



University of
Massachusetts
Amherst

Anaerobic Membrane Bioreactors as a Treatment for Wastewater and Biogas Production at University of Massachusetts Amherst

Item Type	article;article
Authors	Norton, Marley;Bell, Brady;Fine, Ariel
Download date	2025-07-04 07:54:02
Link to Item	https://hdl.handle.net/20.500.14394/44268

UNIVERSITY OF MASSACHUSETTS AMHERST

Integrated Concentrations in Science i2E

Renewable Energy Tenth Cohort

Brady Bell, Civil Engineering, Londonderry, NH

Ariel Fine, Industrial Engineering, Newton, MA

Marley Norton, Biochemistry and German, Beverly, MA

Anaerobic Membrane Bioreactors as a Treatment for Wastewater and Biogas Production at

University of Massachusetts Amherst

May 13, 2021



TABLE OF CONTENTS

Abstract 3

Introduction 3

Problem Explanation 5

Water Consumption

Solution Explanation 7

Process Explanation

Types of Membranes

System Configurations

Implementation Specifications 13

Selecting a Polymeric Membrane

Selecting a System Configuration

Benefits and Drawbacks 16

Conclusion 17

Appendix 18

References 20

Abstract

The usage of water also requires the usage of energy, as both are inextricable commodities, high in demand and often non-renewable. In an attempt to decarbonize the University of Massachusetts Amherst, a Carbon Mitigation Plan (CMP) was developed, offering a set of possible solutions to bring UMass to carbon net neutrality by 2032. Deep evaluation and analysis of a solution presented in the CMP, a low-temperature hot water system (LTHW), was conducted. In order to offset the water consumption of a LTHW system, a thorough deliberation of an anaerobic membrane bioreactor (AnMBR) for municipal wastewater treatment is included, with the intention of recycling reclaimed water in the LTHW system, specifically at UMass. Wastewater should not always be considered a waste, as it has the potential to convert the biodegradable organic carbon into usable energy in the form of biogas, and in this case, the source of replacement water to run a LTHW system. With impending urgency to meet the 2032 deadline, this paper offers a hypothetical solution for this energy-water nexus.

Introduction

The University of Massachusetts Amherst has its eyes set on a futuristic vision. The goal of revolutionizing campus to an all time level of sustainability is no simple one. Achieving net zero carbon emissions by the year 2032 would require an unprecedented scale of renovation over the given span of time. However, we stand before an opportunity to set a regional and nationwide standard in college campus sustainability [1]. The UMass Carbon Mitigation Plan (CMP) outlines a wide array of solutions to be implemented to achieve its goal.

The heating plant that centralizes the production and distribution of heat across the 1,400+ acre campus consumes copious amounts of natural resources, primarily non renewable energy supplies such as natural gas. While the CHP has won several awards for being ahead of

its time in terms of energy efficiency, it is still in desperate need of innovation [1]. A viable solution to relieving stress off of the CHP without having to decommission it revolves around the implementation of a low temperature hot water system (LTHW) and an anaerobic membrane bioreactor (AnMBR). To supplement the LTHW system, an AnMBR will assimilate a self-sustaining wastewater treatment facility, and produce a harvestable, renewable biogas as a byproduct.

The CHP currently utilizes steam to heat the campus, whereas a LTHW system would use hot water. Distributed hot water with a temperature of roughly 49 to 60°C requires a significantly lower amount of energy to be heated compared to steam [1]. Using hot water would save lots of energy and mitigate non renewable energy consumption, but using more hot water implies that we use more water in general.

In order to deliver the same heat as steam, LTHW systems have to use a greater mass of the lower temperature heat carrier (in this case water). As a result, LTHW uses a significantly greater amount of water compared to steam. This is the key focus of the implementation of an AnMBR, taking our proposed solution one step further. This nascent technology could greatly decrease water consumption: by recycling non-potable treated wastewater, known as effluent, we can supply that level of water demanded to drive the LTHW distribution [2]. To accomplish this, wastewater must be filtered. The contaminants, suspended solids, and pathogens in the water could be detrimental to environmental health as well as our own, and could degrade the mechanical integrity of the system over time [2]. AnMBR technology utilizes a permeable membrane lined with a culture of anaerobic bacteria that continuously consumes organic matter (OM) and filters other unwanted contaminants from the water [3].

By augmenting the LTHW system to utilize a recycled water supply, and integrating a self-sustaining AnMBR wastewater treatment facility, the CHP will require less non-renewable energy consumption. We can create a system that allows for renewable heating and water processing, that is, a sustainable energy-water nexus.

