Energy from Wastewater

Global Methane Initiative (GMI) Partnership-wide meeting,
12-14 October 2011, Krakow Poland

Global Methane Initiative

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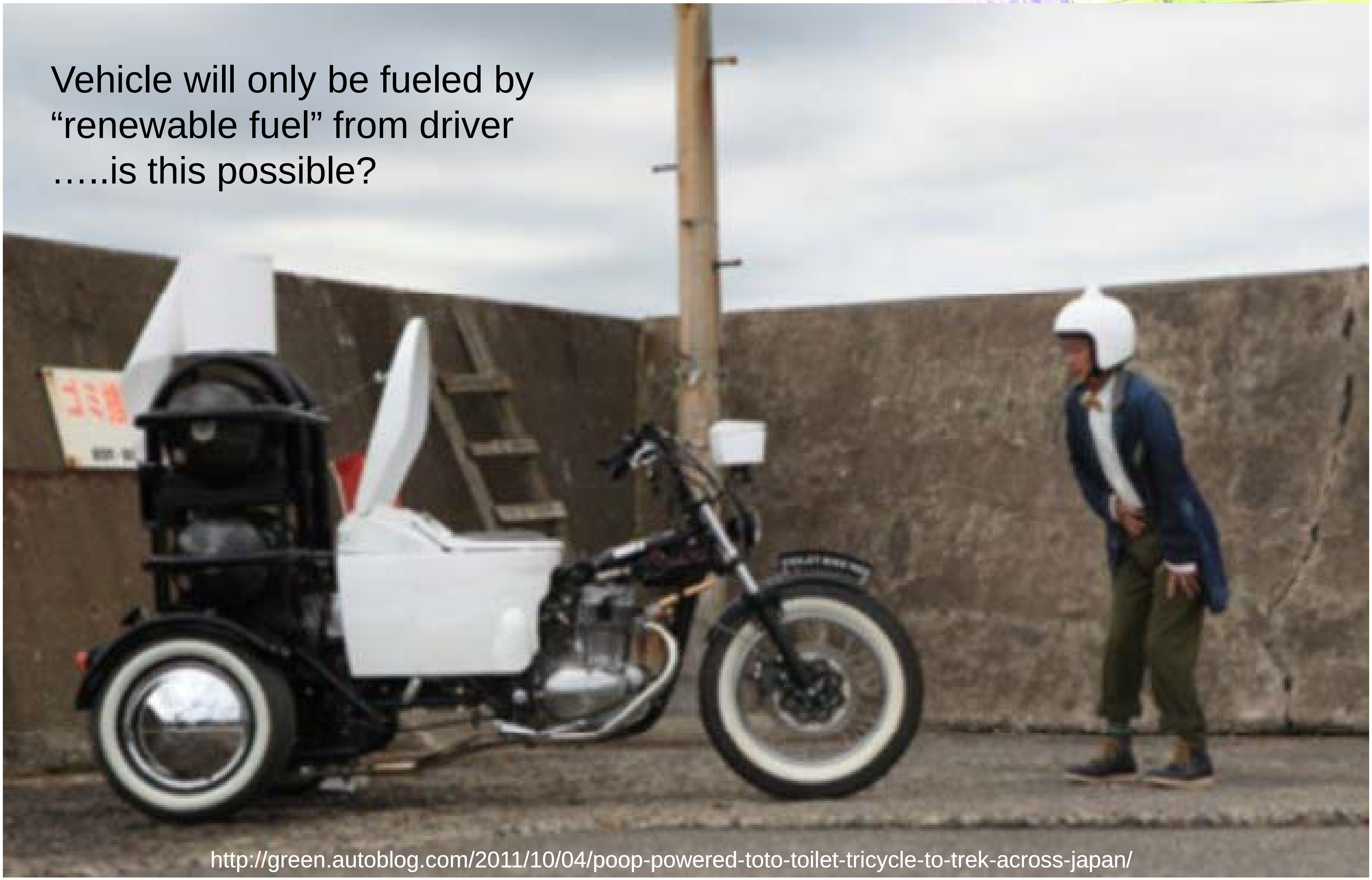
Acknowledgement

- Craig Criddle (Stanford University)
  - A constant source of knowledge and inspiration from whom I have learned much about wastewater treatment and sustainable water reuse via anaerobic processes
- Other Contributors:
  - Jeremy Guest, UM
  - Jim Mihelcic, USF
  - Robert Bair, USF
  - Ivy Cormier, USF

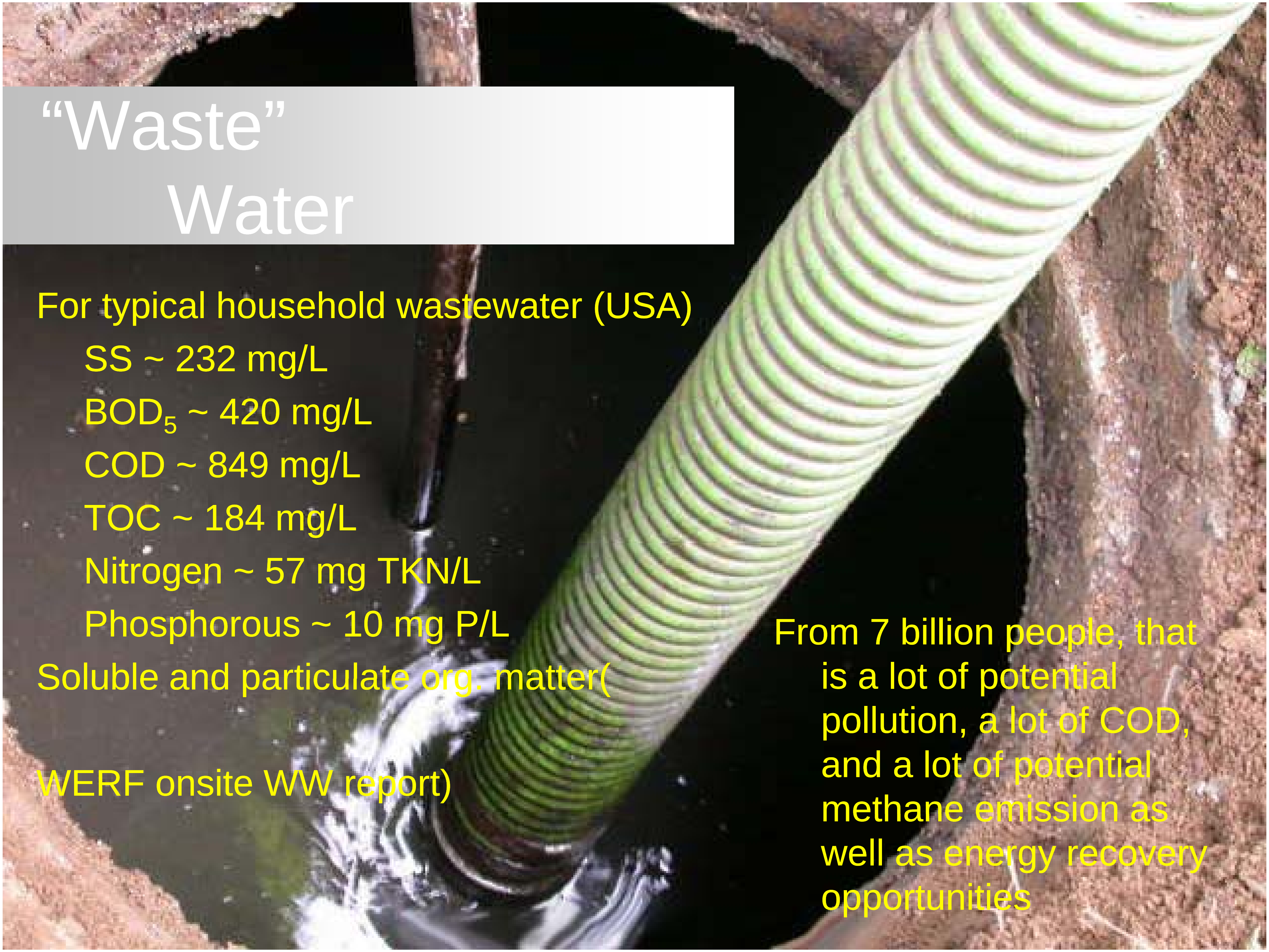
Oct 2011 - Toilet mfgr TOTO announces toilet-powered vehicle to trek across Japan



Vehicle will only be fueled by
“renewable fuel” from driver
…..is this possible?

http://green.autoblog.com/2011/10/04/poop-powered-toto-toilet-tricycle-to-trek-across-japan/

“Waste” Water



For typical household wastewater (USA)

- SS ~ 232 mg/L
- BOD_5 ~ 420 mg/L
- COD ~ 849 mg/L
- TOC ~ 184 mg/L
- Nitrogen ~ 57 mg TKN/L
- Phosphorous ~ 10 mg P/L

Soluble and particulate org. matter(

WERF onsite WW report)

From 7 billion people, that is a lot of potential pollution, a lot of COD, and a lot of potential methane emission as well as energy recovery opportunities

How do we clean our wastewater?

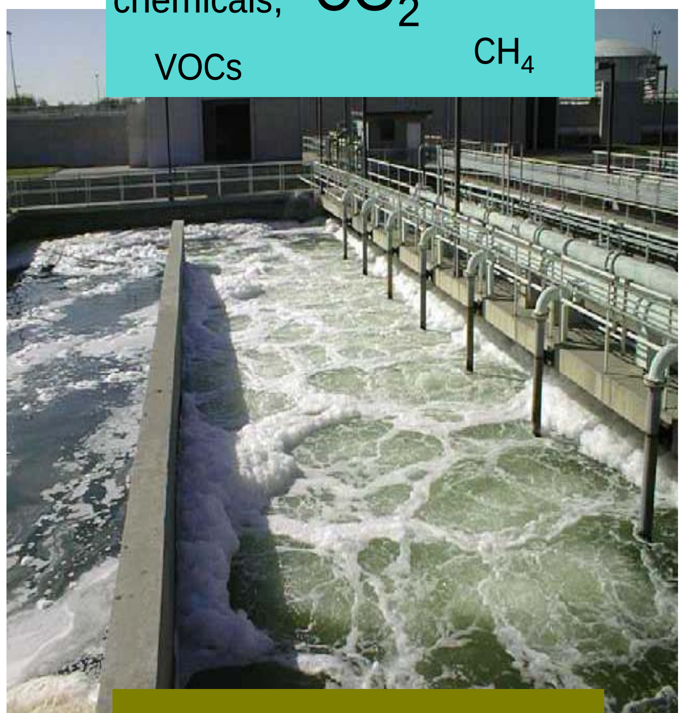
- Energy:
  - Pumping
  - Mixing
  - Aeration
  - Disinfection
  - Heat for digester
  - Chem transportation
- Chemicals:
  - Flocculation
  - Precipitation
  - Disinfection
- Labor:
  - O&M

Trace chemicals, VOCs

CO_2

H_2S

CH_4



Unrecoverable waste residuals

Clean Water

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How do we clean our wastewater?

- **Energy:**
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  - Mixing
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- **Chemicals:**
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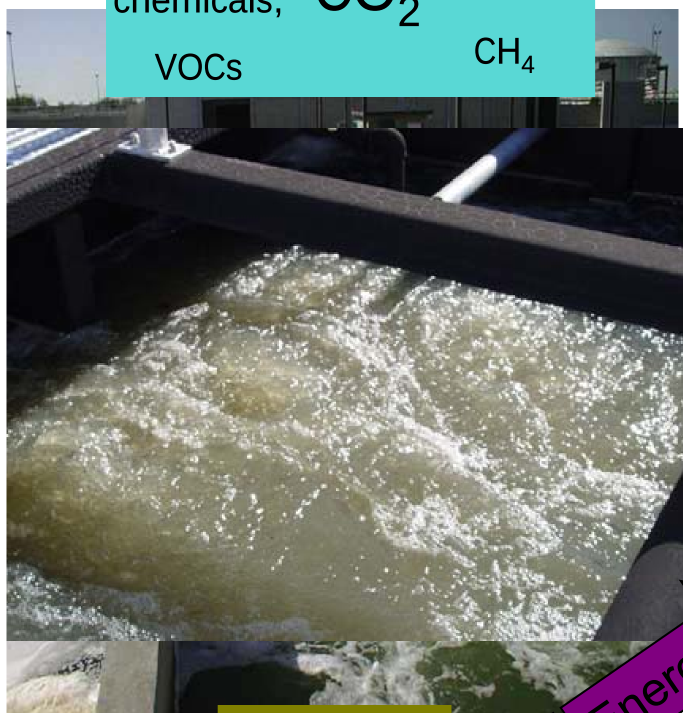
- **Labor:**
  - O&M

Trace chemicals, VOCs

CO_2

H_2S

CH_4



Unrecoverable waste residuals

Energy?

