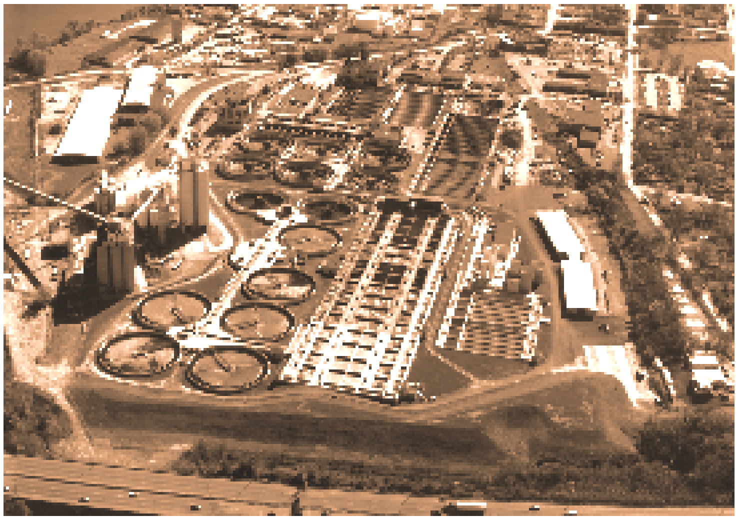
Energy Management in Wastewater Treatment Systems: Biogas Energy Recovery Management Application



Luke Hellgren
lukehellgren@berkeley.edu
Olga Kavvada
okavvada@berkeley.edu
Cody Phelps
crphelps@berkeley.edu

CEE 295
Energy Systems and Control
May 8, 2015

Abstract

Anaerobic digestion is an established technology for the treatment of wastewater. This process utilizes bacteria to break down organics in wastewater under oxygen-free conditions, which naturally creates biogas as a byproduct. Primarily a mixture of methane and carbon dioxide, biogas is a valuable resource that can potentially be used for electricity generation. By capturing and recovering this typically flared waste stream, some of the grid electricity demand of the wastewater treatment plant can be offset through a combined cycle natural gas electricity generation technology. Because biogas generation does not always match the energy demand of a wastewater treatment plant, electricity consumption must be optimized with respect to energy source (biogas and grid) in order to minimize cost. This report plans to model the energy potential of a wastewater treatment plant and optimally manage the energy resources to minimize the variable electricity costs. Environmental pressures on low carbon policies and sustainable energy sources enhance the potential for biogas reuse at the wastewater treatment facilities, especially if the economics are favorable. Our results showcase that optimal biogas energy management can significantly reduce costs, with up to a 90+% reduction in electricity charges.

Introduction

Motivation and Background

The goal of this study is to optimize the energy management of a wastewater treatment plant in order to minimize electricity costs. In the US, wastewater treatment processes are responsible for 0.1-0.3% of the total energy consumption but looking into a local scale these operations are often a substantial energy consumer [1]. Additionally, the energy demand for future wastewater treatment is expected to substantially increase due to a growing global population, outdated infrastructure, and the perceived trajectory towards stricter wastewater treatment regulations. Wastewater treatment plants that utilize anaerobic digestion to treat the wastewater have the benefit of producing methane as a byproduct of the treatment process. Anaerobic digestion is an established technology for wastewater treatment that produces biogas which consists of 55-75% of methane and 25-45% carbon dioxide [2]. Methane produced by the treatment process can be utilized on site to offset some of the electricity consumption for the operation of the wastewater sector in order to reduce energy costs and greenhouse gas (GHG) emissions. Hence, wastewater treatment plants should be recognized as a valuable resource instead of an energy consumer [3]. Organics, nitrogen and phosphorus present in the wastewater can be utilized to produce energy and raw materials.

