Energy from Wastewater

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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

USF

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

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

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

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.

WERF onsite WW report
How do we clean our wastewater?

- **Energy:**
  - Pumping
  - Mixing
  - Aeration
  - Disinfection
  - Heat for digester
  - Chem transportation

- **Chemicals:**
  - Flocculation
  - Precipitation
  - Disinfection

- **Labor:**
  - O&M

Unrecoverable waste residuals

Clean Water

Trace chemicals, CO₂, H₂S, CH₄

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How do we clean our wastewater?

**Energy:**
- Pumping
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- Chem transportation

**Chemicals:**
- Flocculation
- Precipitation
- Disinfection

**Labor:**
- O&M

---

Trace chemicals, 

CO₂, H₂S, CH₄

Clean water

Bioproducts
- Biosolids, Nutrients, biopolymers

A more sustainable approach
How do we clean our wastewater?

- Energy
- Chemicals
- Labor

Trace chemicals, CO₂, H₂S, VOCs, CH₄

Clean water

Bioproducts: Biosolids, Nutrients, biopolymers

Energy

Unrecoverable waste residuals

An even more sustainable approach
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
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

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Recovery of nutrients

- Struvite and other precipitates
- Biosolids
  - Bio-P phosphorus recovery
- Crop growth / Algae
- Liquid fertilizer
  - Best opportunities for recovery in digester filtrate/cenrate.
    - 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)

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The Carbon Cycle

Aerobic – “with oxygen”

Anaerobic – “without oxygen”

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Energy states of carbon

**Reduction (gaining e⁻)**
- Anaerobic digestion

**Oxidation (losing e⁻)**
- Combustion, respiration

<table>
<thead>
<tr>
<th></th>
<th>Methane</th>
<th>biomass</th>
<th>Carbon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>rich</td>
<td>moderate</td>
<td>none</td>
</tr>
<tr>
<td>Redox state</td>
<td>-4</td>
<td>In between</td>
<td>+4</td>
</tr>
<tr>
<td>COD (energy)</td>
<td>4 g OD/g (180.4 Wh /g)</td>
<td>Typically 1-3 g OD/g</td>
<td>zero</td>
</tr>
</tbody>
</table>
AD and sun recharge spent carbon!

**FIGURE 16.37** Redox cycle for carbon; note in particular the contrasts between autotrophic (CO$_2$ → 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$_2$O)

$$\text{OrgC} \rightarrow \text{CO}_2 + e^-$$
$$e^- + \text{O}_2 \rightarrow \text{H}_2\text{O}$$

$$\text{OrgC} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$$

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

Please note 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.

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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.

\[
0.5 \text{ g COD/L} \times 0.25 \text{ g CH}_4/\text{g COD} \times 1000\text{L/m}^3 = 125 \text{ g CH}_4/\text{m}^3 \text{ of wastewater (typical conc)}
\]

\[(3784 \text{ m}^3/\text{MG})\]

\[
125 \text{ g CH}_4/\text{m}^3 \times 50.1 \text{ kJ/g CH}_4 \times 3.6 \text{ Wh/kJ} = 22.55 \text{ kWh/m}^3 \text{ of wastewater (85 MWh/MG)}
\]

Ex. loading: 85 MWh/MG \times 50 \text{ MG/d} \times d/24hr = 177 \text{ MW from wastewater (max potential)}

(Tampa WWTP)

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

<table>
<thead>
<tr>
<th>Process</th>
<th>Average power consumption (kWh) of 1000 m³ crude sewage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Preliminary treatment</td>
<td>12.67</td>
</tr>
<tr>
<td>2. Primary sedimentation</td>
<td>0.91</td>
</tr>
<tr>
<td>3. Recirculation pumping of activated sludge</td>
<td>34.19</td>
</tr>
<tr>
<td>4. Aeration</td>
<td>230.84</td>
</tr>
<tr>
<td>5. Digestion tank (Mixing and Pumping)</td>
<td>20.86</td>
</tr>
<tr>
<td>6. Final sedimentation</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>Total input</strong></td>
<td><strong>300.1458</strong></td>
</tr>
</tbody>
</table>

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/m$^3$ consumed for WWT (Nouri et al 2007)

2.2 kWh/m$^3$ potential from waste organic matter (assume harvesting 10% of max potential)

Excess energy for export???