Clean water

Bioproducts

Biosolids, Nutrients, biopolymers

A more sustainable approach

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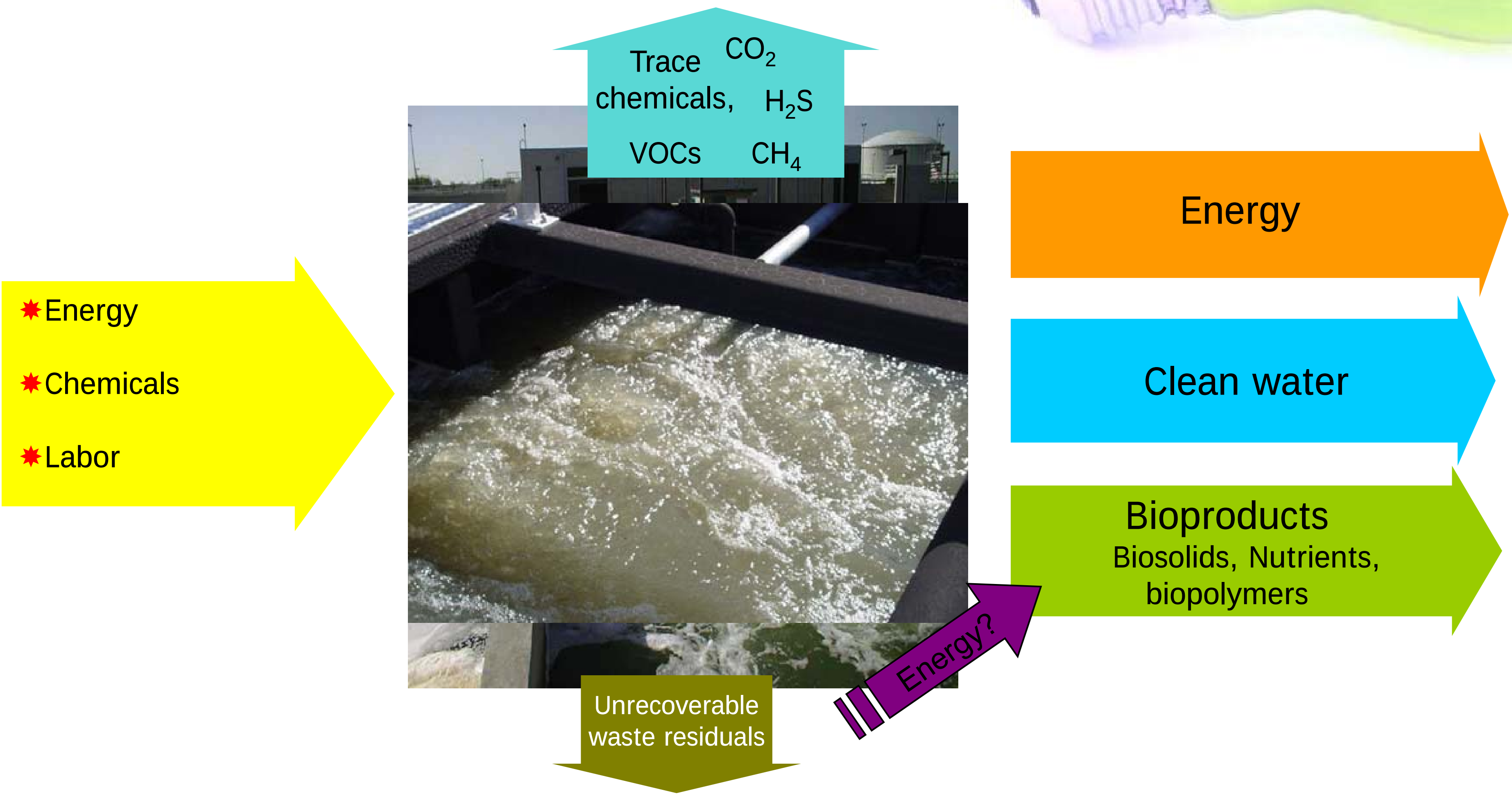
How do we clean our wastewater?



An even more sustainable approach

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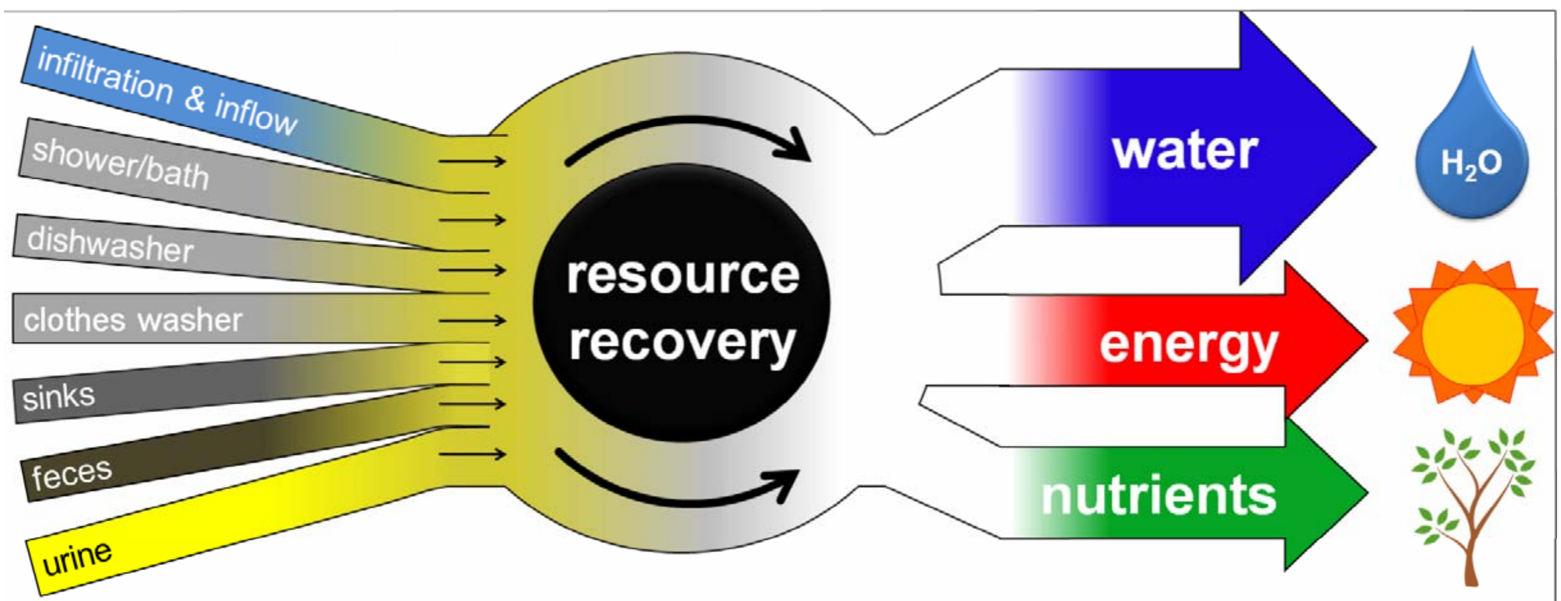
Wastewater as a renewable resource

A paradigm shift is underway!

http://www.sustainlane.com/reviews/getting-the-most-from-human-waste/ICF8A2T14UAQ9HTV27Q8VLQXRTOI



Graphics: Jeremy Guest

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Recovery of water

- Direct or indirect reuse for agriculture
- Potable water offset
- Sewer mining

- Secondary treatment
- Soil aquifer treatment (SAT)
- Tertiary treatment
- Membrane effluent filtration
- MBR(+AOP)
- MBR+RO (+AOP)

- Need some sort of infrastructure for delivery of recovered water to customers, depending on use

Recovery of nutrients

- Struvite and other precipitates
- Biosolids
  - Bio-P phosphorus recovery
- Crop growth / Algae
- Liquid fertilizer
  - Best opportunities for recovery in digester filtrate/centrate.
    - 30% of N loading at HCAWTP is associated with AD filtrate
  - Recovery of nutrients at WWTP vs. decentralized onsite nutrient recovery
    - Source separation toilets in Europe

Energy potential in wastewater

Waste organic matter = Reservoirs of energy

View **chemical oxygen demand (COD)** as energy potential, rather than pollution

The **choices** lie in how we recover this potential energy

Further, how sustainable are the choices?

Energy recovery from wastewater

✸Energy:
- Pumping
- Mixing
- Aeration
- Disinfection
- Heat for digester
- Chem transp.

Reduced WW organic matter

- CH_4 and H_2 (anaerobic digestion)
- Electricity and H_2 (Microbial fuel cells)
- Biosolids for combustion
- Also, algae biofuel

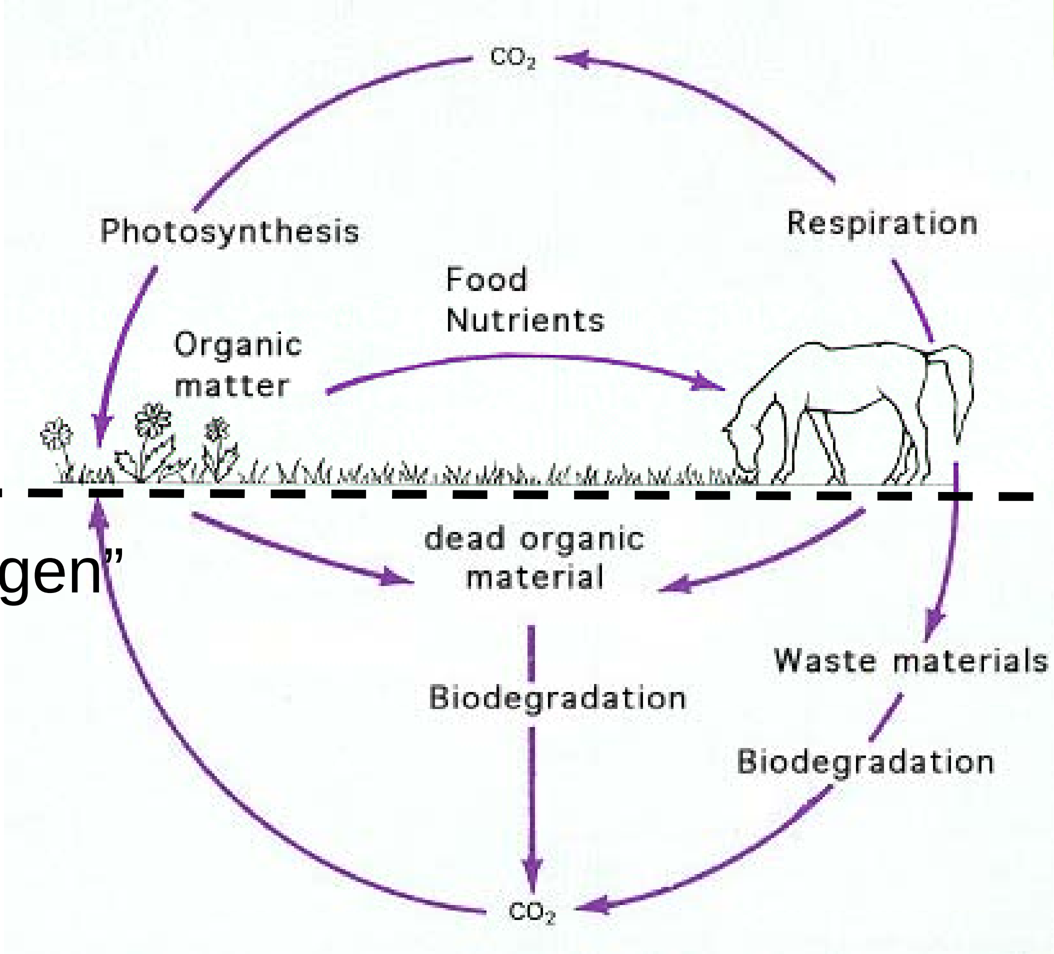
Electron donors (energy reservoirs)

Figure from: Howard F. Curren WWTP post-aeration basin (www.tampagov.net/dept_wastewater/information_resources/Advanced_Wastewater_Treatment_Plant)

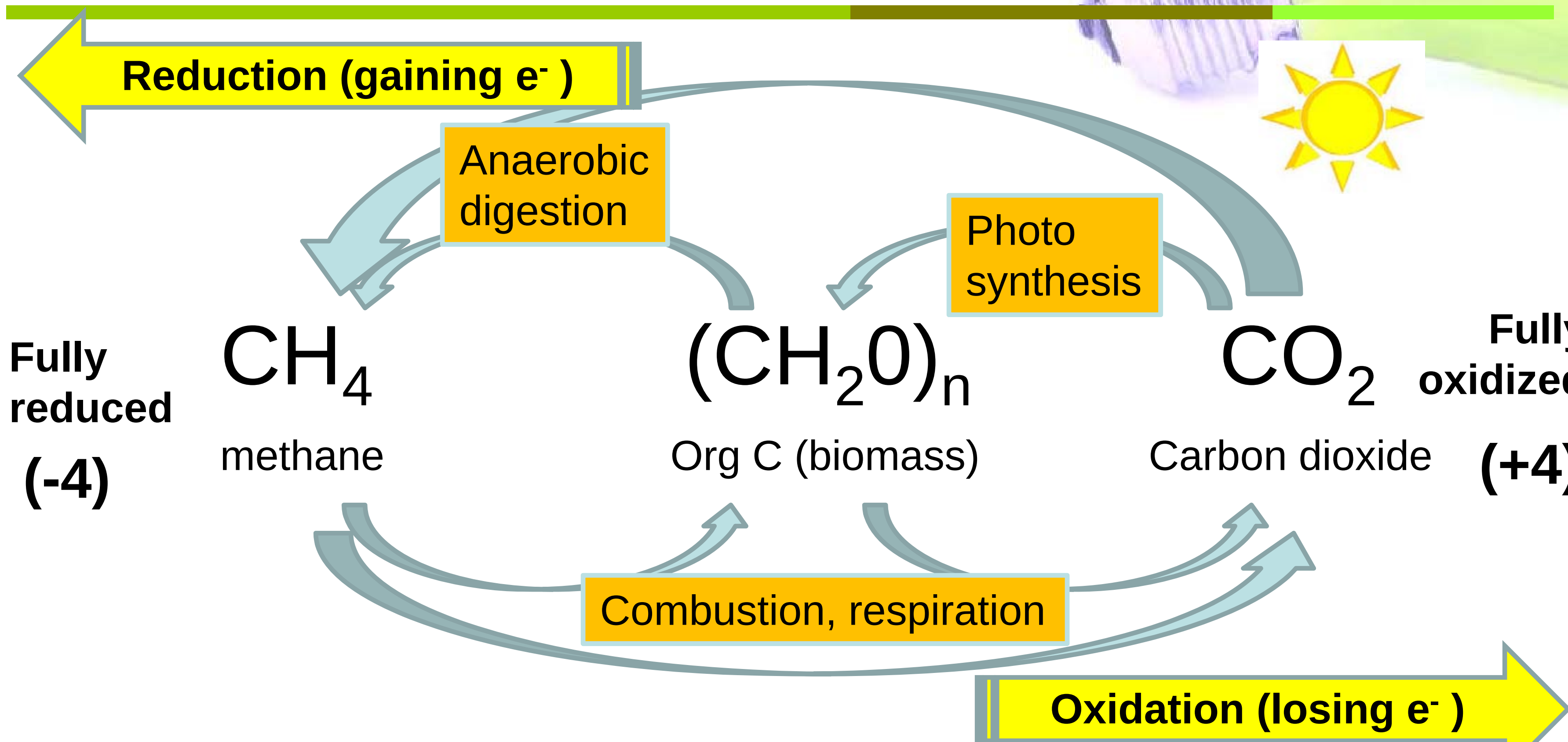
The Carbon Cycle

Aerobic – "with oxygen"

Anaerobic – "without oxygen"



Energy states of carbon



	Methane	**biomass**	**Carbon dioxide**
Energy	rich	moderate	none
Redox state	-4	In between	+4
COD (energy)	4 g OD/g (180.4 Wh /g)	Typically 1-3 g OD/g	zero

AD and sun recharge spent carbon !

