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Retrofitting Municipal Wastewater and Sludge Treatment Facility toward a Greener and Circular Economy

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The conventional wastewater treatment facilities (WWTFs) are designed with the prime directive of simply purifying sewage by solids, pathogens, and nutrients removal. However, this ill-considered design philosophy stands chance to render the WWTFs unfavorably energy intensive and wasteful of nutrients. A promising route to raise the energy and nutrients utilization efficiencies of WWTFs is to retrofit the existing systems with smart upgrades for resource recovery. In this article, promising retrofits based on the benchmark design of WWTFs are proposed by virtue of process modifications and biosolids upcycling. This study directly assesses the economics and life cycle environmental impacts of the proposed retrofits of WWTFs, which are in turn compared to the reference design. Emerging thermochemical technologies and more complicated bioreactors are considered to maximize the biogas production, nutrient recovery, and biosolids upcycling. The results show the retrofit with hydrothermal liquefaction and secondary anaerobic digester demonstrates the highest net present value of − $ 97.93 MM, despite the highest annual production costs. The life cycle assessment results identify chlorination as the major contributor for most impact categories.

1. Introduction

Domestic wastewater is currently more regarded as a resource for water, energy, and nutrients, rather than a waste (McCarty et al., 2011). However, conventional practice of wastewater treatment integrated with anaerobic digesters is energy intensive and wasteful of nutrients (Garcia et al., 2017). On the one hand, wastewater treatment facilities bring about up to 41 % of the total U.S. electric power consumption in 2017 (Gu et al., 2017), while wastewater itself embodies decuple amount of usable energy (McCarty et al., 2011) than required during the treatment (Shen et al., 2015). On the other hand, more than 90 % of the plant fertilizing elements, namely nitrogen and phosphorus retain in the residual biosolids produced at wastewater treatment facilities (WWTFs) (Werle and Wilk, 2012), which are unfavorably untapped and end up with landfill (Garcia et al. 2019). These waste biomass resources, if properly recovered, would offset energy use and significantly reduce the environmental impacts induced by wastewater treatment (Yue et al., 2014). There are many promising options for energy and nutrient recovery from waste biomass (Nicoletti et al., 2019). As for energy recovery, more complex bioreactor such as up-flow anaerobic sludge blanket (UASB) reactor and anaerobic membrane bioreactor (AnMBR) (Cashman and Mosely, 2016) can enhance biogas production (Zhao and You, 2019). Struvite precipitation could facilitate the phosphorous recovery (Garrido-Baserba et al., 2018) and more nitrogen could be removed by using anaerobic ammonia oxidation (Anammox) (Fernández-Arévalo et al., 2017). Biosolids from anaerobic digester are usually not completely converted. Thermochemical technologies including hydrothermal liquefaction (HTL) (Snowden-Swan et al., 2016), slow pyrolysis (Kim and Parker, 2008), fast pyrolysis (Gebreslassie et al. 2013), and gasification (Wang et al. 2013), can be used to convert the residual organic wastes into extra fuels and valuable co-products for land application (Bora et al. 2020), such as biochar and hydrochar (Siti et al., 2018). Recent publications have illustrated the applicability of HTL in dairy sector (Kassem et al., 2020) and sewer sludge conversion (Marrone et al, 2018); slow pyrolysis (Baniasadi et al., 2016) and fast pyrolysis (Agblevor et al., 2010) in poultry litter valorization (Zhao et al., 2020).

In this work, an innovative processing network that integrates the upstream wastewater treatment and downstream sewage sludge treatment for the retrieval of usable energy and nutrient products is first proposed.

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To redesign the currently practiced WWTFs into net energy producers and retrieve plant fertilizing nutrients, two categories of upgrading strategies and operations modifications for WWTFs are proposed. These categories include process modifications and optimal use of nutrient-rich residual biosolids instead of landfill. Several representative process designs are meticulously selected from the broad range of feasible alternatives and perform comprehensive techno-economic analyses and life cycle assessment (LCA) to quantify the corresponding economic feasibility and environmental implications (Gong and You, 2015). The comparative analysis results of the upgraded configurations are in turn compared to the current practice of WWTFs to critically evaluate the upgrading strategies and gain insights with respect to the future development. The novelties of this work include (1) a novel processing network integrating the sewage treatment with sludge treatment in a decentralized manner; (2) a novel perspective for technology selection, including advanced bioreactors and thermochemical processes, to enhance energy and nutrient recovery from wastewater.

