Incorporation of LCA into the Systematic Synthesis of Wastewater Treatment Plants

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Water, energy and food security nexus

- Wastewater
  - N P recovery from WWT
  - Water required for WWT
  - Phytoremediation
- Fertilizer
  - Co-digestion
  - NPK nutrients
- Energy
  - Energy for WWT
  - Energy for bioenergy production
- Food crops
  - Energy for plantation
  - Bioenergy production from renewable resources
- Non-food biomass
  - WWT to produce bioenergy

- Energy for fertilizer production
Why nutrient recovery from wastewater treatment (WWT)?

**Economic driver**
- Fertilizer supply-demand issue

**Ecosystem quality**
- Emissions from WWT
- Emissions from agricultural systems

**Resource depletion**
- P resource depletion
- Energy-intensive fertilizer industry

(Mehta et al., 2015)
An integrated WWT concept

Integrated WWTP

Physico-chemical treatment

Biological treatment

Thermo-chemical process

Electrical thermal energy recovery

Resource recovery (N/P/C)

Treated water recycling and reuse

Integrated WWTP
An integrated WWT concept

- Degritted, Fine Screened Wastewater with Screenings Washing
- Membrane Thickened Waste Solids
- FP Pretreatment/Solubilization of Organics
- Anaerobic Digester/MBR System
- Aerobic Membrane Bioreactor/SRT 1 to 2 Days
- P Removal Reactive Filtration System
- Solid-Liquid Separation
- Zeolite Ammonia Removal System
- Effluent for Reuse Following Disinfection

- N Recovery as Ammonium Sulfate
- Waste Solids for P Recovery
- Gas Production/Utilization
- Excess Solids

An example ...
(Sutton et al., 2011)
Wastewater treatment plant (WWTP) synthesis

- A range of promising treatment & recovery technologies
- A number of possible interconnections
- Trade-offs - economic viability vs. environmental objectives

Calls for a systems approach
What is Life Cycle Assessment (LCA)?

**Phase 1 - LCA goal & scope**
- Functional unit
- System boundary
- Impact categories
- Allocation approach

**Phase 2 - LCI analysis**
- LCA data (energy and resource flow)

**Phase 3 - Impact assessment**
- Classification
- Characterisation
- Normalisation, aggregation, weighting – optional

**Phase 4 - LCA interpretation**
- ‘Hotspot’ analysis
- LCA comparison
- Data quality analysis
- Other concerns (time horizon etc.)

(ISO, 2006)
Environmental assessment - midpoint vs. endpoint

(UNEP/SETAC Life Cycle Initiative 2011)
An example – How to apply LCA to WWTP

A wet (dry solid less than 15%), continuous-feeding multiple-stage digestion system operated at mesophilic temperature

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLR of OFMSW</td>
<td>2.393g COD/L/day</td>
<td>A UK commercial AD plant three month operational data; experimental results</td>
</tr>
<tr>
<td>TSS</td>
<td>50.56±3.74 g/L</td>
<td>Waste and Resources Assessment Tool for the Environment (WRATE) model</td>
</tr>
<tr>
<td>VSS</td>
<td>25.01±3.02g/L</td>
<td></td>
</tr>
<tr>
<td>Electricity for operation</td>
<td>1704.70 kwh/day equivalent to 15.7% of the generated electricity</td>
<td></td>
</tr>
<tr>
<td>Thermal energy for operation</td>
<td>3.37 MJ/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>Makeup water</td>
<td>150 m³/day Equivalent to 3.34E-3 kg/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>Internally recycled water</td>
<td>150 m³/day</td>
<td></td>
</tr>
<tr>
<td>NaOCl</td>
<td>5.02 E-5 kg/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Concrete, steel, cement, HDPE,</td>
<td></td>
</tr>
<tr>
<td>Life span</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Exported surplus electricity</td>
<td>3.01 MJ/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>Exported heat</td>
<td>5.5 MJ/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>1.63 kg/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>NOₓ emissions</td>
<td>3.15 E-5 kg/kg bio-waste treated</td>
<td></td>
</tr>
<tr>
<td>Digestate cake</td>
<td>1.12 E-1 kg/kg bio-waste treated</td>
<td></td>
</tr>
</tbody>
</table>

(Guo et al., 2012)
A: Characterized LCIA profiles for AD treatment of bio-waste; B: Acidifying gas profiles for AD infrastructure; C: GHG profiles for AD infrastructure; D: Precursors of eutrophication caused by AD infrastructure.

(unit: per kg biowaste treated; method: CML 2 baseline 2000)
Integration of LCA into WWTP Synthesis

- GPS-X™ (batch mode)
- CapdetWorks™ (batch mode)
- Multi-objective optimization
- Regression model
- Detailed design & costing
- Performance model

Input ranges
Parameters
Configuration
Input-output flows
Environmental profile
Validation
Performance data
Costing data
Optimal Superstructures
Superstructure modelling and optimization

Superstructure

Synthesis problem

Given:
- A set of waste water streams
- A set of water sinks and specification
- A set of treatment & separation units

