May 2020

ANCHOR QEA

Highlights of the Integrated Algal Flow-Way, Digester, and Fuel Cell Demonstration Project

Prepared for: U.S. Department of Transportation Maritime Administration
Maryland Department of Transportation Maryland Port Administration
Maryland Environmental Service

May 2020

Highlights of the Integrated Algal Flow-Way, Digester, and Fuel Cell Demonstration Project

Prepared for
U.S. Department of Transportation
Maritime Administration
1200 New Jersey Avenue SE
Washington, DC 20590

Maryland Department of Transportation
Maryland Port Administration
401 East Pratt Street
Baltimore, Maryland 21202

Maryland Environmental Service
259 Najoles Road
Millersville, Maryland 21108

Prepared by
Anchor QEA, LLC
10320 Little Patuxent Parkway, Suite 1140
Columbia, Maryland 21044

TABLE OF CONTENTS

FIGURES

ABBREVIATIONS

CH_4	methane
D1	Digester 1
D2	Digester 2
D3	Digester 3
DMT	Dundalk Marine Terminal
H_2S	hydrogen sulfide
kg	kilogram
kW	kilowatt
L	liter
LHLR	linear hydraulic loading rate
MARAD	U.S. Department of Transportation Maritime Administration
MDOT MPA	Maryland Department of Transportation Maryland Port Administration
MES	Maryland Environmental Service
UMD	University of Maryland
VS	volatile solids

1 Introduction

The U.S. Department of Transportation Maritime Administration (MARAD) and Maryland Department of Transportation Maryland Port Administration (MDOT MPA), through a cooperative agreement, provided funding for an Integrated Algal Flow-Way, Digester, and Fuel Cell Demonstration Project at Dundalk Marine Terminal (DMT) in Baltimore, Maryland. This project furthers both the use of innovative technology in a marine industrial environment and MDOT MPA's commitment to the environment in multiple ways: improving water quality, reducing air emissions, and incorporating alternative energy sources.

MDOT MPA, working with Maryland Environmental Service (MES), selected Anchor QEA, LLC, to complete this project with assistance from HydroMentia Technologies, LLC; NMP Engineering Consultants, Inc.; and the University of Maryland (UMD) Department of Environmental Science and Technology. The project began in 2016 as an innovative multi-phase demonstration project designed, built, and operated to close the energy loop by producing on-site electricity. Phases 1 and 2 successfully established the feasibility of integrating an algal flow-way,[1] anaerobic algal digesters, a biogas collection and conditioning unit, and a fuel cell to convert algae to energy (Anchor QEA 2018). In 2018, Phase 3 was added in order to test methods for improving biomass handling, separation, and recovery of the harvested algae and optimizing digester operations; the biogas conditioning unit and fuel cell were not used during this and the next phase (Anchor QEA 2019). In 2019, Phase 4 was added for supplemental testing of the algal flow-way and digesters (Anchor QEA et al. 2020). This report summarizes the four phases of the demonstration project, presents highlights and lessons learned, and provides considerations to other ports that may be interested in applying the technology.

Full documentation can be found in the following reports:

- **Phases 1 and 2**: *Integrated Algal Flow-Way, Digester, and Fuel Cell Demonstration Project* (Anchor QEA 2018)
- **Phase 3**: *Phase 3 Algal Flow-Way Pilot Testing Program at Dundalk Marine Terminal* (Anchor QEA 2019)
- **Phase 4**: *Phase 4 Algal Flow-Way Pilot Testing Program at Dundalk Marine Terminal* (Anchor QEA et al. 2020)

[1] Algal flow-ways are inclined (typically 1 to 2 degrees) systems designed to improve water quality by using natural algal assemblages that colonize on screens and assimilate nutrients from the overlying water pumped into the algal biomass (Bott et al. 2015). The algae are then harvested, typically once every 7 to 14 days.

1.1 Objectives

The use of fuel cells has been limited in industrial or marine environments largely due to the lack of availability of fuel, such as hydrogen or natural gas. However, producing biogas on site for fuel provides opportunities for fuel cell deployment at waterfront facilities. This demonstration project addressed the feasibility of coupling an algal flow-way, algal digesters, a biogas collection and storage system, and a fuel cell for continuous operations and the ability to run a fuel cell relatively maintenance-free using biogas feedstock produced on site at DMT. The main objectives of the demonstration project included coupling each of the technologies into an operational process, testing and operating individual units, quantifying and improving renewable energy production in terms of biogas production and biogas quality during anaerobic digestion, and understanding nutrient transformation during algal digestion. Phase-specific objectives are presented in Sections 2 through 5.

1.2 Project Concept

This project was designed to demonstrate the ability to produce electricity through a series of steps, starting with algae already being grown at the site and used as feedstock to an algal digester. The algal flow-way had been tested at MDOT MPA facilities each year since 2013, proving the ability to remove nutrients (nitrogen and phosphorus) from Patapsco River surface waters as part of a program to meet Total Maximum Daily Load criteria (Selby et al. 2016).

