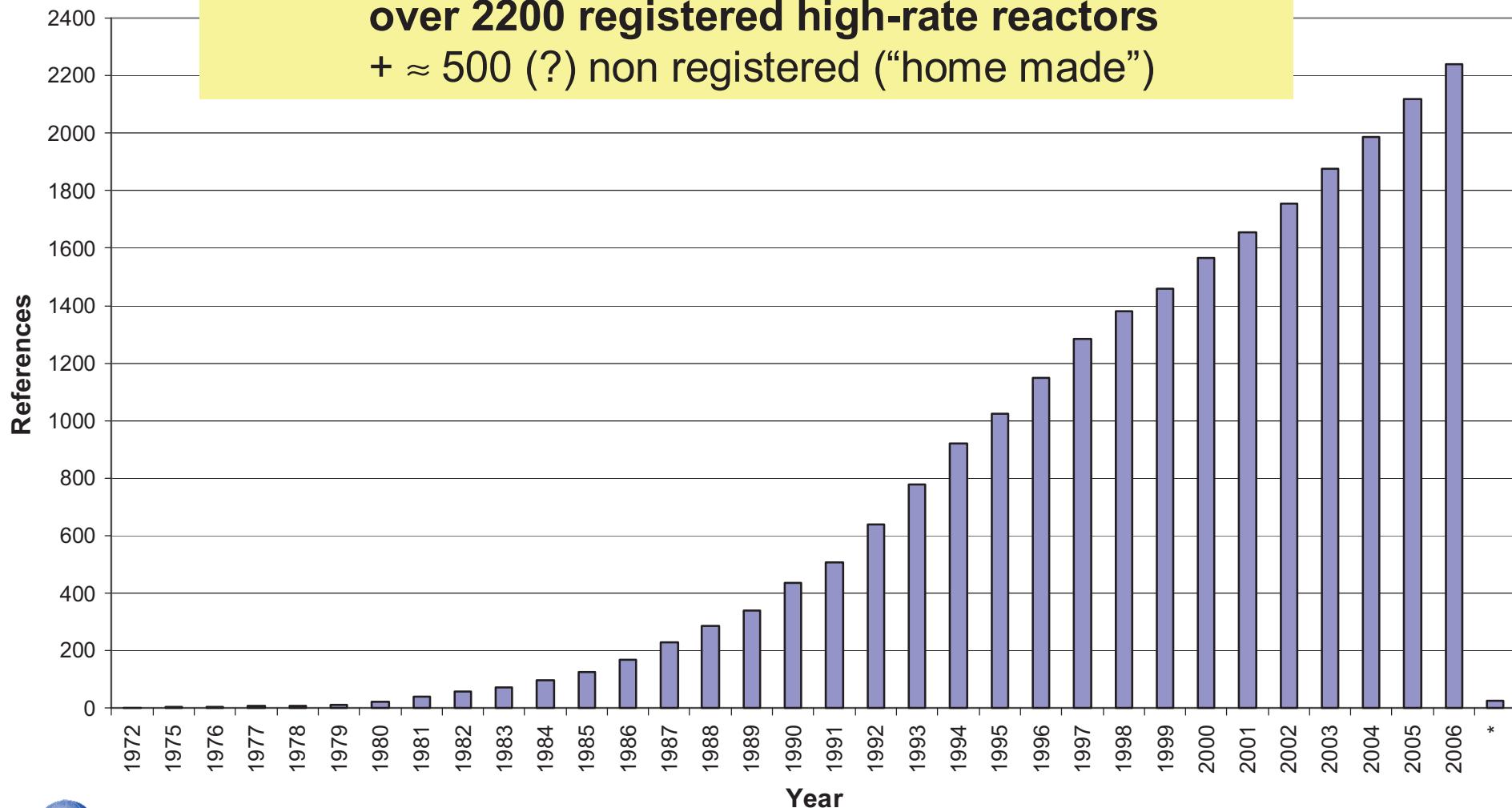
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Worldwide cumulative anaerobic references

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Anaerobic Industrial Wastewater Reactors, census 2007
over 2200 registered high-rate reactors
+ \approx 500 (?) non registered ("home made")



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Van Lier, Wat.Sci.Technol. 57(8), 2008; Data collected by Yolanda Yspeert

High-rate Anaerobic Applications in Industries

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Number of installed reactors, N= 2266 (Jan. 2007)

AGRO-FOOD INDUSTRY 36%		BEVERAGE 29%	ALCOHOL DISTILLERY 10%	PULP & PAPER 11%	MISCELLANEOUS 14%
Sugar	Cannery	Beer	Sugar cane juice	Recycle paper	Chemical
Potato	Confectionery	Malting	Sugar cane molasses	Mechanical pulp	Pharmaceutical
Starch	Fruit	Soft drink	Sugar beet molasses	NSSC	Sludge liquor
Yeast	Vegetable	Fruit juice	Grape wine	Sulphite pulp	Municipal sewage
Pectin	Dairy	Wine	Grain	Straw	Landfill leachate
Citric acid	Bakery	Coffee	Fruit	Bagasse	Acid mine water



Yeast, Italy



Beer, Brazil



Distillery,
Japan



Paper,
Netherlands



Chemical,
Netherlands

Full scale example: Brewery Effluent

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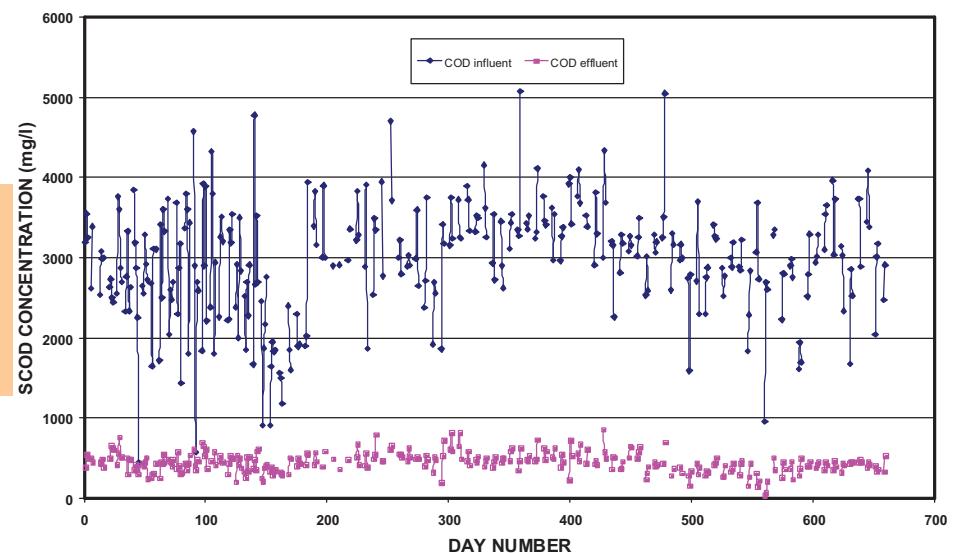
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PARAMETER	UNIT	Brewery
Flow	m ³ /d	2720 – 5780
COD average	mg/l	4043
COD range	mg/l	2020 – 5790
SS	mg/l	260 – 2160
Temperature	°C	21 – 40
pH		2.6 – 7.0



COD-load: 17 ton/day
Required reactor dimensions:
 $V = 500 \text{ m}^3$ only, $h = 25 \text{ m}$, $d = 5 \text{ m}$



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Brewery effluent: Energy benefit!



