Harnessing Wastewater for Renewable Energy (2013-2)

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This case study explores the options for using wastewater to produce renewable energy in the context of a public wastewater treatment plant. It provides an opportunity for students to synthesize knowledge from resource economics, engineering, environmental science, agriculture, and public policy to develop a transdisciplinary approach to a socio-environmental issue. The case is designed for upper division undergraduate courses in resource economics or environmental engineering, but several modifications are provided graduate course applications. Students assume the role of a newly hired analyst at a consulting firm in Washington, DC, that specializes in renewable energy solutions. They are charged with proposing a system that uses wastewater to produce energy, while accounting for multiple constraints across disciplines. Students are provided with economic, political, environmental, and engineering data on four different solid waste disposal options and work in small groups to develop a proposed solution that balances these factors. They present and justify their suggested solutions in small-group presentations, and the case concludes with an instructor-led discussion of the relevant considerations.

- Student Notes and Teaching Handout [1]

Associated Project:
Teaching Socio-Environmental Synthesis with Case Studies 2013 [2]
Has this been tested in the class room:
Yes

Student Handout

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Scenario

As she entered the elevator from the parking garage, Janine recognized that vaguely familiar feeling of excitement and nervousness in her stomach. She got off on the third floor and was immediately transported back to her first day of high school: new smells, new people, and new opportunities.

Just a month prior, Janine graduated from college, and today was her first day of work as an analyst for Energy Associates, Inc., a consulting firm in Washington, D.C., that specializes in renewable energy solutions. She made her way to her cubicle, got settled, and then her boss Martha called her in for her first official meeting.

Pen and pad in hand, Janine entered Martha's office.

Martha closed the door and immediately asked, "So, Janine, what do you know about renewable energy?"

Having just graduated with a degree in environmental engineering, Janine had her bases covered. She began, "Well, there are a number of possible sources: hydro, solar, wind, geothermal, tidal, and biofuels. Is there one in particular you'd like to discuss?"

"Aren't you forgetting about one?" Martha asked.

"I don't think so…"

Martha went on, "What if I told you there was another renewable energy source with none of the intermittency problems of wind or solar and capacity factors that rival those of coal plants? Beyond that, the fuel source is abundant and free."

Janine laughed nervously. "This must be a thought exercise to test my ability to think on my feet," she thought. At that moment, Martha tossed a large file folder on the desk labeled "Wastewater-to-Energy."

"This is your first project. We're pitching to a new client in two weeks—D.C. Water and Sewer Authority—and we need to propose a system to use their wastewater to produce energy. We need to account for *everything*: engineering constraints, investment costs and potential revenue, political concerns, environmental credits, CO2e emissions, you name it! This is a huge project, and if our company wins the bid, you can rest assured you'll have a job here for at least the next two years. So get to work. My door is always open if you have any questions."

Janine went back to her desk, glanced down at her coffee, and then opened the folder.

Procedure

Step 1: Proposing a solid management processes based on individual factors

1. Gather important information on the four possible types of solid management processes by reading the provided information sheets on each management system with your team.
2. In combination with the pre-reading, consider the types of information that you will use for prioritizing solid management processes. There are two overarching factors. You will examine each factor individually according to the order assigned to your team by the instructor.
3. For each factor, read the provided information and discuss a strategy for incorporating it into your decision framework with your team.
4. Prioritize the solid management processes base on the information provided. Develop a detailed and justifiable strategy for incorporating the information. Write down your team's proposed solution.
5. Present your recommendation with your team's rationale. Avoid generalities and anecdotal arguments--as a consultant you must provide a data-driven solution to this problem!

Step 2: Develop a final recommendation based on all the factors

1. Synthesis all of your information based on the two factors.
2. You may think about other factors and combine them into your team's final proposed solution. However, you should provide a detailed explanation of your team's rationale and any supporting information.
3. Write a brief report summarizing your method of synthesis and reasons for your recommendation.

Step 3: Present your team's proposed solution

Your presentation should include your team's final recommendation, the method that you used to synthesize information across factors, reasons why you proposed this solution, problems that made it hard to develop a final recommendation, and any additional information that would have helped you in designing a solution.