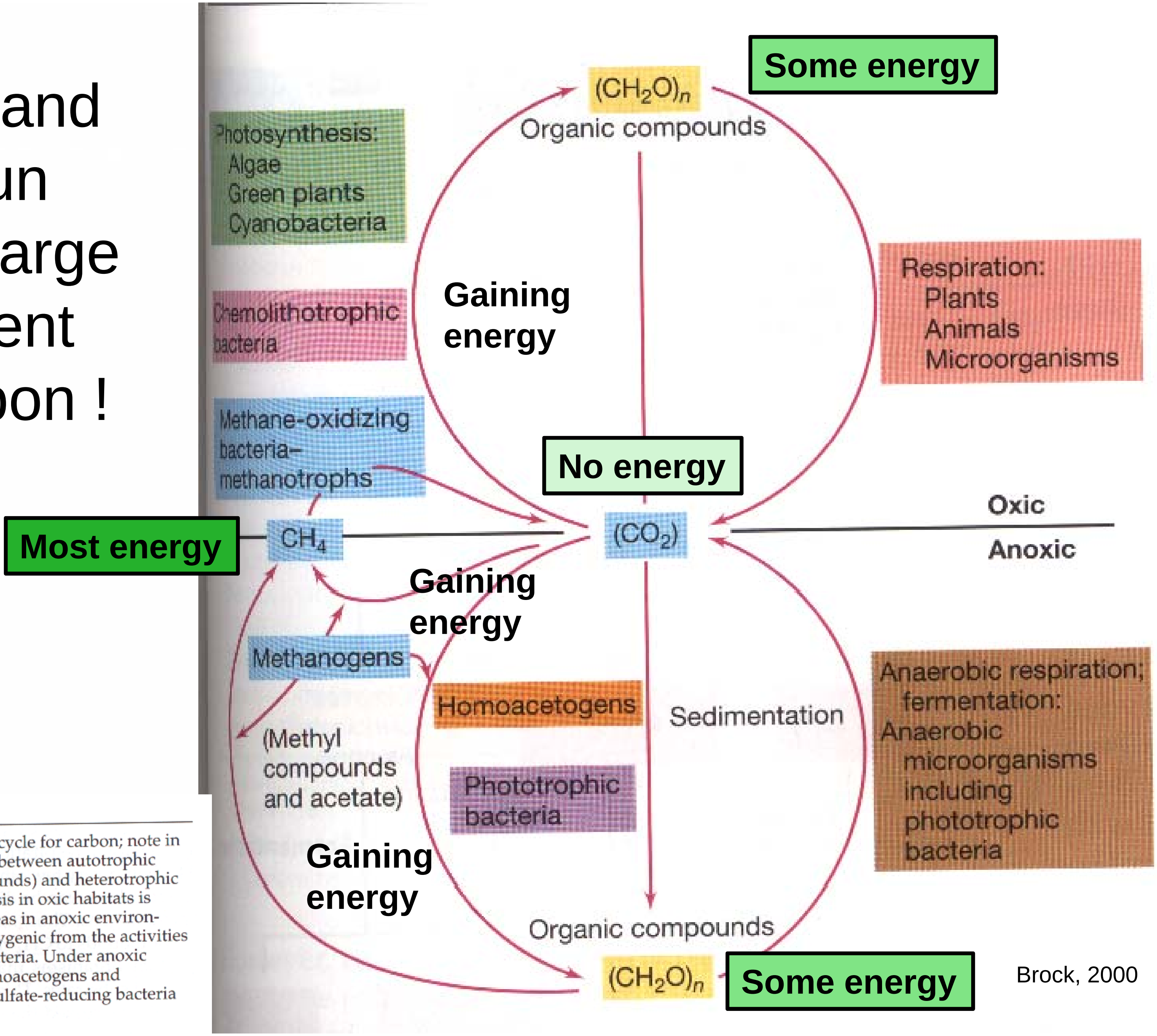


FIGURE 16.37 Redox cycle for carbon; note in particular the contrasts between autotrophic ($CO_2 \rightarrow$ organic compounds) and heterotrophic processes. Photosynthesis in oxic habitats is mainly oxygenic, whereas in anoxic environments it is mainly anoxygenic from the activities of purple and green bacteria. Under anoxic conditions, besides homoacetogens and methanogens, certain sulfate-reducing bacteria are also autotrophic.

Brock, 2000

COD represents potential energy!

- What is COD?
  - **Chemical oxygen demand**, or the ability for *reduced (i.e., electron rich) WW organic matter* to donate electrons to an electron-hungry *electron acceptor* (e.g., O_2) and converting it to a reduced form (H_2O)

$$\text{OrgC} \rightarrow CO_2 + e^-$$
$$e^- + O_2 \rightarrow H_2O$$

$$\text{OrgC} + O_2 \rightarrow CO_2 + H_2O$$

  - COD is a measure of the potential energy stored within WW organic matter

Please not that energy can potentially be extracted from the oxidation of any reduced chemical species (e.g., N and S). Reduced N species such as NH_4^+ exert a nitrogenous oxygen demand (NOD) and can also be a significant source of energy (40 mg/L TKN-N x 4.57 mg OD/mg TKN-N = **183 mg OD/L**). However, the focus of this particular presentation is only on energy from organic matter.

How much energy can we potentially get from wastewater organic matter?

Maximum potential from COD (assuming no growth)

please note that potential energy from NOD (from reduced N such as NH4+) is not included in this calculation

0.5 g COD/L x 0.25 g CH_4/g COD x 1000L/m^3 = **125 g CH_4/m^3 of wastewater**
(typical conc) **(473 kg CH_4/ MG)**
(3784 m^3/MG)

125 g CH_4/m^3 x 50.1 kJ/g CH_4 x 3.6 Wh/kJ = **22.55 kWh/m^3 of wastewater**
(85 MWh/MG)

Ex. loading: 85 MWh/MG x 50 MG/d x d/24hr = **177 MW from wastewater**
(Tampa WWTP) **(max potential)**

Compare to Tampa Electric's 2000 MW Big Bend power plant (natural gas)

Comparison: the Barycz landfill in Krakow, Poland generates 1 MW

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Energy consumption for wastewater treatment, example from Iran

Table 3: Average electrical energy consumption in various processes of plant

Process	*Average power consumption (kWh) of 1000 m^3 crude sewage*
1. Preliminary treatment	12.67
2. Primary sedimentation	0.91
3. Recirculation pumping of activated sludge	34.19
4. Aeration	230.84
5. Digestion tank (Mixing and Pumping)	20.86
6. Final sedimentation	0.68
Total input	300.1458

0.3 kWh/m³ consumed for WWT

Source: Nouri et al 2007 (data from WWTP in Iran)

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Can WWT be energy neutral?

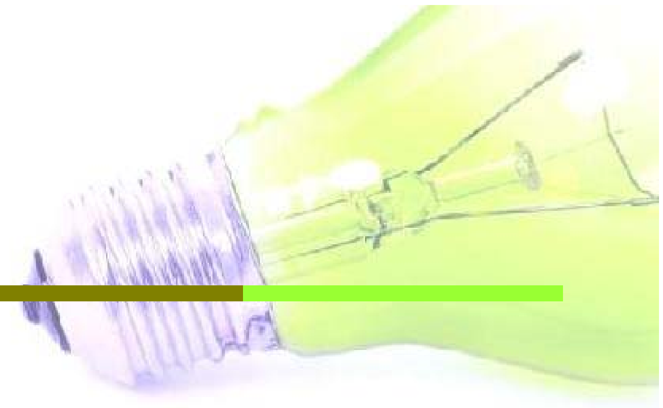
- Can WWTP be energy neutral, or even energy surplus to export energy to the grid?

0.3 kWh/m³ consumed for WWT (Nouri et al 2007)

Excess energy for export???

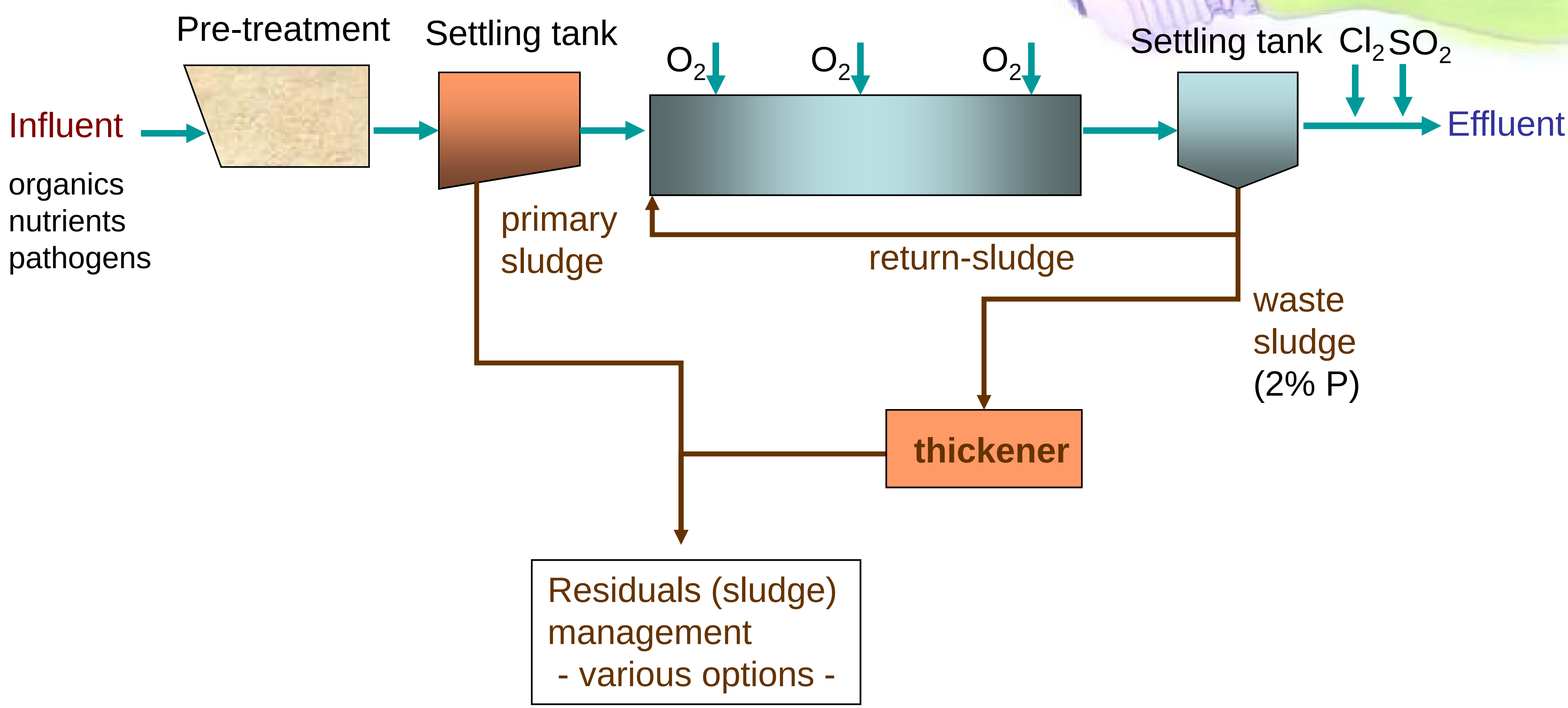
2.2 kWh/m³ potential from waste organic matter (assume harvesting 10% of max potential)

Example, small (20,000 p.e.) WWTP in Czech Republic generate AD biogas to heat nearby homes



So, how do we extract this energy from wastewater?

