Tailoring Innovation to Achieve Financially-Viable Energy and Nutrient Recovery from Wastewater

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Our central goal is to increase access to and the sustainability of sanitation.

create perceived value with technologies that are:

→ financially viable
→ energy positive
→ nutrient recovering
→ sustainable

environmental, economic, and social capacity to endure
We integrate experimentation, modeling, and quantitative sustainable design (QSD) for technology development.
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Today I’ll focus on QSD and the development of an anaerobic technology.

wastewater as a renewable resource

elucidating sustainability trade-offs

tailoring innovation
Treatment plants consume \(\sim 1\text{-}3\%\) of U.S. electricity to decrease the energetic content of WW.
Treatment plants consume \( \sim 1-3\% \) of U.S. electricity to decrease the energetic content of WW.

\[ \sim 40-115 \times 10^9 \text{ MWh/year} \]

\[ \sim 0.15-0.30 \text{ GJ/capita-year} \]

\[ \sim 40-80 \text{ kWh/capita-year} \]

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\( a \) Based on EPA estimates that include industrial wastewaters [USEPA, Wastewater Management Fact Sheet: Energy Conservation, Office of Water, 2006].

\( b \) Based on many life cycle assessments that have been completed around the treatment plant itself, normalized to a per capita equivalent based on typical wastewater generation rates.
R&D on energy production has focused on conversion of organic-C to usable energy.

ASBR - Anaerobic Sequencing Batch Reactor
UASB - Upflow Anaerobic Sludge Blanket
ABR - Anaerobic Baffled Reactor
AFB - Anaerobic Fluidized Bed
AnMBR - Anaerobic Membrane Bioreactor
MEC - Microbial Electrolysis Cell
MFC - Microbial Fuel Cell
R&D on energy production has focused on conversion of organic-C to usable energy.

[Shoener et al. (2014) Environmental Science: Processes & Impacts; 16(6): 1204-1222]
Maximizing nutrient and energy recovery would integrate **anaerobic** and **phototrophic** processes.

[Shoener et al. (2014) *Environmental Science: Processes & Impacts*, 16(6): 1204-1222]
Anaerobic membrane bioreactors (AnMBR) can achieve high levels of COD removal.

[Shoener et al. (2014) Environmental Science: Processes & Impacts; 16(6): 1204-1222]
Existing AnMBR designs could be very expensive and won’t be energy positive.

[Shoener et al. (2014) Environmental Science: Processes & Impacts; 16(6): 1204-1222]
How do we design and operate an AnMBR to enable affordable, energy positive wastewater treatment?

[Shoener et al. (in preparation)]
How do we design and operate an AnMBR to enable affordable, energy positive wastewater treatment?

144 discrete designs

infinite number of design and operating conditions

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What is sustainable design?

**in theory**

“...meets the needs of the present without compromising the ability of future generations to meet their own needs.”

[World Commission on Environment & Development, 1987]

**in practice**

decision-making criteria:
- social
- environmental
- economic
- functional

triple bottom line (TBL)
We started by developing a qualitative planning and design process to address social factors.

The quantitative backbone of this larger design process can drive technology innovation.
First, we need to define our design/innovation challenge.
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constraints

risk

effluent quality

footprint

operational labor

capital costs
First, we need to define our design/innovation challenge.

**Constraints**  
risk, water quality, cost, etc.

**Objective**

“minimize likelihood of permit violations”

“minimize cost”

“minimize greenhouse gas (GHG) emissions”

“minimize cost & GHG emissions”

…
First, we need to define our design/innovation challenge.

**constraints** risk, water quality, cost, etc.

**objective** minimize cost & GHG emissions

**decision variables (DV)** discrete

configuration/material 1 vs. configuration/material 2
First, we need to define our design/innovation challenge.

**constraints** risk, water quality, cost, etc.

**objective** minimize cost & GHG emissions

**decision variables (DV)**

*discrete* configuration/material 1 or 2

*continuous*

Q ↔ 4Q internal recycle flow rate
Sustainable design is a process to navigate trade-offs and set targets under uncertainty.

Select decision variables

- Technology A

Conceptual/detailed design of technology

**Technology A**

- **Functional**
  - Performance
  - Feasibility
  - Manageability

- **Environmental**
  - Local impacts
  - Life cycle impacts

- **Economic**
  - Life cycle costs

- **Social**
  - Stakeholder influence on decision-making

**Decision Analysis**

- WWTP designs: A, B, C, D, E
- Optimal design: B
- Stakeholder participation

**Tools**

- GPS-X
- CAPD-ET WorkS
Start with a model to predict the performance of the technology.

functional environmental economic social

this can be any kind of process model that predicts performance
We quantify global environmental impacts using life cycle assessment (LCA).

Functional, environmental, economic, social

Construction, operation

Goal & scope definition

Inventory analysis

Impact assessment
- Classification
- Characterization
- Valuation

Interpretation

Greenhouse gas emissions

Fossil fuels
We use established cost equations for life cycle costing (LCC).

**cost equations**

-U.S. EPA, 1982-

[@U.S. EPA, 1982@]

[sensitivity & uncertainty analyses]

[1.5c.png]

[1.5.png]
Designers can also identify tensions and synergies across decision variables.

life cycle costs  
effluent contaminants  
global warming potential

DV 2

DV 1

DV 1
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infinite number of design and operating conditions

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[Shoener et al. (in preparation)]
[Pretel et al. (submitted)]
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experimentation + modeling

selecting a configuration

developing a detailed design

[Shoener et al. (in preparation)] [Pretel et al. (submitted)]
Bench scale reactors were run at KAUST the Urbana WWTP, a pilot-scale system was operated at Carraixet WWTP (Valencia, Spain).

Photo by Na Kyung Kim, UIUC

[Ruth Pretel Jolis]
Experimental data was leveraged to predict the design of full-scale systems.
When every design is evaluated under uncertainty, we identify **which configurations should be pursued**.
Once we identify a configuration, the relative importance of detailed design & operational decisions.

MLSS  
mixed liquor suspended solids

SRT  
solids residence time

r  
internal recycle ratio

J  
membrane flux

SGD  
specific gas demand

[ Pretel et al. (submitted) ]
Once we identify a configuration, the relative importance of detailed **design & operational decisions**.
Through QSD identify tensions and synergies in design, enabling us to navigate trade-offs.

[Diagram showing cost of decreasing life cycle CO₂ emissions against J [% of J₀] with annotations for trade-offs and synergies.]

[Pretel et al. (submitted)]
This enables utilities to identify **financially viable** and **environmentally sustainable** technologies and designs.

experimentation + modeling  
selecting a configuration  
developing a detailed design

[Shoener et al. (in preparation)]  [Pretel et al. (submitted)]
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In conclusion, leveraging quantitative sustainable design can enable strategic technology innovation.

- identify needs
- identify technology alternatives
- navigate trade-offs
- identify opportunities for innovation