Problem Explanation

LTHW and open the door to moving away from natural-gas combustion and towards renewable methods for temperature control of the UMass Amherst campus. But there are still several questions that must be answered. One of the most imperative being: Does LTHW consume more freshwater than steam? Our team will explore why this is an important and non-trivial question to answer.

Foremost, steam is used as the heat carrier at UMass. The proposed switch from steam to liquid water as the heat carrier may increase the water consumption needs of campus. The heat transfer between two heat distribution mediums is ultimately controlled by the difference in their respective temperatures. Steam is about 100°C while comfortable room temperature is only around 22°C . These two temperatures have a much greater difference between one another compared to the difference in LTHW. LTHW circulates water at around 65°C . Thus, the difference in temperature of the system and the surrounding is only 43°C , compared to the 72°C with steam. Ultimately, this means that steam must be circulated through radiators fewer times than water to evolve the same amount of heat. Assuming steam is circulated at around 112°C and the room being heated is around 25°C , steam radiators require less surface area than a LTHW radiator with an estimated temperature of 65°C . The increase in surface area may account for an

increase in water mass circulated throughout the system, which is part of this solution that must be studied.

Another area for concern is the adjusted makeup water in either system. Research from a Cold Regions Research & Engineering Laboratory (CRREL) report indicates that nearly 50% of steam produced is not required for heating, and is wasted as such [4]. This could potentially be due to leaks in the steam pipes, or the fact that steam contains significantly more heat than the surrounding environment requires to reach a comfortable room temperature. Comfortable temperatures lie around 80°C less than the temperature of steam. Leaks in the steam pipes are more frequent and severe than with LTHW, and more water must be added to the system to account for the lost thermal energy [4]. If the surface area of a steam pipe contains a leak, the gaseous steam will exit that leak spot as the gas will fill the volume of the pipe, whereas with a leak in a water pipe, it is not always certain that the liquid water will exit the leak. The question to be answered, is whether a LTHW system requires more or less makeup water due to its liquid nature, than compared to the current adjusted makeup water related to steam heat distribution.

These two components -- the initial change in the volume of circulated water between steam and LTHW systems as well as the uncertainty of adjusted makeup water between the two systems -- are the core problems that must be understood before implementing LTHW at UMass. These uncertainties in water consumption are directly related to the university's scope three carbon emissions. Scope three carbon emissions are part of a set of regulations designed to organize the various carbon emissions and their respective pernicious effects. Scope 1 and 2 emissions are directly related to the university's operations. Scope 3 emissions are related to activities outside the universities operations, such as student transportation or how much food is

wasted in dining halls, as well as carbon emissions produced from offsite entities. Offsite entities that supply our water create carbon emissions that UMass is not accepting responsibility for.

According to a River Network Report, annually in the U.S. commercial and institutional water-related carbon emissions are responsible for more than 35 million metric tons of CO₂ [5]. The carbon emissions are a product of water's entire lifecycle; from transport to treatment at a waste facility after its use. Currently, the CHP produces 1.2 billion metric tons of steam per year, at a rate of 356,200 lbs/hr [6]. This is equivalent to roughly 1.01×10^7 lbs/hr, if UMass switches to hot water as the heat carrier, assuming the CHP does not increase in efficiency or capacity. Increases in the rate at which water is circulated could, therefore, have an effect on the water usage of UMass and thus energy usage and carbon emissions as well.

In conclusion, UMass must determine how the transition to LTHW will impact water consumption, as well as quantify how any increased water consumption will relate to carbon emissions and how to offset and decarbonize this to ensure we are truly approaching a carbon net neutral campus.

Solution Explanation

An Anaerobic Membrane Bioreactor (AnMBR) is a possible self sustaining solution assimilating wastewater filtration and the production of a renewable biogas energy. AnMBR could provide any replacement water needed to have a proficient and abundant LTHW system, and can reduce operational energy demand in reference to typical wastewater treatment by at least 70% [7] To have an AnMBR, a membrane is required. The membrane facilitates the physical filtration process, so it is crucial to have an adequate membrane. A basic schematic of the operational process is shown in figure 1 [8]. The membrane contains pores in order to allow

the water itself to pass through, whilst withholding adverse debris, bacteria, minerals, etc. Pore size can vary from 1000 microns in diameter, which will only capture particles the size of beach sand, down to ~ 0 microns in diameter, qualifying as reverse osmosis (RO), which is miniscule enough to contain all particles as small as an atomic radius.