Energy content 1 ton COD \approx 13.5 GJ \approx 3.8 MWh

Energy recovered:

17 ton COD x 0.85 (eff) x 3820 kWh** x 40% CHP eff.
= 22 MWh-e/day \approx 1MW powerplant



No energy consumption:

Average energy requirement activated sludge: \approx 1 kWh-e/kg COD removed

Saved: 17 ton COD x 0.85 (eff.)
= 15 MWh-e/day

Total energy benefit:

22 + 15 = 37 MWh-e/day
 \approx 3300 €/d (with 0.09 €/kWh)
 \approx 1.2 \times 10⁶ €/year



Brewery effluent: CO₂ emission reduction!

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Energy recovered:

17 ton COD x 0.85 (eff) x 3820 kWh** x 40% CHP eff.
= 22 MWh-e/day ≈ **19 ton CO₂ reduction/day (coal)**

No energy consumption:

17 ton COD x 0.9 (eff.) = 15 MWh-e/day
≈ **13 ton CO₂ reduction/day (coal)**

Coal powered electricity plant:
0.86 ton CO₂/MWh-e



Total CO₂ emission reduction:
19 + 13 = 32 ton CO₂ /day



≈ 380 €/d (with 20 €/ton CO₂)
≈ 140.000 €/year

Energy output and CO₂ emission reduction using AD systems

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2008 state-of-the-art

Loading capacity (kg COD.m ⁻³ .d ⁻¹)	10 – 35
Energy output (MJ.m ⁻³ reactor installed.d ⁻¹)	55 – 390
Electric power output (kW-e.m ⁻³ reactor installed)	0.25 – 1.7
CO₂ emission reduction (tonCO ₂ .m ⁻³ .y ⁻¹ , compared to coal-driven power plant)	1.9 – 13

Assumptions:

- 80% CH₄ recovery relative to influent COD load
- 40% electric conversion efficiency using a modern combined heat power (CHP) generator
- Intermediate values are obtained by linear interpolation.



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Importance for developing countries:

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Energy recovery & CO₂ credits as an incentive to implement environmental technologies in developing countries ?

Treatment alcohol distillery effluents Cuba (Santa Clara):

- 800 m³.d⁻¹,
- 65 kg COD.m⁻³

Anaerobics: 13,500 m³ CH₄.d⁻¹
or: about **2.2 MW-electric** (40% eff.)
At a price of 0.12 US\$.kWh⁻¹ this
equals: **2.300.000 US\$.y⁻¹**
CO₂ credits: **330.000 US\$.y⁻¹ (coal)**



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More energy from “end-of-the-pipe” to “zero-discharge”

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1000 ton/d
paper



55 °C

fresh water
1000 m³/d

evaporation
1000 m³/d

Energy savings

no effluent 1045* MJ/ton
(115 MWh-e/dag)
anaerobics 200 MJ/ton
(22 MWh-e/dag)



steam
80 ton/d

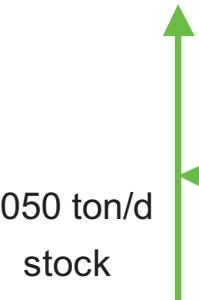


sulfur
0.2 ton/d

35 °C



1050 ton/d
stock



1 ton/d
waste
sludge

4000 m³/d

cooling
4000 m³/d

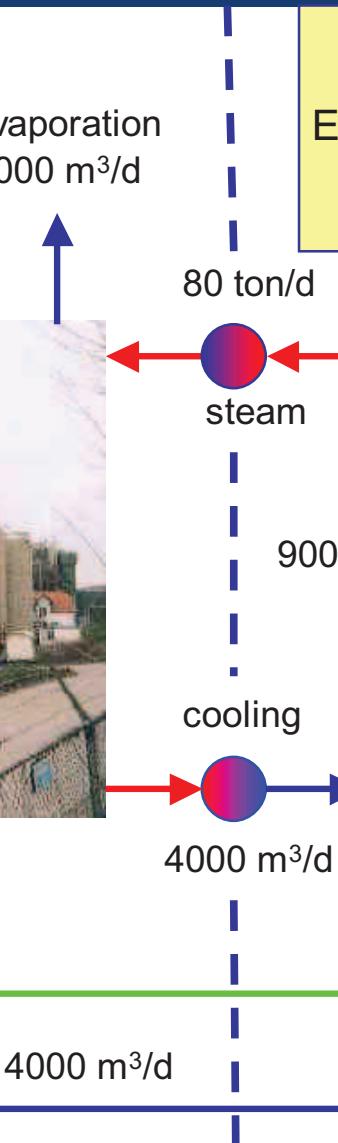


anaerobic



aerobic

H_2S removal
biogas
9000 m³/d



corrugated card board industry



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Anaerobics as “kidney technology”?

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1. How to cope with more extreme conditions?:
 - Accumulation of toxic / recalcitrant compounds
 - temperature increase (thermophilic)
 - salinity increase (Na^+)
2. Biofilm/granule stability guaranteed?
3. Integration with complementary technologies?

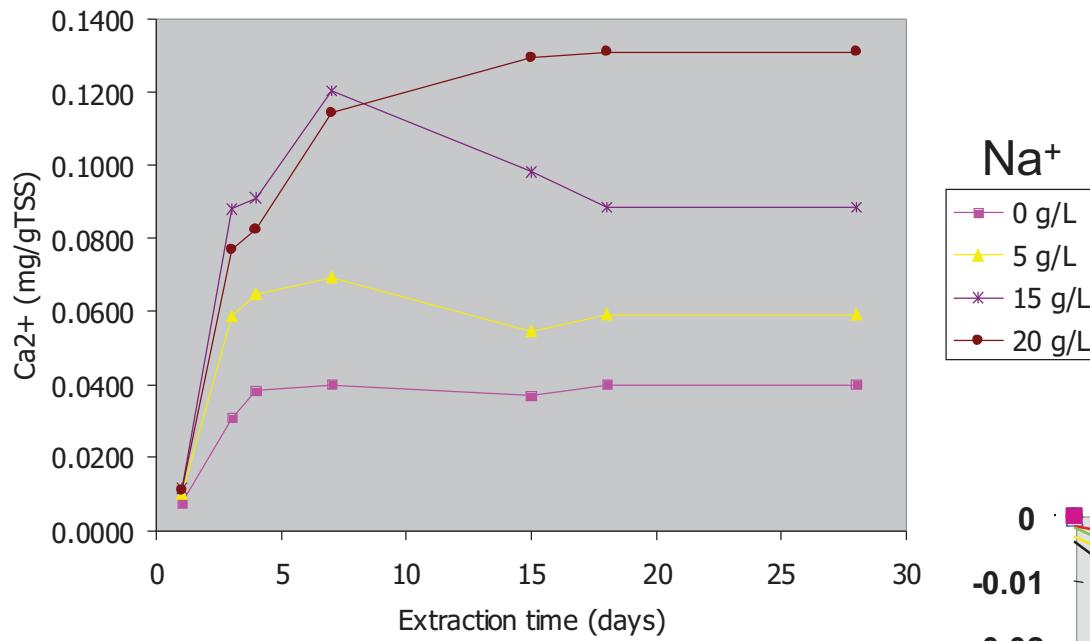
- Adapting / optimising sludge bed systems?
- Alternative anaerobic technologies?



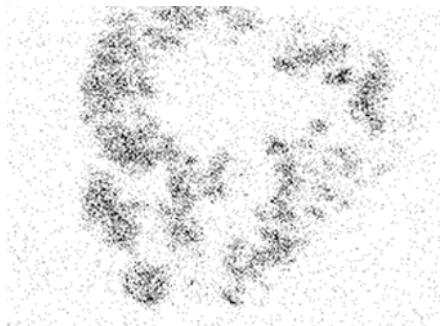
High salinity decreases granule stability!

