Supply-chain environmental effects of wastewater utilities

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Abstract
This letter describes a comprehensive modeling framework and the Wastewater-Energy Sustainability Tool (WWEST) designed for conducting hybrid life-cycle assessments of the wastewater collection, treatment, and discharge infrastructure in the United States. Results from a case study treatment plant which produces electricity using methane offgas are discussed. The case study system supplements influent with ‘high-strength organic waste’ to augment electricity production. The system balance is 55 kg of greenhouse gases per million liters of wastewater. Sensitivity analysis confirms that reusing biogas from anaerobic digestion for electricity reduces life-cycle greenhouse gas emissions by nine times. When biogas is captured and reused for electricity, material production (e.g., chemicals and pipes) and the corresponding supply chains, rather than energy production, are responsible for most of the environmental effects. When biogas is flared, the material and energy production contributions are similar.

Keywords: life-cycle assessment, wastewater treatment, greenhouse gases

Online supplementary data available from stacks.iop.org/ERL/5/014015/mmedia

1. Background

Wastewater treatment plants (WWTPs) are regulated to limit their impact on the environment. However, regulations focus on chemical concentrations in liquid effluent and solid waste. They rarely consider the broader effects associated with the wastewater system’s life cycle, including material production and use, infrastructure construction and maintenance, and energy production impacts. For example, recent California legislation, the Global Warming Solutions Act, regulates greenhouse gas (GHG) emissions associated with WWTPs. The potentially significant environmental effects of energy use and GHGs from cradle to grave need to be captured too.

Wastewater services and energy consumption are tightly connected. Broadly viewed, California’s water-related services use approximately 19% of the state’s electricity and 30% of natural gas [1]. Worldwide, pumping and treating urban water and wastewater consumes 2%–3% of energy [2]. As population grows and demand for water and sanitation services increases, the energy consumption is expected to grow by 33% over a 20 year period.

Infrastructure construction and maintenance as well as material production and delivery also contribute to energy use and the environmental burden. Though the infrastructure is hidden from view, it can be substantial. Water, sewer, district heating pipelines and similar infrastructure account for 10%–20% of urban building mass [3]. The energy and materials used and the construction processes needed to install this infrastructure increase a wastewater utility’s life-cycle environmental effects.

This research analyzed a large wastewater utility in California using a decision-support tool developed to conduct wastewater system life-cycle assessments (LCA). The analysis compares the energy requirements and certain air emissions due to energy and material consumption for wastewater systems.

2. Methodology

LCA is a systematic, comprehensive tool which can help practitioners quantify energy and emissions implications of decisions related to products, processes and services from
L = from wastewater systems, and incorporated it into a and energy inputs into and certain environmental outputs

3. The Wastewater-Energy Sustainability Tool

The authors created a framework to quantify material and energy inputs into and certain environmental outputs from wastewater systems, and incorporated it into a decision-support tool, the Wastewater-Energy Sustainability Tool (WWEST). Its structure was modeled after a tool developed previously by the authors, the Water-Energy Sustainability Tool (WEST) [20, 21]. A figure defining the boundaries of WEST and WWEST is included in the supplementary data available at stacks.iop.org/ERL/5/014015/mmedia.

WWEST reports emissions and energy use by wastewater system phase, life-cycle phase, and activity. Each is described in table 2.

WWEST was created for several audiences, including utility administrators and plant operators, regulators, engineering firms, construction contractors, and policy analysts. It can be used to evaluate the effects of a variety of wastewater decisions, including:

- designing system expansions (e.g., centralized versus distributed treatment),
- changing treatment standards (e.g., reduced receiving waters),
- evaluating alternative treatment processes (e.g., membrane versus conventional filtration, chlorine versus ultraviolet disinfection),
- choosing materials for infrastructure improvements (e.g., steel versus concrete, plastic versus steel pipe),
- energy efficiency improvements and pollution prevention, and
- material use reductions.

Descriptions of WWEST, emission factor sources, and equations are included in the supplementary data available at stacks.iop.org/ERL/5/014015/mmedia. Default data for treatment processes, obtained primarily from [23, 24], are available in WWEST.