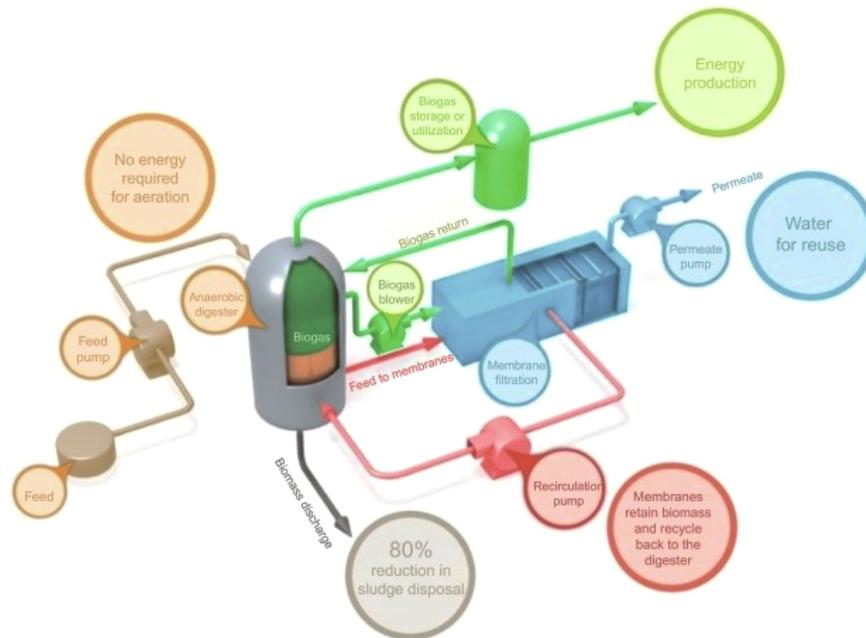


Figure 1: Basic operational design of an AnMBR

In order to have an optimized system, the pores should not be too small as to allow limited influent flow through the pores, but should not be too wide as to allow pollutants or micropollutants to pass through that could compromise the human, environmental, or mechanical system health. Some contaminants that are necessary for removal for a municipal wastewater treatment process are: suspended solids, organic matter (OM), ammonia, nitrates, phosphates, pathogenic bacteria, and micropollutants. Removal of pathogenic bacteria is crucial if the effluent is being discharged into the environment, or will be included in possible bathing areas. AnMBR has a remarkable disinfecting and clarification capability, which can also increase ultraviolet irradiation disinfection processes [9].

The pores of the membrane in question for the purposes of UMass are 0.01 - 0.1 microns in diameter, qualifying as ultrafiltration, and can be seen compared to other filtration methods in the filtration spectrum diagram in figure 2 [10]. Ultrafiltration will completely or significantly reduce bacteria, benzene chlorine, crypto, pesticides, rust, viruses, and odor, and partially reduce algae, chloride, copper, lead, and mercury, while at the same time preserving essential mineral content in the water [10]. Removal of these pollutants and micropollutants will remove hazards such as heavy metals, pesticides, herbicides, pharmaceutical products, and fire retardant chemicals [9] Removal of these various particles will still qualify the water as non potable, but will decrease contaminants that can cause calcification, corrosion, and overall fouling within the pipes. Ultrafiltration operates at a low pressure, applying less stress on the piping. The removal of bacteria ensures the human health safety of the system and the removal of minerals and debris ensures the preservation of the longevity of the system.

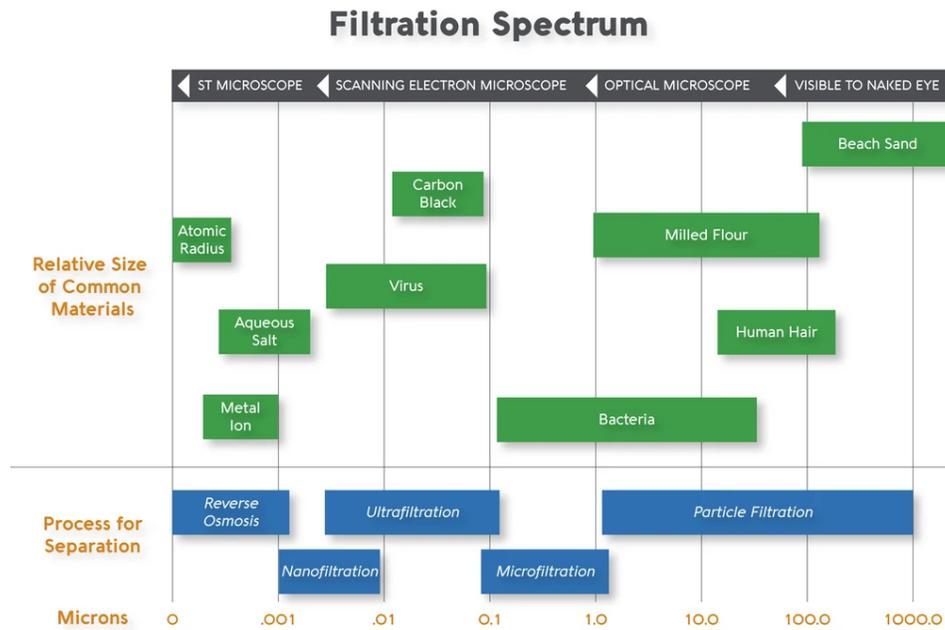


Figure 2: Filtration spectrum depicting separation capabilities in reference to other filtration systems and their respective sizes [11].

