UnWastewater

Revolutionizing Wastewater Treatment Through **MES**

WEGE PRIZE

SOLUTION SUMMARY

With the cycle of nature as its model, the premise of a circular economy is to create a world without waste by designing closed loop systems that maximize efficiency, reduce waste and promote sustainability. To realize this ambitious vision, UnWastewater aspires to revolutionize the treatment of domestic wastewater by utilizing microbial electrosynthesis (MES), a novel method of biochemical carbon capture and utilization, to valorize domestic wastewater into organic chemical feedstocks, and, ultimately, protect and regenerate the environment.

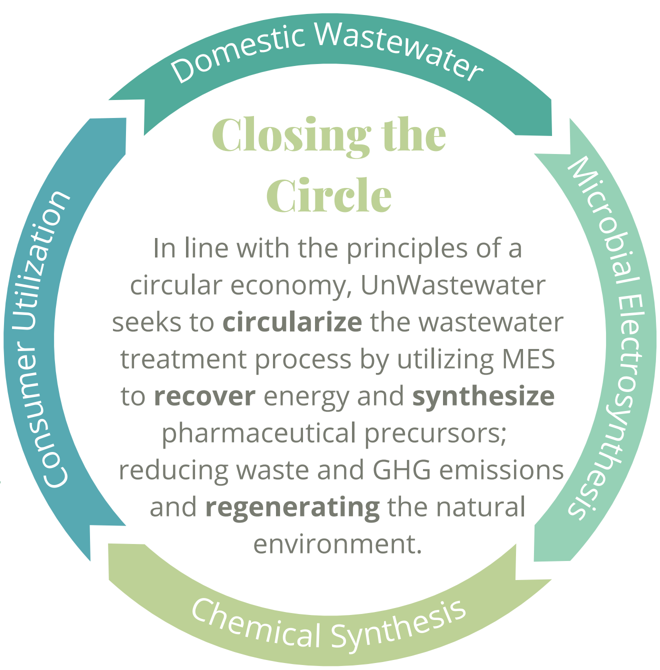
OUR OBJECTIVE

We believe that MES is poised to trigger disruptive innovation in the water treatment sector. We envision domestic wastewater valorization as a means to advance industry-wide decarbonization efforts while maintaining water quality standards critical to environmental and human health. Our objective is to conduct a MES pilot study in a domestic wastewater treatment plant (WWTP). In particular, we intend to retrofit existing treatment plants and target highly concentrated sludge recirculation streams that are already challenging to treat via conventional methods. Ultimately, we anticipate that MES will become an integral part of the wastewater treatment process.

This illustration represents how a wastewater treatment can be circularized to accomplish both energy recovery and waste reduction.

First, waste is excreted into domestic plumbing, which then flows as wastewater to a local centralized treatment facility.

Typically, this wastewater would likely be treated via activated sludge (AS), an energy intensive and GHG-emitting process.



MES would work with, or independently from AS, to allow electroactive microorganisms to oxidize organic matter and reduce carbon dioxide into industrially relevant products such as pharmaceutical precursors.

This novel carbon capture and utilization method would mitigate emissions, and reduce dependence on fossil fuels for the manufacturing of chemical feedstocks.

OUR **TEAM**

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Materials Science & Engineering, Molecular and Cell Biology

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Computer Science, Mathematics

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GLOBAL CLIMATE **GOALS**

The 2015 Paris Climate Agreement identified wastewater treatment as critical to achieving transformative climate action. According to the Climate Action Pathway Vision Statement, harnessing the embedded energy and nutrient content of wastewater will enable the decarbonization of the water sector and circular reuse of wastewater globally.

5% "Currently, wastewater accounts for ~5% of the global total non-CO2 GHG emissions" — **Ren & Pagilla, 3**

Currently, wastewater treatment is costly and the energy demands, primarily for aeration, dominate municipal energy budgets. New York City alone spends over $540 million on wastewater treatment which corresponds to an annual electricity usage of ~480 GWh.