2. Process description

In this section, the proposed processing network that integrates the sewage treatment with sludge treatment is introduced in detail. First, the benchmark design of WWTFs that is widely practiced in the U.S. is presented, which is also referred to as the reference design. Second, feasible retrofitting configurations derived from the reference design are proposed and the respective upgrades are highlighted in Figure 1.

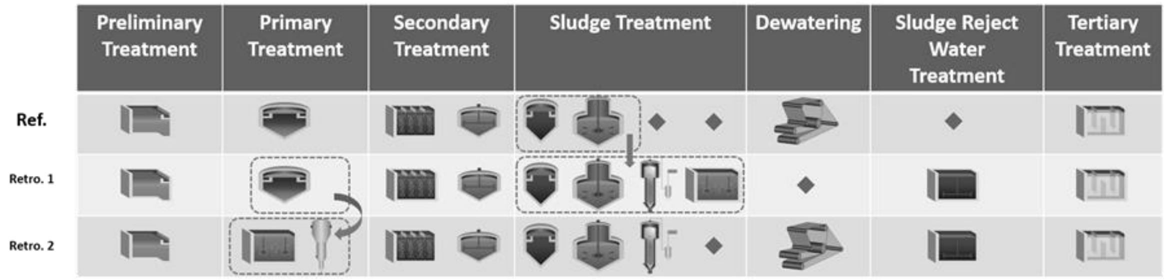

Figure 1: Overview of the reference design and investigated retrofits of WWTFs

The retrofitting technologies are selected toward the goal of maximizing the biogas generation, nutrient recovery, and biosolids upcycling. The arrows represent the process modifications and the diamonds indicate certain technology is not employed in the corresponding row (or configuration) but is utilized in other rows (or configurations). The wastewater treatment process consists of seven major sections, namely the preliminary treatment, primary treatment, secondary treatment, sludge treatment, dewatering, sludge reject water treatment, and tertiary treatment. Detailed process description for each design is given in the following subsections.

2.1 Reference design

In this study, the investigated municipal WWTF is located in Ithaca, New York State. With a designed capacity of 13.1 million gallon per day (MGD). Rigorously speaking, the Ithaca Area WWTF (IAWWTF) does not comply with the reference design because progressive combined heat and power (CHP) system has already been in service for years. To this end, the CHP system is excluded from the system boundary.

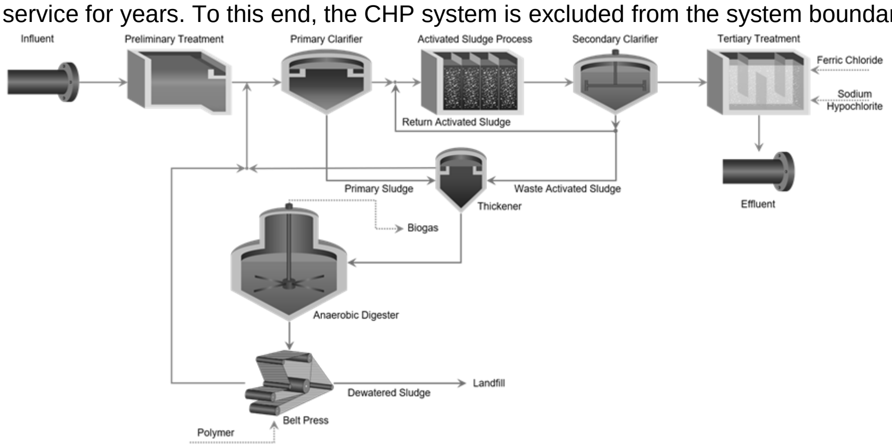

Figure 2: Schematic of the reference design of WWTFs.