The material of the membrane is another vital consideration to the construction of AnMBR. Metallic, ceramic, and polymeric membranes are available, but there are over 80 membrane derivatives from these options on the market, as shown in figure 3. Ceramic is used for more specialized applications, as it is naturally hydrophilic, which resists flocculation. In terms of mechanical proficiency, ceramic membranes are generally inferior, and used for exceptionally acidic or basic environments, or with significant corrosion and abrasion, as they are considerably robust. Ceramic membranes require less frequent cleaning, and remain more resilient under cleaning processes, but are susceptible to cracking because of a higher sensitivity to temperature gradients [10]. For the purposes of UMass which resides in a climate with highly variable temperature, a ceramic membrane is illogical. Metallic membranes exhibit remarkable permeability recovery after fouling, but they can cause surface poisoning, and are much more expensive than polymer, so are primarily used for specialized applications [10 & 14].

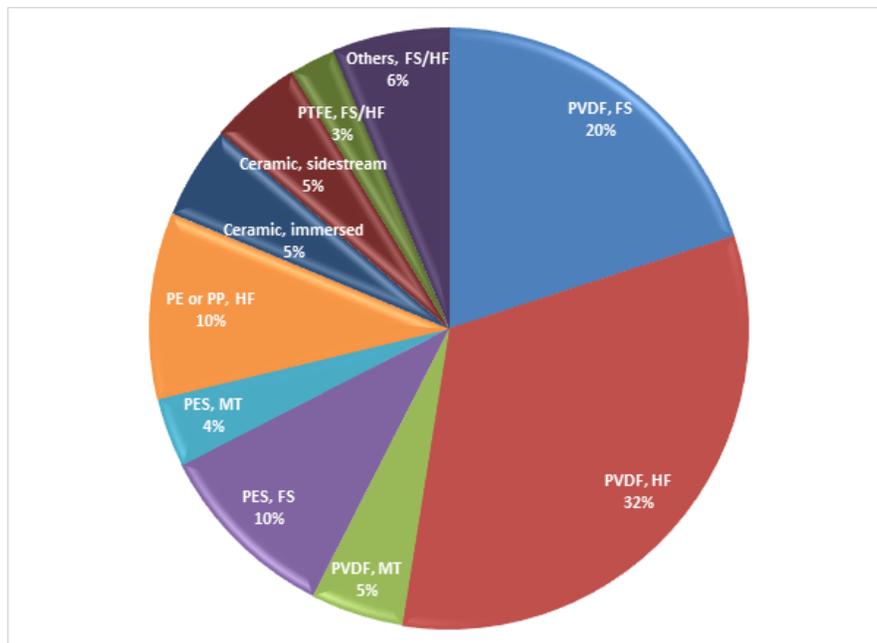


Figure 3: Distribution of possible membrane materials [12].

While polymeric membranes are the weaker adversary compared to ceramic membranes, the purpose is still fulfilled, and at a less expensive cost with more availability. The reason that polymeric membranes are more commonly used is due to their incredible mechanical capabilities, as the elastic nature allows them to stretch. There are many materials a polymeric membrane can be made from, but the most common is polyvinylidene difluoride (PVDF) [12]. Another advantage of polymeric membranes over ceramic is that the pore sizes are more variable, and can be adjusted for the specific municipal wastewater content. Polymers are naturally hydrophobic, stimulating flocculation, but this can be counteracted with a process called “wetting out,” where the pores are treated to be made hydrophilic [12]. For this reason, an AnMBR at UMass should use a polymer membrane, as they are resilient under vast temperature gradients and more cost effective.

With the incursion of influent the membrane is consistently being subjected to, it is wise to integrate a security precaution of some kind to prolong the health and longevity of the membrane itself, as they are the key component to a robust AnMBR. Oftentimes, a screen is used to protect the membrane from abrasive or sharp particles and fiber matting, which can occur from filamentous particle such as cotton or hair fragments. A screen is considered one of the most critical aspects when considering an AnMBR for municipal wastewater treatment. A type of mechanical complication known as “rag formation” is a certain type of fouling, where particles retained by the membrane entangle with fibers, and form matted masses that resemble braids or rags, shown in figure 2. A screen can protect against these extreme cases, and as with all things AnMBR, the type of screen is variable, and can be adjusted to meet the needs of the system.