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Ca⁺⁺ extraction by Na⁺



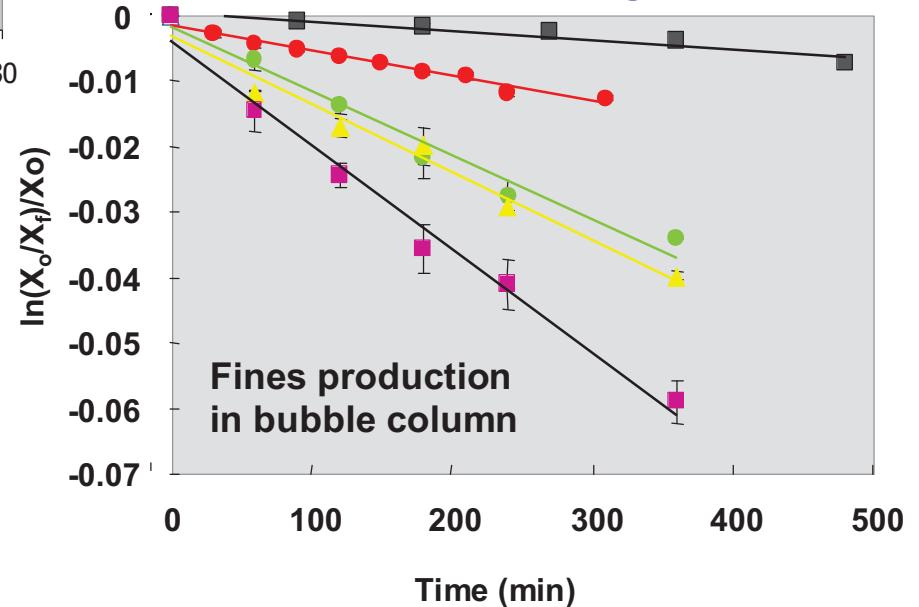
0.6 mm



EDX analysis:
Ca⁺⁺ distribution in
Shell sludge

Jeison et al, Wat.Sci.Technol., 2008
Ismail et al., Wat.Sci.Technol., 2008

Granule Strength Decrease after 6 months of UASB operation

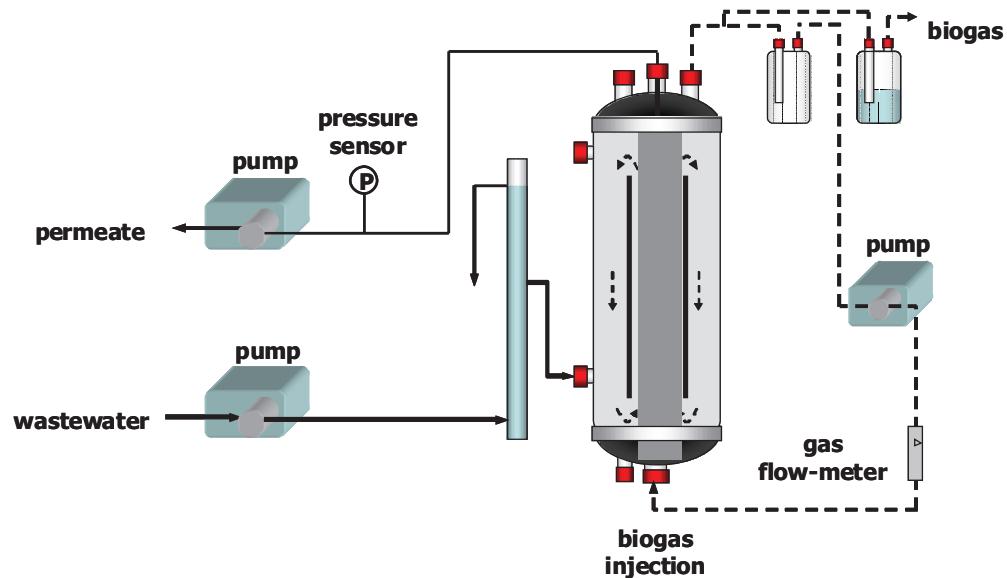


Anaerobic MBR technology for extreme conditions?

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Application potential:

- when sludge immobilisation is not likely (high temperatures, high salinity, fluct. pH)
- presence of recalcitrant compounds (spec. bacteria)
- high solids concentrations
- other extremes?

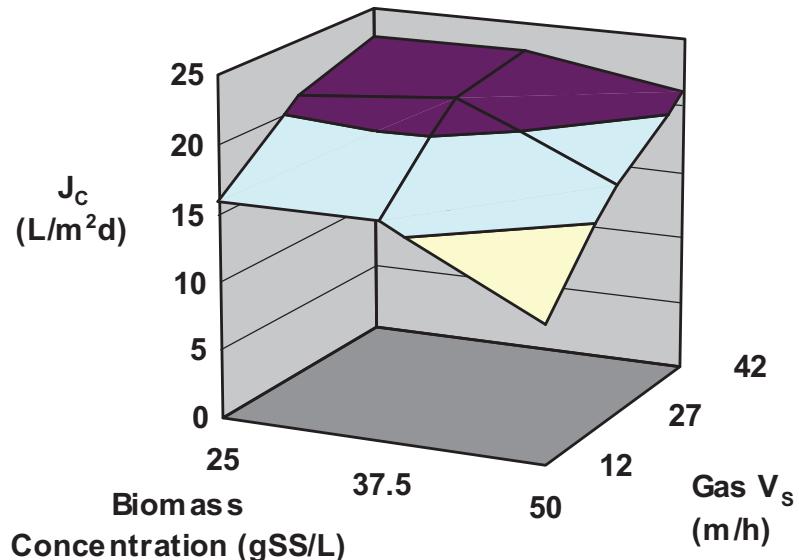


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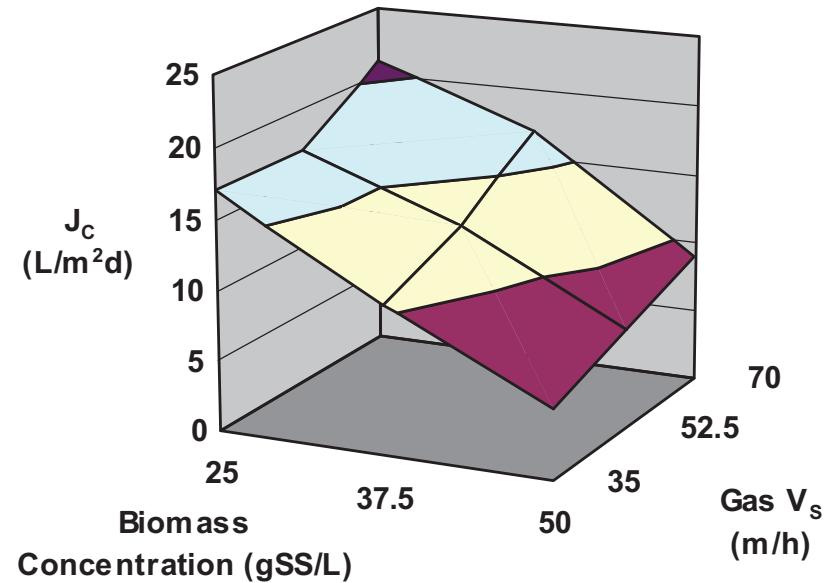
Extreme conditions beneficial for membrane filtration ?