In the demonstration project, water from the Patapsco River was pumped onto an algal flow-way (a long runway consisting of plastic sheeting covered by a screen where naturally occurring algae was allowed to grow). As the algae grew, it consumed undesirable nutrients (nitrogen and phosphorus) from the water, thereby improving water quality in the river. Harvested algae from the algal flow-way was fed through a series of three digesters—small, greenhouse-like structures with internal sealed bags—where microorganisms broke down the algae and produced biogas. The generated biogas supplemented natural gas as fuel to a fuel cell that produced electricity. Ideally, the electricity generated from the fuel cell would have powered the flow-way water intake pump, thereby reducing the energy footprint of the demonstration project and moving toward a completely sustainable system. However, the physical size of the algal flow-way limited biogas production, and the lowest wattage of a commercially available fuel cell (i.e., 500 watts) was undersized to run the flow-way water intake pump. Instead, area lights and a small recirculation pump were powered by the fuel cell.

Figure 1-1 illustrates the conceptual model of the integrated system. Figure 1-2 shows a schematic of the integrated system. Figure 1-3 provides photographs of the flow-way, decant tanks and digesters, and biogas conditioning unit and fuel cell.

Figure 1-1
Conceptual Model of the Integrated System

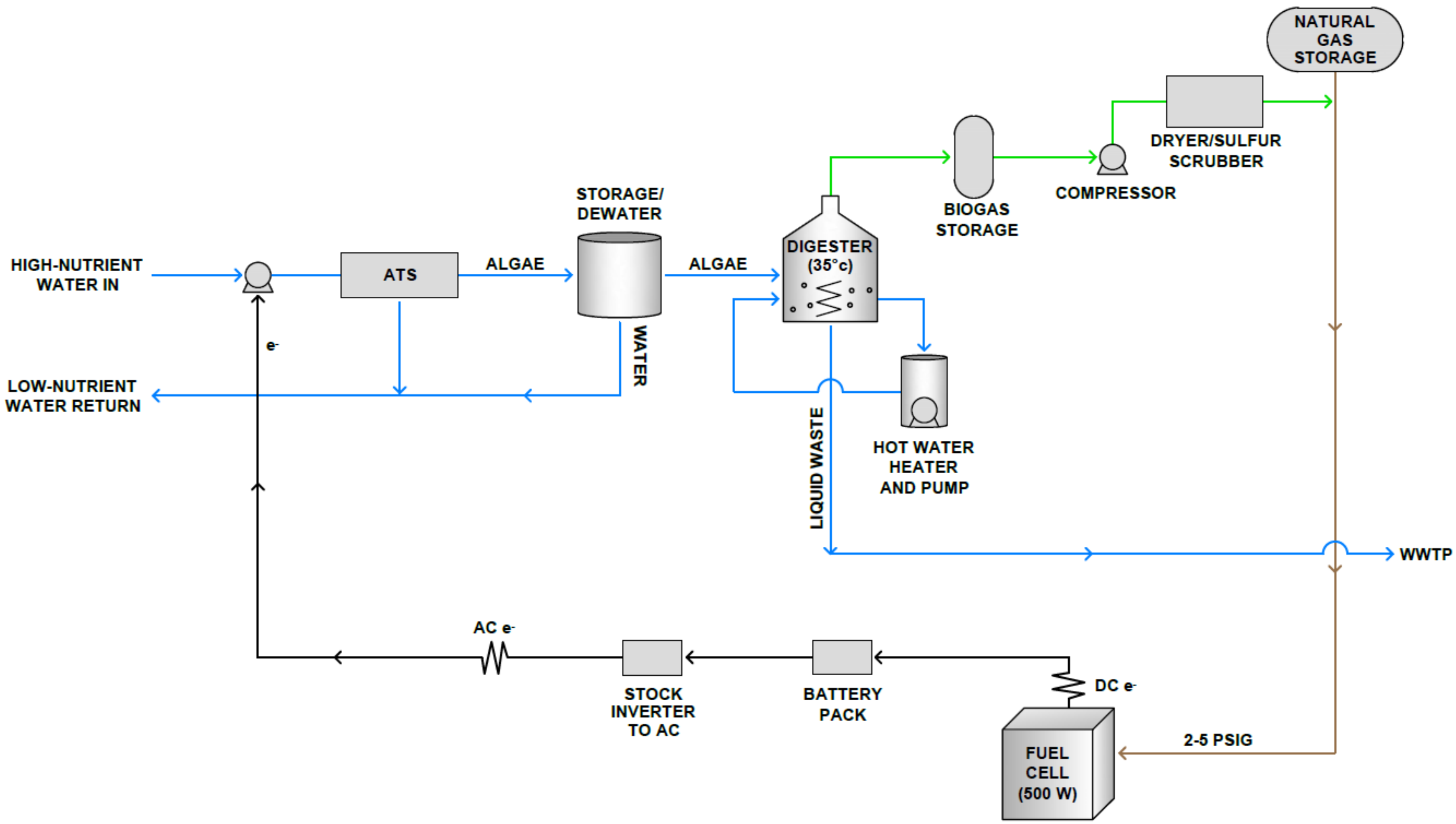
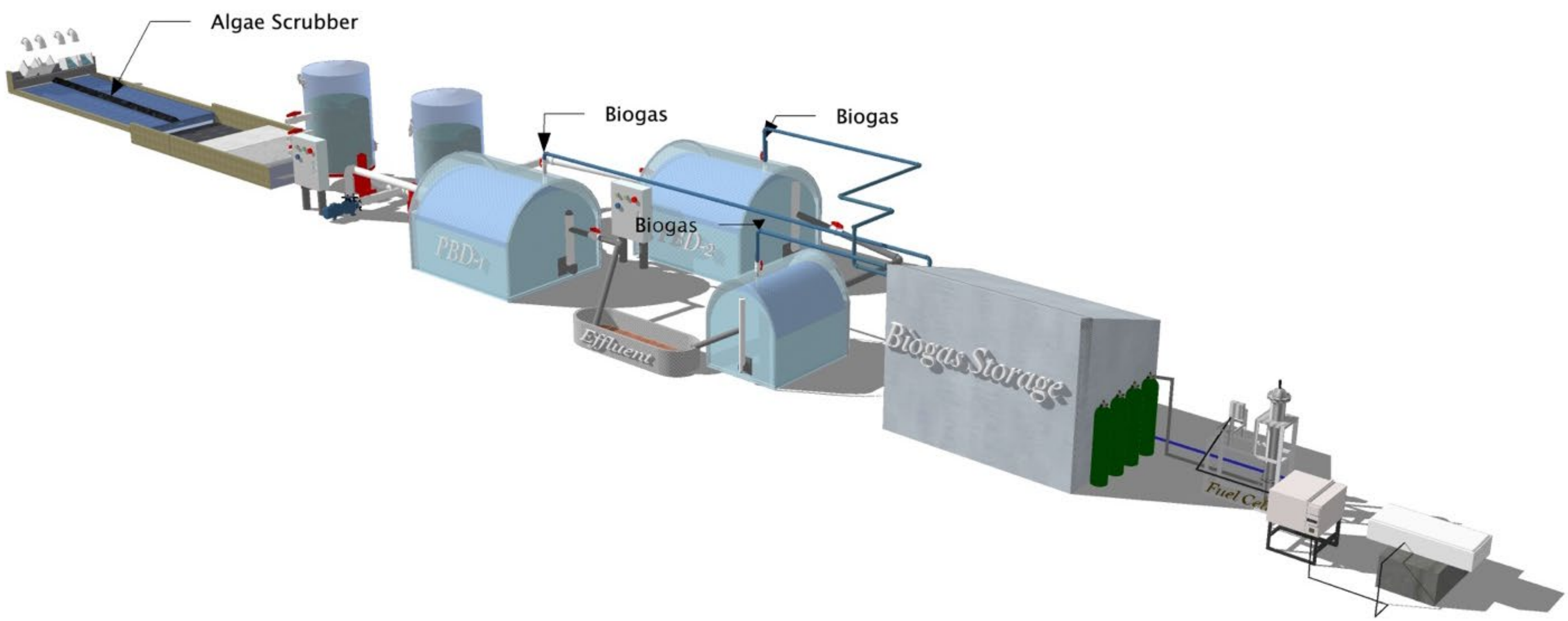