Figure 4: A membrane that needs immediate attention, due to rag formation [13].

The first consideration when choosing a screen is the size of the pores, and there are three options: coarse, fine, and ultra-fine. Fine screens are typically used for flat sheet membranes, whereas ultra-fine are typically used for hollow fiber membranes. A fine screen has pores about 3 mm wide, whereas an ultra-fine screen has pores typically 2 mm wide. The next consideration is the specific screen design, for which there are several options: spiral-screw gravity-flow stationary screens, through-flow escalator step screens, pumped-flow rotating drum screens, gravity-flow rotating drum screens, center-flow rotating drum screens, and single-entry double-entry and duet drum screens, to name a few. Spiral screw, through-flow escalator, and pumped flow rotational screens are used for coarse screening processes, whereas gravity-flow rotational is optimal for fine or ultra-fine, and single-entry double-entry duet drum screens utilizing both coarse and fine screening. In the *Implementation Specifications* section of this report, the optimal screening method for UMass is deliberated [13].

After the comprehensive physical filtration process, wastewater passes through the membrane, it undergoes the biological filtration process. This is where the production of biogas, a renewable energy source, occurs, coining the term “bioreactor”. Biogas is formed from the

interaction of microorganisms with the OM on the surface of the membrane. Similar to the variety of membranes and screens, there are also a variety of microorganisms that will optimize performance of the system, allowing for maximum biogas production and overall health of the microorganisms. Selecting the correct microorganisms for the system is essential, otherwise complications can occur, such as: process overloads, variations in acidity, toxicity, foaming, rheological changes, and membrane surface fouling and clogging. Process overloads would be catastrophic, as this would mean the system is overloaded with wastewater and unable to process it all with adequate speed, but wastewater treatment facilities are designed to compensate for maximum influxes in wastewater. Toxicity can cause toxic shocks which decrease biological activity [14], and variations in acidity can have the same effect on biological activity. Foaming can reduce oxygen transfer, biomass concentration within the bioreactor, and can increase maintenance costs [15].

Implementation Specifications

As discussed in the solution section, there are multiple types of membranes, offering options so UMass can utilize one that is optimal for the specific wastewater inducances. Polymer is the best material for a membrane to serve the purposes of UMass, considering they are less expensive than ceramic and metallic, can withstand extreme temperature gradients, and have a variety of pore sizes and configurations to choose from. Polymer membranes are typically derived from polyvinylidene difluoride (PVDF), but can include other types such as, but not limited to: Polyethersulfone (PES), polyethylene (PE), polypropylene (PP), and polysulfone (PSF) [8]. While it is important to consider that polymer membranes have lower permeability and are less stable compared to ceramic or metallic membranes under consistent chemical

cleaning processes, with a side-stream system configuration, where the membrane is outside of the bioreactor (and will be addressed in this section), cleaning will be less frequent, thus ceramic or metallic membranes are not necessary [16].

