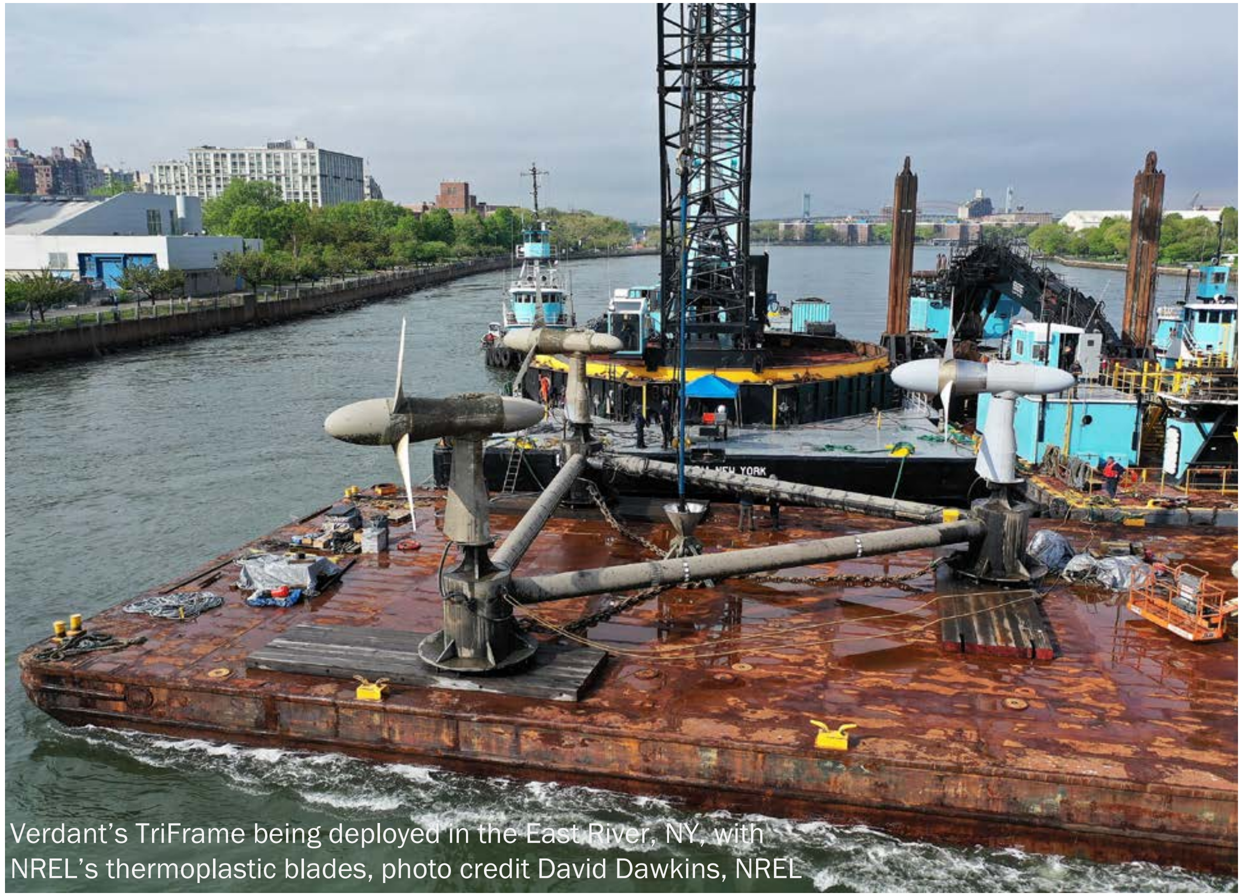
2.2.2.405 – Verdant/NREL Research Measurement Campaign



Verdant's TriFrame being deployed in the East River, NY, with NREL's thermoplastic blades, photo credit David Dawkins, NREL

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NREL/PR-5000-83263

Project Overview

Project Summary

- The marine renewable energy industry primarily uses thermoset composite materials for blades and other hydrodynamic components, which can have up to 50% reduction in strength when exposed to seawater and are not recyclable. Thermoplastic composite materials have been shown at a coupon scale to have improved seawater saturated properties but *have not been validated at full scale*.
- Industry needs rigorously validated design codes to accelerate technology and drive down costs, which requires data from large devices operating in real conditions.
- Through this work, NREL manufactured, tested, and deployed thermoplastic blades and a data acquisition system on Verdant Power's turbine, TriFrame, in the East River, NYC.