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Impact of temp. on achievable membrane flux



Thermophilic



Mesophilic

Submerged MBRs, VFA as substrate

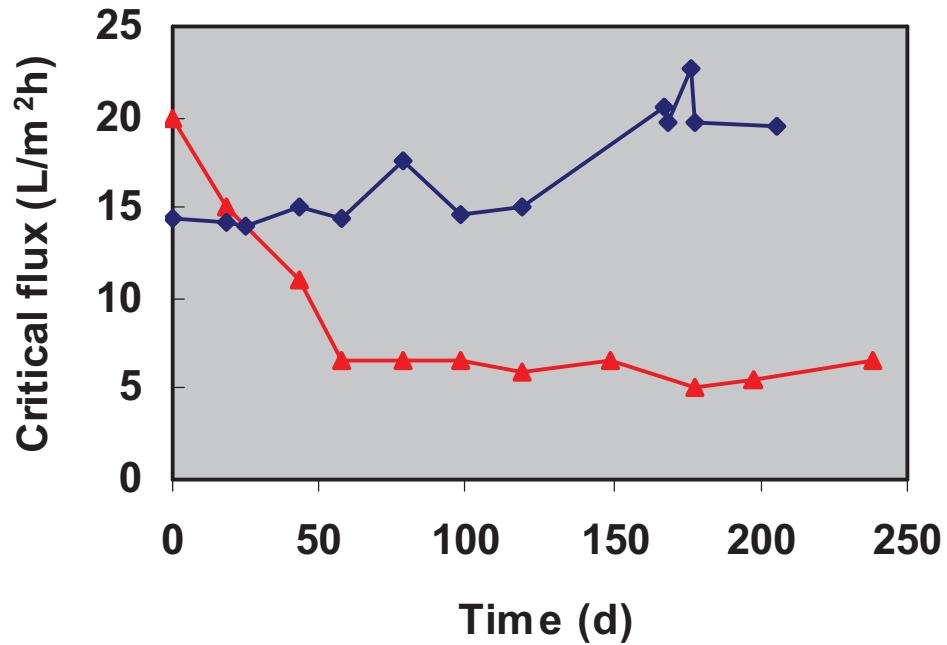


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(Jeison and van Lier, J. of Membr. Sci., 2006)

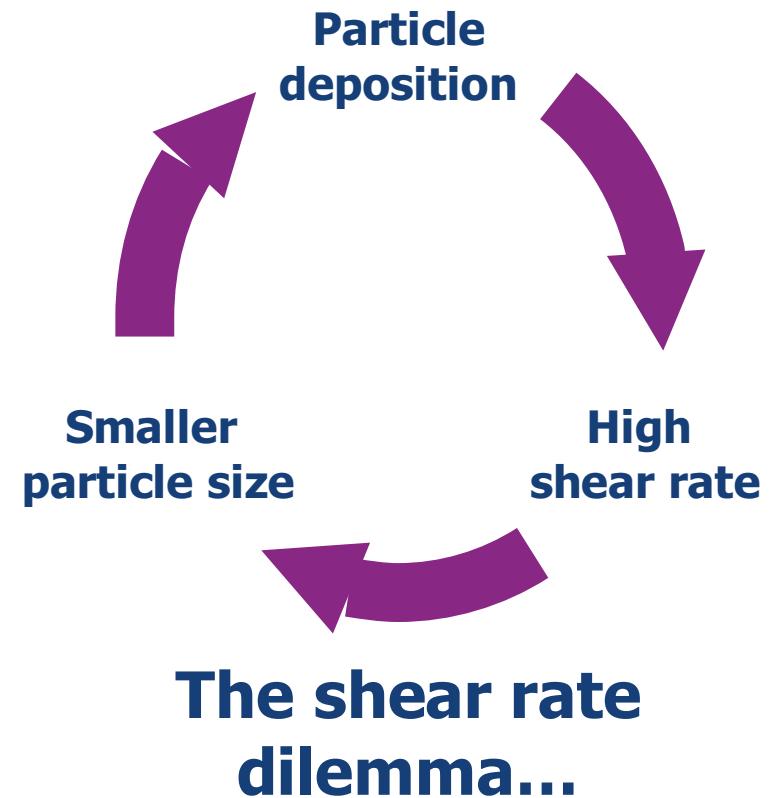
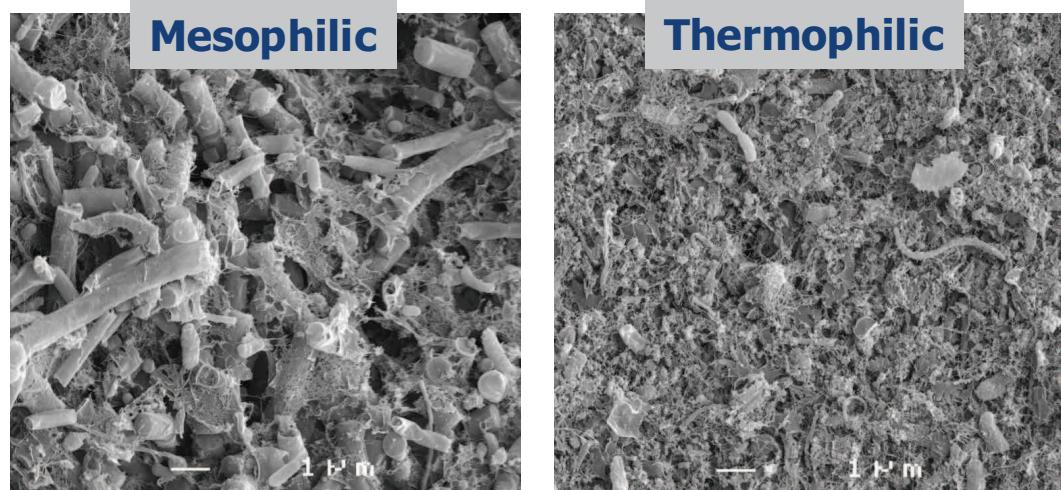
Flux determining factors in anaerobic MBRs

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Jeison PhD thesis, 2008

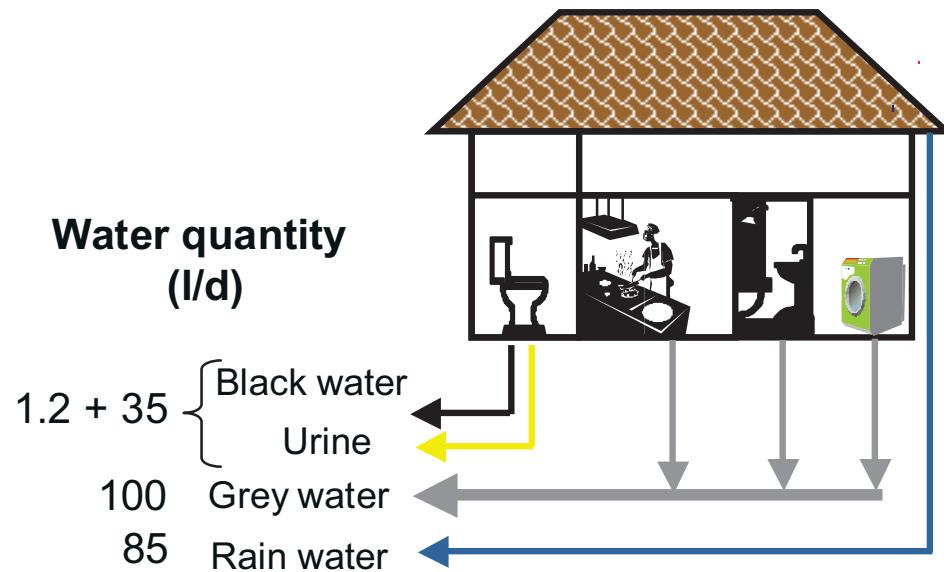
Thermophilic
Mesophilic



Role of anaerobics in novel sanitation concepts

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(Re)source oriented sanitation concepts (Desar):