Literature Review

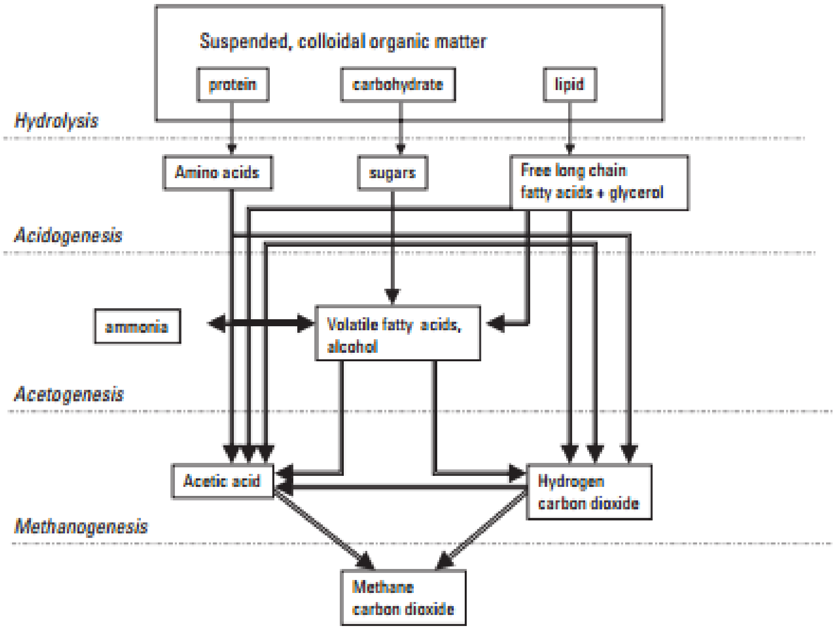


Figure 1: Simplified schematic representation of anaerobic digestion process [2]

The Chemical Oxygen Demand (COD) is used to quantify the amount of organic matter in waste streams and predict the potential for biogas production in wastewater treatment plants according to the Buswell equation [2]:

$$C_nH_aO_bN_d + (n-a/4 - b/2 +3d/4)\ H_2O \rightarrow (n/2 +a/8 -b/4 -3d/8)CH_4 + (n/2-a/8+b/4+3d/8)\ CO_2+dNH_3 \tag{1}$$

The COD can alternatively be used to determine methane generated through anaerobic decomposition of organic content with the following equation [4]:

$$CH_4 = \sum(Q*COD*Bo*MCF) \tag{2}$$

where,

CH_4 = CH_4 emissions from domestic wastewater treatment (kg/year)
Q = Flow through anaerobic treatment system (m^3/month)
COD = Average monthly organics loading in anaerobic reactor influent (kg/m^3)
Bo = Maximum CH_4 production potential of domestic wastewater (~0.25 kg CH4 /kg COD)
MCF = CH_4 correction factor (BOD, extent to which organic content can degrade anaerobically)

According to the Electric Power Research Institute (EPRI) and Environmental Protection Agency (EPA), direct combustion of biogas produced via anaerobic digestion can produce between 350-617 kWh per million gallons of treated wastewater [5][6]. In addition, Stillwell et al. states the widespread implementation of anaerobic digestion with biogas recovery at wastewater treatment plants in the United States may result in 628 to 4,940 million kWh of electrical energy per year [1].

The potential electrical energy recovery from biogas combustion can be given by the following simple formula [1]:

$$ER_{anaerobic} = Q * BEF \tag{3}$$

w,here $ER_{anaerobic}$ symbolizes the electrical energy recovered from anaerobic digestion + biogas combustion in units of kWh per unit time, Q is the wastewater flow rate in a user specified resolution of million gallons per unit time, and BEF stands for the biogas energy factor and accounts for overall system efficiency, as well as average yield of biosolids per volume of wastewater in units of kWh per million gallons. Research also indicates that wastewater treatment plants that possess treatment capacities that are less than 5 million gallons per day (mgd) (18,900 m^3/d) do not generate enough biogas to make energy recovery a feasible cost-effective option [1].

Please note that although not ideal in academia, the utilization of mixed U.S. customary and S.I. units are consistent with wastewater industry standards.

Zhou et al., 2014 performed a comprehensive study developing a control strategy to optimize energy flows in a household system with real-time updates of electricity prices [7]. Tischer and Verbic computed an energy management system of a smart home using dynamic programming for the optimization of energy flows [8]. This work plans to utilize tools and methods for energy management optimization used for various applications and apply them to the energy management of a wastewater treatment plant as there are a lot of similarities between those systems.

Focus

Currently, most wastewater treatment plants run 100% on grid electricity and the ones that do produce biogas from their anaerobic process, flare it on site without recovering the energy. Ideally, wastewater treatment plants should aim to utilize their produced biogas to offset 100% of their electricity consumption. However, energy demands do not always match the energy generation as the amount of biogas produced is a factor of the wastewater flow quality and quantity. Stored on-site biogas can help to decouple this mismatch between energy generation and demand as it can be utilized as a supplementary form of energy to the grid. Due to the time-varying cost of electricity, a control system approach can optimize the amounts of energy used from the grid and on-site biogas to minimize the electricity costs of the system. This report will use linear systems optimization to minimize grid electricity costs on an hour by hour basis by satisfying some of the energy demand with on-site utilization of the biogas produced. We will also look into the sensitivity of the parameters of the system and try to quantify their effect on the output electricity cost. We aim to control the sources of energy in the system to determine an optimal operation management scheme.