Figure 1-2
Schematic of the Integrated System



Source: University of Maryland

Figure 1-3
Photographs of the Components of the Integrated System

Notes:
The upper left photograph shows the algal flow-way. The upper right photograph shows the decant tanks (with red bases) and one of the algal digesters. The bottom left photograph shows the three algal digesters. The bottom right photograph shows the biogas conditioning unit on the left and fuel cell on the right.

2 Phase 1: Laboratory-Scale Anaerobic Digestion Experiments

Phase 1 of the demonstration project consisted of laboratory studies to characterize biogas and evaluate biogas production on a bench scale to inform the pilot-scale digester design. This effort was led by the UMD (Department of Environmental Science and Technology). Initial tests involved batch digestion of algae grown at the DMT algal flow-way. Studies focused on the following:

- Testing the impact of pre-treatment methods (i.e., level of drying, physical grinding, and chemical addition) on biogas quantity
- Determining biogas quality by measuring constituents in the gas (carbon dioxide, hydrogen sulfide [H_2S], and methane [CH_4] concentrations)
- Estimating the overall production of biogas possible with digestion operations

Using the results from the batch digestion testing, a second laboratory-based study was conducted to mimic expected field operations (i.e., feeding every 3 days with continuous removal of liquid waste and biogas) and to characterize the liquid waste and biogas produced from the digester. The results from the laboratory studies informed the need for and extent of H_2S removal, biogas storage necessary based on estimated biogas production, and effluent concentrations expected from the digestion process. In addition, based on the laboratory studies, the specifications and operating conditions for the field algal digesters were developed. Full results from the laboratory-based studies and Phase 2 pilot-scale studies, with analysis of scientific literature, are available in Witarsa et al. (2020). Phase 1 details can be found in Anchor QEA (2018).

2.1 Objectives

The overall objectives for Phase 1 were to conduct laboratory-scale studies to determine the expected biogas production rate from algae harvested from an algal flow-way and use the results to design a pilot-scale anaerobic digestion system.