3% "Wastewater treatment could account for up to 3% of global electricity if treated with conventional technologies" — **Lu et al., 750**

The environmental impact of conventional wastewater treatment plants (WWTPs) is inconsistent with the sustainability priorities of the United Nations, and a classic example of an industry that urgently needs to be re-conceptualized and redesigned to operate as a carbon neutral, circular system.

Sludge, a toxic by-product of conventional wastewater treatment, is a significant challenge for WWTPs. Under the current paradigm with existing technology, wastewater is exactly what it sounds like: **WASTE**. MES can transform this waste into commercially viable products and harvest the embedded energy, effectively closing the loop on wastewater treatment.

10x "Wastewater contains... around 10 times more energy than is currently used to treat it" — **Aiken et al., 2426**

SUSTAINABLE DEVELOPMENT GOALS

Over **2 billion** people lack safe drinking water and more than **4 billion** are impacted by poorly managed sanitation. Consequently, there is a desperate need to modernize sanitation infrastructure and **MES offers an excellent opportunity** to transform water treatment from an economic liability into an economic asset. Policymakers may have interest in incentivizing adoption of MES technology toward achieving domestic and international goals.

The renewable energy transition is a **global priority**, and energy recovery from wastewater via microbial electrochemical technologies (METs), such as MES, could be a game changer for the actualization of the **circular economy**. Conventional wastewater treatment accounts for up to **40%** of municipal energy budgets. Accessing the latent chemical energy in wastewater using METs could dramatically **reduce fossil fuel dependence** for chemicals and energy.

Fuels, **plastics**, **fertilizers** and **solvents** are just a few examples of everyday products derived from fossil fuels. As climate change intensifies and resource availability tightens, quality of life will be predicated on shifting to more sustainable production practices. The flexibility of the MET platform, and MES specifically, promises to **catalyze innovation** concerning feedstocks for sustainable production and alternative supply chains.

OUR VISION

Advances in MES technologies will transform the wastewater treatment industry into a hub for sustainable manufacturing and energy recovery aiding the transition to a net-zero carbon economy.

THE **WICKED** PROBLEM

Conventional Wastewater Treatment is Ripe for Innovation

- Conventional technologies are antiquated, largely unchanged since their inception in early twentieth century.
- Activated Sludge is an inefficient linear system, which is costly to operate and energy intensive.
- The current approach produces significant GHGs, which is unsustainable and inconsistent with the UNSDGs.

HEALTH

- **Inadequate wastewater infrastructure and contaminated water cause a variety of preventable, often severe, human health risks.**

ENVIRONMENT

- **The current activated sludge process is GHG intensive and a localized source of gross CO2 emissions contributing to climate change.**