Technical Description

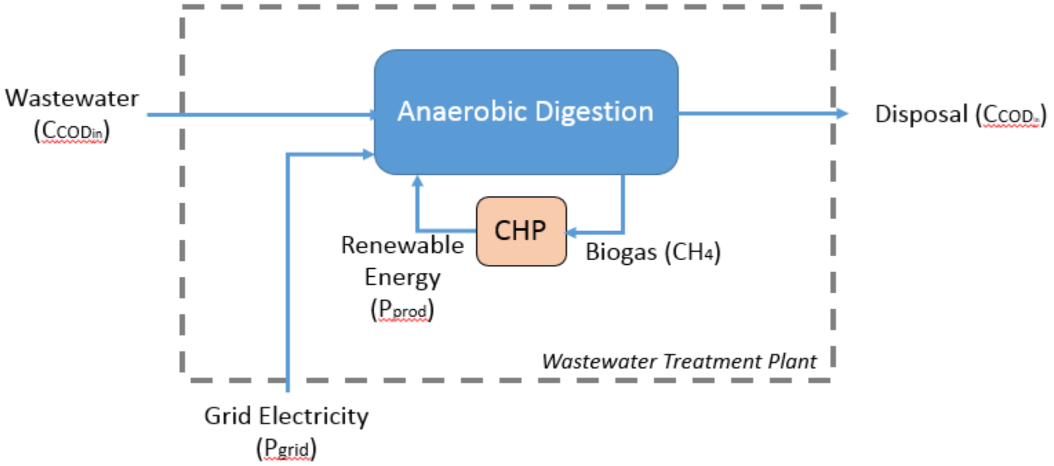


Figure 2. Problem Formulation

Global Assumptions

- Wastewater Treatment Plant is located within the East Bay region and is serviced by Pacific Gas & Electric Company
- Bay Area per capita gross water use: 0.333 m^3/day [11]
- Bay Area per capita residential water use: 0.185 m^3/day [11]
- Biogas composition: 60-65% methane, 30-35% CO_2 [12]
- Methane heating value: 36.5 MJ/m^3 [12]
- Biogas heating value: 25 MJ/m^3 [12]
- Methane production potential: 0.25 m^3 CH_4/kg COD [13]
- Typical anaerobic digester COD composition: 0.4 kg COD/m3 anaerobic sludge [14]
- Typical anaerobic digester COD removal rate: 80% [15]
- Overall thermal efficiency of natural gas IC: 45% [16]
- Minimum MWWTP capacity for economically feasible biogas recovery: 18,900 m^3/day
- Anaerobic digester flow rate: 7,100 m3/day [14]
- Corresponding upper-limit (maximum) parameter calculations:
  - 570 m^3 recoverable CH_4/day
  - 9,750 MJ/day → ~113 kW capacity
  - Hydraulic retention time: 13 hrs
  - Anaerobic tank volume: 3,850 m3
  - Biogas recovery tank volume: 200 m3

Although a wastewater treatment plant with the minimum capacity necessary for feasible biogas recovery was used in this study, flow rates and sludge compositions can easily be adjusted. Plant parameters and specifications were calculated using the Albert Lea Wastewater Treatment Plant, a conventional wastewater treatment plant with biogas recovery located in Minnesota. Approximately 37.5% of a plant's capacity flows through the anaerobic digester as sludge [14]. Despite a constant flow rate through the plant and digesters (rate is normalized by an equalization tank), COD concentration tends to have an inverse relationship with the flow rate of wastewater *into* a treatment plant. Because the COD concentrations of wastewater and sludge vary relatively significantly, our baseline models and subsequent sensitivity analyses account for COD fluctuations [17]. The power generation of the calculated biogas generation agrees with both energy and biogas recovery equations given in the Literature Review.