SOLID END PRODUCT MANAGEMENT OPTIONS

About one ton of solid end product is produced from one million gallons of wastewater that is passed through a wastewater treatment process.

1. Land application

Source: http://www.appleton.org/departments/page_f93a1877928c/?department=b69309298e6b&subdepartment=6a0e8b8ac166

Land application is a process to spread or spray biosolids on an agricultural land surface, forestland and/or mining site. However, solid end products from a wastewater treatment plant (WWTP) have to be treated to meet all regulatory[1] requirements, which is standard for the use and disposal of sewage sludge 40 CFR 503 (US. EPA, 1993).

Solid end products from a WWTP can therefore be used directly to produce Class B biosolids through a lime stabilization process.

[1] http://yosemite.epa.gov/r10/water.nsf/NPDES%2BPermits/Sewage%2BS825/$FILE/503-032007.pdf

SOLID END PRODUCT MANAGEMENT OPTIONS

2. High-end fertilizer

Source: http://envstudies.brown.edu/research/LULCC/research/brazil.html

Fertilizer can be categorized into two groups based on its composition:

1. Inorganic fertilizer
2. Organic fertilizer.

Solid end products from a WWTP can be composted, which kills pathogens, reduces odor, and produces a stable and marketable product. They can therefore be used directly to produce Class A fertilizer through a composting process.

SOLID END PRODUCT MANAGEMENT OPTIONS

3. Anaerobic Digester

Source: *http://sites.duke.edu/environ398_10_f2010_ct95/?page_id=46*

Anaerobic digestion is the biological solid treatment process that stabilizes organic matter in solid end products from WWTP without oxygen. The important byproduct is biogas, which contains methane, carbon dioxide and trace gases. Biogas can be used to produce natural gas (NG), compressed natural gas (CNG), and/or biogas-based electricity. The biogas[2] from a digester must be cleaned of CO2 and trace gases to produce methane (CH4). Biogas is comprised of approximately 60% biomethane, which can be used in several ways:

- Use directly as natural gas.
- Compress it to make compressed natural gas (CNG) and use for transportation sector, called bio-CNG. The amount of bio-CNG[3] is roughly 96.5% of the original biomethane.
- Generated biogas-based electricity. In this case, A reciprocating engine CHP system is employed to generate electricity and the capacity is 2.0 megawatts.

In addition to biogas, another valuable byproduct of anaerobic digestion is class A biosolids that can be sold and used as organic fertilizer.

[2] The biogas ($CH_4 + CO_2 + H_2O$ + trace gases) can be broken down into the following component shares: 55-65% methane gas (CH_4) , 30-40% carbon dioxide gas (CO_2), and 0-5% water vapor, traces of hydrogen sulfide H_2S and hydrogen H_2 (Appels et al. 2008)

[3] http://www.environmental-expert.com/products/biogas-to-compressed-natural-gas-35510.

SOLID END PRODUCT MANAGEMENT OPTIONS

4. Incineration

Source: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/al/newsroom/photos/?cid=nrcs141p2_023017

Incineration or thermal oxidation is a rapid process to dispose of solid end products from a WWTP with the maximum volume. We can use an incinerator to dispose of solids in any and all amounts.

ECONOMIC CONSIDERATIONS

This fact sheet describes the economic considerations relevant to a WWTP when choosing a solid end waste management option. This includes the investment costs, operation and maintenance (O&M) costs, potential revenue, carbon credits and/or renewable energy credits (RECs), and political/regulatory concerns.