Results are displayed both numerically and graphically. Energy use, GHGs in terms of 100 year CO₂ equivalents (CO₂eq), nitrogen oxides (NOₓ), particulate matter (PM),

### Table 1. Literature summary. (Note. Abbreviations: CO₂eq = carbon dioxide equivalents; D = disposal; GHG = greenhouse gas; L = liquid; S = sludge; T = treatment; Tg = Teragrams; UV = ultraviolet disinfection; WWTP = wastewater treatment plant.)

| Scope (location) and source | Findings summary |
|----------------------------|-----------------|
| S, T, D (Spain) [10] | Examined four biogas reuse options and five sludge disposal or reuse options; anaerobic treatment with biogas used for electricity/heat and a combination of sludge reuse for land application and in cement making are preferred |
| S, T, D (China) [11] | Explored sludge reuse options (as fertilizer and in concrete); anaerobic treatment most environmentally benign; incineration most economically and environmentally costly |
| L, S, T (Canada) [12] | Analyzed onsite treatment at WWTP; GHG emissions range from 0.14 to 0.63 kg CO₂eq m⁻³ |
| L, S, T (Canada) [13] | Evaluated GHGs due to liquid and sludge treatment; wastewater treatment in Canada was responsible for 1 Tg CO₂eq in 2000 |
| S, T, D (France) [14] | GHGs are lowest for cement kiln incineration and highest for landfill and agricultural spreading |
| L, S, T, D (Sweden) [15] | The sludge disposal alternatives considered had different nutrient and energy recovery efficiencies; agricultural spreading is environmentally preferable |
| L, S, T, D (Australia) [16] | WWTPs contribute 41% of energy use and 49% of GHGs in the full water cycle; biosolid disposal by land application is environmentally preferred |
| L, S, T (Australia) [17] | Analyzed disinfection and digestion options; UV has highest environmental costs; energy use and GHGs are lower for anaerobic than aerobic digestion but results are mixed for other emissions |
| L, S, T (Australia) [18] | Evaluated case studies with aerobic or anaerobic digestion; combining activated sludge and aerobic digestion creates highest GHGs; processes that captured methane for use in electricity production have lowest emissions |
| S, T, D (France) [19] | Explored treatment, stabilization, and sludge disposal; resource depletion lowest for incineration and landfilling; anaerobic digestion with land application has lowest climate change and overall weighted results |

‘cradle to grave’. LCA has been extensively described (see, e.g., [4]). Two LCA approaches are commonly used. Process-based LCA breaks down a product or service into distinct processes, and collects data from available sources to evaluate the inputs and outputs of the processes. Economic input–output analysis-based LCA (EIO-LCA) is a matrix-based approach using the US Department of Commerce’s economic input–output model augmented with publicly available resource consumption and environmental emissions data [5, 6].

This research incorporates hybrid LCA, combining the two LCA methods to leverage the strengths of each approach and minimize the disadvantages (similarly to the practice in studies [7, 8]). The two methods were applied to the appropriate life-cycle phases. EIO-LCA was used to estimate manufacturing and supply-chain emissions for most materials. Process-based LCA was used to obtain results for manufacturing certain materials, including plastic pipes and chemicals [9]. Operational effects, such as electricity generation and utility vehicle tailpipe emissions, were estimated using process-based LCA.

Several wastewater system LCAs have been conducted to date outside the United States. Table 1 summarizes the literature [10–19]. A more detailed description of these and other papers is available as supplementary data (available at stacks.iop.org/ERL/5/014015/mmedia). Generally, the studies focus on treatment processes. Few studies include infrastructure construction or maintenance, especially collection and discharge piping. While informative, these international studies do not necessarily apply to US conditions.
sludge treatment, as shown in figure 1. The utility captures lift stations. Included in the analysis. The collection system includes fifteen independent sewer systems. Only the utility’s infrastructure is it to the treatment plant. Some of these communities operate sewage from several contiguous communities and transports it to the treatment plant. Energy use and emissions from producing chemicals and other routinely used materials (including supply chains); direct emissions from the treatment process. Includes energy use and emissions from producing replacement parts for components with service lives shorter than the analysis period (including supply chain); fuel use and emissions from maintenance and delivery vehicles. Includes fuel use and emissions for transporting and disposing of sludge; long-term emissions, energy generation offsets, and co-product offsets from disposal (e.g., fertilizers). Decommissioning water infrastructure contributes <0.01% to overall results [22]; wastewater results are expected to be similar, thus were not calculated.