2.2 Highlights and Lessons Learned

Highlights and lessons learned from Phase 1 include the following:

- Results from the batch reactors indicated that wet algae (6.7% total solids) was most efficient in CH_4 production, with 158 ±13 liters (L) CH_4 per kilogram (kg) volatile solids (VS) in the algae. The continuous laboratory-based reactors produced 103 ±7 L CH_4/kg VS, which was lower than the results of the batch-scale reactor experiments.
- The laboratory results supported a prediction that 642 L CH_4/week could be produced based on algae with 10% total solids, loaded three times per week, and that the biogas would be composed of approximately 59% CH_4 for the Phase 2 pilot-scale system. These results informed the sizing, design, and operating conditions for the Phase 2 pilot-scale digesters.

3 Phase 2: Pilot-Scale Integration of Algal Flow-Way, Digester, and Fuel Cell

Phase 2 occurred in 2017 with the design, construction, and testing of a complete operating system to generate energy from algae on site at DMT. The project integrated several technologies into one operating system. First, water from the Patapsco River was pumped onto an algal flow-way, a 200-foot-long by 6-foot-wide runway consisting of plastic sheeting covered by a screen where naturally occurring algae was allowed to grow. The water was applied via tipping buckets to encourage algal growth with pulses of inflow. As the algae grew, it consumed undesirable nutrients (nitrogen and phosphorus) from the water. The algae was then harvested and fed through a series of three digesters—small, greenhouse-like structures—where microorganisms broke down the algae, producing biogas. After removal of water and H_2S, the biogas produced was supplemented with natural gas and fed into a fuel cell. This fuel cell generated electricity to power lights and a circulation pump.

Phase 2 details can be found in Anchor QEA (2018). Phase 1 and 2 efforts were also presented, and a paper submitted, at the 2018 International GreenPorts Congress held in Baltimore, Maryland (May et al. 2018).

3.1 Objectives

This demonstration project addresses the feasibility of coupling an algal flow-way, algal digesters, a biogas collection and storage system, and a fuel cell for continuous operations and the ability to run a fuel cell relatively maintenance-free using biogas feedstock produced on site at DMT. Coupling each of the technologies into an operational process and testing and operating individual unit operations were the objectives of the demonstration project. The key components needed to achieve these objectives were as follows:

- Characterization of biogas from site-grown algal assemblages
- Design and procurement of appropriately sized algal digesters
- Engineering and design of the biomass handling system from the flow-way to the digesters
- Collection, storage, conditioning, and compression of biogas
- Design, procurement, and installation of a gas feed system to the fuel cell
- Engineering, design, and testing of a fuel cell
- Operations and testing of the integration system while defining operational parameters and constraints

3.2 Highlights and Lessons Learned

Highlights and lessons learned from Phase 2 include the following:

- Integration of each component into a process system was successful but required a higher level of daily support and management than anticipated due to operational troubleshooting.
- The algal flow-way portion of the demonstration project benefited from the team's multi-year experience in start-up, operations, and harvesting of the algal flow-way at DMT. Replacement of the 2D mesh screen with a 3D mesh screen increased the growth of algae.
- Harvest methods of the algae from the flow-way were adequate, but better biomass handling during harvest could benefit the algal digestion process by increasing the percent solids in the feedstock of algae to the digesters. This became one of the objectives of Phase 3.
- The digesters produced a higher quality biogas than expected; biogas was generated with a higher percentage of CH_4 and lower percentage of H_2S than was measured in the laboratory. Biogas quantity was slightly lower than anticipated. The digesters produced 557 L CH_4/week (107 ±15 L CH_4/kg VS) after an 8-week stabilization period, 15% less than predicted from the laboratory-scale studies. The algae feeding volumes were highly variable from week to week, and the digester temperature fluctuated with ambient temperatures, so this reduction in biogas was expected when compared to the controlled laboratory conditions.
- While the biogas quantity was influenced by other factors external to the digesters (e.g., flow-way productivity), several operations involving the digesters have the potential to be optimized. This was one of the objectives of Phase 3.
- The biogas bags needed to be continually monitored for leaks.
- The biogas compression and conditioning unit worked as designed. Removal of water and H_2S did not saturate the desiccant beds or iron sponge. Future designs need close collaboration between design engineers and fuel cell engineers to ensure that fittings match, pressure relief systems are in place, and flow meters are calibrated with some redundancy. The larger diaphragm pump was superior to the smaller, initially installed pump.
- For the supplemental gas supply, compressed CH_4 worked well in this demonstration project. However, for long-term deployment, a more economical and reliable delivery of CH_4 or natural gas (perhaps by pipeline or via a larger fuel tank) is recommended.
- For large-scale or future demonstration unit design, spares of equipment (e.g., transfer pumps and compression pumps) should be installed to provide back-up because failures in these pumps will result in a system shutdown. In addition, monitoring biogas production and controlling biogas transfers remotely will reduce labor requirements. In this demonstration project, biogas was stored and only used periodically, which necessitated manual labor to start and stop the biogas flow; an automated system would alleviate the need for manual labor.

4 Phase 3: Refinement of Biomass Handling Procedures for Algal Flow-Way

Based on the results and lessons learned during Phase 2, Phase 3 focused on the algal flow-way and algal digester portions of the integrated system. The biogas collection and conditioning unit and fuel cell were kept offline during this phase and Phase 4. Phase 3 focused on enhancing the efficiency of dewatering and handling of the algal biomass grown on the algal flow-way and used as feedstock to the algal digesters. By decreasing the water content in the feedstock, the algal digesters should be able to more efficiently convert the algal biomass to biogas.