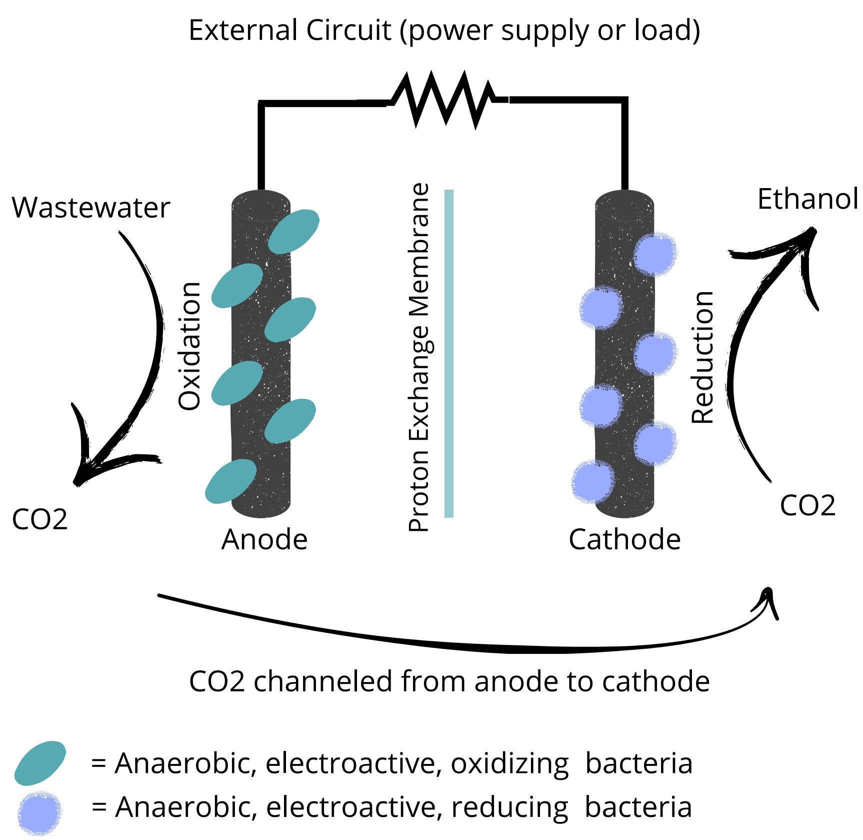
ECONOMIC

- **Only 20% of global domestic wastewater is treated; treatment is an economic burden on many communities.**

OUR **INNOVATIVE** SOLUTION

Domestic Wastewater Microbial Electrosynthesis (MES)

- Represents a paradigm shift rebranding wastewater as a resource for biomanufacturing and carbon capture.
- Utilizes latent chemical energy to produce valuable chemicals, reducing fossil fuel dependence.
- Can be retrofitted to existing infrastructure to minimize sludge production and mitigate management issues.
- Incentivizes communities with inadequate sanitation to establish or upgrade wastewater treatment facilities.

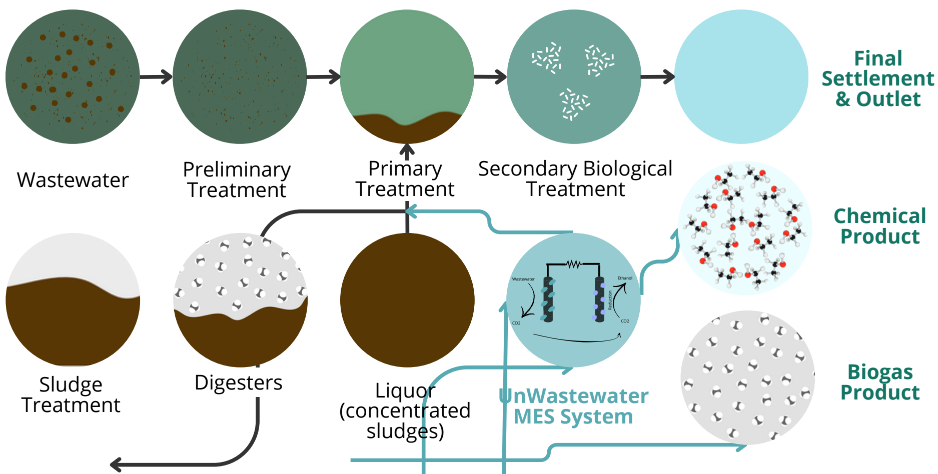


HOW **MES** WORKS

Microbial electrosynthesis refers to the synthesis of organic chemical compounds by combining electrochemical reactions with the metabolic pathways of microorganisms. This process is perfect for wastewater treatment given the latent chemical energy that it contains. In this application, the organic content of wastewater is oxidized into carbon dioxide at the anode of an electrochemical cell, releasing energy in the form of free electrons. The CO2 is then channeled from the anode to the cathode where the electrons drive a reduction reaction to convert the CO2 into **value-added products**, such as acetic acid, ethanol, butanol, formic acid and hydrogen gas. In order to ensure product purity and reactor efficiency, the anode and cathode chambers are separated by a proton exchange membrane.

EMBRACING THE **CIRCULAR** ECONOMY

MES integration in Existing Treatment



- The UnWastewater solution seeks to eliminate waste by capitalizing on the latent potential of sewage liquor (concentrated sludges), **decreasing** the energy and carbon burden of aerobic respiration, which consumes 66% of the energy, and is the primary emission step.
- Our MES system uses established renewable biogas infrastructure in wastewater plants to decrease its GHG footprint.
- We plan to integrate Unwastewater's MES directly into the liquor line to maximize environmental and financial impact and decrease MES costs.