| Phase/category   | Description                                                                                                                                                                                                 |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Life cycle       |                                                                                                                                                                                                             |
| Construction     | Includes energy use and emissions from producing construction materials, treatment equipment, and energy used in initial installation, including supply chains; fuel use and emissions from construction equipment and delivery vehicles. |
| Operation        | Includes energy and emissions from the collection, treatment, and discharge phases; energy generation offsets from treatment operation; fuel use and emissions from delivery and operational vehicles; energy use and emissions from producing chemicals and other routinely used materials (including supply chains); direct emissions from the treatment process. |
| Maintenance      | Includes energy use and emissions from producing replacement parts for components with service lives shorter than the analysis period (including supply chain); fuel use and emissions from maintenance and delivery vehicles. |
| End-of-life      | Includes fuel use and emissions for transporting and disposing of sludge; long-term emissions, energy generation offsets, and co-product offsets from disposal (e.g., fertilizers). Decommissioning water infrastructure contributes <0.01% to overall results [22]; wastewater results are expected to be similar, thus were not calculated. |
| System           |                                                                                                                                                                                                             |
| Collection       | Transporting sewage from consumer to the treatment plant, and related infrastructure.                                                                                                                                 |
| Treatment        | Ensuring effluent meets regulatory standards and necessary infrastructure; includes liquid and sludge treatment.                                                                                               |
| Distribution     | Transporting treated effluent to the discharge point and required infrastructure.                                                                                                                             |
| Activity         |                                                                                                                                                                                                             |
| Material production | Quantifies materials used in the system and the energy/environmental effects of their manufacture and provision; primarily uses EIO-LCA supplemented with process-based LCA.                                      |
| Material delivery | Assesses the energy used and emissions from transportation of materials by truck, train, ship, or airplane; uses process-based LCA.                                                                               |
| Equipment use    | Evaluates emissions and fuel use from operating non-transport construction equipment and maintenance vehicles; uses process-based LCA.                                                                        |
| Energy production | Quantifies effects of electricity production and fuel production (e.g., gasoline, diesel) needed to operate vehicles; uses process-based LCA for electricity and EIO-LCA for fuel.                              |
| Direct emissions | Estimates the GHG emissions from treatment processes which exceed the inevitable biogenic CO₂ emissions; uses process-based LCA.                                                                                 |
| Disposal         | Analyzer the effects of transporting and disposing of sludge; uses process-based LCA, except co-product offsets.                                                                                             |

4. Case study

The capabilities of WWEST are demonstrated herein using a case study, a large wastewater utility in California. The utility asked to remain anonymous. It serves more than half a million people over a 200 km² area. Table 3 summarizes the utility’s system. The information was obtained through the utility’s website, publicly available publications, and communications with utility employees. The functional unit selected was one million liters (MI) of wastewater.

The utility owns and operates infrastructure which collects sewage from several contiguous communities and transports it to the treatment plant. Some of these communities operate independent sewer systems. Only the utility’s infrastructure is included in the analysis. The collection system includes fifteen lift stations. Treatment consists of two process streams, liquid and sludge treatment, as shown in figure 1. The utility captures methane from its treatment process and uses it to produce approximately 40 000 MWh of electric energy onsite annually. The utility reports a near-perfect capture rate, assumed for the

| Parameter          | Collection | Treatment |
|--------------------|------------|-----------|
| Liquid volume      | 91 000     | 95 000    | 95 000    |
| (1000 m³ year⁻¹)   |            |           |           |
| Biosolids produced | —          | —         | 720 000   |
| (wet tonnes)       |            |           |           |
| Electricity        | 1500       | 42 300    | (40 000)  |
| (MWh year⁻¹)       |            |           |           |
| Natural gas        | —          | 10 000    | —         |
| (MBTU year⁻¹)      |            |           |           |
| Diesel             | 1900       | 120 000   | —         |
| (l year⁻¹)         |            |           |           |
| Chemicals          | —          | 19 000    | 1400      |
| (l year⁻¹)         |            |           |           |
| Pipelines (m)      | 62 000     | —         | —         |
| —                  |            |           | 4700      |
| Pumps (#)          | 39         | 480       | 160       |
| Maintenance truck use (km year⁻¹) | 620 000 | —    | — | — |
| Hybrid automobile use (km year⁻¹) | 88 000 | —          | —         |

* Values are average energy consumption between 2005 and 2007. Treatment energy use includes both liquid and sludge treatment. The utility recovers energy during sludge treatment by capturing methane biogas for electricity generation.
analysis to be 98%. Most of the treated biosolids (78% in 2007) are used as alternative daily cover at a landfill located approximately 65 km away. The remainder is land-applied 200 km away. The utility discharges to a diffuser located about 1.5 km offshore.

In addition to the case study, a hypothetical system was analyzed to test the sensitivity of the results to particular design decisions. This system is similar to the case study except methane from the treatment process is flared rather than captured for electricity (assumed capture rate of 90%) and methane is released from the landfill. The hypothetical system quantifies the benefits of these design decisions. Figure 1 shows the process diagram for the hypothetical system (the processes shown in unbolded outline are excluded).