In 2018, the algal flow-way underwent a few changes. The flow rate of inflow water to the flow-way was tested with the installation of a self-siphoning surge system to allow for larger water pulses of inflow to occur at a predictable frequency; this replaced the tipping buckets from Phase 2. Small sections of different surface materials (e.g., bare concrete, geomembrane liner with nylon screen, concrete with screen) were installed and tested for their impact on algal productivity.

Dewatering methods tested during Phase 3 included the following:

- Evaporation bed
- Dewatering pad
- Hanging bag
- Merit tile
- Wedge wire screen
- Perpendicular harvest and side channel
- Sand filter

For Phase 3, the three algal digesters were reconfigured so that instead of working in series like in Phase 2, two digesters (D1 and D2) operated in parallel, while the third (D3) remained in series with D2. This change enabled replication between biogas production in D1 and D2 and allowed for testing of a higher hydraulic retention time in the D2-D3 series.

Phase 3 details can be found in Anchor QEA (2019).

4.1 Objective

The overall objective of Phase 3 was to study optimal operational conditions and biomass handling procedures to maximize algal growth and recovery from the algal flow-way.

4.2 Highlights and Lessons Learned

Highlights and lessons learned from Phase 3 include the following:

- Weather conditions in 2018 for the Baltimore region were unusual, with record-breaking precipitation. By the end of the year, Baltimore had received nearly 72 inches of precipitation, approximately twice the amount that occurs in a typical year.
- Results from the dewatering tests supported a combination of the following methods:
  - Perpendicular harvest + side or central dewatering channel
  - Wedge wire screen for material that flows freely from the dewatering channel
  - Sand filter (with a weir discharge option) as a final solids retention step
- Additional testing was recommended to quantify the potential impact on algal biomass growth of using concrete as a flow-way surface. Additional testing may include installing concrete sections larger than 3 feet and using a rougher concrete surface to increase surface area for algae to attach. This became a focus for Phase 4.
- The self-siphoning surge system required little maintenance compared to almost daily maintenance needed for the Phase 2 tipping buckets.
- The impact of biofouling on the linear hydraulic loading rate (LHLR) was observed, even though modifications to the inflow pump were implemented prior to the start of flow-way operations. Because LHLR is known to affect the growth rate and algal species on the flow-way, additional strategies were recommended to address biofouling of the intake pump so a consistent, higher LHLR can be maintained.
- Additional testing was recommended to directly compare the algal biomass growth and algal species dominance between a surge system and a continuous flow system. This became an objective for Phase 4.
- A focused water quality testing program for the inflow water was recommended. These data would be useful for understanding the algal biomass growth relative to inflow water quality and for comparing site conditions to historical data. This was added in Phase 4.
- Biogas quality from the anaerobic digestion of algal biomass continued to be high. However, Phase 3 had 41% less biogas production than Phase 2 due to reduced biomass production from the flow-way. Although the algal digester system received a similar quantity of algae in Phase 3 compared to Phase 2, the percent solids was lower (i.e., 4% in Phase 3; range of 3% to 10% in Phase 2), resulting in less biomass for bioenergy production. During Phase 3, D1 averaged 115 L CH_4/week (64.1 L CH_4/kg VS), and the D2-D3 system produced 146 L CH_4/week (55.9 L CH_4/kg VS for D2 and 19.7 L CH_4/kg VS in D3), resulting in an average of 261 L CH_4/week for all digesters during peak production (August to mid-October). The year 2018 was the wettest on record for the Baltimore area, and the excessive precipitation likely disrupted algal settling and algal growth on the flow-way.

- Additional testing of the algal digester system was recommended to allow for modification of the system design to include a more efficient recirculation system that would completely mix the digestate and enhance full digestion of nutrients, and to install and operate a heating system to maintain internal temperatures during a full operating season. These were evaluated in Phase 4.

5 Phase 4: Improving Operating Efficiency of Algal Digesters

Conducted in 2019, Phase 4 focused on refining flow-way operation and biomass handling approaches and increasing energy production from digestion using the algal flow-way feedstock. Phase 4 included the following four investigations:

- Testing whether the method by which water is introduced onto the flow-way—pulses of water or continuous flow—results in a quantifiable change in algal productivity
- Evaluating whether flow-way surface material has a quantifiable effect on algal productivity
- Assessing the effectiveness of using a harvest and dewatering channel for increasing the efficiency of recovering solids without losing or bypassing substantial biomass while increasing percent solids of the harvested algae
- Measuring energy production from harvested algal biomass using algal digestion after several digester improvements, including installation of a new heating and recirculation system to add mixing and increase biogas production during colder months

The flow-way was modified for Phase 4 to support these investigations. It was divided into two adjacent parallel flow-ways, which were operated side by side to allow for direct comparison of algal productivity from pulsed and continuous inflows. Larger test sections of surface material were added compared to Phase 3 to evaluate the impact of such materials on algal productivity. A channel was constructed along the side of the flow-way as a dewatering channel to be used during algae harvest.

Phase 4 details can be found in Anchor QEA et al. (2020).