As shown in Figure 2, the influent wastewater is first introduced into a preliminary treatment unit with screens where large solids are removed. The subsequent primary clarifier is where most of the solids are removed due to the difference of density. The clarified primary wastewater is then fed to aerobic microorganisms under constant aeration in the activated sludge process, where organics are assimilated by the agglomerate microorganisms in the aeration tanks. The resulting clumps of microbes are further removed via the secondary settling tanks. A fraction of activated sludge that settles in the secondary clarifier is pumped back to the aeration tanks to keep a constant, healthy ratio of organisms to their "food". In the following tertiary treatment, chemicals are added for the optimal removal of phosphorus and disinfection before discharge to the Cayuga Lake. A thickener is used to remove the excessive water carried by the waste sludge, including the primary sludge and waste activated sludge. The thickened sludge is then pumped into the anaerobic digester total biomass is drastically reduced for stabilization. Finally, the digestate is dewatered via a belt press, with sludge reject water pumped back to the primary settling tanks and dried cake transported for further disposal, such as landfill.

2.2 Retrofitting design with HTL

Compared to the reference design, HTL, an emerging thermochemical treatment option for wet biomass, is introduced to treat the digestate and further exploit the embodied organic carbon, as shown in Figure 3.

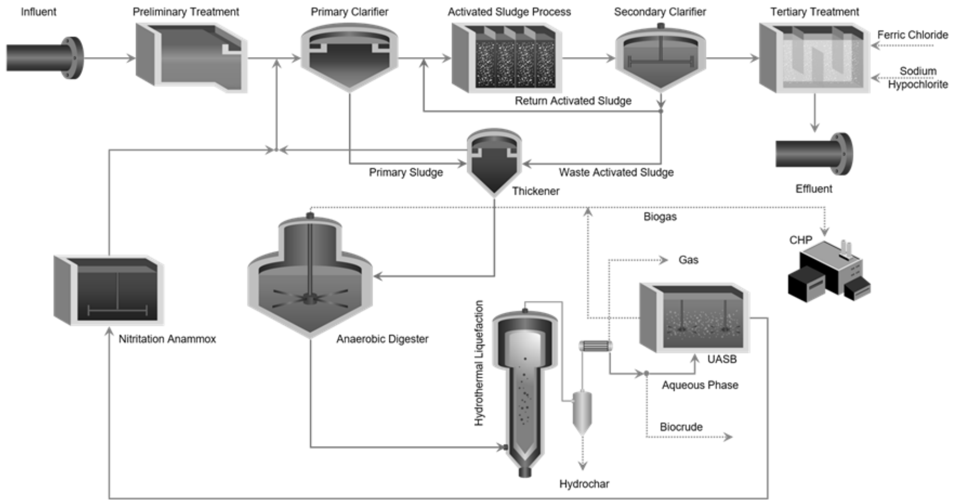

Figure 3: Schematic of the retrofitting design of WWTFs considering hydrothermal liquefaction, secondary upflow anaerobic sludge blanket reactor, and combined heat and power

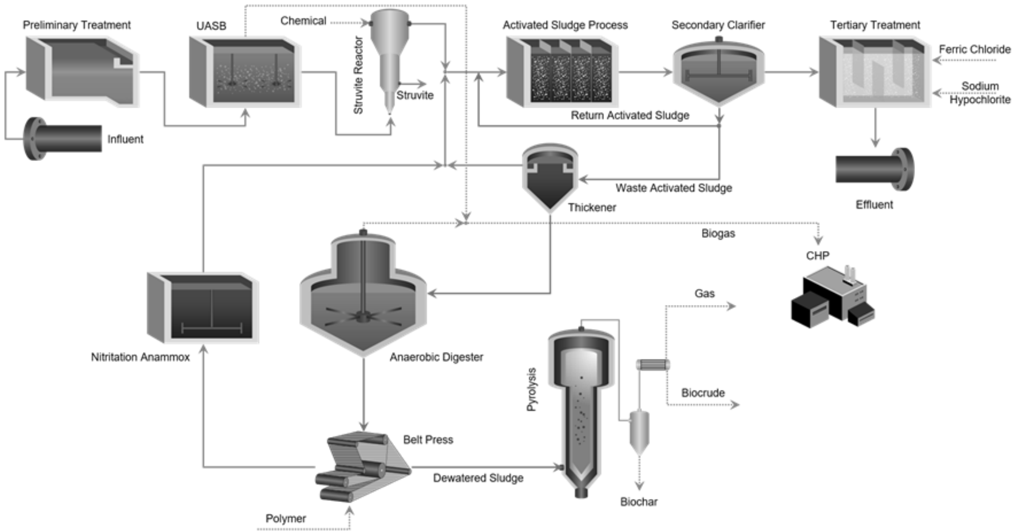

Figure 4: Schematic of the retrofitting design of WWTFs considering slow and/or fast pyrolysis, primary upflow anaerobic sludge blanket reactor, and combined heat and power