5. Results

Results for the case study and the hypothetical systems, including energy use, GHG and criteria air emissions are summarized in table 4. The case study utility consumes 2.3 GJ of energy per Ml and emits 55 kg of GHGs. The hypothetical system consumes three times more energy and emits nine times more GHGs. In some cases, emissions are negative for the case study utility because onsite electricity generation offsets purchased electricity produced from sources with higher emissions.

The treatment phase dominates the results, contributing 63–106% to each emission category for both the case study and the hypothetical system. The treatment phase contribution may be overstated because the collection system analysis is limited to infrastructure owned and operated by the utility. The utility primarily operates trunk sewer lines, while some smaller collection pipelines are owned by municipalities within its service area. No information was collected about the physical extent of the municipalities’ collection system infrastructure or operations.

However, the treatment system analysis is also limited. The utility did not provide a complete inventory of some process equipment. The inventory included pumps, process basins and tanks, and estimates of piping, electrical, and control equipment needs based on known plant costs. Cleaning, mixing, and aerating equipment, for example, were excluded from the analysis because of lack of data. Though the
electricity use. In contrast, figure 2 shows that the GHG result demonstrates the advantages of capturing methane for production consistently dominated material production. Because for the previously analyzed water systems energy production offsets all emissions. This result was unexpected because for the entire study utility’s energy production activity offsets 0.76 GJ. In fact, energy is responsible for 2.9 GJ of energy production per Ml whereas for pollution prevention. The material production supply chain is substantial, the material production activity comes into focus for GHGs, NO\textsubscript{x}, and VOC emissions. Equipment for broad environmental analyses. In addition, WWEST currently emphasizes the most common treatment processes. The authors will continue to develop more detailed evaluations of alternative treatment processes in WWEST.

6. Discussion

6.1. WWEST

The current version of WWEST has limitations. It does not assess all emissions, account for ecological effects, or quantify other environmental impacts such as the potential for smog production. Though this assessment for wastewater systems is limited, it does fill a gap by allowing utilities to quantify aspects of environmental sustainability, the life-cycle effects of energy and infrastructure use, which previously have been ignored. Improvements are needed to make WWEST more useful for broader environmental analyses. In addition, WWEST currently emphasizes the most common treatment processes. The authors will continue to develop more detailed evaluations of alternative treatment processes in WWEST.

6.2. Case study analyses

The data obtained from the case study utility were limited. They did not include inventory and costs for some auxiliary equipment and for portions of the collection system owned by other entities. In spite of these limitations, the results are still informative.

Certain wastewater treatment processes allow opportunities for heat and energy recovery which can offset fossil fuel consumption and prevent GHG emissions, reducing the system’s environmental costs. Anaerobic digestion processes are good candidates because they produce methane. For the utility, the plant produces approximately 90% of its electricity needs using captured methane. As a result, the utility plant’s GHG emissions from energy production are negative, compared to 240 kg from the hypothetical plant. GHG recovery can greatly affect the overall environmental burden of a WWTP and should be implemented when feasible. It should be noted again that the case study utility augments their influent with ‘high-strength organic waste’ to improve contribution of both the treatment and the collection systems may be underestimated, the treatment system will likely still dominate the results if the entire system were analyzed.

The operation phase is a less significant contributor to the case study results than would be expected. The utility captures methane from anaerobic digestion and uses it to generate electricity onsite which offsets purchased electricity from alternate sources, thereby reducing operational impacts relative to other phases. The onsite electricity generation process and other treatment processes emit CO\textsubscript{2}, but these emissions are not included in the plant’s GHG result because they are biogenic. The operation phase is most important for energy use (about three-quarters of the total) and contributes to PM emission savings. Construction is most significant for GHGs, NO\textsubscript{x}, SO\textsubscript{2}, and VOC. In the hypothetical system, the operation phase dominates the construction phase for all environmental effects except PM.

For the case study, where onsite biogenic electricity use is substantial, the material production activity comes into focus for pollution prevention. The material production supply chain is responsible for 2.9 GJ of energy production per Ml whereas the energy production activity offsets 0.76 GJ. In fact, energy production offsets all emissions. This result was unexpected because for the previously analyzed water systems energy production consistently dominated material production. The result demonstrates the advantages of capturing methane for electricity use. In contrast, figure 2 shows that the GHG contributions of material and energy production activities are comparable for the hypothetical system.

Chemicals constitute 78% of the material production results, overwhelming the contribution of less-frequently-used materials. The next largest contributor to material production is reinforced concrete used in buildings, basins, and pipes. The 25 year analysis period used may exaggerate the contribution of materials like concrete which may be in service much longer. Twenty-five years is a typical planning time horizon for capital investments for this utility and within the wastewater industry.