COMPETITOR TECHNOLOGIES

"Microbial electrochemical technologies" (METs) is an umbrella term that encompasses microbial fuel cells (MFC), microbial electrolysis (MEC), and microbial electrosynthesis (MES). These technologies share a similar architecture: an anode and cathode chamber separated by a membrane and an external circuit that either supplies or harvests power depending on the application. The tables below describe these technologies as well as conventional wastewater treatment methods such as Anaerobic Digestion, Activated Sludge, and Natural Treatment.

Table 1a. Competitor Technologies

Acronym	Description	Companies
MES	**Microbial Electrosynthesis** pairs anodic wastewater oxidation with microbe mediated cathodic CO2 reduction to synthesize organic compounds.	Not Commercialized (mature for field pilot testing)
MEC	**Microbial Electrolysis Cells** pair anodic wastewater oxidation with cathodic water reduction to generate hydrogen.	Not Commercialized (Pilot testing in progress)
MFC	**Microbial Fuel Cells** pair anodic wastewater oxidation with cathodic oxygen reduction (into water) to generate electricity.	• Aquacycl • MicrOrganics • Cambrian Innovation

Table 1b. Conventional Technologies

Acronym	Description	Companies
AD	**Anaerobic Digestion** uses anaerobic methanogens to convert organic compounds in wastewater into methane.	• Anaergia • Veolia • BioFerm Energy
AS	**Activated Sludge** uses aerobic bacteria to convert organic compounds in wastewater into carbon dioxide.	• EcoLogix • Danaher
NT	**Natural Treatment** uses microbes available in wetlands to sequester organic compounds in wastewater or convert them into methane.	• Microbial Discovery Group (MDG) • MicroBio Corp

One advantage of MES is that it can be paired with conventional technologies, a synergy which UnWastewater intends to explore as a first step in the process of industry adaptation. By focusing our initial efforts on concentrated sludge liquors as opposed to raw intake, we hope to establish credibility and a foothold in the water treatment sector.

What sets MES apart from competing and conventional technologies is that MES allows for the mediation of cathodic reduction reactions by a variety of biological agents, greatly expanding the possible products that can be synthesized and hence the value that can be extracted from the system.

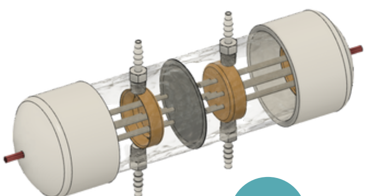
Ultimately, we intend to target the production of statin precursors due to their high market value in order to offset the high material costs associated with kickstarting a nascent field. Such precursors can aid in the cost reduction of critical drug therapies. *Lipitor*, for example, is a cholesterol-moderating statin deemed essential medication by the World Health Organization.