1. Investment costs
    a. **Land application**: $48,000 of capital cost
    b. **High-end fertilizer**: See O&M costs
    c. **Digester**: Reciprocating engine CHP systems over 1 MW in size cost $2000/kW to $3000/kW. 1 MGD of influent flow can produce 26 kW of electric capacity.[4]
    d. **Incineration**: $61,504 of capital cost[5]

2. O&M costs
    a. **Land application**: $490 per dry ton of solid
    b. **High-end fertilizer**: About $249.60 per dry ton of solid[6]
    c. **Digester**: An anaerobic digester in this climate requires about 2.3 MMBtu/day/MGD of thermal energy to operate. 1 MGD of influent flow can produce 2.4 MMBtu/day of thermal energy. The estimated cost to generate electricity from anaerobic digester gas is $0.040/kWh.[7]
    d. **Incineration**: $92 per dry ton of solid[8]

3. Potential revenue
    a. **Land application**: This process does not generate any revenue because the treated biosolids are given to farmers for free.
    b. **High-end fertilizer**: The March 2013 price of 30% nitrogen solutions fertilizer is $410 per dry ton[9].
    c. **Digester:** The 2009 average gas price in D.C. was $13.98 per thousand cu. ft.[10] The

[4] U.S. EPA. (2011). Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field.
[5] This figure is an assumption based on our research.
[6] The composting process cost in 2008 was $208 per dry ton of fertilizer, which included $8 per dry ton of capital cost and $200 per dry ton for operation and maintenance cost (EPA 2002; Harkness et al. 1994; Wang et al. 2009), and a 20% management cost was added to that.
[7] U.S. EPA. (2011). Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field.
[8] This figure is an assumption based on our research.
[9] Agricultural Prices, National Agricultural Statistics Service, USDA.
[10] Chittum, A., & Kaufman, N. (2011). Challenges facing combined heat and power today: A state-by-state

2010 average electric rates was 13.84 cents per kWh.

  d. **Incineration**: This process does not generate any revenue for the WWTP.

4. Carbon credits and/or RECs
   a. **Land application**: No carbon credits or RECs for the WWTP.
   b. **High-end fertilizer**: No carbon credits or RECs for the WWTP.
   c. **Digester**: Presently there is no carbon pricing scheme in D.C. or any other state-level credits, but digester/CHP systems are eligible for a 10% federal investment tax credit.
   d. **Incineration**: No carbon credits or RECs for the WWTP.

5. Political/regulatory
   a. **Land application**: Sewage sludge must be treated to meet the pollutant concentration levels outlined in § 503.13 of EPA Title 40: Protection of Environment. There may also be some political resistance to land application because of public's concerns about food safety, the spread of pathogens, and unregulated metal contaminants.
   b. **High-end fertilizer**: For produce to be USDA-certified organic, biosolid-based fertilizer cannot be used. Class A biosolids have been treated to reduce bacteria and therefore pose significantly lower risks in terms of pathogens. However, they may still contain unregulated metals.
   c. **Digester**: There have been new federal mandates to reduce greenhouse gas emissions from federal buildings. D.C. recently adopted new interconnection standards, and the local utility (PEPCO) offers standby rates that are favorable for CHP[11].
   d. **Incineration**: This process is a controversial political issue because it emits ash, flue gas, and CO2e into the air, which may have adverse health affects for people. Furthermore, local communities are often highly opposed to having incinerators near their neighborhoods.

assessment. http://www.uschpa.org/files/public/ie111.pdf.

[11] Chittum, A., & Kaufman, N. (2011). Challenges facing combined heat and power today: A state-by-state assessment. http://www.uschpa.org/files/public/ie111.pdf.

ENVIRONMENTAL CONSIDERATIONS

This fact sheet describes the environmental considerations relevant to a WWTP when choosing a solid end waste management option. This includes the net carbon dioxide equivalent emissions, nutrients provided, energy consumption / energy result, and odor problems associated with each option.

1. Net carbon dioxide equivalent emissions (CO2e)[12]
   a. **Land application**
      Emissions: Calculated from transportation biosolids process to land application fields (0.2 ton CO2e / dry ton of biosolids (Brown et al., 2004)).
      Offsets: Calculated based on the amount of biosolids are used instead of fertilizer in farms (0.1 ton CO2e / dry ton of biosolids (Brown et al., 2004)).
   b. **High-end fertilizer**
      Emissions: None.
      Offsets: Calculated based on the amount of biosolids are used instead of fertilizer in farms (0.1 ton CO2e / dry ton of biosolids (Brown et al., 2004)).
   c. **Digestion**
      Emissions: Calculated from transportation by-product (Class A biosolids) to agricultural market (0.2 ton CO2e / dry ton of biosolids (Brown et al., 2004)) .
      Note that: Class A biosolids production is 0.4838 dt per dt of solid end product[13].
      Offsets: Including the benefits from using biogas as natural gas (0.000056 ton CO2e / cubic foot of NG), CNG (0.000054 ton CO2e / cubic foot of CNG), and/or biogas-based electricity (0.00055 ton CO2e / kilowatt hour) (The Climate Registry, 2008).
   d. **Incineration**
      Emissions: Calculated from combustion process (1.443 ton CO2e / ton of biosolids) (The Climate Registry, 2008).
      Offsets: None.