Conventional Wastewater Treatment



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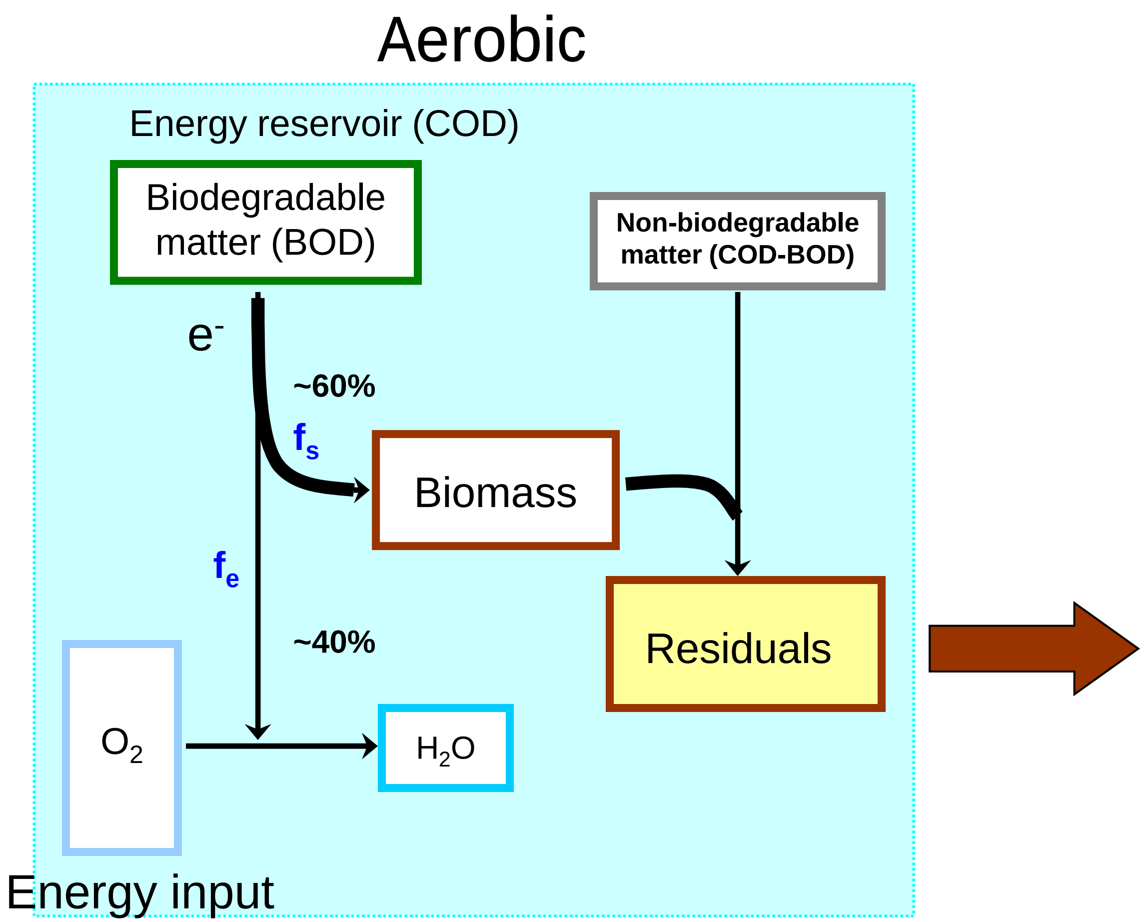
Graphics courtesy of Craig Criddle

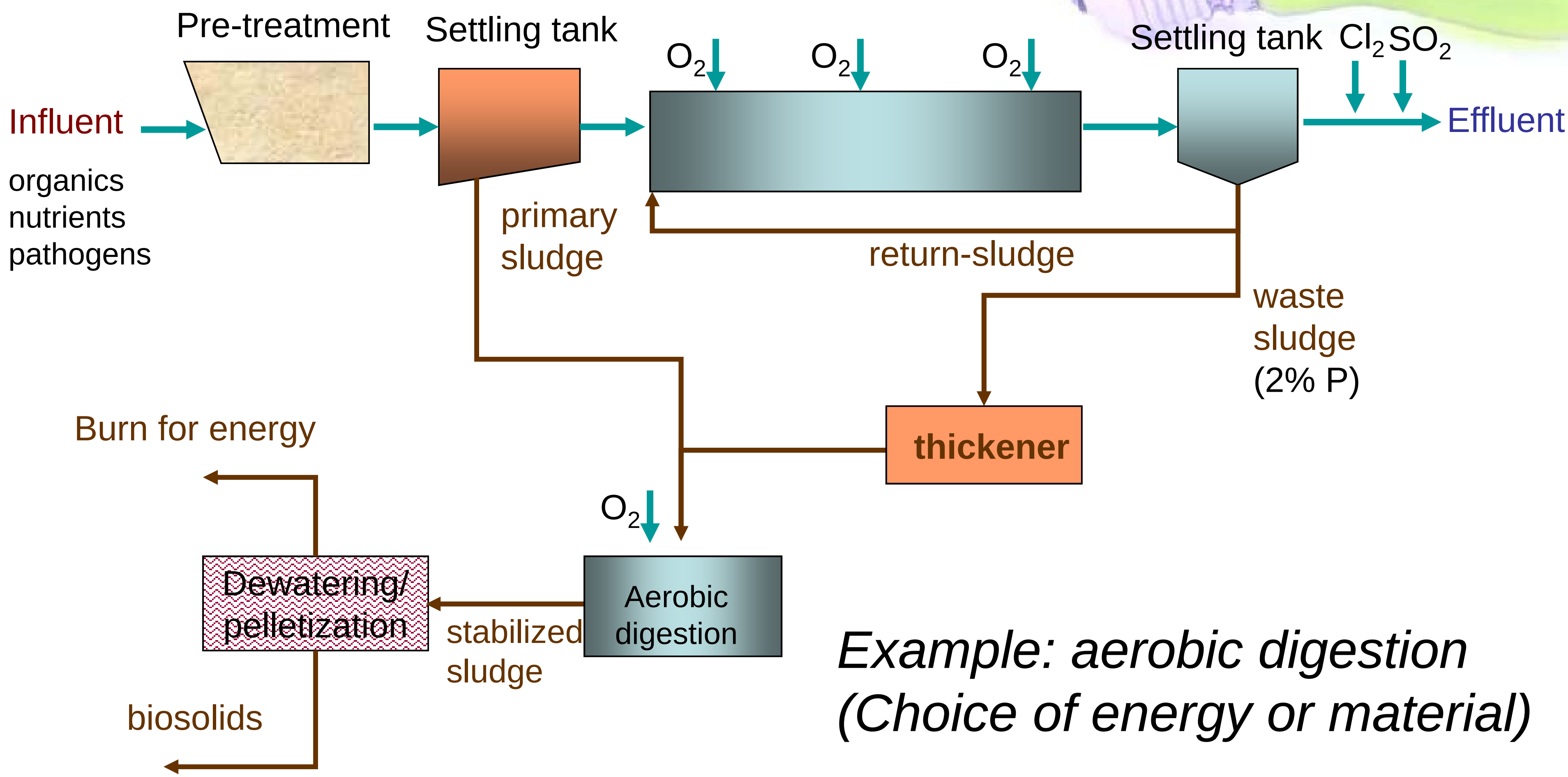
Waste organic matter as e- donor



Choices!
- Disposal
- Burn for fuel (coal substitute)
- Biosolids (fertilizer, biopolymer)

Bioenergetics concept from Rittmann and McCarty, 2000

Conventional Wastewater Treatment



Example: aerobic digestion
(Choice of energy or material)

Graphics courtesy of Craig Criddle

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Aerobic digestion and pelletization at Largo, FL

Some energy preserved through biosolids

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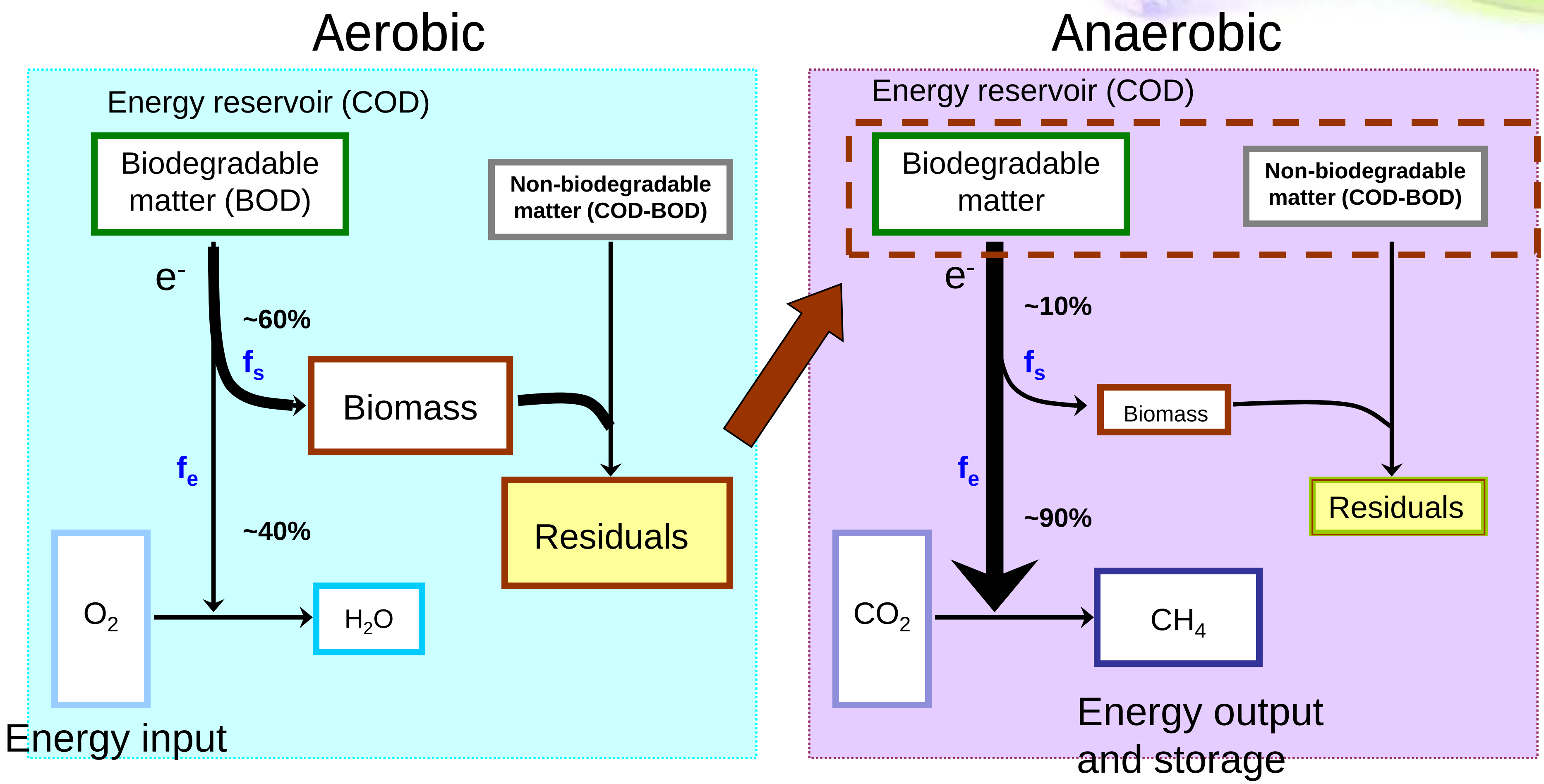
Waste organic matter as e^- donor



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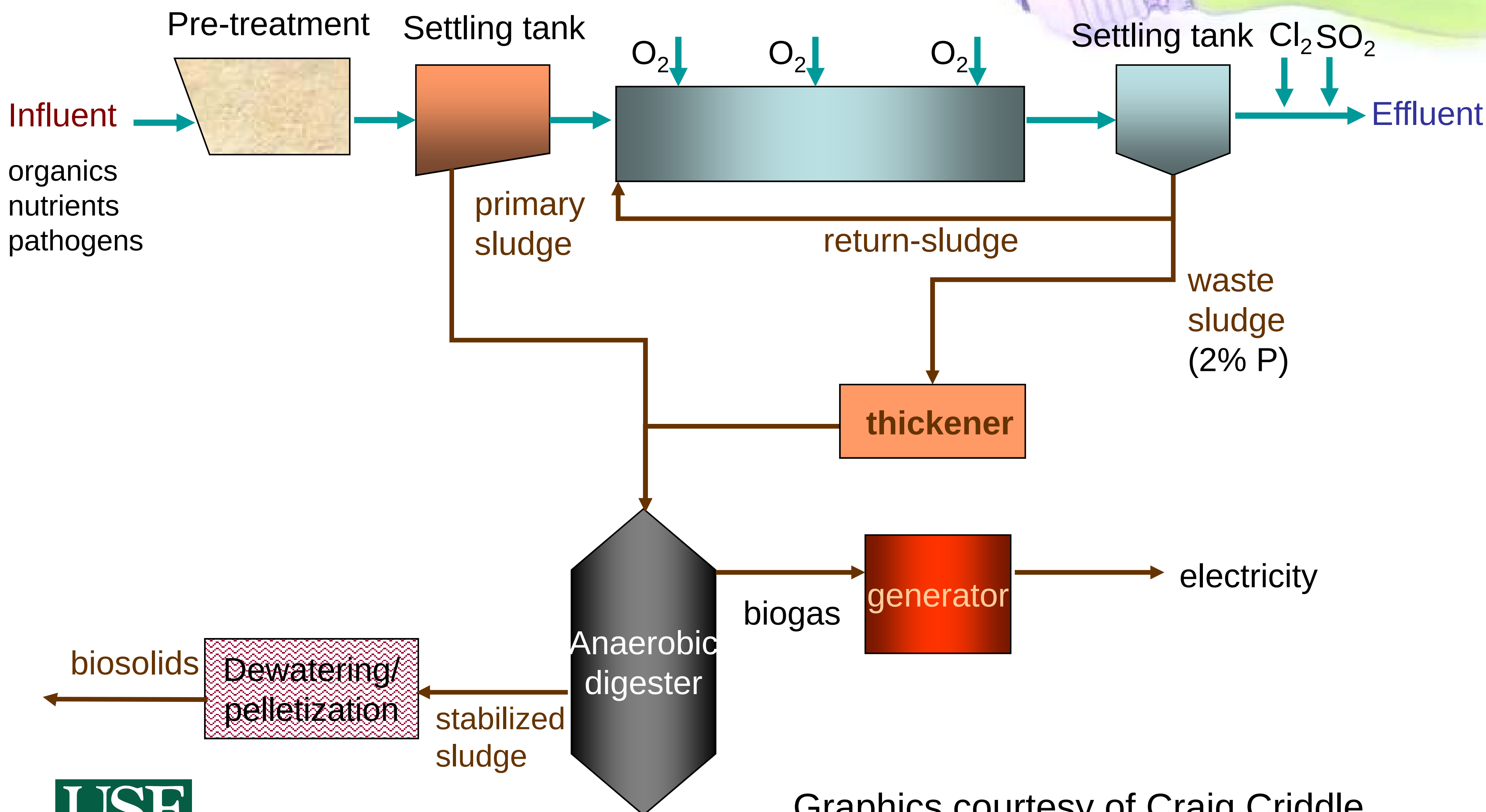
Conventional Wastewater Treatment