PERSPECTIVES, LEARNING AND **OUTREACH**

Table 2a. Academic Mentors & Consultants	
Jason Ren, Water and Energy Technologies (WET) Lab Director, *Princeton University*	Professor Ren serves as the primary academic mentor for our team. His research on microbial electrochemistry has greatly informed our approach to prototyping.
Yanhong Bian, WET Lab Member, *Princeton University*	A leading researcher on wastewater MES, Yanhong's advice has been instrumental in refining the design of our electrochemical cells.
Bruce Rittmann, Swette Center for Biotechnology Director, *Arizona State University*	A pioneer in the field of microbial electrochemistry, Professor Rittmann offers our team invaluable insight into the history of the field and contemporary research.
Table 2b. Industry Mentors & Stakeholders	
Bonnie Hacking, Entrepreneurship Centre Manager, *University of St. Andrews*	Ms. Hacking has provided our team with guidance on developing a successful business model and information on successful startup strategies.
Sofia Babanova, Co-founder & Chief Technology Officer, *Aquacycl*	Dr. Babanova has shared valuable lessons related to MET commercialization based on her experience scaling-up microbial fuel cells at Aquacycl.
Kyle Stewart, Assistant Plant Manager, *Stony Brook Regional Sewerage Authority*	Mr. Stewart has provided the UnWastewater team with tours of the SBRSA, and is open to the idea of an on-site demonstration project.
Ken McKay, Process Controller, *Scarborough Wastewater Treatment Facility*	Mr. McKay has provided the UnWastewater team with tours of the SWTF and is open to the idea of an on-site demonstration project.
Ijeoma Nwagwu, Office of Sustainability Assistant Director, *Princeton University*	Dr. Nwagwu manages the High Meadows Sustainability Fund, a grant program for student-led sustainability initiatives, supportive of the our team application.
Paul Banfield and **Duncan Ord**, Technical Mangers at Veolia Environment S.A.	Mr. Banfield and Mr. Ord shared insights into the future of wastewater treatment. Mr. Ord gave the team a tour of the Hatton wastewater treatment facility.

In order to better assess the market landscape and develop an understanding of the feasibility of this technology, the UnWastewater team conducted interviews with mentors and stakeholders throughout academia and industry. Based on these expert's insights, we refined our product design and are now actively testing our prototype.

PROGRESS REPORT



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PROTOTYPE EVOLUTION

(1) Our initial electrochemical cell design was inexpensive and simple, but inefficient. (2) The prototype based on this design served as a proof of concept. (3) Based on feedback from mentors and stakeholders (See Table 2), we refined the cell design with an emphasis on modularity to facilitate scale up. (4) We invested in more efficient materials, such as carbon felt electrodes and commercial proton exchange membranes, to make our cell longer-lived and circularly recoverable. (5) The prototype cells have been inoculated with bacteria cultures and we are ready to begin testing on wastewater.

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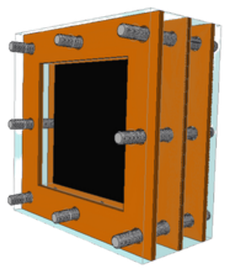

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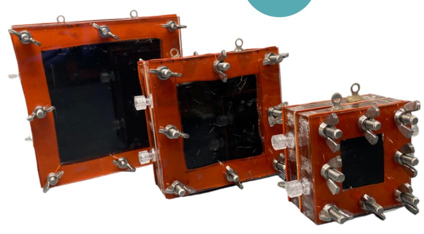

MATERIAL **RECOVERY** AND **CIRCULARIZATION**

Table 3. Prototype Budget To Date

COMPONENT	Total Cost
2 x Acrylic Sheet 12" x 12" x 1/4"	18.38
1 x Acrylic Sheet 12" x 12" x 45/64"	42.6
2 x Silicone Rubber Sheet 12" x 12" 1/16"	81.74
2 x ft Steel Threaded Rod 1/4"-28, 3"	20.82
4 x Steel Wing Nut, 1/4"-28	40.92
10 x Steel Threaded Rod 1/4"-28, 1'	29.1
Plastic Quick-Turn Tube Coupling, 3 x Sockets	16.02
Plastic Quick-Turn Tube Coupling, 3 x Plugs	17.73
Plastic Quick-Turn Tube Coupling, 3 x Polycarbonate Plastic Caps	11.13
2 x 50GPH 3W Mini Water Pump	23.18
1 x Clear Vinyl Tubing, 25' x 1/8"	11.99
4x Activated Carbon Felt Sheets (1600) 0.078" x 8.5" x 11.75"	128.00
Proton Exchange Membrane	200.00
Titanium Wire (24 gauge), 25'	8.95
OVERALL COST	$650.56

Table 3 highlights the structural components utilized for our Phase III prototype. These materials were selected based on the recommendations of our academic mentors and with a focus on the principles of a circular economy. Our goal is to ensure that our electrochemical cells are robust and that structural components are recoverable for reuse. We designed our reactors to be modular so that if one cell becomes defective other cells remains functional. Our research regarding the design of durable electrodes and proton exchange membranes that can resist biofouling is ongoing.