MDG can not be reached!
2008: UN year of sanitation

AD in Desar:

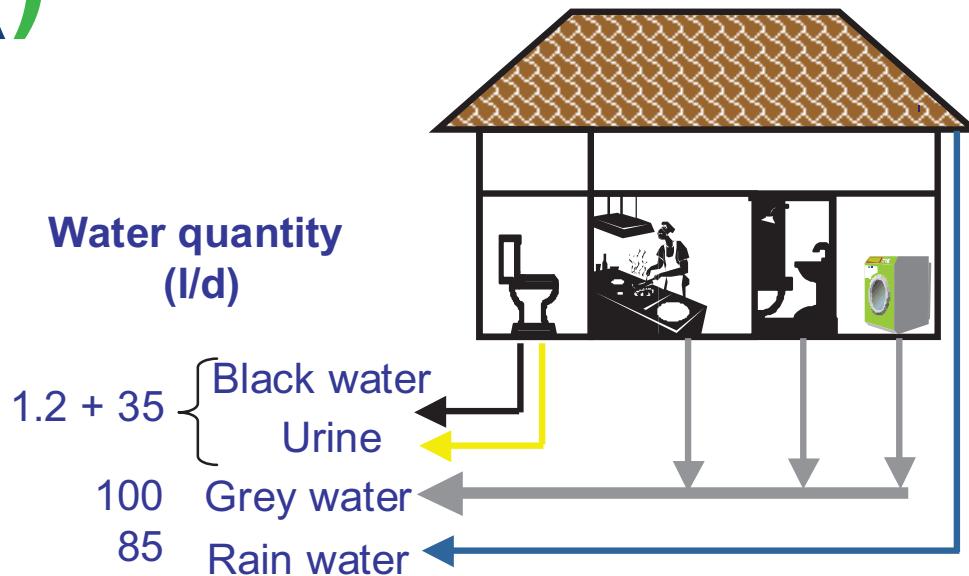
- sludge stabilisation
- nutrients production
- energy production
- scavenger micropollutants



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Resources from domestic wastewater?

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Urine + faeces + kitchen waste:

- 1.5 l in volume
- 91 % N
- 69 % P
- 70 % COD
- Pathogens
- salts
- micro pollutants



(Zeeman et al.,
2007)

Urine + faeces
= 1.2
l/pers./day !!

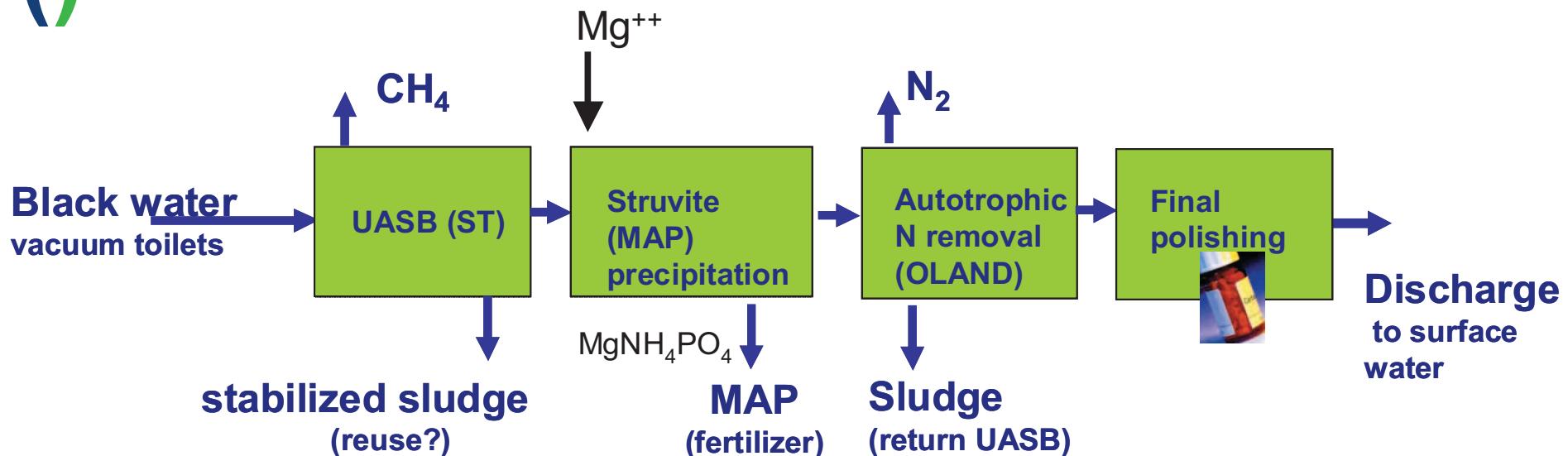


**Recovery of energy &
nutrients feasible
Grey water for irrigation!!**



Black water treatment: Sneek

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UASB (ST)	$HRT_{min} = 7d$; $T_{max} = 30^\circ C$
Struvite	$t_{contact} = 30min$
N-removal	$HRT_{min} = 3.5d$



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Zeeman et al., Wat.Sci.Technol., 2008

Energy balance of the Sneek concept:

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	Utility	Energy	Energy in MJ _{electric} .p ⁻¹ .year ⁻¹
Biogas production (black/grey water, kitchen waste)	Waste(water) treatment	$10,5 \text{ m}^3 \text{ CH}_4 \cdot \text{p}^{-1} \cdot \text{y}^{-1}$ $= 374 \text{ MJ} \cdot \text{p}^{-1} \cdot \text{y}^{-1}$	131
Energy consumption	Vacuum transport	$25 \text{ kWh} \cdot \text{p}^{-1} \cdot \text{y}^{-1}$	-90
	Kitchen waste grinders	-5 kWh.p ⁻¹ .y ⁻¹	-18,0
	Post- treatment		-43
Energy saving	STP	$24 \text{ kWh} \cdot \text{p}^{-1} \cdot \text{y}^{-1}$	86
	Conventional sewer	$30 \text{ kWh} \cdot \text{p}^{-1} \cdot \text{y}^{-1}$	108
	Drinking water	$0.5 \text{ kWh} \cdot \text{m}^3 \text{ produced}$	26
Total			200

Domestic wastewater as a resource (Sneek results):

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Total energy savings in Sneek: $200 \text{ MJ} \cdot \text{person}^{-1} \cdot \text{year}^{-1}$