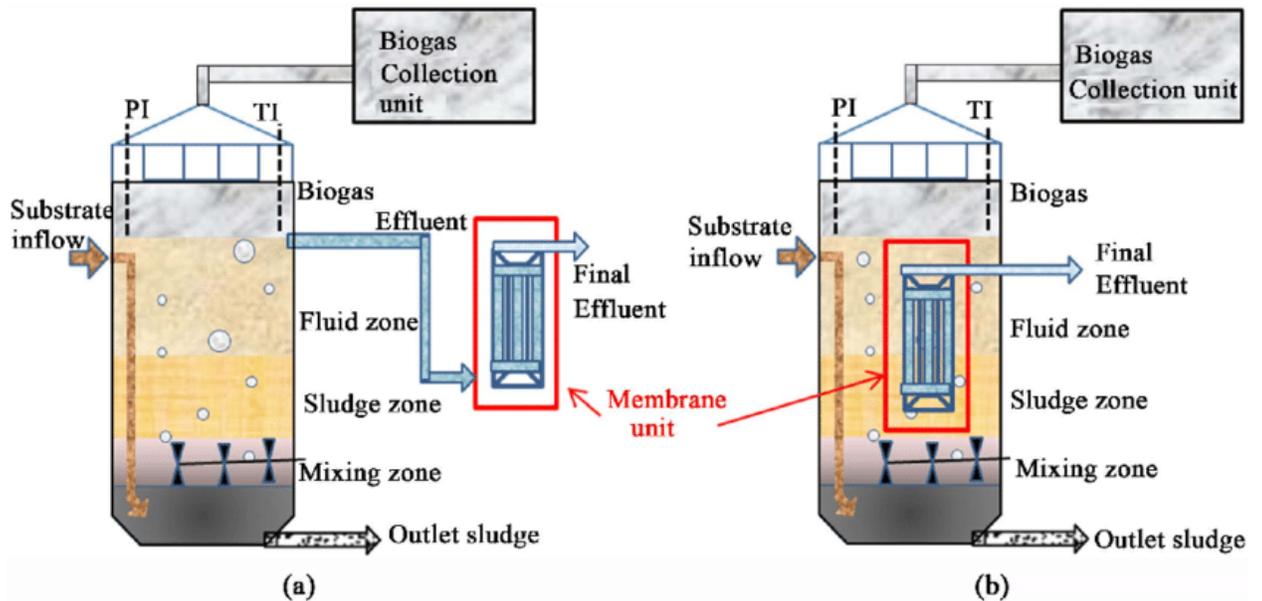


Figure 5: Different membrane configurations of an AnMBR. Shown on the left, (a), is the side-stream configuration, and shown on the right, (b) is the submerged configuration [17].

Another aspect for consideration is the system configuration of the membrane within the bioreactor. There are two types of configurations: Side-stream, and submerged. The submerged membrane utilizes a vacuum chamber to pass the influent through the membrane. Using a vacuum requires no energy in order to move the influent through the membrane. However, this method requires complete disruption of the filtration process in order to provide chemical cleaning of the buildup of debris, known as filtration cake, that forms on the membrane over time. In the submerged configuration, formation of a cake and flocculation can also occur more quickly, due to the lower shear force from the cross velocity of the water passing over the membrane. Overall, a side stream configuration offers more benefits in terms of maintenance while still providing sufficiently proficient performance.

The side-stream configuration of the membrane locates the membrane outside of the bioreactor. This requires use of a recirculation pump to pass the influent through the membrane, using more energy than the submerged membrane. While this uses more energy, having the membrane located outside of the bioreactor allows for access for cleanings and maintenance without complete disruption of the filtration process. The cross velocity passing over the membrane creates a higher shear force which allows flocculation and cakes to form more infrequently, and less substantially, requiring less maintenance. For this purpose, UMass should use the side-stream configuration, despite the slightly higher energy usage.

As addressed in the solution section of this paper, a screen is vital to protect the membrane from rag formation and abrasives. There are two things to consider when choosing a protective screen: Size of solids in the influent, and flow velocity of the influent. Given that there isn't adequate information yet about the flow velocity or the concentration of solids in the UMass influent, this is a wet-finger-in-the-air estimate that can be explored further in the future. The screen system our team deemed optimal is pumped-flow rotary drum screens. This method, shown in figure 4, has been used for municipal wastewater treatment. This design keeps any captured debris totally contained, as opposed to not totally contained, where there is opportunity for the debris to move onto the next step of filtration. Pumped-flow rotary drum screens are optimal for high solid concentration and low flow velocity, as the allowable flow rate is not variable because it is totally contained. If these standards are not found to be true for UMass, another screen system must be evaluated.



Figure 6: Pump-flow Rotary Drum Screens [13].

Benefits and Drawbacks

LTHW has much to offer for our campus and its effort to achieve a net zero carbon footprint, the first and foremost upside being energy efficiency. LTHW could help UMass diminish the immense amount of wasted heat through steam, and make one of the most energy expensive infrastructures a more thermodynamically cyclical and wasteless system. As the pinnacle of UMass energy usage, retrofitting the CHP with an efficiency enhancement such as LTHW is crucial to achieving net zero without decommissioning the CHP.

The primary burdens of the implementation of LTHW come from the developmental phases. A bulk of the renovation required is in the piping infrastructure. As a result, necessary digging and subterranean construction will need to take place. In a similar project at Stanford, the Stanford Energy System Innovations (SESI), the university found that less than half of their current steam piping was reusable for hot water infrastructure, indicating that UMass would need to leave their steam pipes where they are in the ground and invest in new pipes [18]. Furthermore, like any infrastructural change, a significant sum of capital investment is required. However, estimates claim the return on investment for LTHW could span just 10 years, as LTHW can save hundreds of thousands of dollars annually on energy costs [4]. Finally, LTHW

pipes tend to operate at a higher efficiency than steam pipes, coming equipped with better insulation and valves [18].

Compatibly, one great benefit of using the AnMBR is that maintenance is accessible and safer than the current steam lines. LTHW are shallower and less volatile than streamlines, so repairing leaks in these is less dangerous [18]. Additionally, despite fouling being a major concern, the side stream configuration allows access more readily to the membrane and a simple chemical treatment can remove debris. Another great benefit of an AnMBR is the production of biogas. This biogas could potentially be used to create a self-sustainable water treatment facility on campus. This would be the primary location where grey water is filtered to be used in LTHW lines. It could also potentially help reduce the CHPs dependence on non-renewable fuels. Once the CHP is fully transitioned away from burning natural gasses, this biogas could be sold as carbon offsets to other off-campus entities.

