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Original Paper

Modeling Energy Recovery in (Distributed) Wastewater Treatment Systems

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Abstract

Energy recovery from biogas generated during waste treatment offers an opportunity to leverage a recurring source for public good. Effectively utilizing wastewater helps to achieve sustainable energy goals, addresses emissions challenges, and incentivizes innovative solutions like distributed waste treatment. When implementing energy recovery in distributed systems, there is a need for technological advancements to provide a smooth transition from centralized systems through resolving issues of membrane efficiency and low gas yield from the system on smaller scales. The technology, or otherwise referred to as innovation, needed can be optimally identified through data mining and modeling that seeks to address the challenges of these distributed systems. This article discusses a developing path of innovation within waste treatment and presents preliminary investigations that inform the author's perspective on the need to leverage data in navigating the challenges (US EPA & CHP, 2012) that accompany distributed waste treatment.

Keywords

wastewater, distributed, data, energy, biogas, innovation, challenges

1. Making a Case for Waste as a Sustainable Energy Technology

The term sustainable energy is quickly becoming a synonym for energy sources like solar, wind or hydrogen. Other viable technologies like energy recovery from waste are often not recognized as a potential energy source. Several societies across the globe have policies to be 70-100% renewable by as early as 2030 (IonE, 2019); therefore, it is crucial to leverage sectors beyond transportation and primary electricity production. Waste is ubiquitous, and its responsible treatment offers multiple opportunities from direct use in agriculture to energy recovery for power generation, or for heating. Energy recovery from waste sources, known colloquially as “waste-to-energy”, encompasses a broad array of efforts to use the heating value of organic compounds within a waste stream. Anaerobic wastewater treatment is of increasing interest to researchers as a viable waste-to-energy option and is the focus of this article. The US Department of Energy in 2011 estimated that over 400MW can be generated by the country from processing 100 gallons of wastewater per person per day (US EPA, 2011).

An anaerobic waste treatment system typically includes a reactor that takes in a liquid waste influent, where anaerobic means the treatment processes takes place in the absence of oxygen. Sources of liquid waste include food and beverage companies, sewer systems, and other industrial, agricultural, or commercial activities (Henze et al., 2008). Waste can be broken down by organisms and separated into solid or liquid components through sedimentation that can be aided by chemical treatment (Kuo et al., 2017). Reactor products are passed through a membrane to separate dissolved gases, known as biogas, components of interest, and other by-products in addition to sludge. Biogas contains species like methane and hydrogen that can be readily oxidized in energy conversion devices to generate heat and/or power, known as prime movers. Biogas oxidation does not add to the carbon cycle and can displace fossil fuels.

2. The Transition from Centralized Waste Systems

An average biogas composition from wastewater is 30-40% carbon dioxide, 50-60% methane and in some cases ~5% hydrogen (Kulkarni, 2009; Prieto et al., 2016). Biogas from waste treatment generated from large waste treatment sites are currently refined to obtain higher quality gases that are compressed and transported to end users. Areas for innovation within this system include addressing direct or indirect emissions and improving energy recovery (Shoener et al., 2016). Current research efforts focus on improving membrane efficiency or increasing prime mover efficiency, in waste treatment itself (Shoener et al., 2016). There are aspects of the system to explore when viewing from a life cycle perspective, pre- and post- reactor operations. A source of emissions easily overlooked is transportation from waste source to treatment sites and further to by-product utilization points, reflecting the nature of centralized waste treatment (Kulkarni, 2009). Another consideration is the practice of flaring biogas, a process where greenhouse gases escape as fugitive emissions and energy recovery efforts are absent (Lasode et al., 2021).

Transportation is a major contributor to emissions, and the centralized model for waste treatment has been challenged by distributed systems that bring waste source, treatment and by-product utilization into proximity. In addition, there have been an increasing number of initiatives within the US Department of Energy to encourage use of prime movers for energy recovery in waste treatment (ARPA-E, 2015). These efforts map out individual paths for the future of the waste treatment system that overlap in a change in scale for energy recovery technologies. As straightforward as the idea of a distributed system with energy recovery seems, there are lots of data needed to understand this waste treatment territory- technology capabilities, cost, feasibility, site operations and more.