Extrapolating to the Netherlands: $915 \text{ million kWh/year}$

$\approx 100 \text{ MW}$

$\approx 200.000 \text{ 4-persons households}$

Nutrients: $0.14 \text{ kg P} \cdot \text{person}^{-1} \cdot \text{year}^{-1}$

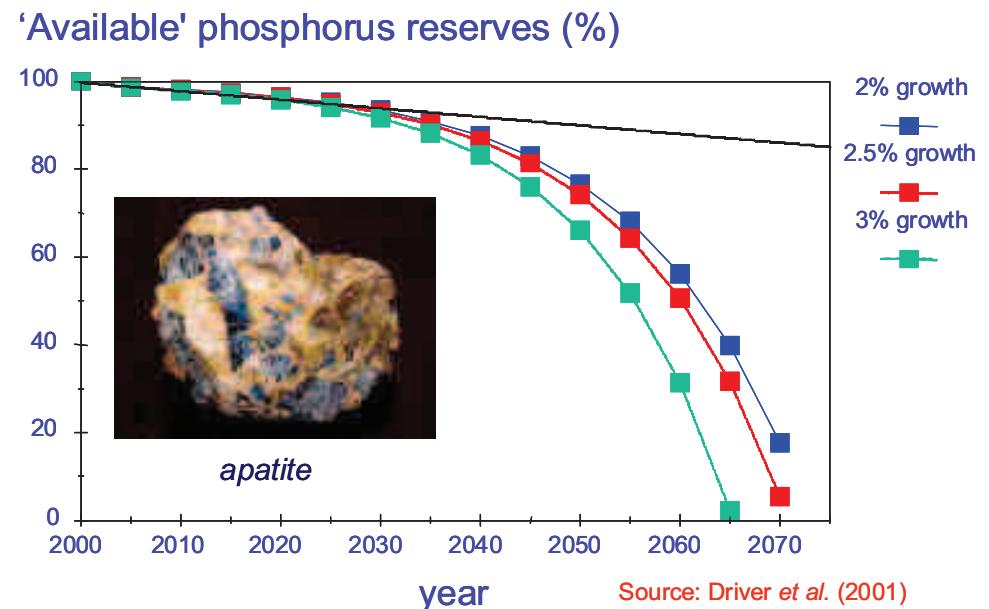
or: $2.310 \text{ ton P} \cdot \text{year}^{-1}$ as struvite (NH_4MgPO_4)

Potentially reusable grey water:

$90 \text{ l} \cdot \text{person}^{-1} \cdot \text{year}^{-1}$

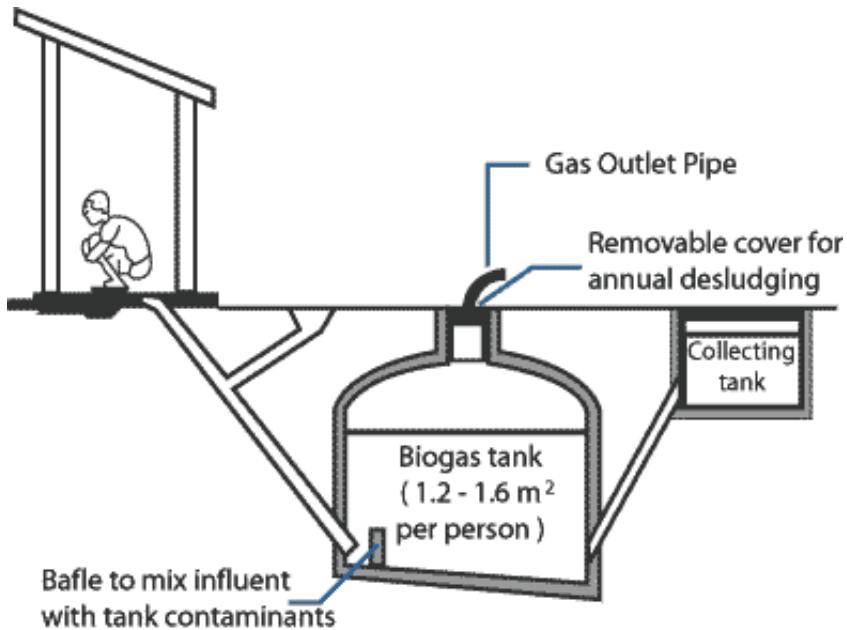
$\approx 540 \text{ million m}^3 \cdot \text{year}^{-1}$ in NL

$\approx (8-11 \text{ million ha irrigated area...})$



AD sanitation potentials for developing countries??

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- prevent diseases
- prevent water pollution
- protect drinking water source
- produce nutrients
- produce energy



Community on-site bio-digester toilet blocks in Kibera, Kenia

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Conclusions

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- AD is consolidated technology for wastewater treatment
- Energy efficiency and actual energy recovery is a driver of increasing importance!... 1 ton COD \approx 13.5 GJ....
- AD needs adaptation to more extreme environments! Need for stable sludge bed systems, anaerobic MBR, other?
- AD may play a prominent role in sustainable sanitation approaches coupling: hygiene, disease prevention, energy recovery, production of fertilisers, protection water resources/environment.