Looking ahead, LTHW shows promise in aiding the CHP in keeping heat distribution efficient; the system is reliable, modular, and can adapt to further retrofitted adjustments within heating and cooling infrastructure. However, AnMBRs are a relatively new technology. There is little research of these filters functioning at municipal scales. This means there is some risk involved and UMass would need to invest in research and development of this specific technology on campus in order to reap its benefits.

Conclusion

By retrofitting the CHP with the combined LTHW distribution and AnMBR reclaimed wastewater, UMass could see 28.7% of its carbon emissions reduced [1]. The ultimate goal of supplying campus with more sustainable heat must be met by tackling an underlying burden; the excessive water consumption of the proposed LTHW system. This water usage is a significant

impediment to the long term mission of mitigating resource consumption, and by using an AnMBR to reclaim and recycle campus sourced wastewater, we can both decrease the water consumption and wasted energy of the CHP. Granted this concept is unprecedented, the potential for its impact on our campus is immense; as a result more research on the implementation of LTHW and AnMBR hybrid systems is necessary. While the costs and necessary investment to renovate the CHP with the proposed solution are high and pose questions about its realistic efficacy [3], UMass has the opportunity to incorporate an innovative solution to college campus heating, and can serve as a model for other institutions and communities beyond the scope of just our region. The potential benefits for further research for possible implementation greatly outweigh the potential drawbacks, and breaking barriers as a university and community will go a long way for UMass and the innovating world around it.

Appendix

Calculations

The following calculation was to determine the increase in water mass circulated through a LTHW system compared to the water mass circulated in the steam system.

Reference 19 indicates that the CHP runs at 75% energy efficiency, with that higher-than-normal efficiency coming from the cogeneration of steam and electricity. Reference 19 also indicates that the maximum steam generation capacity is 475,000 lbs/hour. To estimate actual steam generation rates, we assume this 75% value also applies to steam generation, giving an estimated actual steam generation rate of 356,250 lbs/hour.

Prediction: Water Consumption for Steam

Thermodynamic equation used:

$$Q = m c \Delta T$$

Temperature of steam = T high = 100 C

Temperature of returning water = T low = 12 degree C

Specific heat capacity of steam = c = 4.184 (J/g*C)

Mass of water circulated in current steam system = 356,250 lbs/hr

Conversion using conversion factors:

$$m = 356,250 \text{ lbs/hr} (1 \text{ kg} / 2.2\text{lb}) = 161,931 \text{ kg/hr}$$

$$161,931 \text{ kg/hr} (1000\text{g} / 1 \text{ kg}) = 162,000,000 \text{ g/hr}$$

$$Q = 162,000,000 \text{ g} (4.184 \text{ J/g}\cdot\text{C}) (12 \text{ C} - 100 \text{ C})$$

$Q = -60,000,000,000 \text{ J/hr}$ This will be used in the following calculation to find the mass of liquid water circulated in the LTHW system, assuming the CHP efficiency stays at 75% its capacity.

Prediction: Water Consumption for LTHW

Thermodynamic equation used:

$$Q = m c \Delta T$$

Temperature of hot water = $T_{\text{high}} = 65 \text{ C}$

Temperature of returning water = $T_{\text{low}} = 12 \text{ C}$

Specific heat capacity of liquid water $C = 4.148 \text{ (J/g}\cdot\text{c)}$

$$-60,000,000,000 \text{ J} / (4.148 \text{ J/g}\cdot\text{c}) (12 \text{ C} - 65\text{C}) = m = 271,000,000 \text{ g/hr}$$

Conversion using conversion factors:

$$271,000,000 \text{ g/hr} (1 \text{ kg} / 1000\text{g}) = 271,000 \text{ kg/hr}$$

$$271,000 \text{ kg/hr} (2.2 \text{ lb} / 1 \text{ kg}) = 596,000 \text{ lbs/hr}$$

The steam system circulates 356,250 lbs/hr of steam whereas the LTHW theoretically circulates 596,000 lbs/hr. The switch between systems appears to cause an increase in circulated water.

According to a report from the American Society of Heating, Refrigerating, and Air-Conditioning, in a study that compared water usage of buildings before and after retrofitting to LTHW systems from steam, there was a 79% decrease in water use [20]. This is related to the entire building, so it may be an assumption that the retrofit was entirely responsible for this observation, however, these calculations prove that the amount of circulated water does increase. The decrease in water utilization may be due to the increased efficiency of the LTHW system, or easier maintenance, fewer leaks and condensate.