COD Variability

Because we are focusing on a hypothetical wastewater treatment plant that is located in the East Bay, the irregularity in the amount of wastewater entering the plant is largely determined by residential water use. Although the plant's equalization basin normalizes flow into subsequent treatment steps, low wastewater flow rates entering the plant often correspond with higher BOD and COD levels. As the flow rate of wastewater increases, dilution tends to decrease the BOD/COD content [17]. To determine how wastewater entering the treatment plant fluctuates, the following graph was used:

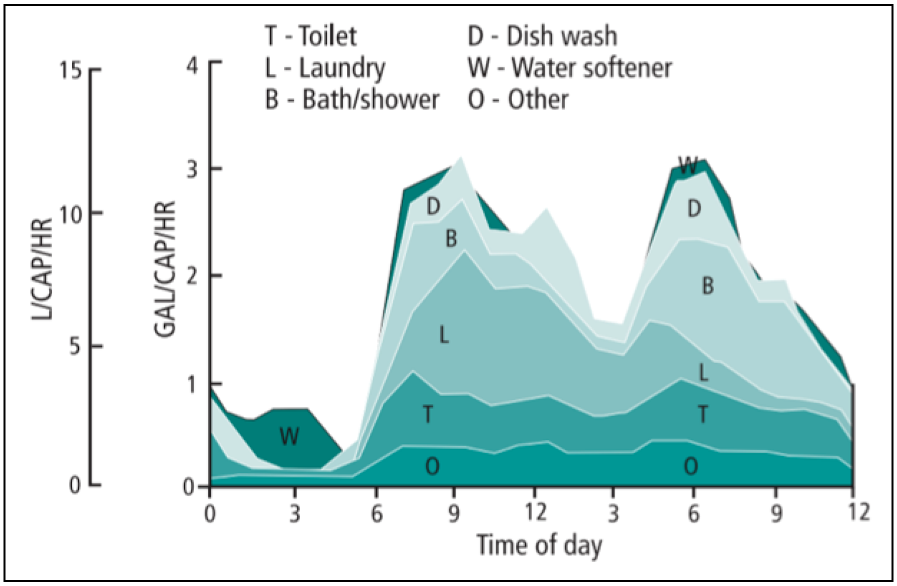


Figure 3. Residential wastewater flow rate [17]

Although the typical COD content of anaerobic sludge is approximately 0.4 kg COD/m^3 sludge, figure 3 was utilized to assess how the incoming COD concentration also changes. For sake of variability, we assumed a relatively inversely proportional relationship between residential water use and COD content entering the plant; in reality, COD content is not as significantly affected by changes in water use [17]. The flux of COD levels throughout the day was then determined (rather arbitrarily):

Time	**Residential water use**	**COD mass flow**	**Corresponding COD content (kg/m3)**
0:00-6:00	low	high	0.6
6:00-10:00	high	low	0.2
10:00-16:00	medium	medium	0.4
16:00-20:00	high	low	0.2
20:00-22:00	medium	medium	0.4
22:00-24:00	low-medium	medium-high	0.5

Table 1. Water use and COD fluctuation

Because the flow rate of sludge into the anaerobic digester is constant, these COD concentrations were applied to calculate the mass of COD removed in the digester each hour. The update equations were then used to evaluate the mass of methane generated at each one-hour time step.

Biogas generation model

We aim to develop a simplified energy-balance model that estimates the amount of biogas generated for different COD levels and flows. The modeling process is based on the reactor dynamics with a mass balance equation. The idea behind the modeling process is that wastewater with some COD concentration level enters an anaerobic digester and by this process methane gas is created as a by-product. There are two mass balance equations we have to take into consideration. The mass balance of COD and the mass balance of CH_4 (equations 4 & 5 respectively). A constraint in this modeling process is that the COD concentration that comes out of the treatment plant must reach the standard for disposal (equation 6). Methane produced is captured and entered in a Combined Heat and Power (CHP) plant to create electricity that is used on-site to offset the grid electricity use.

$$\text{COD:} \quad \dot{m}_{COD} = \frac{Q}{V} m_{COD}^{in} - m_{COD}\left(\frac{Q}{V} + k_{COD}\right) \tag{4}$$

CH$_4$: $$\dot{m}_{CH4} = k_{COD} \times m_{COD} - u \quad (5)$$

$$\text{Constraint: } C_{COD} \leq C_{COD}^{req} \quad (6)$$

where, m_x is the mass of the compound of interest, Q in the water flow, V is the reactor volume, k$_{COD}$ [10] is the reaction coefficient of the anaerobic technology, m_{COD}^{in} in the initial mass of COD in the wastewater and u is the mass of methane used to produce energy.