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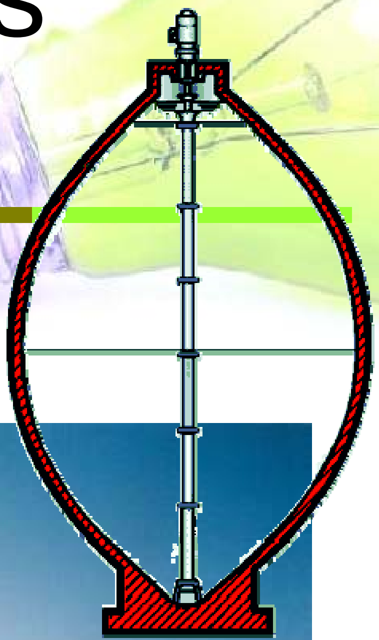
Graphics courtesy of Craig Criddle

Anaerobic digesters for sludge

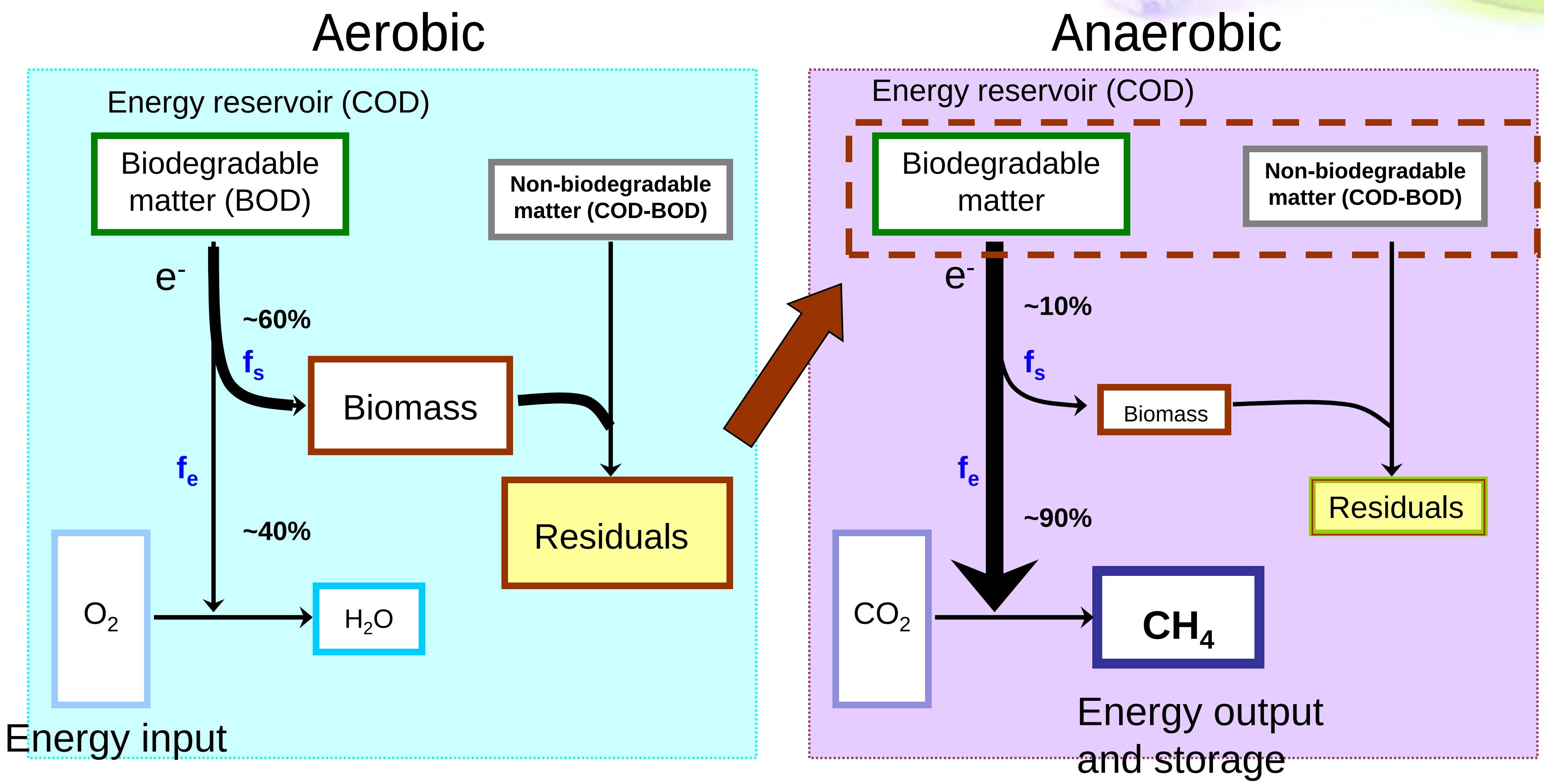
Flared methane

Conventional digesters (floating top)



Egg-shaped digesters in Baltimore: designed to improve mixing and ease of solids removal (courtesy Sterling Fluid Systems)

Waste organic matter as e⁻ donor



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However, sludge AD will only recover **max. of about 0.9 x 0.6 = 54%** of energy potential from waste organic matter

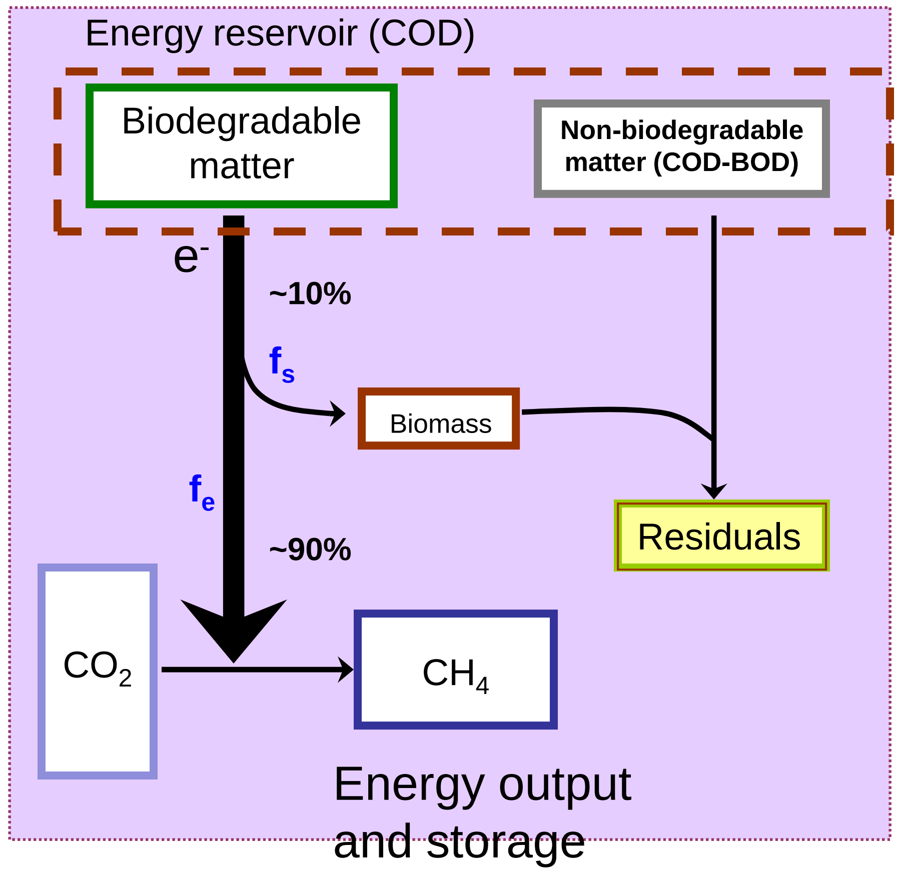
Fundamental barriers

- Fundamental issues with energy recovery via AD of <u>sludge</u>
  - Only about half of the embedded energy can be recovered to CH_4
  - Considerable energy expenditure (and assoc. CO_2 emission) to generate activated sludge
  - Waste activated sludge (dead microbes) is less digestible than primary sludge (excreta + food waste).
- Thus, we are expending energy to convert embedded energy in WW from a *more* accessible form to a *less* accessible form

Waste organic matter as e^- donor

- **Fundamental question:**
- If we want to route WW organic matter to methane, why go through activated sludge, thereby expending considerable energy and only recovering half of the energy?
- Why not go to anaerobic treatment of WW directly? Less energy input and more energy recovery potential!

Anaerobic



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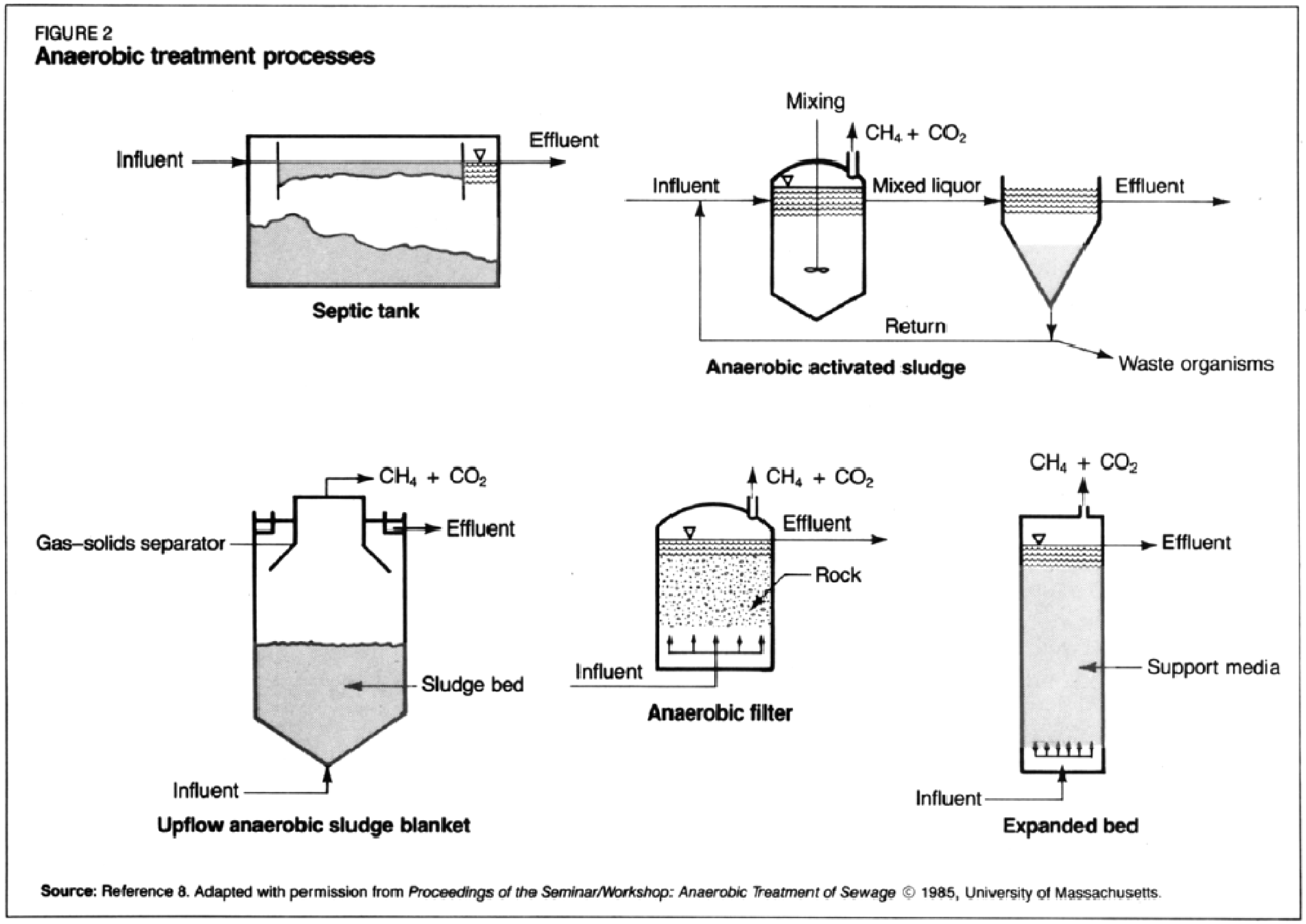
Ex. of anaerobic processes for sewage treatment



USF D. Yeh From William Jewell (1987)

History of anaerobic processes for sewage treatment

TABLE 2
Process developments in anaerobic treatment of domestic wastewater

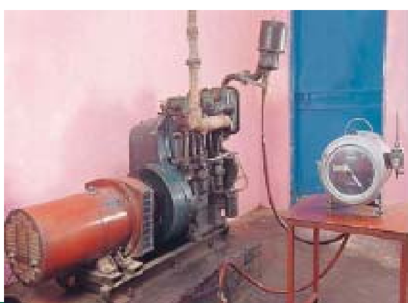
Date	Device	Principal investigators
1881	Mouras's Automatic Scavenger	Moigno, 1881, 1882
1891	Upflow sludge blanket and anaerobic filter	Scott-Moncrieff, 1891
1895	Septic tank	Metcalf and Eddy, 1915
1899, 1904	Septic tank with separate sludge storage and fermentation tank	Metcalf and Eddy, 1915 Buswell and Hatfield, 1938
1905	Imhoff tank	Metcalf and Eddy, 1915 Buswell and Hatfield, 1938
1910	Biolytic tank, hydrolytic tank, upflow sludge blanket	Winslow and Phelps, 1911
1951	Anaerobic contact process, anaerobic activated sludge	Schroepfer et al., 1955
1956	Upflow sludge blanket, anaerobic rock filter	Coulter, Soneda, and Ettinger, 1964, 1969
1969	Anaerobic filter	Young and McCarty, 1969
1979	Upflow sludge blanket	Lettinger et al., 1979
1981	Attached-film expanded bed	Jewell et al., 1981

Source: Reference 9. Adapted with permission from *Proceedings of the Seminar/Workshop: Anaerobic Treatment of Sewage* © 1985, University of Massachusetts.