References

1. Small, E. Breger, D. “Academic Call to Action” *Carbon Mitigation Plan*, Rep. UMass Amherst (Jan 2020).
2. Allen, Lucy, et. al. “Overview of Greywater Reuse: The Potential of Greywater Systems to Aid Sustainable Water Management” *Pacific Institute*, (2010). Available at https://pacinst.org/wp-content/uploads/sites/21/2013/02/greywater_overview1.pdf
3. Li, Wen-Wei. “Advances in Energy-Producing Anaerobic Biotechnologies for Municipal Wastewater Treatment” *Engineering*, vol. 2-4 (2016); 438-466. Available at <https://doi.org/10.1016/J.ENG.2016.04.017>
4. Phetteplace, G. “Efficiency of Steam and Hot Water Heat Distribution Systems” *CRREL Report*, vol. 95-18 (1995): 1-32. Available at <https://apps.dtic.mil/dtic/tr/fulltext/u2/a302338.pdf>
5. Griffiths-Sattenspiel, B. Wilson, W. “The Carbon Footprint of Water” *A River Network Report*, (2009); 1-54. Available at <http://www.solaripedia.com/files/1332>
6. University of Massachusetts, Amherst. “16-MW CHP & District Energy System.” *U.S. DOE, Clean Energy Application Center*, (2012). Available at <https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=0a084df3-3df5-35f4-c101-a9a9ae730937&forceDialog=0>
7. Judd, Simon. “MBRs -- towards zero energy and zero waste” *The MBR Site*, (2014). Available at <https://www.thembrsite.com/blog/membrane-bioreactors-towards-zero-energy-zero-waste/>
8. Bokhary, Alnour, et. al. “Anaerobic membrane bioreactors: Basic process design and operation” *Current Developments in Biotechnology and Bioengineering*, (2020); 25-54. Available at <https://doi.org/10.1016/B978-0-12-819852-0.00002-6>
9. Judd, Simon. “MBRs for municipal for wastewater treatment” *The MBR Site*, (2017-2021). Available at <https://www.thembrsite.com/membrane-bioreactors-for-municipal-wastewater-treatment/>
10. MEP Associates. “Final Report” *Carbon Mitigation Plan*, Rep. UMass Amherst (Jan 2021).
11. “Membrane Materials: Organic v. Inorganic” *Synder Filtration*, (2021). Available at <https://synderfiltration.com/learning-center/articles/introduction-to-membranes/membrane-materials-organic-inorganic/>
12. Judd, Simon. “The material question -- choosing MBR membrane materials” *The MBR Site*, (2017). Available at <https://www.thembrsite.com/blog/the-material-question-choosing-mbr-membrane-materials/>
13. Impero, James & Hammler, Kevin. “MBR Screening Part 1: MBR screen designs and performance - an overview” *The MBR Site*, (2015). Available at

- <https://www.thembrsite.com/features/membrane-bioreactor-screening-part-1-mbr-screen-designs-and-performance-an-overview/>
14. Woodard, John. "What is Ultrafiltration? How an Ultrafiltration Membrane Works" *Fresh Water Systems*, (2019). Available at <https://www.freshwatersystems.com/blogs/blog/how-an-ultrafiltration-membrane-works>
 15. Collivignarelli, Maria Christina, et. al. "Foams in Wastewater Treatment Plants: From Causes to Control Methods" *MDPI Applied Sciences*, vol. 10-2716 (2020); 1-2. Available at <http://dx.doi.org/10.3390/app10082716>
 16. Woodard, John. "What is Ultrafiltration? How an Ultrafiltration Membrane Works" *Fresh Water Systems*, (2019). Available at <https://www.freshwatersystems.com/blogs/blog/how-an-ultrafiltration-membrane-works>
 17. Jain, Meenu. "Anaerobic Membrane Bioreactor as Highly Efficient and Reliable Technology for Wastewater Treatment -- A Review" *Scientific Research Publishing: Advances in Chemical Engineering and Science*, vol. 8 (2018); 82-100. Available at <http://www.scirp.org/journal/aces>
 18. Kearney, Joe. "Stanford Energy System Innovations (SESI) Program: Steam to Hot Water Conversion" *Stanford Energy System Innovations*, Rep. Stanford University (2018). Available at https://sustainable.stanford.edu/sites/default/files/documents/SESI_Hot_Water_-_Steam.pdf
 19. University of Massachusetts, Amherst. "16-MW CHP & District Energy System." *U.S. DOE, Clean Energy Application Center*, (2012). Available at <https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=0a084df3-3df5-35f4-c101-a9a9ae730937&forceDialog=0>
 20. Sharpio, Ian. "Water & Energy Use in Steam-Heated Buildings" *ASHREA Journal*, (2010). Available at <https://www.taitem.com/wp-content/uploads/SteamBoilerReplacements.pdf>