2. Nutrients provided
   a. **Land application**: Nitrogen substance is the main plant nutrient released to the soil from Class B biosolids produced using a lime stabilization process. However, pathogen contamination is a significant concern to farmers.
   b. **High-end fertilizer**: Nitrogen substance is the main plant nutrient released to the soil

[12] amount of greenhouse gas , using the functionally equivalent amount or concentration of carbon dioxide (CO_2) as the reference.
[13] This figure is an assumption based on our research.

from Class A biosolids produced through a composting process.

c. **Digester**: Nitrogen substance is the main plant nutrient released to the soil from Class A biosolids produced using a lime stabilization process.
d. **Incineration**: None.

3. Energy consumption / energy result
    a. **Land application**: Fossil fuel is used (diesel or gasoline) to transport Class B biosolids to land application fields.
    b. **High-end fertilizer**: Fossil fuel is used to transport Class A biosolids to agricultural markets.
    c. **Digester**: Fossil fuel is used for the operational process. However, biogas that contains methane is an end-product of the anaerobic digestion process.
    d. **Incineration**: Fossil fuel is used for the operational process.

4. Odor problems
    a. **Land application**: Lime stabilization does not eliminate odor problem from the production, delivery, and application of Class B biosolids to the field (Gabriel, 2006 and 2007).
    b. **High-end fertilizer**: None.
    c. **Digester**: None
    d. **Incineration**: None

Teaching Notes

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Abstract
This case study explores the options for using wastewater to produce renewable energy in the context of a public wastewater treatment plant. It provides an opportunity for students to synthesize knowledge from resource economics, engineering, environmental science, agriculture, and public policy to develop a trans-disciplinary approach to a socio-environmental issue. The case is designed for upper division undergraduate courses in resource economics or environmental engineering, but several modifications are provided graduate course applications. Students assume the role of a newly hired analyst at a consulting firm in Washington, D.C. that specializes in renewable energy solutions. They are charged with proposing a system that uses wastewater to produce energy, while accounting for multiple constraints across disciplines. Students are provided with economic, political, environmental, and engineering data on four different solid waste disposal options and work in small groups to develop a proposed solution that balances these factors. They present and justify their suggested solutions in small-group presentations, and the case concludes with an instructor-led discussion of the relevant considerations.

Topical areas/courses:	Renewable energy, wastewater, environmental engineering, resource economics, and sustainability
Education level:	Undergraduate upper division, Graduate
Type/method:	Small group, Student presentations

SES Learning Goals
This case study will address the following Socio-Environmental Synthesis learning goals:

1. Ability to describe a socio-environmental system, including the environmental and social components and their interactions.
   Related Activities: Through the background reading and data, students will explicitly see the socio-environmental components in a wastewater-to-energy system and be able to describe the linkages in the system.
2. Ability to identify disciplines and approaches relevant to the problem.
   Related Activities: In designing a solution, students will incorporate concepts from economics, agriculture, engineering, environmental science, and public policy.
3. Ability to find, analyze, and synthesize existing data (for Modification 2).
   Related Activities: Students will use U.S. state population data and engineering estimates to

forecast the potential energy production capacity from wastewater using simulation and an optimization model.

4. Understand the different kinds of data and research methods used by relevant disciplines in the natural and social sciences (for Modification 1).
   Related Activities: Students will use engineering estimates, cost-benefit analyses, and qualitative data to build a basic economic optimization model.
5. Understand that ecological and social processes often vary across differing contexts, including space, time, and conditions (for Modification 3).
   Related Activities: Students will investigate how regulatory differences across states would affect their proposed solution and offer potential revisions.