From William Jewell (1987)

The Sulabh Expirience (India)

- The biggest public toilet in the world has been constructed at Shirdi (India).
- 120 WCs, 108 bathing cubicles, 28 special toilets and other facilities coupled with a biogas generation system.
- Biogas used for different purposes
  - Electricity generation,
  - Lighting of lamps,
  - Cooking
  - Heating in winter seasons



Low cost WW treatment for a small community in Cali (Colombia)

La Voragine

- 400 people
- 2500 – 5000 floating population
- Water and wastewater system by gravity
- WW flow of 2.4 L/s

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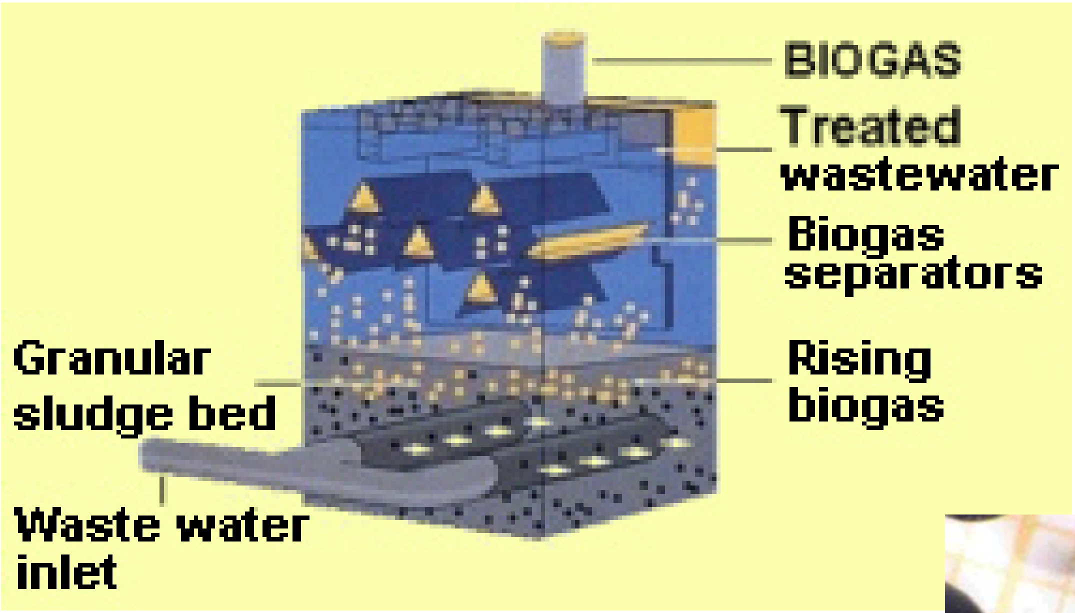
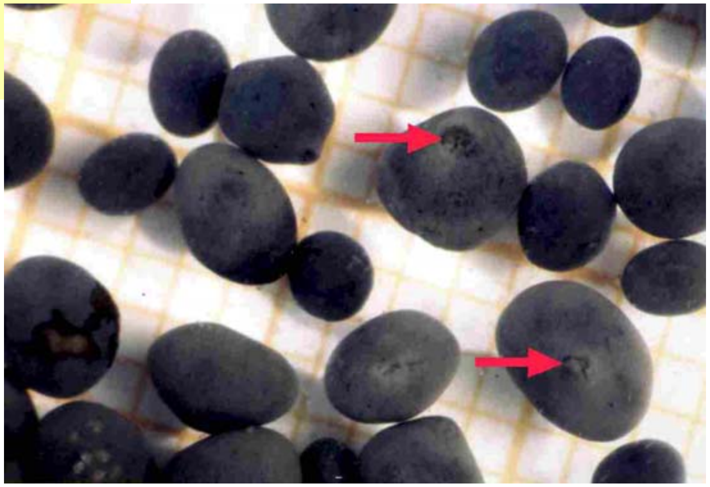
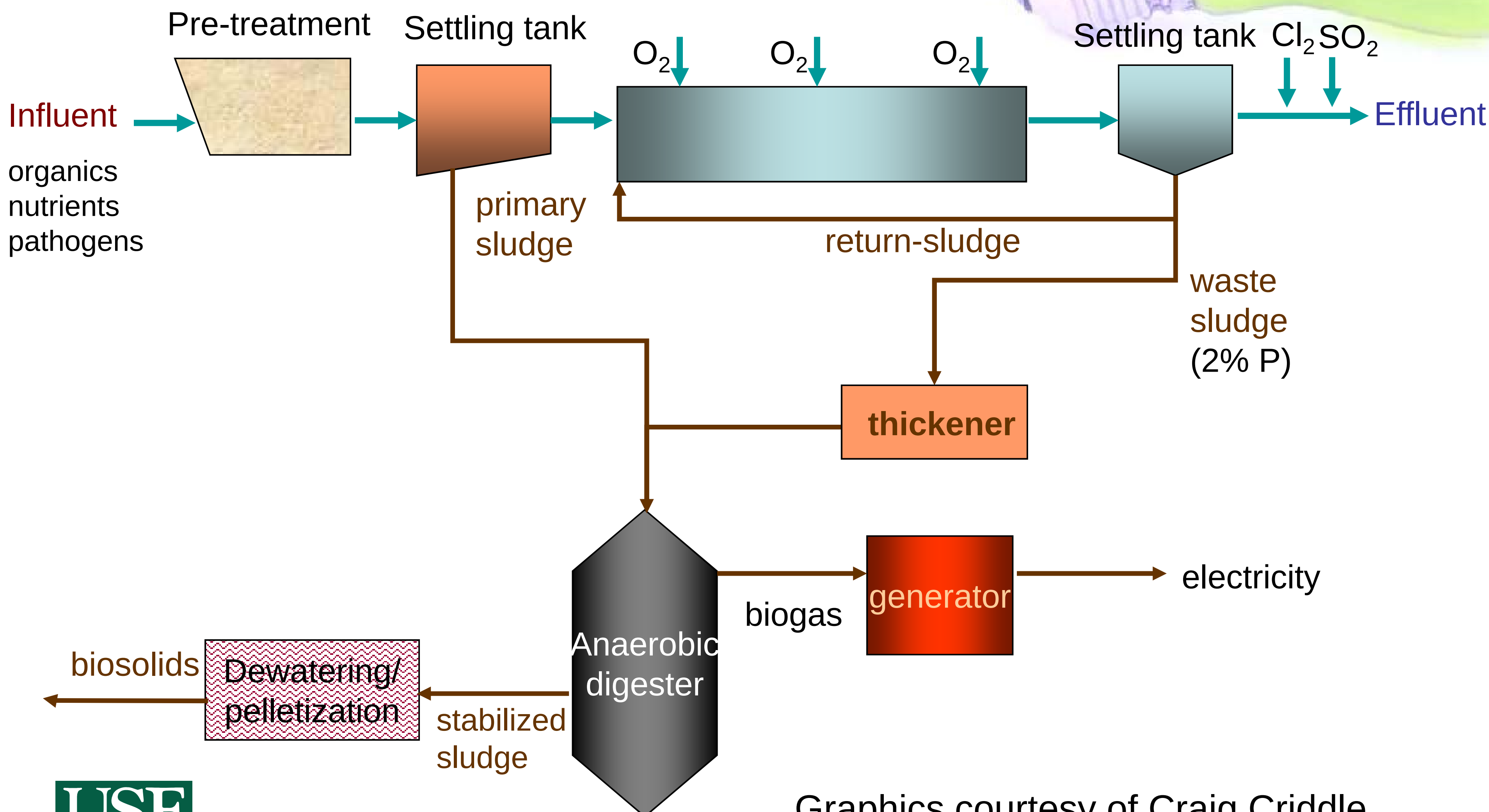
Upflow anaerobic sludge blanket (UASB)





Conventional Wastewater Treatment



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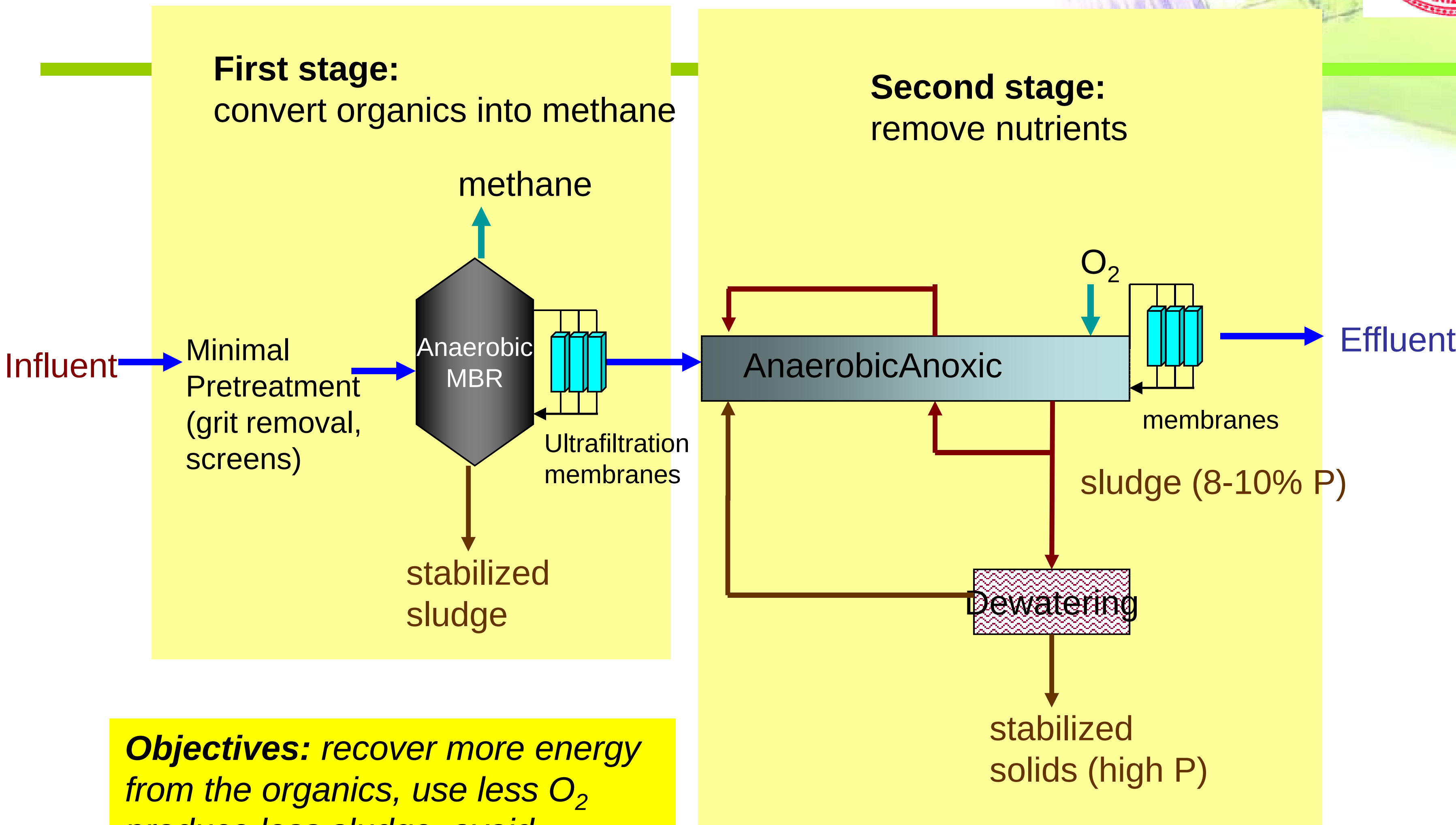
Graphics courtesy of Craig Criddle

MBR system at Stanford



Objectives: *recover more energy from the organics, use less O_2 produce less sludge, avoid chemicals for disinfection.*