MATERIAL **SOURCING**

Wastewater is the primary material necessary to test and refine our solution. To date companies in the MET space have focused on treatment of wastewater with heavy biological loads (such as from breweries and industrial facilities). We, however, plan to focus our work on **domestic wastewater** because it is abundant, available without cost, and represents the largest untapped market for MET technologies. We believe that successful field demonstration of our design and infrastructure will catalyze community and industry support for MES.

As a part of our ongoing community engagement efforts, we are negotiating pilot testing with the Scarborough Wastewater Treatment Facility in Narragansett, RI and the Stony Brook Regional Sewerage Authority in Princeton, NJ. We are also seeking to integrate our systems in a larger pilot study via the Private Finance Initiatives in the UK.

> "The best way to involve the general public and to gain its support and acceptance is through **successful demonstration projects.**"
> — Saad et al., 258

FROM PROTOTYPE TO **PROFIT**

PHASE 1

UnWastewater is seeking sources of funding to develop an effective pilot study. We are currently engaging in outreach to WWTPs and pharmaceutical ventures to build industry partnerships. Since our pursuit is collaborative and academic, we are interested in establishing partnerships with any and all relevant actors .

PHASE 2

We will seek to scale up our technology and lease our system to WWTPs at subsidized rates. WWTPs can offset system costs via sale of chemical feedstocks and pharmaceutical precursors and earn carbon offsets.

PHASE 3

As we grow, we intend to align with the WWTP industry to to develop synthetic biologies to increase efficiency and create novel products. We hope to cultivate partnerships in communities that lack wastewater treatment infrastructure to enable afford-able and effective sanitation.

In order to refine our business concept, we consulted with the St. Andrews Entrepreneur Centre and technical managers at various WWTPs. Upon pilot study system validation, we intend to incorporate as a benefit corporation and seek intellectual property protection, lease our MES system and propriety microbial cultures to domestic WWTPS, and monetize our maintenance and consulting services.

OUR **BUSINESS**

To facilitate the transition from a linear to circular economy, Unwastewater intends to collaborate with major domestic wastewater companies, such as Veolia, and regional treatment plants, such as SBRSA, to develop tailored MES systems that we can license to individual treatment plants. Following installation, we envision ourselves serving as contracted technicians and consultants for the MES system, developing novel bacterial strains for product specialization and building partnerships between WWTPs and chemical manufacturers.

SWOT ANALYSIS

STRENGTHS

- MES valorizes waste products offsetting treatment costs
- MES offers flexible product development
- Sizable market potential for chemical precursors
- MES can be retrofitted to augment existing infrastructure
- MES can lead to carbon neutrality or even carbon negativity
- Lower energy costs than conventional AS and AD

WEAKNESSES

- Nascent technology; research and development ongoing
- Currently high material and operational energy costs
- Lack of empirical data regarding financial feasibility; need for pilot scale demonstration studies
- Electrogenic biofilm maintenance
- Requires development of remote sensing software

OPPORTUNITIES

- Policymakers may incentivize industry adoption to meet emissions targets and climate goals.
- Direct competitors are focused on industrial wastewater
- Market gap is advantageous to market entry of our MES
- Reusable materials could reduce capital costs
- Social and governmental pressure to achieve net-zero

THREATS

- Competitors are pre-established with tested systems
- Initial investment costs deterrent to commercial adoption
- Uncertainty regarding financial competitiveness with existing technologies
- Competitive technology development
- Unsustainable monetization of MES wastewater treatment

BUSINESS **BREAKDOWN**

KEY PARTNERS

- Academic institutions
- Biomanufacturing and waste water companies (Veolia)
- Indirect Competitors (Aquacycl, MicrOrganics)

KEY RESOURCES

- Repository of proprietary modified bacterial strains
- Connections to academic/industry advisors and WWTP companies
- Connections to material/equipment suppliers
- Ongoing R&D funding resources