Learning Objectives

Through this case study, students will:

1. Understand and recognize waste and resource management in a specific local application.
2. Understand how the political and regulatory environment can affect scientific decisions.
3. Recognize interactions between economic and scientific factors in an environmental issue (wastewater management and energy recovery) and the associated tradeoffs.
4. Develop and compare ways to synthesize different sources and types of data (political, agricultural, environmental, economic, engineering).
5. Learn how to justify and defend a proposal that involves tradeoffs across several disciplines, when a single optimal solution does not exist.

Introduction/Background

Increasing levels of waste (solid waste and wastewater) is a national problem for every country around the world. One important factor that contributes to this problem is population growth. The U.S. population[14] in 2012 was about 314 million people, and the projection for 2030 is 360 million people, roughly a 14% increase.

The U.S. capital city of Washington, D.C., faces a problem of increasing wastewater and requires a good management plan to address this issue. Based on its population (632,323 people in 2012) and wastewater production rate[15] (100 gal/person/day), the approximate wastewater produced by the Washington, D.C., is 63 million gallons per day (MGD).

Wastewater is collected and flows to wastewater treatment facilities. Generally speaking, physical, chemical and/or biological treatment processes are used to separate soluble and insoluble solids contained in used water. The end products from wastewater treatment plants (WWTPs) are

[14] http://www.census.gov/popest/data/national/totals/2012/index.html
[15] Great Lakes-Upper Mississippi Board of State and Provincial Public Health and Environmental Managers, "Recommended Standards for Wastewater Facilities (Ten-State Standards)," 2004.

normally clean water and solids. Clean water flows back to a natural water source such as a river or ocean, but the solid end product is always a significant problem for WWTPs.

Four possible methods are introduced for a WWTP to handle solid end product including land application, high-end fertilizer, anaerobic digestion, and incineration. Solid end product must be stabilized or transformed to different products. It can be converted to Class B biosolids by lime stabilization and delivered to a land application field (farm, mine, or forest). It can be transformed to Class A biosolids through a composting process and sold as organic fertilizer. Biogas can be produced through an anaerobic digestion process and used as natural gas, further processed to produce compressed natural gas (CNG), and/or used to generate biogas-based electricity. Lastly, incineration is another option to dispose of solids and produce energy from heat. However, which option should be used to dispose of solid end product from WWTPs if environmental impacts and economic benefits are considered?

In this case, students assume the role a recently graduated, newly hired analyst named Janine at a renewable energy consulting firm in Washington, D.C. Her first assignment is to develop a proposal that they can pitch to the D.C. Water and Sewer Authority for a system to use wastewater to produce energy, which requires accounting for and synthesizing a multitude of economic and environmental considerations.

This case is designed for upper division undergraduate courses in environmental science/engineering or resource economics. It can also be modified for graduate courses as described in the **Suggested modifications for upper-level courses** section. The unmodified case study requires 3-3.5 hours to complete, with more time required for modifications. For 50-minute class sessions, the authors suggest using four class sessions to allow ample time for discussion.

Classroom management & blocks of analysis

Summary

- Several days before class, students are assigned readings that provide background information for the case study.
- At the beginning of class, the instructor introduces important information from the assigned readings for the case study that will be relevant for designing a solution (10 min).
- The instructor reviews the case study, and students read the student handout describing their assignment to prioritize the four types of solid management processes (10-15 min).
- Instructor describes the types of data required to perform this assignment (5-10 min).
- Students are divided into teams (4 people per team) and given two types of information, one at a time: economic considerations and environmental considerations (10 min).
- Students read and examine each type of data individually and develop a proposed solution based only on those considerations, which includes recommending a specific solid management process for the WWTP. Each team writes a summary of their recommendation for each factor

(economic or environmental) and presents it to the class (1 hr).