5.1 Objective

The overall objective of Phase 4 was to address the following three challenges encountered during Phase 3 that affected the operating efficiency of the algal digesters: 1) increasing the total amount of algae (i.e., productivity) available for testing; 2) increasing the percent solids of the harvested algae through biomass handling; and 3) increasing energy production from algal digestion of the harvested algal biomass.

5.2 Highlights and Lessons Learned

Highlights and lessons learned from Phase 4 include the following:

- Based on the environmental conditions that occurred during Phase 4, no quantifiable difference in algal productivity was observed due to pulsed flow.
- No substantial increase in algal productivity was observed for any of the surface materials tested.

- The harvest and dewatering channel, as a first stage solids recovery approach, was generally confirmed as effective for recovering harvested solids without losing or bypassing substantial biomass to the second-stage recovery system (sand filter) while efficiently increasing the percent solids of the harvested algae material.
- If more immediate monitoring results for dryness of the material in the harvest and dewatering channel (beyond physical inspection) are desired, the desktop microwave drying procedure employed during Phase 4 for determining percent solids should be evaluated further.
- Low phosphorus in the inflow water was found to limit algal productivity on the flow-way.
- During Phase 4, biomass production from the algal flow-way was higher than Phase 3 and similar to Phase 2. The loading to the algal digester system was 665 L/week, which was the highest of all three phases.
- The biogas production from D1 (117 L CH_4/week; 40.5 L CH_4/kg VS) was less than the D2-D3 system (367 L CH_4/week; 157 L CH_4/kg VS) due to persistent leaks in D1 that prevented biogas from accumulating inside D1. This resulted in 484 L CH_4/week for the entire digester system, which was similar to previous years.
- The biomass to CH_4 efficiency (157 L CH_4/kg VS) results from D2-D3 were similar to the CH_4 potential predicted by the experiments in Phase 1. This indicates that maximum biogas production from the DMT algae can be achieved with regular feeding, recirculation, and heating in field conditions compared to laboratory-scale predictions.

6 Applicability of Technology to Other Ports

The demonstration project showed that algae produced from a flow-way can be a viable feedstock for algal digestion at the Port of Baltimore. The quality of biogas produced in the algal digesters exceeded that from laboratory experiments, and the quantity of biogas produced was consistent with the laboratory results when digester heating and mixing were integrated into the system. The design and integration of several processes demonstrated that a fuel cell could be powered, in part, by biogas generated by the anerobic digestion of algae grown on a flow-way. This section highlights considerations for the application of this technology at other ports.

6.1 Experience and Collaboration

6.1.1 Algal Flow-Way History at Port of Baltimore

Flow-way operational experience gained by field personnel over several years contributed to the success of the demonstration project. The first algal flow-way was constructed at DMT in 2013 to assess the potential for improving water quality by removing nutrients and sediment from the Patapsco River (Smith et al. 2013). An algal flow-way has operated each year from 2013 to 2019 at DMT, and each year improvements to the system design, method of operation, and biomass handling techniques were implemented (Smith et al. 2013, May et al. 2014, Smith et al. 2016, Selby et al. 2016, Selby et al. 2018, Anchor QEA 2019).

Previous versions of the flow-way experimented with various lengths of flow-way surface, different pump rates at which Patapsco River water was delivered to the flow-way, changes to flow-way slope, use of tipping buckets to deliver Patapsco River water to the flow-way in a pulsed manner, operation for varying lengths of time and seasons, various manual harvest methods, transportation of harvested algae to a truck scale via vacuum truck, and air drying of harvested algae by evaporation in an open area.

It is important to understand that the algal communities growing on a flow-way may vary from season to season and year to year. Growth is impacted by environmental factors not within control, such as rainfall and nutrient concentrations in inflow water. Flexibility in project design and implementation is key.

6.1.2 Project Management and Team Collaboration

The demonstration project team structure, management, and clearly identified roles and responsibilities contributed to the success of this demonstration project. Expectations were laid out in paperwork, such as a cooperative agreement between MARAD and MDOT MPA and a contract between MES and Anchor QEA for project management. Subject matter experts from UMD; HydroMentia Technologies, LLC; NMP Engineering Consultants, Inc.; Tourgee & Associates, Inc.; and

Atrex Energy, Inc., completed the demonstration project team. MES provided financial tracking, procurement of all equipment, and day-to-day operations at DMT. Collaboration amongst demonstration project team members and subconsultants allowed for real-time problem solving and solution-driven brainstorming when problems arose.

6.2 Maintenance and Durability Considerations

Biofouling of the intake structure to the flow-way was a challenge during the demonstration project, despite modifications to the intake. Biofouling reduced the inflow rate to the flow-way and impacted algal productivity. A self-cleaning intake screen installed for Phase 4 allowed for less laborious operation. Additional options to reduce the impact of biofouling should be considered in the future.

For future work, a more durable digester design is recommended if the digestion units will be operated outside. The pilot-scale units from Puxin operated effectively during their first stages of operation, but they began to wear down quickly after the first season of overwintering. By the end of Phase 4, fluid and gas leaks were more frequent, with associated repair costs and down time. While the initial price may be higher for a higher quality unit, it would ultimately save money over the lifetime of the unit due to increased reliability and reduced need for labor and supplies for repair. Use of a digester supplier using standard pipe sizes and fittings is recommended. All materials associated with the Puxin units were proprietary sizes and shipped from China, which incurred significant time and operating costs.