Thanks to all colleagues, PhDs and research fellows

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David Jeison



Grietje Zeeman



Hardy Temmink



Tania Fernandes



Thobias Bigambo



Shahrul Ismail



RosaElena Beas



Lina Abu Ghunmi



Ghada Kassab



Kirsten
Steinbush



Sammy Letema



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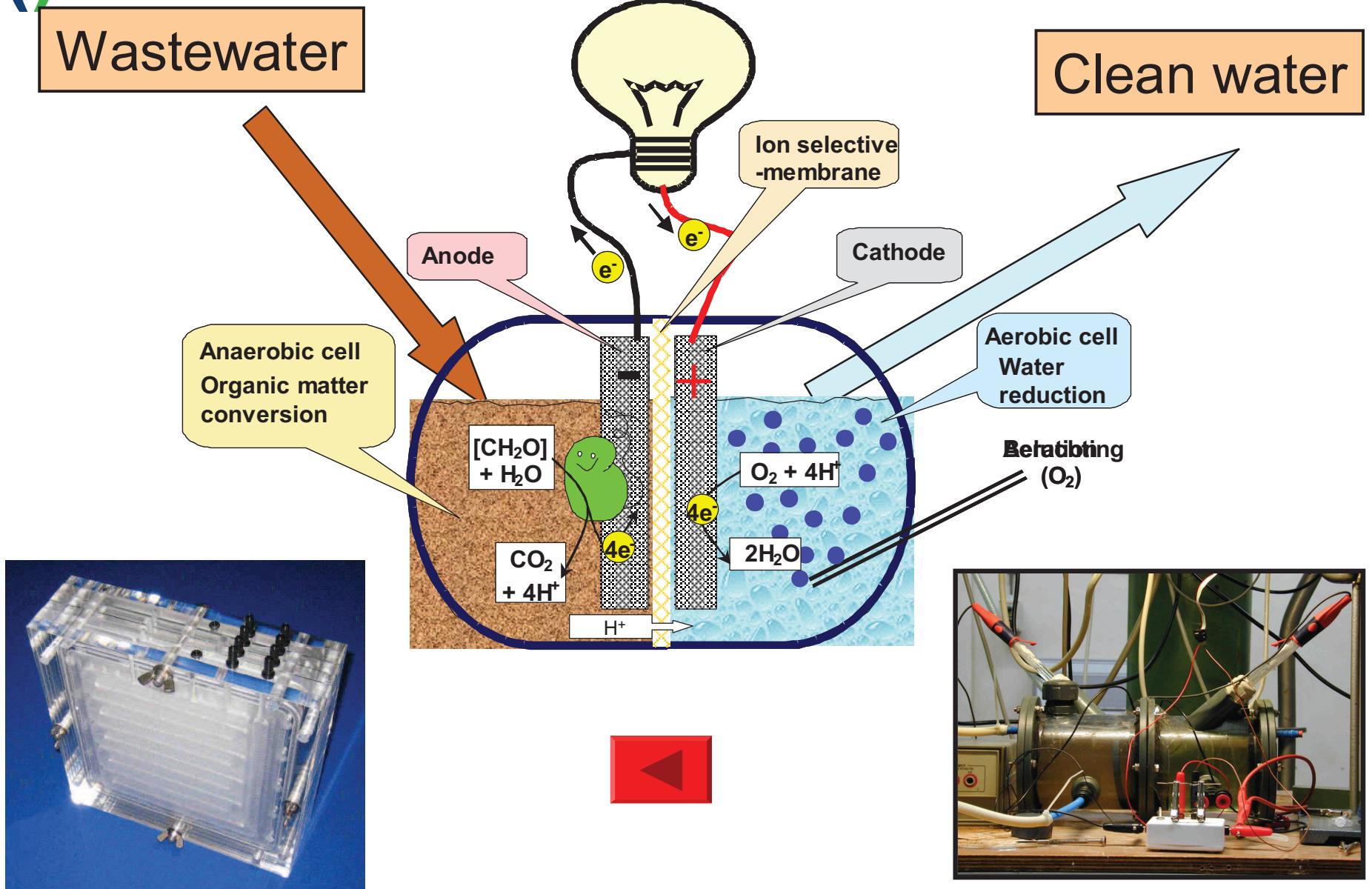
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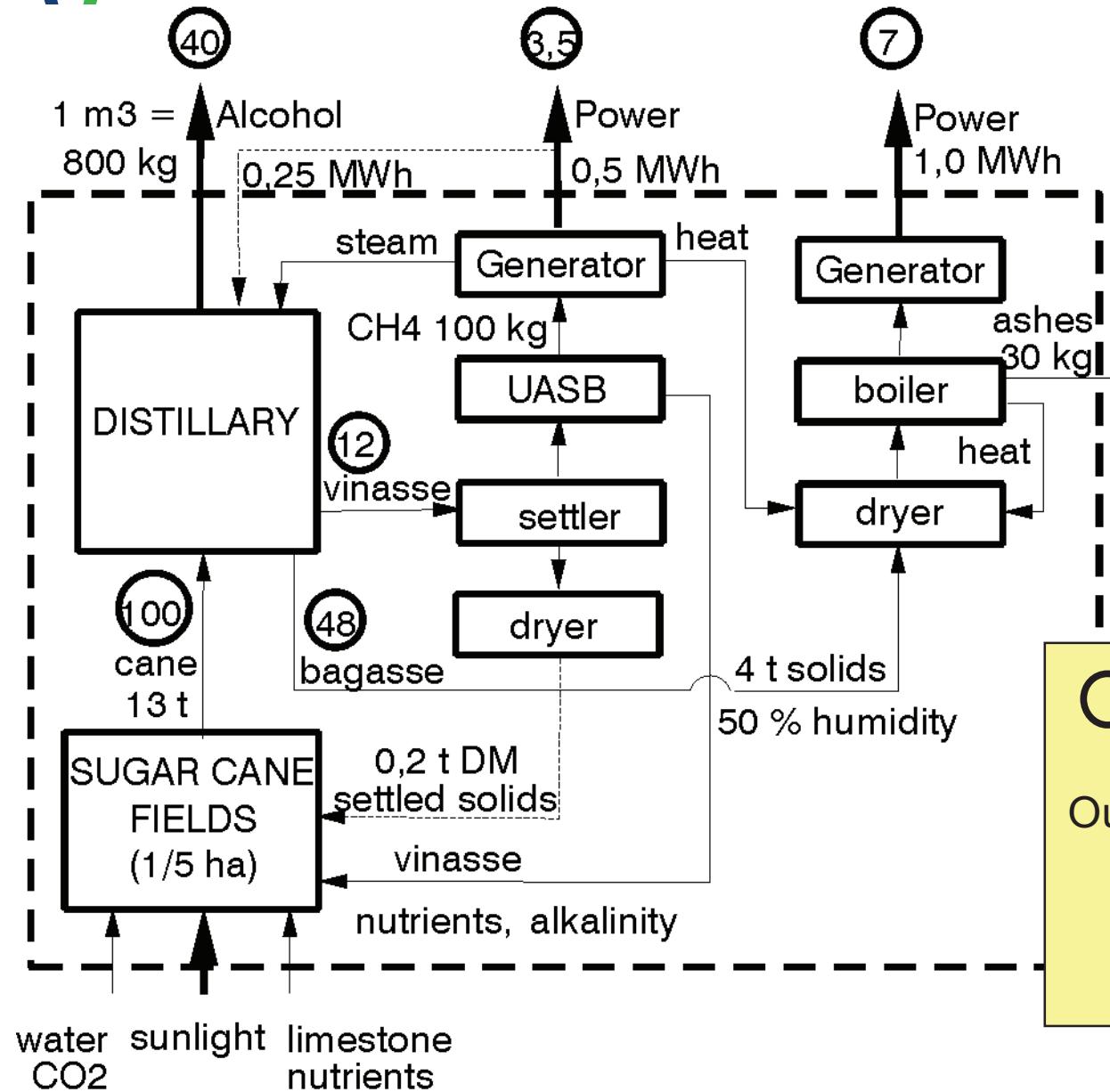
Direct scavenging of electrons

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Biomass cascading in alcohol distilleries, Brasil

115



Van Haandel, 2004

Van Haandel & Van Lier, 2006



○ = percentage of cane energy
Output without AD of wastes
= 5 m³ EtOH/ha
= 4 ton EtOH
= 40% cane energy

Biomass cascading in alcohol distilleries, Brasil

(15)

Optimised energy output alcohol distillery:

(using all by-products)

- Heat (steam production for local use)
- Surplus Electric (35% eff.): $6.3 \text{ MWh-e}/(\text{ha.y}) (\approx 0.7 \text{ kW/ha})$
- Liquid: alcohol: $5 \text{ m}^3/(\text{ha.y})$

alcohol price (2006): $400 \text{ US\$}/\text{m}^3 (\approx 300 \text{ €}/\text{m}^3)$

Total economic benefit: $1500 + 630 = 2130 \text{ €}/(\text{ha.y}).$

Full digestion of cane: $24 \text{ MWh-e}/(\text{ha.y}) \approx 2.8 \text{ kW/ha}$