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

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So, how do we extract this energy from wastewater?
Waste organic matter as e⁻ donor

Aerobic

Energy reservoir (COD)

Biodegradable matter (BOD)

Non-biodegradable matter (COD-BOD)

Biomass

Residuals

Energy input

O₂ → H₂O

\( e^- \)

\( f_s \)

\( f_e \)

~60%

~40%

Choices!

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

Bioenergetics concept from Rittmann and McCarty, 2000

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Conventional Wastewater Treatment

1. **Influent**
   - organics
   - nutrients
   - pathogens

2. **Pre-treatment**
   - primary sludge
   - return-sludge

3. **Settling tank**
   - O₂

4. **Cl₂SO₂**

5. **Effluent**

6. **Primary sludge**
   - Dewatering/pelletization
   - Biosolids
   - Stabilized sludge
   - Aerobic digestion
   - Stabilized sludge
   - Example: aerobic digestion
   - (Choice of energy or material)

7. **Thickener**
   - Waste sludge (2% P)

8. **Burn for energy**

9. **USF**
   - D. Yeh

Graphics courtesy of Craig Criddle
Aerobic digestion and pelletization at Largo, FL

Some energy preserved through biosolids

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Waste organic matter as e⁻ donor

**Aerobic**
- Energy reservoir (COD)
  - Biodegradable matter (BOD)
  - Non-biodegradable matter (COD-BOD)

  *e⁻*  
  \[ f_s \sim 60\% \]
  \[ f_e \sim 40\% \]

  Biomass ➔ Residuals

  \[ \text{O}_2 \rightarrow \text{H}_2\text{O} \]

**Anaerobic**
- Energy reservoir (COD)
  - Biodegradable matter
  - Non-biodegradable matter (COD-BOD)

  *e⁻*  
  \[ f_s \sim 10\% \]
  \[ f_e \sim 90\% \]

  Biomass ➔ Residuals

  \[ \text{CO}_2 \rightarrow \text{CH}_4 \]

Energy input and storage

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Conventional Wastewater Treatment

Influent → Pre-treatment → Settling tank (primary sludge) → Settling tank → Anaerobic digester → Dewatering/pelletization → Thickener → Generator (biogas) → Electricity

- Influent: organics, nutrients, pathogens
- Pre-treatment: removal of settleable solids
- Settling tank: removal of floating and settleable solids
- Anaerobic digester: stabilization of sludge
- Thickener: thickening of sludge
- Generator: production of biogas and electricity
- Effluent: treated wastewater

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)

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Waste organic matter as e⁻ donor

Aerobic

Energy reservoir (COD)

- Biodegradable matter (BOD)
  - Energy output: CO₂, H₂O
  - Residuals

- Non-biodegradable matter (COD-BOD)
  - Energy output: CO₂, H₂O
  - Residuals

Energy input:
- e⁻
- O₂

Anaerobic

Energy reservoir (COD)

- Biodegradable matter
  - Energy output: CH₄
  - Residuals

- Non-biodegradable matter (COD-BOD)
  - Energy output: CO₂, H₂O
  - Residuals

Energy input:
- e⁻

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 sludge
  - Only about half of the embedded energy can be recovered to CH\textsubscript{4}
  - Considerable energy expenditure (and assoc. CO\textsubscript{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!

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Ex. of anaerobic processes for sewage treatment

Source: Reference 8. Adapted with permission from Proceedings of the Seminar/Workshop: Anaerobic Treatment of Sewage © 1985, University of Massachusetts.