6.3 Scale-Up Considerations

The information gathered during the four phases of the demonstration would aid in designing a scaled-up system to support a larger sized fuel cell at the Port of Baltimore. The size of flow-way can be back-calculated depending on the energy output desired. An example of this calculation is provided in Anchor QEA (2018).

A larger algal flow-way would produce more algae and therefore more feedstock to the algal digestion system. Several scale-up considerations for a flow-way include the following:

- A larger flow-way system should be value engineered to consider if the potential increased productivity, or potential difference in algal community type that could occur under different water quality conditions, is worth the extra investment in infrastructure required to provide pulsed inflow.
- Assuming that the results from Phase 4 would apply under other environmental conditions in other years of operation, a larger flow-way system should be value engineered to consider if the potential increased cost of roughened concrete surface material is worth additional capital investment to reduce the initial starting volume of harvest material and aid in biomass handling operations.

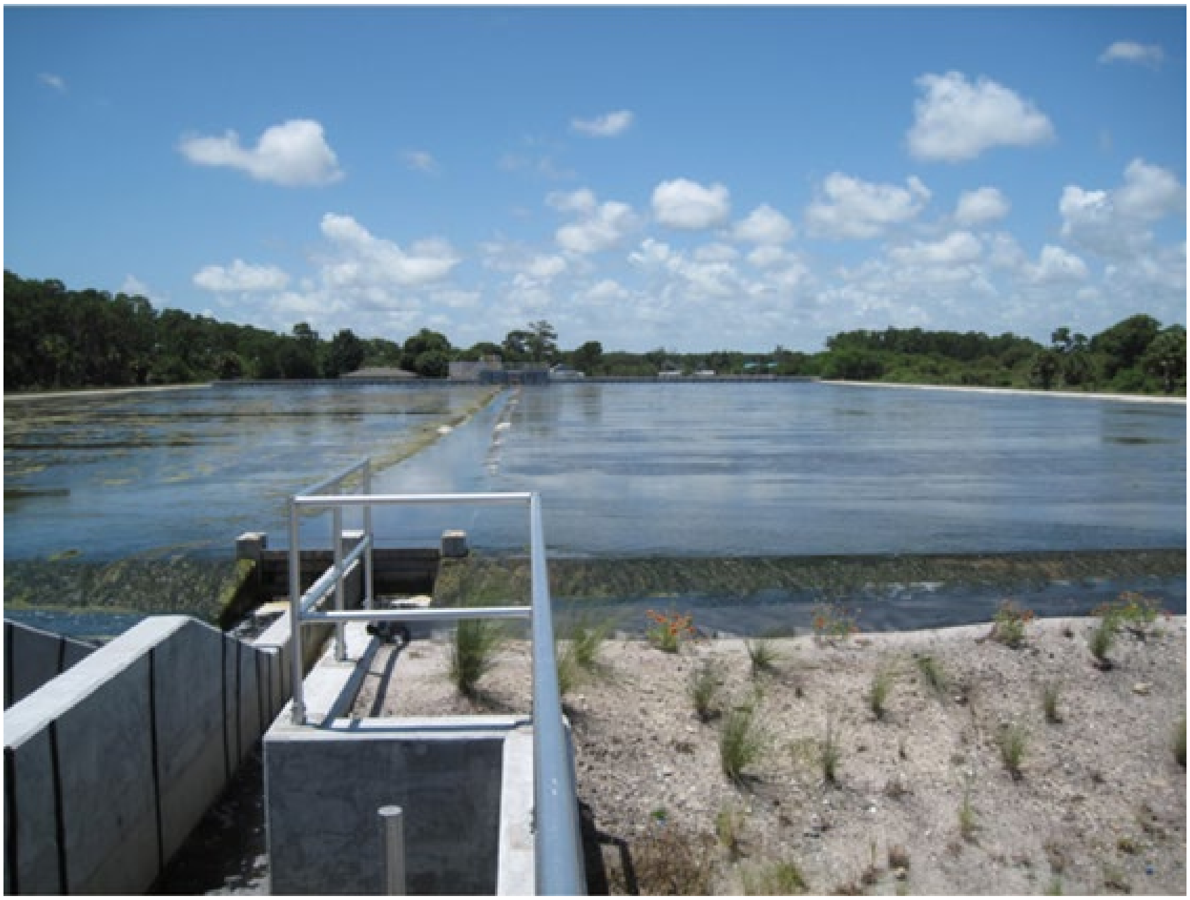
- Other considerations include the potential soil improvements needed at the proposed site for installation of a roughened concrete surface versus a liner and grid on compacted earth. Heaving, which was experienced at this project site, or settlement, could cause damage to a concrete surface that would be more difficult to repair than an HDPE-lined surface.
- A larger flow-way system should be designed with flexibility for biomass handling operations that are appropriate for a diatom-dominated system, as was experienced during Phase 3 and Phase 4, as well as a filamentous green algae-dominated system. Designing a flow-way based on a diatom-dominated algal community would be a more conservative approach; the cost effectiveness would increase when algal communities are dominated by filamentous greens.
- Considerations should be given to operating self-sufficient renewable energy production systems, via anaerobic digestion, on site at port operations versus transporting the algal biomass to adjacent digestion systems based on transportation costs, need for on-site energy production, and available time commitment to the operation of the digestion and fuel cell systems.