50 % digestion eff. of solid fraction
Non-digestable fraction is incinerated

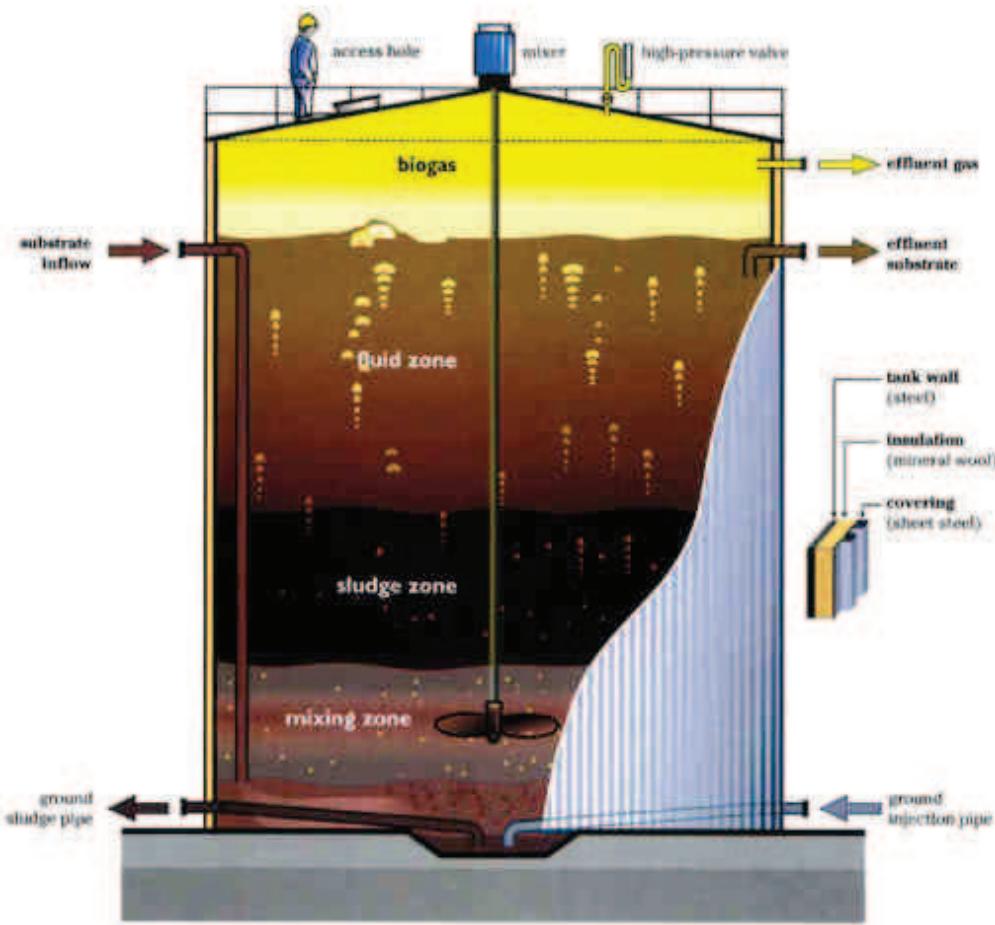
At $0.10 \text{ €}/\text{KWh-e}$: $2400 \text{ €}/(\text{ha.y})\dots\dots\dots$



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Bio-methanation of energy crops: sustainable contribution ?

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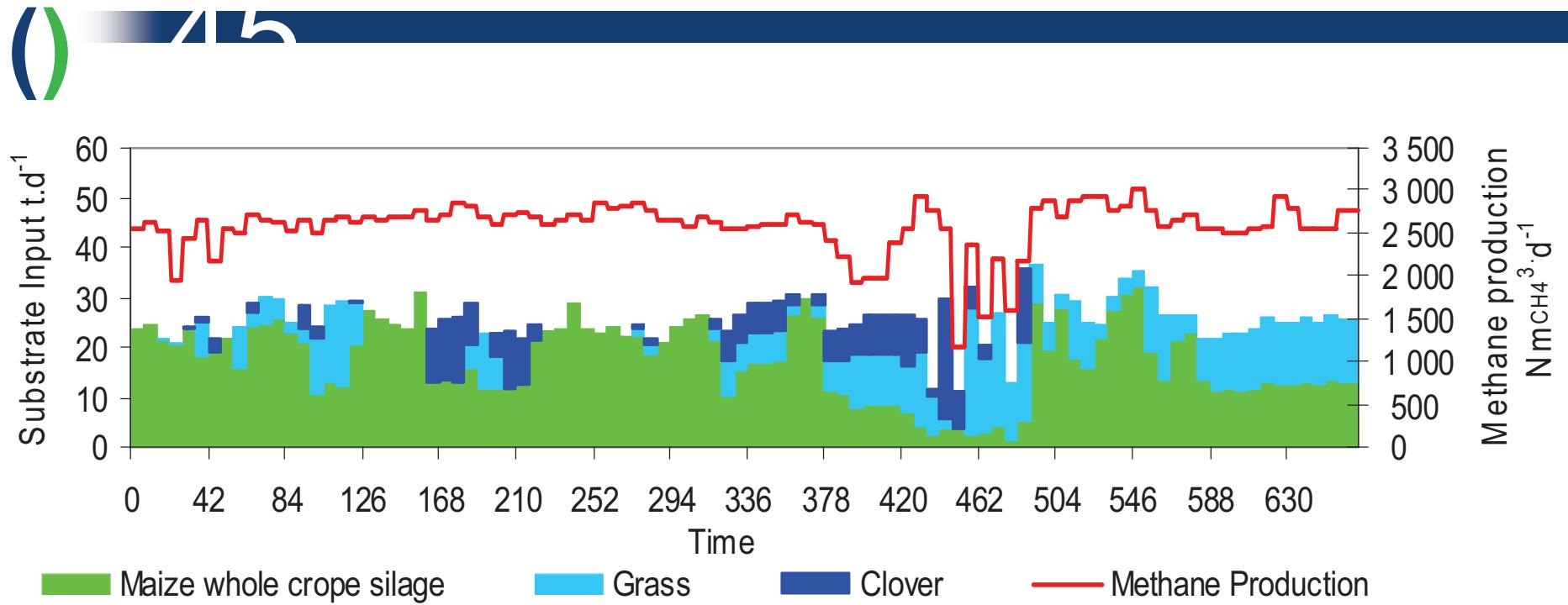
Generally: 0.5 – 1.5 MW-e
HRT up to 90 days...



Let
For

Substrate

Resch, Braun and Kirchmayer, 2007.

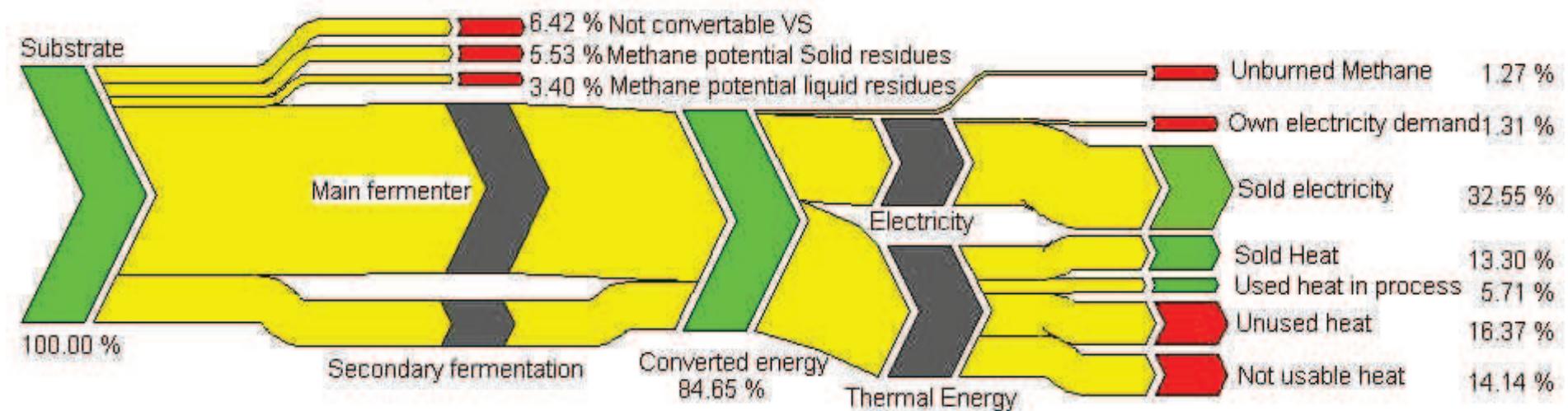


AD reactor not the biggest concern..

- raw materials
- logistics
- maximising energy recovery
- digestate application
- etc.

Energy balance of energy crop digester

(45)



Maiz

Resch, Braun and
Kirchmayer, 2007.
BOKU, Austria



subsidies: up to 0.22 Euro/kWh
- renewable energy
- carbon credits