D. Yeh From William Jewell (1987)
History of anaerobic processes for sewage treatment

**TABLE 2**

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

*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

D. Yeh
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
Upflow anaerobic sludge blanket (UASB)
Conventional Wastewater Treatment

Influent → Pre-treatment → Settling tank → Anaerobic digester → Dewatering/pelletization → Stabilized sludge → Biosolids

Primary sludge → Thickener → Return sludge → Effluent

Organics → Nutrients → Pathogens → Biogas → Generator → Electricity

Graphics courtesy of Craig Criddle
**First stage:**
convert organics into methane

- Influent → Minimal Pretreatment (grit removal, screens) → Anaerobic MBR → methane
- Methane → Ultrafiltration membranes → stabilized sludge

**Second stage:**
remove nutrients

- Effluent → Anaerobic Anoxic → O₂ (membranes) → sludge (8-10% P) → Dewatering → stabilized solids (high P)

**Objectives:**
recover more energy from the organics, use less O₂, 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

AD + UF membrane
## Gas lift-AnMBR: Energy footprint

<table>
<thead>
<tr>
<th>GI-AnMBR energy requirements</th>
<th>Case based Net Energy (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full biogas conversion</td>
</tr>
<tr>
<td>Membrane operation</td>
<td>1.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pump requirements</td>
<td>0.2</td>
</tr>
<tr>
<td>Reactor heating</td>
<td>0.0</td>
</tr>
<tr>
<td>Power from biogas</td>
<td>-2.8&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Energy footprint</td>
<td>-1.2</td>
</tr>
</tbody>
</table>

- **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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### Removal efficiencies

<table>
<thead>
<tr>
<th>Treatment technology</th>
<th>SS</th>
<th>COD</th>
<th>N</th>
<th>P</th>
<th>Pathogens</th>
<th>Energy footprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv. Act. Sludge</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td>Aerobic MBR</td>
<td>HH</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Anaerobic MBR</td>
<td>HH</td>
<td>H</td>
<td>n/a</td>
<td>n/a</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td>UASB</td>
<td>M</td>
<td>H</td>
<td>n/a</td>
<td>n/a</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>Septic tank</td>
<td>M</td>
<td>M</td>
<td>n/a</td>
<td>n/a</td>
<td>L</td>
<td>n/a</td>
</tr>
</tbody>
</table>

H: high    M: medium    L: low

- Mineralized forms of N and P remain in the liquid $\rightarrow \text{NH}_4$, $\text{NO}_3$, and $\text{PO}_4$

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Further thoughts on anaerobic WWT

What if methane is not captured and combusted to CO₂, and results in fugitive methane release? This is a problem since CH₄ is 25X worse GHG than CO₂

- The only way for WW organics to become CO₂ is to be oxidized by oxygen in aerobic environment. If occurs in aquatic environment, will deplete O₂ → 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 CH₄ to CO₂ 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.
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.
Other forms of energy capture (non-methane)
Hydrogen recovery from WW also possible

Towards biohydrogen production

Selection pressure
Temperature
pH
....others

From McCarty and Smith (1986)
Fuel cell

\[ H_2 \rightarrow 2e^- + 2H^+ \]

Electron-donating half reaction

\[ \frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \]

Electron-accepting half reaction

\[ 2H^+ + O^{2-} \rightarrow H_2O \]

Formation of water

Electron donor: \( H_2 + \frac{1}{2}O_2 \rightarrow H_2O \) acceptor

Net reaction

Platinum (expensive & prone to poisoning)

H₂ 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)

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Synergy of Algae and Wastewater

- Produces O₂
- Requires O₂

- Produces CO₂
- Requires CO₂

- Contains Nutrients
- Requires Nutrients

- Requires Energy
- Harnesses Energy

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

http://saferenvironment.files.wordpress.com/2008/10/alge.jpg
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 compliance!
    • 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…)

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Summary

• Anaerobic digestion
  – Primary sludge
  – Secondary sludge
  – Combined primary + secondary

• Direct anaerobic wastewater treatment
• Microbial fuel cell (different variations)
• Biohydrogen
• Biosolids as fuel (coal substitute)
• Algae (biofuel)
• Waste heat

Most promising

Good potential

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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 (CO₂) can be re-energized biologically

• Focus *beyond* AD of aerobic activated sludge and mere CH₄ mitigation  
  – Only ½ of potential energy is recovered this way  
  – aerobic process is energy intensive (CO₂ footprint)  
  – Need to promote **direct anaerobic treatment of WW** for total carbon mgmt

D. Yeh
...perhaps in a not-too-distant future?
Thank you for your attention.
Questions?

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