Several larger scaled algal flow-ways are in operation in the United States. Currently in operation are the Egret Marsh Algal Turf Scrubber® constructed in 2010 (Figure 6-1) and the Osprey Marsh Algal Turf Scrubber® system constructed in 2015 (Figure 6-2). These systems were designed to reduce nitrogen and phosphorus from surface waters impaired by nutrient runoff from urban and agricultural lands. Additionally, the Osprey Marsh system provides treatment of reverse osmosis reject water from a nearby water treatment plant. Both systems were designed and operate at treatment capacities of 10 million gallons per day.

Figure 6-1
Egret Marsh Algal Turf Scrubber™ in Indian River County, Florida

Source: HydroMentia Technologies, LLC

Figure 6-2
Osprey Marsh Algal Turf Scrubber™ in Indian River County, Florida



Source: HydroMentia Technologies, LLC

Sizing of the other components of the integrated system would depend on the amount of algae produced by a scaled-up flow-way. For a scaled-up integrated system, a reliable and economical source of natural gas as supplemental gas should be identified, if natural gas is required to supplement the biogas. Consideration should also be given to the energy output of commercially available fuel cells. For this demonstration project, a 250-watt fuel cell was not available and, therefore, supplemental gas was required to power the 500-watt fuel cell.

6.4 Fuel Cell Deployment Opportunities

The fuel cell used in this demonstration project could be used at the Port of Baltimore as an alternative to diesel or electric power supplies. A feasibility report on the potential future use of a fuel cell to power buildings at DMT was completed by an Environmental Defense Fund Climate Corps fellow. The work included performing an internal energy audit on four buildings, consulting fuel cell vendors and Baltimore Gas and Electric (the regional utility), and evaluating four fuel cell deployment options for power co-generation with the existing electrical grid. These options included solid oxide fuel cells from two different manufacturers capable of producing 0.5 kilowatt (kW), 1.5 kW, 5.5 kW, and 200 kW. The report is included as Attachment B of Anchor QEA (2019).

7 References

Anchor QEA, LLC, 2018. *Integrated Algal Flow-Way, Digester, and Fuel Cell Demonstration Project*. Prepared for U.S. Department of Maritime Administration, Maryland Department of Transportation Maryland Port Administration, and Maryland Environmental Service. April 2018.

Anchor QEA, LLC, 2019. *Phase 3 Algal Flow-Way Pilot Testing Program at Dundalk Marine Terminal*. Prepared for U.S. Department of Maritime Administration, Maryland Department of Transportation Maryland Port Administration, and Maryland Environmental Service. May 2019.

Anchor QEA, LLC, HydroMentia Technologies, LLC, NMP Engineering Consultants, Inc., and University of Maryland, 2020. *Phase 4 Algal Flow-Way Pilot Testing Program at Dundalk Marine Terminal*. Prepared for U.S. Department of Maritime Administration, Maryland Department of Transportation Maryland Port Administration, and Maryland Environmental Service. April 2020.

Bott et al., 2015. *Nutrient and Sediment Reductions from Algal Flow-Way Technologies: Recommendations to the Chesapeake Bay Program's Water Quality Goal Implementation Team from the Algal Flow-Way Technologies BMP Expert Panel*. October 21, 2015.

May, P., E. Darby, S. Lansing, B. Richardson, B. McMahon, P. Kangas, J. Smith, and B. Selby, 2018. *The Innovative Use of an Algal Ecotechnology to Demonstrate Improved Water Quality, Create a Biofuel and Power a Low Emission Fuel Cell at the Port of Baltimore, Maryland, USA*. Conference Proceedings of the 2018 GreenPorts North America Congress (Baltimore, Maryland), May 2018.

May, P., P. Kangas, J. Smith, and B. Selby, 2014. *A Comparison of Methods for Estimating Algal Biomass Productivity at the Port of Baltimore Algal Turf Scrubber*. Unpublished Draft Report. August 18, 2014.

Selby, B., P. Kangas, P. May, W. Mulbry, and S. Calahan, 2016. *Algal Biomass Productivity at the Port of Baltimore Algal Turf Scrubber: Fall 2016.* First draft: December 6, 2016. Submitted to MES.

Selby, B., P. May, S. Calahan, A. Blair, and P. Kangas, 2018. *Algal Biomass Productivity at the Port of Baltimore Algal Turf Scrubber: 2017.* First draft: January 12, 2018.

Smith, J., B. Selby, P. Kangas, and P. May, 2013. *Progress Report on the Port of Baltimore Algal Turf Scrubber Project.* Unpublished report. December 2013.

Smith, J., B. Selby, P. Kangas, P. May, and W. Mulbry, 2016. *2015 Final Progress Report on the Port of Baltimore Algal Turf Scrubber Project*. Unpublished draft report to the Maryland Port Administration. March 27, 2016.

Witarsa, F., A. Yarberry, P. May, P. Kangas, and S. Lansing, 2020. "Complementing Energy Production with Nutrient Management: Anaerobic Digestion System for Algal Turf Scrubber Biomass". *Ecological Engineering* 143.