The capacity level variable (kg), is the biogas stored in the storage tank which is limited by the tank dimensions and density of biogas:

$$0 \leq m_{CH4}(k) \leq m_{CH4}^{max} \quad (7)$$

$$m_{CH4}^{max} = \rho_{CH4} * V_{tank} \quad (8)$$

where, ρ_{CH4} is the density of methane and V_{tank} is th volume of the storage tank.

The renewable energy produced by this anaerobic treatment process is given by equation 9.

Outputs: $$P_{prod} = u * \alpha \quad (9)$$

where, P_{prod} is the produced energy from the combined heat and power (CHP) unit using biogas and α is the corresponding conversion factor of 2.8 [9].

Energy Price Data

It is assumed that the wastewater treatment plant is equipped with on-site transformers, as is customary for most plants and also a necessity for on-site energy recovery utilization, and is therefore serviced by the utility at transmission voltage. The San Francisco Bay Area's electricity provider, Pacific Gas & Electric Company's [17] offers electricity service to industrial sources via their E-20 tariff, which was last updated on March 1, 2015 (Table 2).

Season	Time Period	Demand Charges ($/kW)	Energy Charges ($/kWh)
Summer [a]	Max-Peak [c]	$16.74	$0.10
	Part-Peak [d]	$3.63	$0.08
	Off-Peak [e]	-	$0.06
	Maximum	$6.08	-

Winter [b]	Part-Peak [f]	-	\$0.08
	Off-Peak [g]	-	\$0.07
	Maximum	\$6.08	-

Table 2: Current PG&E E-20T Electricity Schedule (Transmission Voltage Service) [18]

[a] *summer period is from May 1 through October 31*

[b] *winter period is from November 1 through April 30*

[c] *summer max-peak is from 12:00-18:00 M-F*

[d] *summer part-peak is from 8:30-12:00 & 18:00-21:30 M-F*

[e] *summer off-peak is from 21:30-8:30 M-F & all day weekends/holidays*

[f] *winter part-peak is from 8:30-21:30 M-F*

[g] *winter off-peak is from 21:30-8:30 M-F & all day weekends/holidays*

For this analysis, operations were assumed to occur on a summer weekday and demand charges were left outside the scope of the analysis. Therefore, the electricity pricing elements used in our management simulation were summer max-peak, summer part-peak, and summer off-peak energy charges in units of \$/kWh. A decision increment interval of 1 hour was chosen for this analysis, starting at 12:00 AM and spanning over a 24 hour period. As is customary with almost all electricity pricing schemes, costs are higher during middle-of-the-day peak hours and lower during middle-of-the-night off-peak hours. A graphical representation of the pricing scheme is given below in figure 4a.

Optimal Energy Management

For our analysis we wanted to develop a model to simulate the energy use in a wastewater treatment plant. Assuming that the input COD levels and the flow are accurately measured, then our model calculates the biogas produced (P_{prod}). We also assume that the energy demand in the power plant is directly calculated based on the heating requirements which is a factor of the flow rate and the temperature of the anaerobic digester (P_{dem}) given in equation 10 [9]. Given these inputs an energy balance optimization model can describe the energy flows in the system at each time step. The only variable that needs to be determined is the grid energy input which will be used to augment the power demand (P_{grid}). The optimization process will determine the amount of grid energy needed at each time step to balance the demand in order to minimize the electricity costs. Since the objective function and the energy balance are linearly connected to the decision variable P_{grid}, we can design a linear program to minimize the economic cost on a per hour basis in the wastewater treatment plant.

$$P_{dem}= Q*\rho*Cp*(T_{SETPOINT}-T_{in}) \tag{10}$$

where, Q is the flow rate, ρ is the density of water, Cp is the specific heat capacity of water, $T_{SETPOINT}$ is the operational temperature of the anaerobic digester and T_{in} is the temperature of the wastewater. For the conditions described in this report P_{dem} was calculated and assumed to be constant in time.