Direct anaerobic treatment of wastewater

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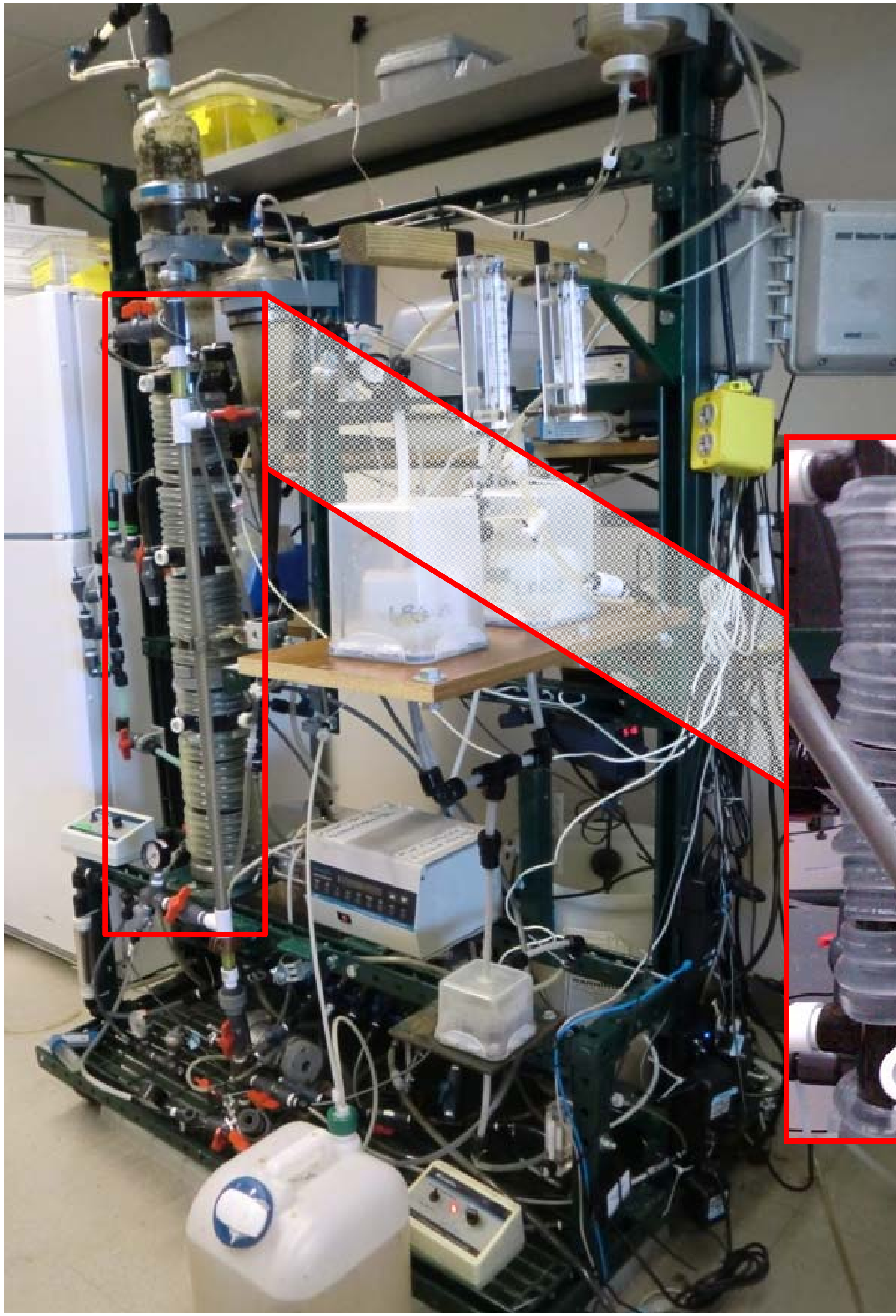
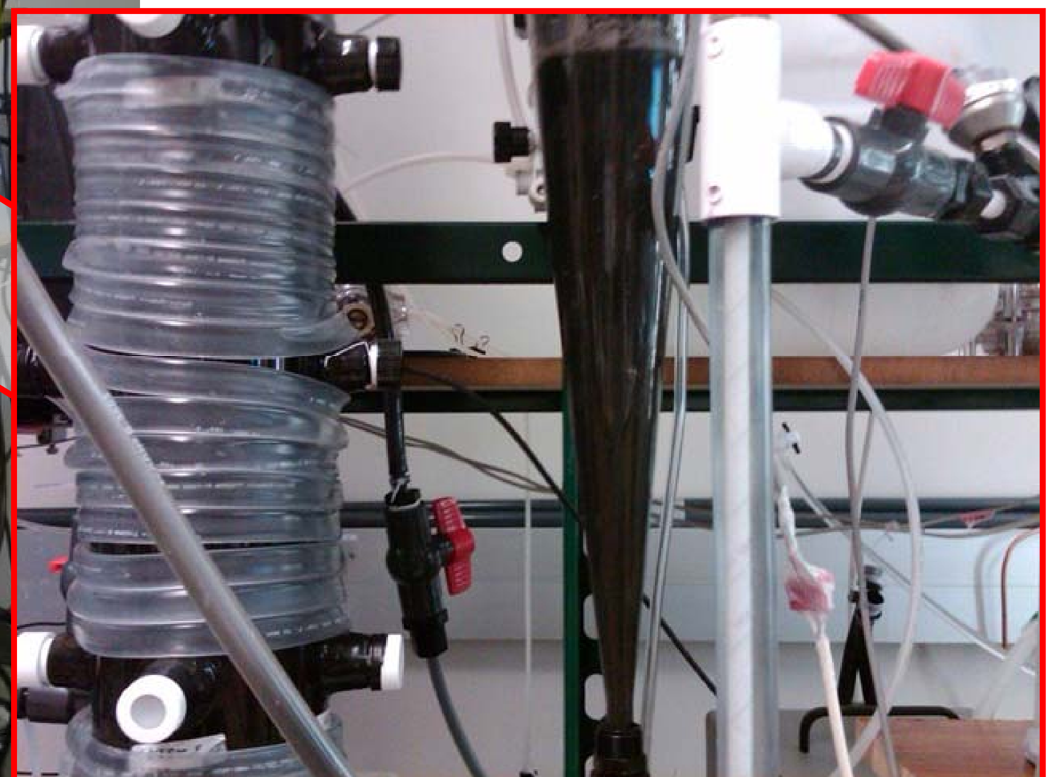
The gas lift anaerobic MBR at Univ. South Florida





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AD + UF membrane

Gas lift-AnMBR: Energy footprint

GI-AnMBR energy requirements	Case based Net Energy (kWh/m^3)					
	Full biogas conversion		CHP conversion		Electricity Conversion	
Membrane operation	1.4[a]	0.2[b]	1.4[a]	0.2[b]	1.4[a]	0.2[b]
Pump requirements [c]	0.2	0.2	0.2	0.2	0.2	0.2
Reactor heating[d]	0.0	0.0	0.0	0.0	0.0	0.0
Power from biogas	-2.8[e]	-2.8[e]	-1.6[f]	-1.6[f]	-1.0[g]	-1.0[g]
Energy footprint	**-1.2**	**-2.3**	**0.1**	**-1.1**	**0.7**	**-0.5**

a) Energy required for membrane operation at lab-scale
b) Energy required for membrane operation at plant-scale (Yeh et al., 2006)
c) Energy for pumping at plant-scale
d) Energy required for mesophilic digestion at plant-scale
e) Energy from full conversion of methane in combustion
f) Energy from CHP conversion of methane
g) Energy from electricity conversion of methane

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The Anaerobic MBR for domestic WWT

Removal efficiencies

Treatment technology	SS	COD	N	P	Pathogens	Energy footprint
Conv. Act. Sludge	H	H	H	H	H	M
Aerobic MBR	HH	H	M	M	H	H
Anaerobic MBR	HH	H	n/a	n/a	H	M
UASB	M	H	n/a	n/a	M	L
Septic tank	M	M	n/a	n/a	L	n/a

H: high M: medium L: low

- Mineralized forms of N and P remain in the liquid ➔ NH_4, NO_3 and PO_4

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Further thoughts on anaerobic WWT

What if methane is not *captured* and *combusted* to CO_2, and results in fugitive methane release? This is a problem since CH_4 is 25X worse GHG than CO_2

- The only way for WW organics to become CO_2 is to be oxidized by oxygen in aerobic environment. If occurs in aquatic environment, will deplete O_2 → pollution
- WW organics (e.g., discharge of raw sewage to rivers or biosolids applied to a field) still becomes methane if natural anaerobic conditions occur, → fugitive emission
- If in anaerobic bioreactor, at least we have the opportunity to manage waste organics in an engineered system and capture/convert CH_4 to CO_2 in safe way, and extract energy in process

Hanoi, Vietnam example

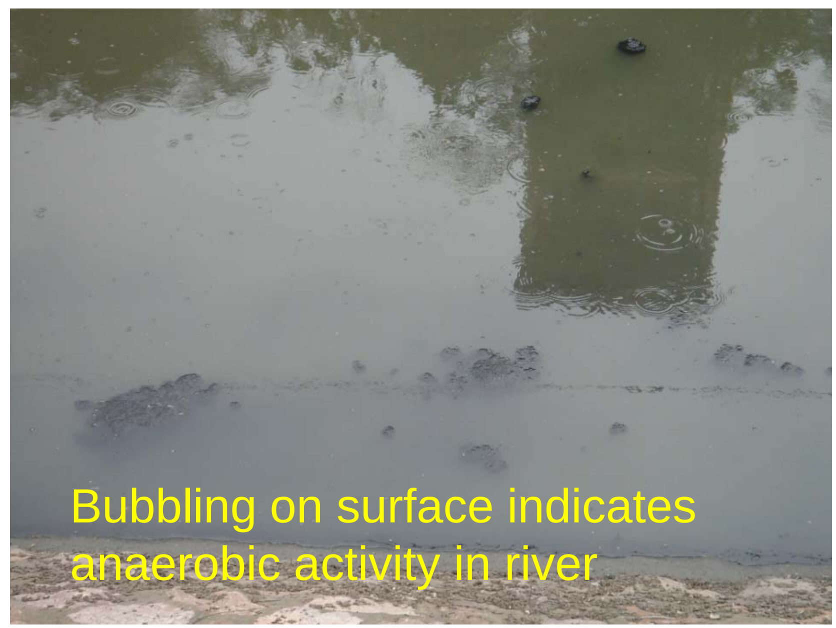
- Only about 15% of the city's household wastewater is intercepted by sewers and treated in advanced WW treatments plants
- The majority of the raw sewage is directly discharged into waterways. Rivers are black, lifeless, and signs of anaerobic activity are evident through bubbles (presumably methane) emerging on water surface.
- There is large-scale uncontrolled methane emission!
- Stories like this are typical in developing countries and countries in transition, or sometimes even in N. America.
- **What is the extent of fugitive methane emissions from untreated raw sewage?**

Hanoi: Most of household sewage in the city is directly discharged to waterways without treatment, resulting in fugitive methane emission, environmental degradation, public health hazard and lost use of green way


Discharge of sewage to river


Workers remove trash from waterway


Lost green way opportunity


Bubbling on surface indicates anaerobic activity in river

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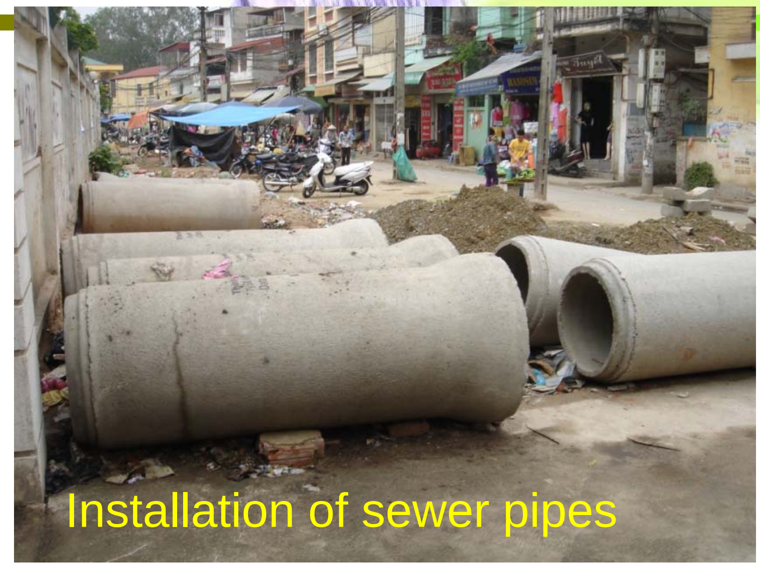
Hanoi: Unfortunately, building sewers and advanced WWTPs are expensive and disruptive to infrastructure. Activated sludge processes also generate sludge that need to be further treated and handled



Installation of sewer pipes

Advanced WWTP nestled in neighborhoods

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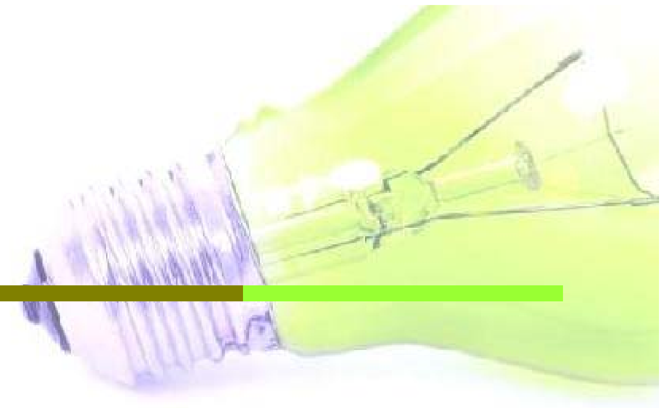
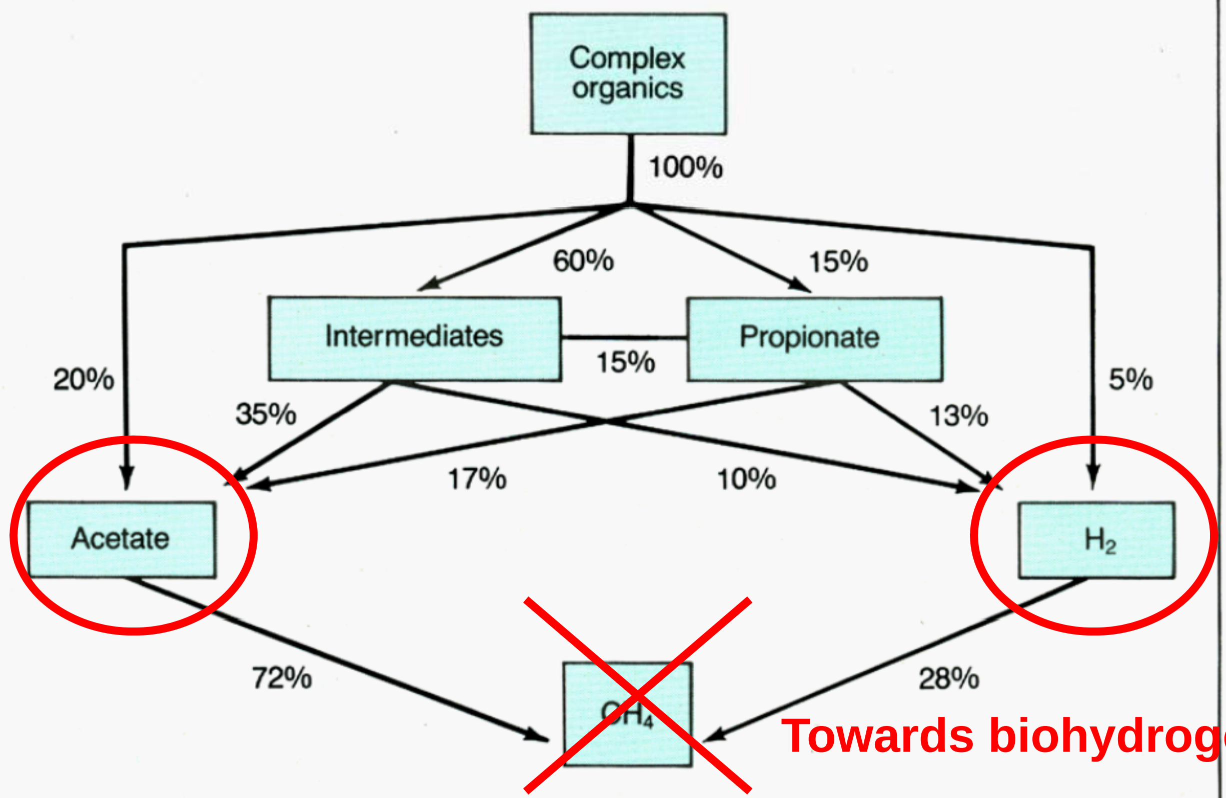