KEY ACTIVITIES

- Develop and supply patented strains of electroactive microbes capable of value-added chemical production
- Maintain MES units, replenish bacteria stocks, servicing and consulting
- Ongoing system and product development
- Negotiate partnerships between WWTPs and chemical manufacturers

VALUE PROPOSITIONS

- Cost offset for wastewater treatment
- Creates value added products from waste
- Satisfies policymaker's objectives on CO2 emissions reduction (UK 2030 Wastewater Carbon Neutral Mandate)
- Shifts WWTP from a treatment facility to a value-added biomanufacturing facility

REVENUE STREAMS

- Early Stage: selling the system and basic cultures to waste water plants
- Late Stage: recurring stream of revenue would come from leasing out patented biosynthetic strains creating complicated products such as Vinblastine (a chemotherapeutic validated to be able to be completely biosynthesized)

CUSTOMER RELATIONSHIPS

- Direct customer contact to maintain microbial cultures and gaining feedback for system optimization
- MES cell is sold to domestic wastewater plant
- Third party manufacturer of the MES cell

CHANNELS

- Distribution and manufacturing channels
- Large Wastewater companies

COST STRUCTURE

- Primary costs are research and development
- Intellectual property expenses
- Cost of unit production

CUSTOMER SEGMENT

- Domestic wastewater management companies such as Veolia (3,299 plants)
- Local municipalities
- Pharmaceutical and manufacturing companies

POTENTIAL **BARRIERS** TO MARKET ENTRY

PERCEPTION

After discussions with Veolia technical managers, one of the major hurdles with monetizing wastewater is a negative consumer perception of products from waste. However, we can improve this perception through public outreach and the successful integration of MES into waste-water treatment.

LONG TERM SUITABILITY

Potential failure points in our business model would stem from unsustainable monetization of the MES prototype. Key criteria to accurately valuing the prototype include the cost effectiveness and scalability of MES cells and the cost of manufacturing system components. Given the public pressure on treatment companies like Veolia to reach net zero, WWTPs are open to incorporating new treatment technologies to mitigate emissions and reach these goals.

FINANCIALS

The expense of materials is a hurdle for MES given the high upfront cost of current collectors and membrane materials. However, material costs may be offset by operation and product production. MES is cost competitive for hydrogen gas, which supports projected profitability for other products. Future cost savings measures may include creating a single chamber (membrane-less) design that eliminates the risk of biofouling.

RELIABILITY

The modern wastewater treatment industry prefers long lived and reliable systems. Thus demonstration and pilot-tested systems are necessary to gain industry confidence. Robust evidence of reliable performance, economic feasibility and scalability is needed prior to industry marketing.

SOLUTIONS

Scaling MES technology requires innovation in manufacturing, biochemistry and remote sensing software. Given the interdisciplinary nature of our team, this is a challenge that we are well equipped to address. Specifically, we intend to use our prototype as a case study to address challenges associated with remote sensing of cell performance, test various additive manufacturing methods (e.g. 3d Printing, injection molding) to reduce costs, and research alternative low cost, high performance materials.

ACKNOWLEDGMENTS

The UnWastewater team would like to thank all of our academic and industry mentors for their invaluable assistance in developing this project. We are especially grateful to the Princeton WET Lab for allowing us to test our prototypes in their laboratory space. We would also like to thank the Hatton Wastewater Works for providing us with a tour of the treatment facility.

PROSPECTIVE OUTLOOK

Microbial electrosynthesis may complement, or provide an alternative to, conventional, linear wastewater treatment technologies; an alternative that goes beyond mere energy recovery and sludge mitigation. With MES, wastewater is directly transformed from a waste into a sustainable feedstock circularizing wastewater treatment and the production of life-saving medications.

The economic outlook of MES is promising as the minimum selling price of MES derived products is anticipated to decrease by up to 97% as the technology matures. Given that there is an annual demand for over 10 Mt of acetic acid and 100 Mt for ethanol, there is a sizable market for MES to capitalize on. Finally, commercialization of MFCs, a sister technology of MES, is already underway, indicating that MES has the potential to make the jump from research to market in the near future.

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