Objective function	$\min[c(t) * P_{grid}(t)]$, t=0,..,n
Energy balance equation	$P_{dem}(t)=P_{prod}(t)+P_{grid}(t)$, t=0,..,n
Constraints	$0 \leq m_{CH4}(t) \leq \max m_{CH4}(t)$, t=0,..,n $0 \leq m_{COD4}(t) \leq \max m_{COD}(t)$, t=0,..,n $0 \leq u(t)$, t=0,..,n $m_{CH4}(0) = m_{CH4}(\text{initial})$ $m_{COD}(0) = m_{COD}(\text{initial})$
Update equations	$m_{COD}(t+1) = m_{COD}(t) + \Delta t \times [\frac{Q}{V} m^{in}_{COD} - m_{COD}(t)\left(\frac{Q}{V} + k_{COD}\right)]$ $m_{CH4}(t+1) = m_{CH4}(t) + \Delta t \times (k_{COD} \times m_{COD}(t) - u(t))$ where, $\Delta t = 1\ hour$

Table 3: Optimization formulation

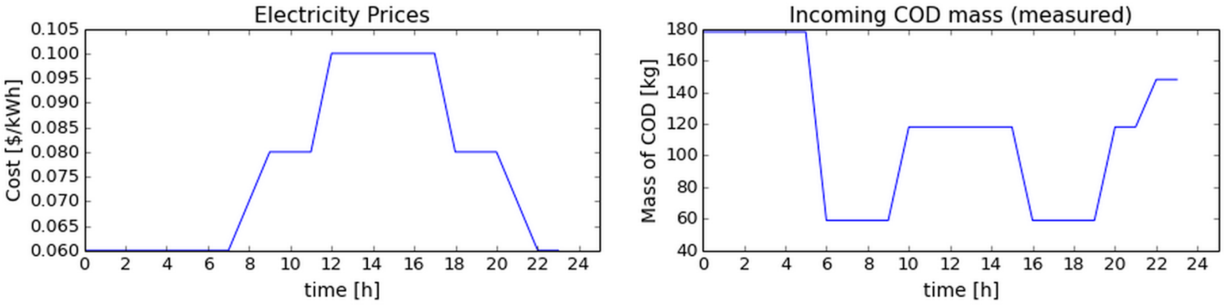


Figure 4: (a) Electricity cost data and (b) Measured COD inflow

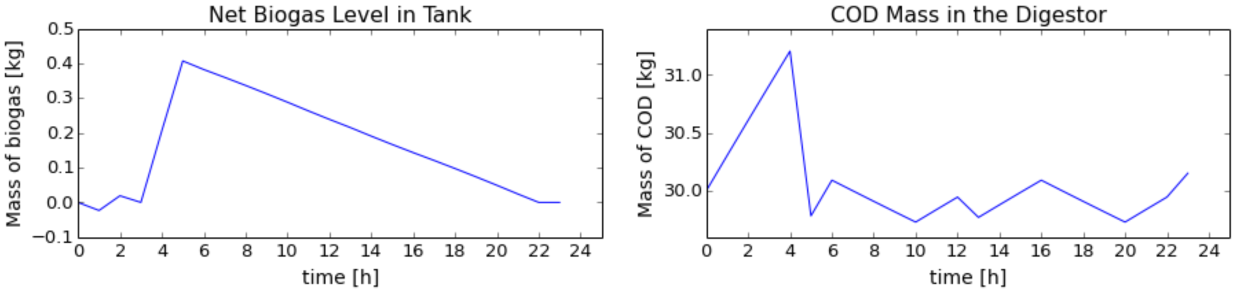


Figure 5: (a) Cumulative amount of biogas n the storage tank at the treatment facility and (b) Outflow of COD