- Instructor reviews the recommendations, and the class discusses why/how this is a socio-environmental issue and requires synthesis (5-10 min).
- Teams consider the two factors in combination and develop final proposed solutions. Each team writes a short report summarizing their proposed solution. This should involve a discussion of which factors are most critical and how inclusion of multiple types of information changed their recommendation (30 min).
- Each team presents their final proposed solution (5 min per team).
- Class discusses and compares each team's recommendation. The instructor reviews the main conclusions of the case (10-15 min).

Estimated time: **3-3.5 hours**

Teaching the case

- Pre-class reading
    - U.S. EPA, *Biogas Recovery Systems*. http://www.epa.gov/agstar/anaerobic/ad101/index.html
    - U.S. EPA. (2012). Case Study Primer for Participant Discussion: Biodigesters and Biogas. Technology Market Summit.
    - U.S. EPA. (2011). Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field.
    - U.S. EPA. (2002). Land Application of Biosolids: http://www.epa.gov/oig/reports/2002/BIOSOLIDS_FINAL_REPORT.pdf
    - Heal, G. (2009). Reflections--The Economics of Renewable Energy in the United States. *Review of Environmental Economics and Policy*, *4*(1), 139–154.
    - Chittum, A., & Kaufman, N. (2011). Challenges facing combined heat and power today: A state-by-state assessment. http://www.uschpa.org/files/public/ie111.pdf.

- Pre-discussion
  Before beginning the case, the instructor should review the assigned readings and highlight the information that will be important for designing a solution in this case. The instructor should begin by discussing Heal (2009), which provides a high-level overview of the state of renewable energy in the U.S. and the challenges that such a system must meet in order to displace conventional energy sources (e.g. coal-fired power plants). The concepts of intermittency and capacity factors should be covered in detail. Next, the instructor should address some of the key questions surrounding anaerobic digesters and CHP systems:
    - What are some of the political, regulatory, and environmental concerns with solid waste

management?
  - What is an anaerobic digester and what are the byproducts of anaerobic digestion?
  - Why would a WWTP consider anaerobic digestion as a solid waste management option?
  - How can a WWTP use biogas recovered from anaerobic digestion?
  - What types of CHP systems are available, and what are the key differences?

- <u>The case study</u>
  Next, the instructor presents the case study scenario and the different solid waste management options available to the WWTP for consideration. The scenario, procedure, and solid end product management options of the student handout are distributed for the students to read on their own. After everyone has read the handout, the instructor formally presents the options. These options reflect the actual choices WWTPs make in the real world, and they represent a set of solutions with significant trade offs:
  - *Land application:* a relatively low-cost solution with well-documented political/environmental ramifications that must be considered.
  - *High-end fertilizer:* an improvement on land application from the standpoint of political/environmental concerns, but more costly.
  - *Anaerobic digestion:* a capital-intensive, expensive solution that requires complex oversight and long-term planning, but it has revenue potential and favorable environmental outcomes.
  - *Incineration:* historically, a widely-used and low-cost option in solid waste management, but now it has become a controversial political issue with potentially negative health effects for local communities.

  Then the instructor briefly discusses the types of data that might be relevant for a WWTP deciding on solid end product management. After the students discuss what information they'd *like* to have, the instructor introduces the factors they will examine in the form of fact sheets:
  - Economic considerations: investment costs, operation and maintenance costs, potential revenue, carbon credits and/or renewable energy credits (RECs), and political/regulatory concerns.
  - Environmental considerations: net carbon dioxide equivalent emissions, nutrients provided, energy consumption / energy result, odor problems

  The instructor divides the class up into groups of 4 students, and each group is given the *economic considerations* fact sheet to consider first. In the first 30 minutes, the students discuss this factor as a team and develop a recommendation for the WWTP that addresses the economic concerns. The instructor should encourage the students to fully diagram the solid waste management process and develop a quantitative framework for analyzing the economics. Once each team reaches a decision, they should write up a brief recommendation and present it to the class. In the next 30 minutes, the teams will repeat this process for the *environmental considerations*. At this stage, the instructor should encourage the students to consider this factor in isolation when proposing a solution. For the environmental considerations, students may also draw on any background they have in environmental science, since the fact sheet presents technical data that may need to be put in a larger perspective.