Biocrude oil, hydrochar and a nutrient-rich aqueous phase are generated. The resulting biocrude oil could be sold to adjacent refinery for upgrading, hydrochar is gauged with the potential to be used as soil amendment, and the aqueous phase is fed to an UASB reactor to maximize energy recovery in the form of biogas. The belt press can be eliminated for energy saving because wet feedstocks are compatible with hydrothermal process. An Anammox reactor is adopted to remove nitrogen within the effluent from the secondary anaerobic digester with low energy input and small sludge output. A CHP unit is employed for on-site biogas combustion to drive the plant-wide reactor and physical processes with heat and electric power.

2.3 Retrofitting design with pyrolysis

As shown in Figure 4, a cascaded UASB reactor with struvite reactor replace the primary clarifier in the designs introduced above in this retrofit. The dried biosolids are pyrolyzed in an inert atmosphere and converted to biocrude oil, biochar, and pyrolysis gas (Foglia et al., 2019). The resulting biogas is burnt in the CHP unit to offset a fraction of electricity and heat demand. Before entering the pyrolysis reactor, the feedstock is sufficiently dried and belt press is used to dewater the digestate from anaerobic digester to reduce the energy consumption.

3. Results and discussions

3.1 Mass and energy balances

A commercially available modeling software, CapdetWorks V4.0, is used to model the reference design and proposed retrofits. Some of the technologies, including the HTL, pyrolysis, and Anammox are not available and data reported in the up-to-date literature are used instead. The mass and energy balances is determined based on both the CapdetWorks simulation results and best available literature data, which cannot be presented in detail due to the length limit of this paper.

3.2 Economic analysis

Table 1: Breakdown of annual production cost for the reference design and proposed retrofits

		Reference design	Retrofit with HTL	Retrofit with slow pyrolysis	Retrofit with fast pyrolysis
Annual Production Cost (MM$/y)	Raw materials	1.43	1.23	1.59	1.59
	Utilities	0.67	0.74	0.54	0.54
	Operations (O)	1.78	1.65	2.05	2.05
	Maintenance (M)	5.33	7.17	5.06	5.22
	Operating overhead	0.98	1.18	1.00	1.02
	Property taxes and insurance	1.03	1.39	0.98	1.01
	Depreciation	1.29	1.73	1.22	1.26
	General expenses	0.04	0.10	0.01	0.03
	Total	12.54	15.19	12.47	12.73
NPV (MM$)		(113.71)	(97.93)	(111.26)	(113.26)

The total annual production cost is estimated by summing up the direct manufacturing costs, operating overhead, fixed costs, and general expense. Detailed breakdown of annual production cost for the reference design and proposed retrofits are given in Table 1.

Net present value (NPV) is also computed to measure the profitability of each design in terms of discounted cash flows. The results show that all the investigated pathways have negative NPVs, indicating none of the proposed retrofits is profitable in current terms, though the three retrofits do improve in terms of NPV. Among the proposed retrofits, the one considering HTL and secondary UASB reactor demonstrates the highest NPV of –$ 97.93 MM, despite its highest production costs. We also analyze the bare-module investment of the retrofit considering HTL with the highest capital investment among the four investigated designs. Aeration process (24 %), anaerobic digester (16 %), and HTL (15 %) are identified as the major contributors. High capital cost of the aeration process and large-scale thermochemical technologies may elucidate the reason of the poor economic performance. Another reason lies in the underestimation of the value of biochar and hydrochar as a promising substitute of conventional soil amendment. The profitability of the proposed retrofits would also benefit from the government incentives and encouraging biogas price.