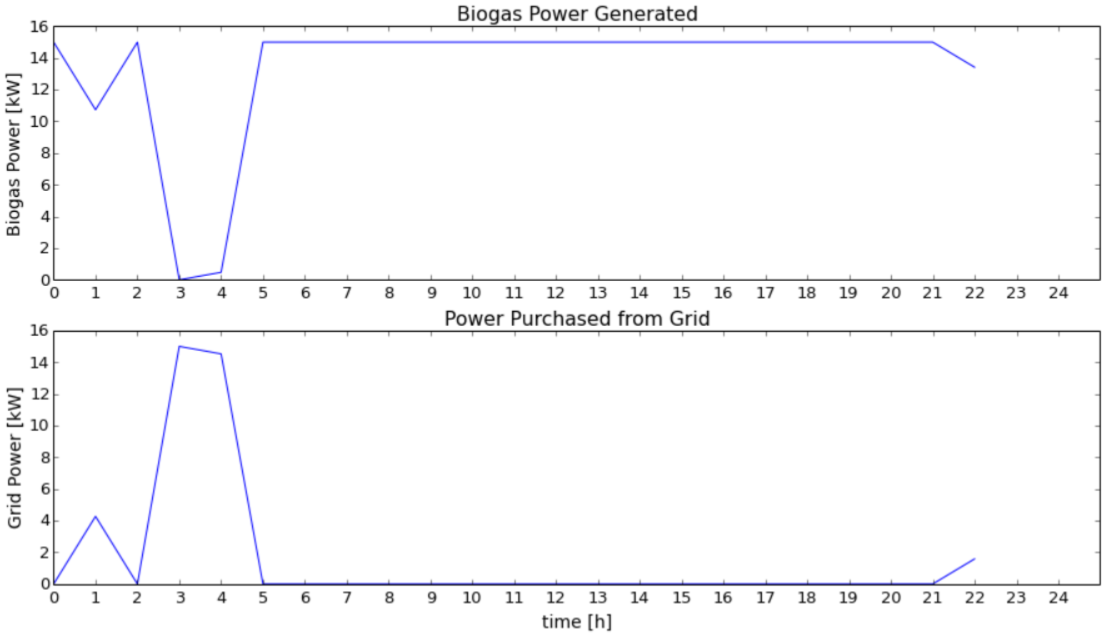


Figure 6: (a) Energy generated from biogas and (b) Energy purchased from the grid

Scenario	Total Electricity Cost ($/day)
No Biogas Energy Recovery	**$27.30**
Optimized Biogas Energy Management	**$2.20**
Absolute Savings	**$25.10**
Relative Savings	**92%**

Table 4: Objective Results

Discussion

Although the outputted results above were the consequence of a single pricing scheme and COD flow rate scenario, the overarching principles and takeaways extend to any comparable situation. The first sanity check that showcases this an effective model is the fact that power purchased from the grid was minimized during the peak pricing hours of 12 pm to 6 pm. When comparing our results of a plant utilizing biogas energy recovery compared to one that is not, a 92% reduction in daily electricity costs was realized. Over the course of an operating year, this amount of savings can add up to a non-trivial amount (close to $10,000 per year in our case study scenario).

Taking a look a figure 5a, one can see that there is a sharp rise in biogas production between hours 3 and 6. This is clearly done by the energy management system to prepare for full utilization during the on-peak pricing hours. This notion is again confirmed by the large increase in biogas power generated starting around hour 4 in figure 6a. It can also be seen that there is enough stored biogas to fully meet power demand during on-peak pricing hours. To refresh, biogas power limitation is not due to storage capacity, but instead because of incoming wastewater COD concentrations. This biological variable could be assumed to be stochastic and handled with a statistical analysis after collecting enough data to create a credible distribution. Based off of that add-on analysis, the optimal tank size can then be determined akin to weather analyses performed for renewable energy sources and the power of dynamic programming can be universally applied to treatment plants across the globe.

While the concepts and tools utilized in this analysis are certainly not novel, their application in the space of waste water management certainly is. This report is a valuable ground-breaking analysis showcasing the surface level potential of exercising biogas energy recovery to efficiently reduce plant operation costs. Our analysis clearly highlights that the beneficial use of an inevitable process byproduct can significantly reduce the amount of energy purchased from the grid on a daily basis. The utilization of optimization principles, specifically dynamic programming, is perfectly equipped to address this biogas energy management problem as we move toward a more efficient and resource-recovery oriented industrial philosophy in light of growing energy security and climate change concerns.

Summary

The main objective of this project was to create a comprehensive online optimization model that wastewater treatment plants may conveniently use to manage their biogas stock (generation, storage, and combustion for electrical energy) in the most economically favorable manner possible. This model determines when it is most economical to combust recovered biogas for plant electricity generation and when to purchase grid electricity to power the plant, while replenishing biogas stock. An optimization model was developed for the energy management operation of the wastewater treatment plant taking into consideration the parameters and constraints of such a system. By developing this model, this project hopes to be a valuable resource for the utilization of the biogas energy recovery process at one of the most common industrial facilities on the globe. Compared to a baseline case with no biogas energy recovery, heating electricity costs were reduced by over a factor of 10, yielding great promise for the economic savings potential of optimal biogas energy management. The next steps would include gathering more comprehensive and representative waste water plant flowrate and COD data to better design for ideal equipment sizing and generate dependable forecasting schedules for a more flexible and robust energy management model.