Determine optimal systems
- Units & interconnections
- Flows and composition

Multi-objective optimization
- Maximize net present value (NPV)
- Minimize environmental impacts for each performance indicator kpi \(EI_{kpi}\)

\[
NPV = \sum_{yr=1}^{\text{lifetime}} \frac{SALES - OPEX}{(1 + RATE_{discount})^{yr}} - CAPEX
\]

\[
EI_{kpi} = \sum_k \alpha_k \sum_c EIf_{c,kpi} x_{k\rightarrow j,c}^{out} F_{k\rightarrow j,c}^{out} + \sum_r EIf_{r,kpi} y_{k,r}^{in}
\]

(Puchongkawarin et al., 2015)
Superstructure modelling and optimization – unit models

Material balance –

\[ F_{in}^{c,k} X_{c,k}^{in} (1 - \rho_{k,c}) = \sum_{k'} F_{c,k\rightarrow k'}^{out} X_{c,k\rightarrow k'}^{out} + \sum_{j} F_{c,k\rightarrow j}^{out} X_{c,k\rightarrow j}^{out} \]

Treatment / separation units

- State-of-the-art wastewater models e.g. ADM1, ASM1-3 or Mantis1-3
- To derive regression models (linear, quadratic, cubic)

\[ X_{k,c}^{out} = f(X_{COD}^{in}, X_{N}^{in}, X_{P}^{in}) \]

Costing - CAPEX, OPEX

- To derive regression models
LCIA profiles - operational & capital environmental impacts

Emissions Factor

<table>
<thead>
<tr>
<th>GWP100 (kg CO₂ eq/kg)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>25</td>
</tr>
<tr>
<td>N₂O</td>
<td>298</td>
</tr>
</tbody>
</table>

Acidification (kg SO₂ eq/kg)

| NH₃ | 1.6 |
| SO₂ | 1.2 |
| SOₓ | 1.2 |
| NO₂ | 0.5 |
| NOₓ | 0.5 |

Eutrophication (kg PO₄³⁻·Eq/kg)

| NH₃    | 0.35 |
| NH₄⁺   | 0.33 |
| NO₃⁻   | 0.1  |
| NO₂⁻   | 0.1  |
| Total N| 0.42 |
| PO₄³⁻  | 1    |
| Total P| 3.6  |
| COD    | 0.022|

Impact categories

| Acidification (kg SO₂ eq/kwh) | 2.12E-03 | 2.18E-03 | 2.14E-03 |
| Eutrophication (kg PO₄³⁻·Eq/kwh) | 7.34E-04 | 7.64E-04 | 7.43E-04 |
| GWP100 (kg CO₂ eq/kwh) | 4.70E-01 | 4.87E-01 | 4.77E-01 |

(Method: CML 2 baseline 2000)
Case study

Case study: Definition

Municipal Wastewater effluent

<table>
<thead>
<tr>
<th>Total COD</th>
<th>Soluble COD</th>
<th>TSS</th>
<th>VSS</th>
<th>VFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>569 mg/L</td>
<td>129 mg/L</td>
<td>259 mg/L</td>
<td>231 mg/L</td>
<td>10 mg/L</td>
</tr>
<tr>
<td>Total N</td>
<td>Ammonia</td>
<td>Total P</td>
<td>Phosphate</td>
<td>Alkalinity</td>
</tr>
<tr>
<td>51.6 mg/L</td>
<td>38 mg/L</td>
<td>7.6 mg/L</td>
<td>4.1 mg/L</td>
<td>253 mgCaCO₃/L</td>
</tr>
</tbody>
</table>

Maximum discharge regulations (EU Directive 91/271/ECC on Urban Wastewater Treatment)

<table>
<thead>
<tr>
<th></th>
<th>Max. Concentration</th>
<th>Min. abatement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total COD</td>
<td>&lt; 143 mg/L</td>
<td>TCOD &gt; 75 %</td>
</tr>
<tr>
<td>TSS</td>
<td>&lt; 25.9 mg/L</td>
<td>TSS &gt; 90 %</td>
</tr>
<tr>
<td>Ammonia</td>
<td>&lt; 7.6 mg/L</td>
<td>TN &gt; 80 %</td>
</tr>
<tr>
<td>Nitrate</td>
<td>&lt; 10.3 mg/L</td>
<td>TP &gt; 80 %</td>
</tr>
<tr>
<td>Phosphates</td>
<td>&lt; 0.82 mg/L</td>
<td></td>
</tr>
</tbody>
</table>

Objective: Maximize NPV – LCA (GWP) over 20 years
Case study – superstructure optimization results

Case 1 – Optimal superstructure

Objective function: \(-13\) M£

- Bottleneck – abatement of TSS
- GWP objectives mostly driven by operation of activated sludge (~80% N₂O/CO₂)
- Beneficial effects by anaerobic digestion (both NPV and GWP due to energy recovery)
Case 2 – No anaerobic digestion (energy recovery)

Objective function: -61 M£

- Case 2 – No contribution from anaerobic digestion and low objective function is driven by higher landfill cost
- Minimal abatement in TSS appears to be bottle neck
Potential collaboration

- Renewable energy (e.g. solar)
- Bioenergy (e.g. electrical and thermal, biofuel)

- Spatially explicit resource map;
- Non-energy technologies (e.g. CCS, high-value chemicals)

- Food security
- Water security
- Multi-period

- Multi-objectives – e.g. min cost vs. GHG targets
- Multi-period

Water for energy system

Water for non-energy systems

Energy demand

Non-energy demand
References

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