3. Potential Innovation Path- Distributed Waste Systems

Data mining, simply put, is a process that extracts insights from a collection of data for the purpose of better understanding a problem or making decisions (Fournier-Viger et al., 2019). In developing systems, the data-driven approach to building a knowledge base is grounded in models. The fundamentals needed here can be identified based on information from past waste treatment systems, namely cost and efficiency. These two factors can be broken down further into several quantitative and qualitative components. For example, efficiency regarding prime mover power or heat generation compared to calorific value of fuel input, efficiency of each prime mover based on fuel type, capital cost of treatment system modifications, cost of personnel and adherence to emission regulations. Historic data on cost and efficiency can be obtained from a variety of sources- research publications, industry catalogues and government documents. Aggregating different data sources and data types into models that help in understanding the feasibility and technology needed in distributed waste treatment is essential.

Some key questions that shape the data models needed to understand distributed waste systems are: What are the current commercial technologies used in energy recovery from waste treatment? What are the efficiencies and power generation capacities of these energy technologies? What fuel types are these technologies compatible with and how do biogas components compare? What are the biogas generation capabilities of waste treatment sites- centralized and distributed? The questions provided so far are not exhaustive and corresponding findings form the basis for further enquiries. Case studies are helpful to explore portions of this extensive system, as seen in one on anaerobic waste treatment sites in Minnesota, United States (Lasode et al., 2021).

4. Lessons and Challenges

In analyzing waste systems from Minnesota (Lasode et al., 2021), the authors identify energy recovery technologies that are commercially available to the sites. In addition, a combination of efficiency factors, system size and waste content are used to lay out a decision tree for prime mover selection. The five commercially available and commonly used prime movers presented are steam turbines, gas turbines, microturbines, reciprocating internal combustion engines and solid oxide fuel cells. Figure 1 shows a summary of the technologies matched with wastewater treatment sites based on system size. Large scale systems are defined as waste influent greater than 10 million gallons per day, while distributed is approximated by influent less than 10 thousand gallons per day (US EPA, 2011 & Lasode et al., 2020). As system size decreases, the currently available energy recovery options decrease till fuel cells are left as optimal efficiency-based choice for distributed sites.

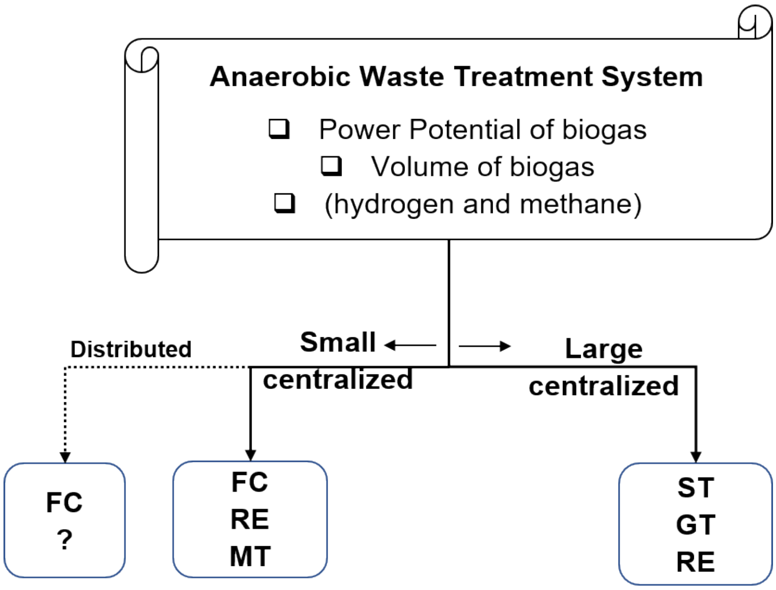

Figure 1. Prime Mover Technology Matched with Waste Treatment System Size. (ST-Steam Turbines, GT-Gas Turbines, RE-Reciprocating Engines, MT-Microturbine, FC-Fuel Cell).

Data Source: Lasode et al., 2021.

The trend observed in Figure 1 is a result of several factors, mainly efficiency of technologies on a distributed size scale. Note that when other factors such as cost and fuel quality, the singular option on the far left becomes non-existent. These bring attention to the need for understanding what drives the streamlining of these energy recovery technologies, focusing on biogas output from the waste treatment system. The amount of biogas generated from a treatment system impacts the potential energy that can be recovered by prime movers, and is variable based on waste content. Keeping waste content constant, one of the major challenges that surfaces is the scaled down biogas output when transitioning from a centralized to distributed treatment model. While a single centralized treatment site can generate power on the megawatt scale, distributed systems on average generate hundreds of kilowatts.