References

1. Stillwell, A.; Hoppock, D.; Webber, M. *Energy Recover from Wastewater Treatment Plants in the United States: A Case Study of the Energy-Water Nexus*. Sustainability **2010**, *2*, 945-962.
2. De Mes, T. Z. D., Stams, A. J. M., Reith, J. H., & Zeeman, G. *Methane production by anaerobic digestion of wastewater and solid wastes.* Bio-methane & Bio-hydrogen. **2003**
3. Wang, X., McCarty, P. L., Liu, J., Ren, N. Q., Lee, D. J., Yu, H. Q., ... & Qu, J. *Probabilistic evaluation of integrating resource recovery into wastewater treatment to improve environmental sustainability*. Proceedings of the National Academy of Sciences. **2015**
4. *Technical Support Document for Wastewater Treatment: Proposed Rule for Mandatory Reporting of Greenhouse Gases*; Climate Change Division, Office of Atmospheric Programs. U.S. Environmental Protection Agency: Washington, DC, **2009**; available online: http://www.epa.gov/ghgreporting/documents/pdf/archived/tsd/TSD%20 wastewater_020409.pdf, accessed 2/22/15.
5. Burton, F.L. *Water and Wastewater Industries: Characteristics and Energy Management Opportunities*; Burton Environmental Engineering, Electric Power Research Institute Community Environmental Center: Los Altos, CA **1996**.
6. *Opportunities for and Benefits of Combined Heat and Power at Wastewater Treatment Facilities*; Eastern Research Group and Energy and Environmental Analysis, U.S. Environmental Protection Agency: Washington, DC, **2007**; pp. ii-10; Available online: http://www.epa.gov/CHP/documents/wwtf_opportunities.pdf, accessed 2/21/15.
7. Zhou, S., Wu, Z., Li, J., & Zhang, X. P. *Real-time energy control approach for smart home energy management system*. Electric Power Components and Systems, 42(3-4), 315-326. **2014**
8. Tischer, H., & Verbic, G. *Towards a smart home energy management system-a dynamic programming approach*. In Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES (pp. 1-7). IEEE. **2011**
9. Khiewwijit, R., Temmink, H., Rijnaarts, H., & Keesman, K. J. *Energy and nutrient recovery for municipal wastewater treatment: How to design a feasible plant layout?*. Environmental Modelling & Software, 68, 156-165. **2015**
10. Gavala, H. N., Angelidaki, I., & Ahring, B. K. Kinetics and modeling of anaerobic digestion process. In Biomethanation I (pp. 57-93). Springer Berlin Heidelberg. **2003**
11. *Water Supply Update*; San Francisco Water, Power, Sewer, SF Public Utilities Commission, **2014**. Available online: http://sfwater.org/index.aspx?page=760, accessed 3/16/15.
12. *Introduction to Anaerobic Digester Biogas Systems*; AgSTAR/Nebraska Public Power District, U.S. Environmental Protection Agency, **2009**. Available online:

http://www.epa.gov/agstar/documents/workshop09/thompson_voell.pdf, last accessed 3/17/15.

13. Grady Jr., C.P. Leslie, Daigger, Glen T., Love, Nancy G., & Filipe, Carlos D.M. Biological Wastewater Treatment. CRC Press, London. **2011**.
14. *Anaerobic Digestion of Wastewater Sludge*; Thayer School of Engineering at Dartmouth, **2010**. Available online: http://engineering.dartmouth.edu/~d30345d/courses/engs37/AnaerobicDigestion.pdf, last accessed 5/4/15.
15. Arceivala, S., Asolekar, S. Wastewater Treatment for Pollution Control and Reuse, (pp. 184). Tata McGraw-Hill Professional. **2007**.
16. Nyberg, M., *Thermal Efficiency of Gas-Fired Generation in California: 2014 Update;* California Energy Commission. CEC 200-2014-005. **2014.**
17. *Onsite Sewage Treatment Program*, University of Minnesota. Manual for Septic System Professionals in Minnesota, 2nd Ed. St. Paul, MN. **2011**. Available online: http://www.septic.umn.edu/prod/groups/cfans/@pub/@cfans/@ostp/documents/asset/cfans_asset_131281.pdf, last accessed 5/4/15.
18. PG&E. Tariff Book 2015. http://www.pge.com/tariffs/ERS.SHTML. last accessed 17/3/2015