3.3 Life cycle assessment

The objective of this LCA is to compare the life cycle environmental impacts of wastewater treatment via different WWTF configurations. The functional unit is defined as one million gallon of wastewater treated. Midpoint impact categories including the global warming potential, cumulative energy demand, and ReCiPe midpoint indicators are selected. A "cradle-to-gate" system boundary is considered in this study, as the use and end-of-life phases of the biocrude and biochar could vary significantly. The midpoint environmental impacts breakdown for the reference design and proposed retrofits are presented in Figure 5.

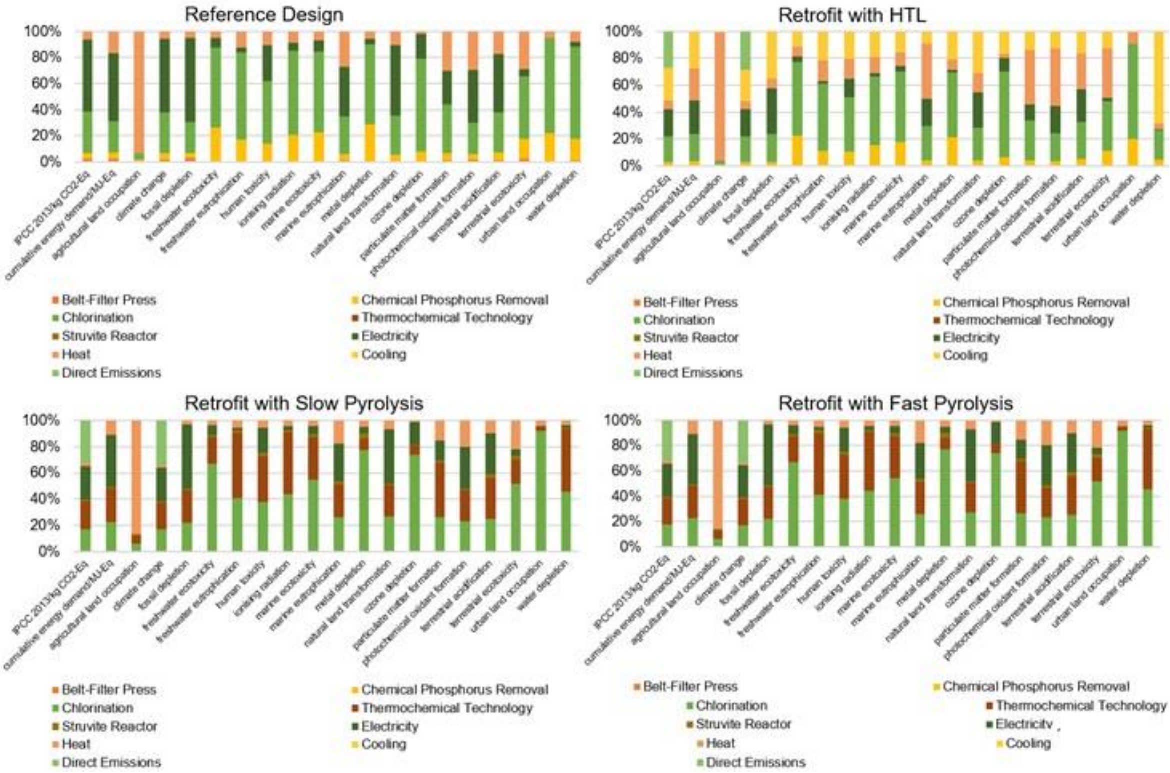

Figure 5: Midpoint environmental impact score breakdowns for the reference design and proposed retrofits

For all the four designs, the chlorination can be intuitively identified as the most influential one due to the use of large amount of sodium hypochlorite for disinfection. For the two designs with pyrolysis, the contribution of thermochemical process is more pronounced.

4. Conclusions

Novel WWTF retrofits were proposed based on the benchmark design toward a greener and circular economy. Systematic techno-economic analyses and LCA were performed to investigate the economics and environmental implications of the reference design and proposed retrofits. The results showed that in current terms, the investigated design stood little chance to be profitable. Possible reasons might be the high capital cost of aeration process and thermochemical processes. The design considering HTL and secondary UASB reactor demonstrated the highest NPV of –$ 97.93 MM, despite its highest production costs. A "cradle-to-gate" LCA was performed that excluded the use and end-of-life phases of the biocrude and biochar. The results showed that chlorination was identified as the major contributor for most impact categories for all the four investigated designs.

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