Benefits of energy recovery in waste treatment systems are realized when heat and power generated are used in internal treatment processes or transmitted for external use. Given the scale of distributed waste treatment systems, higher value can be placed on reuse of recovered energy in internal processes that are typically energy sinks. Up to 80% of total energy expended in waste treatment goes into pumping, mixing and heating for anaerobic digesters, sludge management and general site space conditioning. Meeting some of the energy demand through recovered energy could reduce load on main power grids or additional generators.

5. Addressing Technology & Innovation Challenges

Upon surveying data regarding use of energy recovery technologies in waste treatment, there is a need to navigate the complexity of factors influencing prime mover selection. The variability of waste content and treatment system size, in addition to prime mover power output, efficiency and sensitivity to fuel impurities present a daunting challenge. A data model that aids the advancement of renewable energy efforts in waste treatment is one that simplifies decision making. One way to do this is by decoupling individual factors in a way that recommendations incorporate unique size and content characteristics of a waste treatment system (Lasode et al., 2021).

Individual decision factors can be understood by mining past trends in prime movers used in waste treatment. Figure 2 shows information on recent work exploring data in a digital library. The order-of-magnitude change in data processed at each stage of this research exploration illustrates effort incurred to obtain relevant data. The goal was to extract efficiency, cost and fuel utilization of six prime mover technologies reported in books, research articles and government documents published from 1900-2020. Similar decoupling exercises could provide insight into specific innovation needed to implement distributed waste treatment systems- opportunities to prepare for the future.

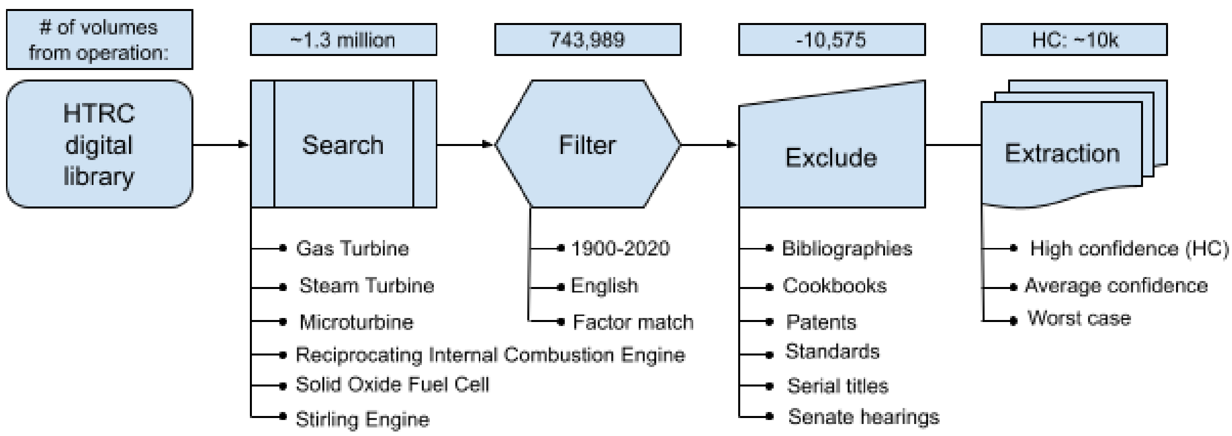

Figure 2. Data Mining Sequence from HathiTrust Digital Library. (A Volume Refers to a Book, Article, or Document in the Library).

Source: Lasode, 2020.

6. What Next?

Leveraging waste treatment in sustainable energy efforts is dependent on implementing energy technologies on relevant size scales. A data-driven approach plays an essential role to understanding innovation gaps in establishing distributed waste treatment with energy recovery components. A key outcome is understanding current commercial prime mover capabilities and identifying technologies that operate in distributed system sizes. These models will offer ease of implementation by providing insight on efficiency, capital and operation costs, emission regulations and other choice factors. Hence, ramping up energy recovery in waste treatment and enabling society to be a step closer to achieving its energy goals.

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