Other forms of energy capture (non-methane)

Hydrogen recovery from WW also possible

FIGURE 1
Three stages of methanogenesis[a]



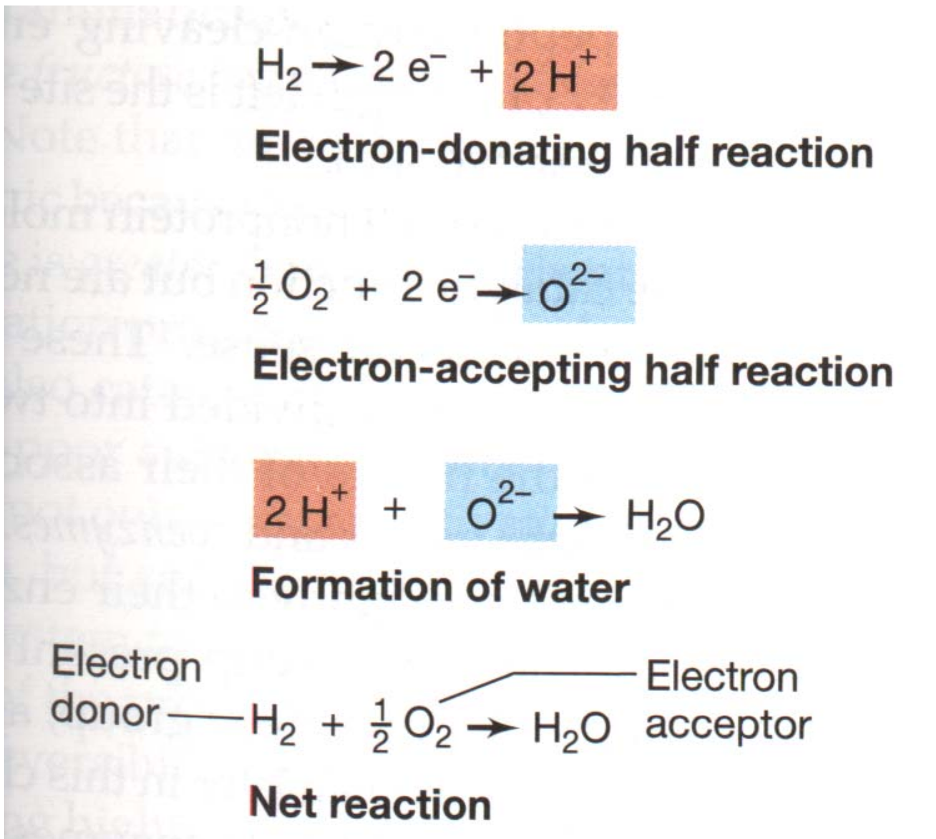
[a]Electron flow and the significance of propionate in the conversion of complex substrates are illustrated.
Source: Reference 8. Adapted with permission from *Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals,* Argonne National Laboratory, 1984.

Towards biohydrogen production

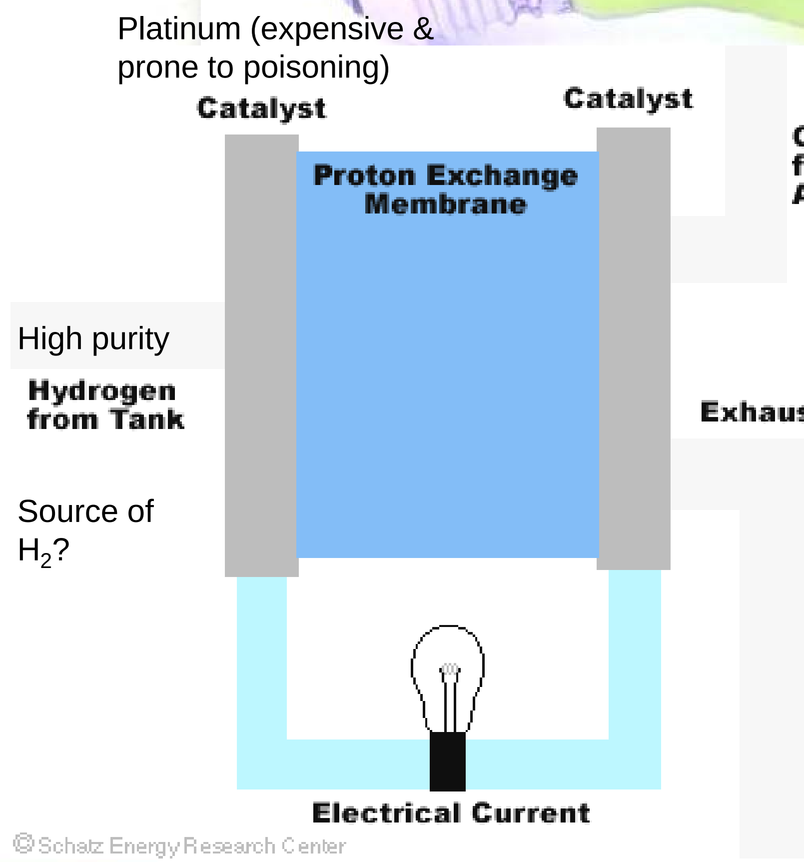
Selection pressure
Temperature
pH
….others

USF D. Yeh From McCarty and Smith (1986)

Fuel cell



RE 4.6 Example of an oxidation–reduction reaction: rmation of H_2O from H_2 and O_2.

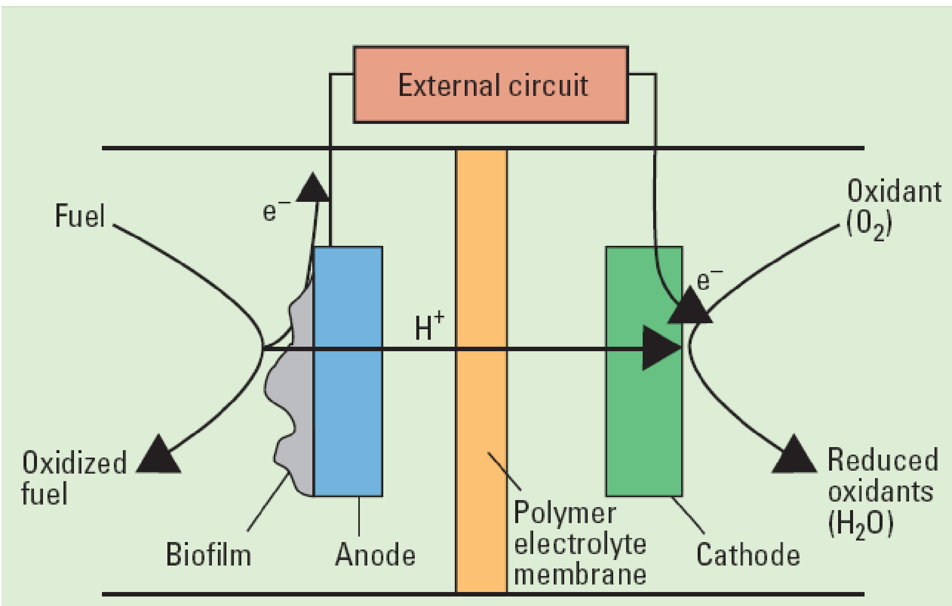


H_2 fuel cell

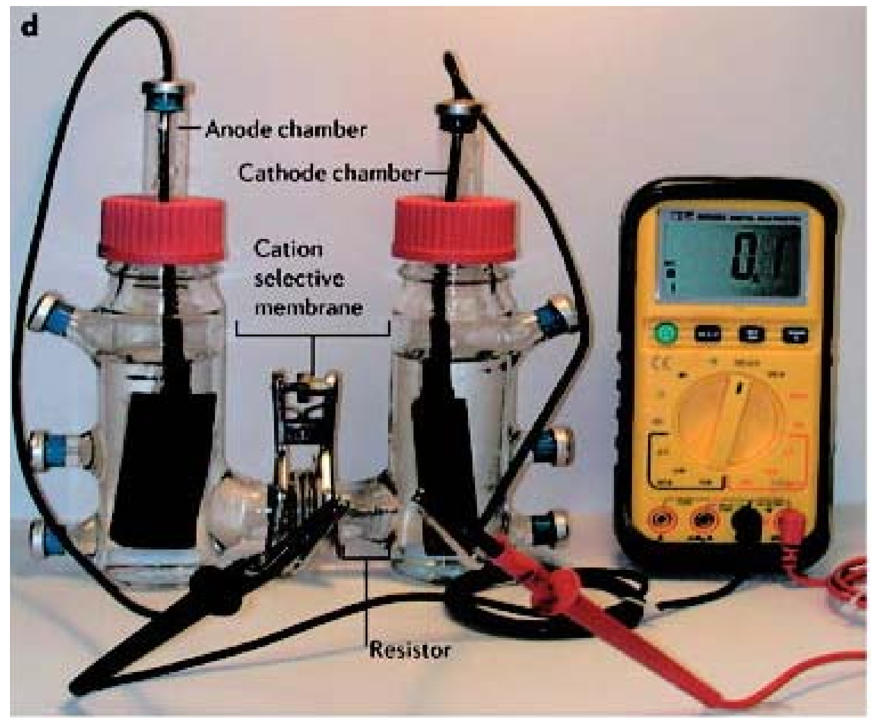
(courtesy Dr. John Wolan, ChE, USF)

Microbial fuel cell

- Getting energy (electricity) from treating wastewater
- Oxidizing organic matter (electron reservoir) and capturing electrons liberated through anode to power an external device
- Have been shown to work on wastewater directly



From Rittmann et al 2006 (ES&T)



A two-chambered microbial fuel cell. This system is not optimized for maximum power production but is convenient for microbiological studies*.

*Lovley, 2006. *Nature Reviews Microbiology* **4**, 497–508

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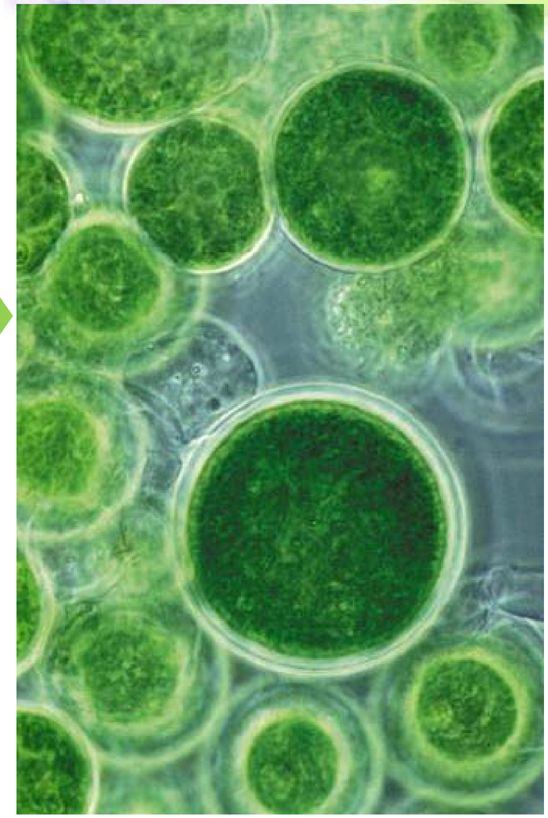
Synergy of Algae and Wastewater

http://www.waterencyclopedia.com/images/wsci_04_img0570.jpg

Wastewater		Algae
Requires O_2	←	Produces O_2
Produces CO_2	→	Requires CO_2
Contains Nutrients	→	Requires Nutrients
Requires Energy	←	Harnesses Energy



http://saferenvironment.files.wordpress.com/2008/10/alge.jpg

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What is the industry doing?

- What are the incentives for energy conservation and recovery?
  - Rising fuel costs
  - Concern/awareness about global warming
  - Voluntary energy audits associated with *green city* designation
    - City of Dunedin, FL

- What are the barriers to energy conservation and recovery?
  - Top priority at WWTP is effluent <u>compliance</u>!
    - Focus on getting rid of the **bad** in WW, rather than potential for capturing the **good**
  - Lack of infrastructure for energy capture
    - Costs money to save money
  - Room for innovation? Hard to overcome momentum associated with habit (if it ain't broke…)

Summary

- Anaerobic digestion ← **Wide application**
  - Primary sludge
  - Secondary sludge
  - Combined primary + secondary
- Direct anaerobic wastewater treatment ← **Most promising**
- Microbial fuel cell (different variations)
- Biohydrogen
- Biosolids as fuel (coal substitute)
- Algae (biofuel) ← **Good potential**
- Waste heat ← **Low hanging fruit**

Recommendations for Wastewater Subcommittee…

- With WW, really think about *co-benefits*:
  - Surface water quality
  - Water reuse and nutrient recovery
  - Energy conservation of WWTP
- Think about *total carbon cycle mgmt*
  - The carbon/electron relationship
  - Spent carbon (CO_2) can be re-energized biologically
- Focus *beyond* AD of aerobic activated sludge and mere CH_4 mitigation
  - Only ½ of potential energy is recovered this way
  - aerobic process is energy intensive (CO_2 footprint)
  - Need to promote **direct anaerobic treatment of WW** for total carbon mgmt

…perhaps in a not-too-distant future?

D. Yeh

Graphics: Ana Lucia Prieto

Thank you for your attention. Questions?

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