Once the students have considered each factor in isolation, the instructor leads a discussion on how the economic and environmental considerations may interact with each other. In particular, the environmental outcomes (such as odor problems) of different waste management options may have political and health ramifications, which will in turn affect the economics of each option. Furthermore, the uncertainty of future carbon pricing (e.g. a carbon tax) may affect the relative importance of carbon credits and CO2e emissions. Ultimately, the students should realize that solid end product management is a socio-environmental issue and requires synthesis of various types of data.

In the next part, the instructor asks each team to develop a final recommendation for the WWTP's solid end product management that incorporates the economic and environmental considerations along with any additional factors they deem important (drawing from their own backgrounds). The teams must also develop a defensible framework for incorporating this information into their proposed solution (e.g. cost-benefit analysis). Once the teams agree on a final recommendation, they should write a short report summarizing their proposed solution. This should involve a discussion of which factors are most critical, the framework they developed to analyze the data, and how inclusion of multiple types of information changed their recommendation.

Each team will present their final proposed solution to the class in a five minute presentation. The presentation should summarizes their decision framework, final recommendation, and potential shortcomings of their methodology and solution.

The case study concludes with an instructor-lead discussion with the whole class. Some relevant points of discussion are:

- Compare each team's recommendation and their decisionmaking framework.
- How did this decision involve tradeoffs between different factors, and how do you assign importance to one factor over another in that case?

- What additional data do you wish you had that is relevant to this problem?
- Develop a diagram/schematic on the whiteboard detailing the entire process.
- Review actual solutions WWTPs have developed to address this issue, in particular that of the Philadelphia Water Department's Northeast Water Pollution Control Plant, and the Gloversville-Johnstown Joint Wastewater Treatment Facility[16].
- Discuss any of suggested modifications for upper-level courses (see below).

Expected outcomes

This case is designed to highlight how wastewater (and its byproducts) can be used to produce renewable energy and when this solution may be economically viable for the WWTP and environmentally beneficial to the community. As such, the expectation is that most teams will recommend some form of anaerobic digestion process for dealing with solid waste. However, within this general solution, a multitude of options for generating energy exist with their own nuances. The best option will depend on the size of the WWTP, market conditions, and the state regulatory environment, so there is not one "correct" answer. In that sense, the purpose of this case study is to help students develop a framework for analyzing this complex issue, better understand the multifaceted nature of wastewater treatment systems, and appreciate the potential of this largely untapped renewable energy source in the U.S.

Suggested modifications for upper-level courses

1. Resource economics - write out a basic optimization model of the technology and downstream markets under the assumption of profit maximization.
2. Environmental engineering - use U.S. state population data to forecast potential energy production capacity for wastewater under various CHP technologies.
3. Public policy - analyze the regulatory environment for electricity markets in each state and consider how the proposed solution would change in each case.

Sample assessment questions

The authors intend to use this case study activity with a group of 40 undergraduate students in the Spring 2014 semester and assess the students' learning with three assessment questions below.

1. What is the most important point that you learned from this case study?

   Example response:

   - There is no single right or wrong answer. It really depends on the objective, which is a major point of discussion in this case.

[16] U.S. EPA. (2012). Case Study Primer for Participant Discussion: Biodigesters and Biogas. Technology Market Summit.

- One possible way to find the answer is through quantitative methods. However, it is too difficult to find the correct one. We may need more information.

2. Please describe how looking at this as a socio-environmental system helped you choose the optimal solid management system.
   - This question aims to help students understand the nature of a socio-environmental system.
   - Students can apply their knowledge about socio-environmental systems to this exercise.

   Example response:
   - Incineration is not a good idea for disposing of solids because of the negative environmental impact of the burning process and the higher costs than digestion, composting, or lime stabilization.

3. Did you have any initial hypotheses about the optimal solution/recommendation for this problem before completing this exercise? Were you able to test those hypotheses?
   - This question aims to help students understand the process of formulating hypotheses and testing them with appropriate data.

   Examples response:
   - A digester is the best choice if decision makers would like more revenue generating end products. It can produce biogas and biosolids for fertilizer.

Acknowledgements

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