For the case study system, material delivery contributes appreciably to GHG, NO\textsubscript{x}, and VOC emissions. Equipment use does not contribute much to any environmental effect in either scenarios.

Direct GHG emissions from the treatment process contribute 11 kg and 34 kg MI\textsuperscript{-1} to the overall GHG results for the case study and the hypothetical systems, respectively. Figure 2 shows the relative contribution of these emissions to the overall results for each scenario. The case study utility’s gas recovery program captures essentially all their methane and prevents these emissions from being a more significant contributor. If methane emissions were not captured, the GHG results for this activity would increase almost 25 times.

Disposal contributes little to the case study results. Land-applied biosolids (78% of the disposed material) typically decompose to CO\textsubscript{2} and are excluded from the results as a biogenic source. The landfill where the remaining biosolids are disposed has a gas recovery system (85% capture rate) that prevents significant GHG emissions. Though still small, disposal GHG emissions are almost seven times higher for the hypothetical system because it is assumed the landfill does not recover methane.

![Figure 2. Greenhouse gas emissions by activity.](image-url)

The operational phase dominates the construction phase for all environmental effects.
their electricity generation, so these results are not typical for most plants.

The indirect effects associated with material production and delivery may be more important for wastewater processes than for water systems. For the utility, chemical delivery is a major contributor to NOx emissions primarily because sodium hypochlorite, a disinfectant used in large volumes, is transported from a manufacturer located 1000 km away. Utilities may be able to reduce their environmental burden by selecting materials with lower supply-chain emissions or delivery distances.

Sludge disposal choices may also allow utilities to control some of their life-cycle environmental effects. Disposal choices may reduce environmental burden because offsets of fuel or electricity consumption or other materials (e.g., fertilizers) can reduce the utility’s overall environmental footprint. For the utility, it was assumed that landfill methane emissions were captured and used for electricity generation but not for the hypothetical system. The utility’s end-of-life choices prevented 6.4 kg of GHG emissions M\(^{-1}\). If the land-applied sludge could be used to replace commercial fertilizer production, the overall GHGs could be reduced by an additional 0.7 kg M\(^{-1}\). However, land application for agricultural use may have impacts on concentrations of metals and other toxics in soil, and has a negative public perception. Sludge reuse as a co-product to replace fertilizers, concrete additives, or other products should be explored and carefully evaluated by utilities wishing to reduce their environmental footprint.

It should be noted that wastewater LCA results are case specific. The results may vary based on process selection, system design, scale, wastewater quality, and other factors. Though the results of this study may inform decisions for other utilities, the actual results, both in magnitude and relative importance, may be different.

6.3. General conclusions

Wastewater design decisions are made based on several factors, including economic, engineering, and political concerns. Heretofore, utilities, designers, and system planners generally have not been able to assess the comprehensive and systemwide life-cycle environmental effects using LCA so it has not been included in decision making. Utilities should be encouraged to take a long-term and life-cycle perspective on energy use and environmental emissions, including indirect emissions associated with the supply chain. When many systems have been analyzed, the industry may develop a comprehensive list of sustainable design solutions for systems of differing parameters (e.g., scale, water quality, process selection).

Fortunately, ground-breaking regulations in California and elsewhere are encouraging utilities to consider long-term environmental burdens in their decisions. However, this research shows that analyzing climate change effects requires a broader vision than the reporting currently required by the legislation. These results quantify energy use and emissions more comprehensively than California’s GHG law, which will require utilities to report the direct emissions from treatment and the smokestack emissions from their electricity and energy providers. This study includes the supply chains.

The GHG emissions which would be reported for the case study and hypothetical utilities, assuming the California state average electricity mix is applicable, would be, respectively, approximately \(-126 \text{ kg and } 230 \text{ kg M}^{-1}\), compared with \(-170 \text{ and } 240 \text{ kg when the life-cycle, rather than just direct energy effects, are included. When the analysis is further broadened to include material production and delivery, equipment use and disposal effects, the overall life-cycle GHG results would be } 55 \text{ kg M}^{-1} \text{ for the case study and 490 kg for the hypothetical utility. The regulatory-required value fails to capture a significant percentage of the overall GHGs for the case study and hypothetical utilities.}

This work expands prior research on the use of energy by water and wastewater systems by identifying the processes that are most energy and pollution intensive in the entire water supply life cycle. Additional research in this area should be encouraged, including analyzing additional wastewater treatment processes. The results of this study can be used to target future research in areas where improvements to the wastewater treatment systems can be made most readily.

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