Intended Outcomes

The project aims/aimed to:

- Better understand mechanisms of seawater degradation on large-scale marine composites through structural validation of pre- and post-deployed thermoplastic *and* thermoset composite blades. This can result in a step-change improvement in the materials used for marine energy devices.
- Demonstrate thermoplastic blade performance compared to thermoset blades at a large scale.
- Produce loads data for an operational turbine to validate numerical models.
- Improve understanding of wakes generated by an array (the Verdant TriFrame) of tidal turbines operating in a real tidal site.

Project Information

Principal Investigator(s)

- Robynne Murray and Levi Kilcher

Project Partners/Subs

- Verdant Power Inc.

Project Status

- Ongoing

Project Duration

- August 1, 2019
- December 31, 2022

Total Costed (FY19–FY21)

- $3,132,870

Project Objectives: Relevance

Relevance to Program Goals:

This project aims to deliver results that address challenges across all four "Challenge Areas":

In the "Difficult Engineering" challenge area, this project is:

- Performing early-stage R&D on materials not previously tested in the marine renewable energy (MRE) industry (thermoplastics)
- Developing modeling tools for device engineering and the structural properties of thermoplastics and other composites
- Delivering data that are critical to a better understanding of tidal and river resource assessment.

In the "Installing and Operating Reliable Systems" challenge area, this project is:

- Performing an in-water test of new materials by leveraging turbine deployments that are planned under other funding sources
- Providing data that is critical to the improvement of international standards.

In the "Prolonged Design and Testing Cycles" challenge area, this project is:

- Working with industry partners to maximize the value of preexisting testing cycles and their test-site including the permits
- Seawater aging large-scale thermoplastic and thermoset rotors for longer time scales than have previously been tested.

In the "Technology/Market Information and Supply Chains" challenge area, this project is:

- Testing recyclable materials
- Delivering data on the performance and reliability of a tidal turbine and comparing these metrics for different blade materials
- Exploring new materials that may provide the "step change" in device engineering that is needed for marine energy technology to accelerate
- Developing modeling capabilities for marine hydrokinetic devices.

Project Objectives: Approach

Approach:

Major Tasks:

- ✓ **Task 1: Blade Design and Build (complete)**
  - External blade shape is identical (with same molds) and internal structure is very similar.
- ✓ **Task 2: Deploy, Operate, and Recover Turbine with Thermoplastic Blades (complete).**
- **Task 3: Blade Characterization (ongoing)**
  - Structural and modal testing of Verdant's epoxy blade (provided by Verdant) and NREL's thermoplastic blades.
- **Task 4: Field Measurements (partially complete)**
  - Collection of field measurements of the blade loads, tower loads, turbine performance, TriFrame wakes, and inflow/outflow velocities to/from the turbine using an NREL-built data acquisition system (NDAQ).
  - Roving wake surveys from a vessel mounted, downward-looking acoustic doppler current profiler.
- **Task 5: Numerical Model Development and Validation (ongoing)**
  - Developing a HydroFAST model of the Gen5d-N turbine and updating HydroFAST with added mass and bouncy forces
- **Task 6: Reporting**
  - Reporting on the outcomes and publishing at least one peer-reviewed journal paper and a technical report.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Dataset showing side-by-side comparison between epoxy thermoset composite blades and thermoplastic composite blades both before and after deployment and operation in realistic submerged conditions.
- A normalized loads dataset for a full-scale current turbine that can be used to validate design codes.
- Wake measurements of the TriFrame array. These measurements are valuable to the development of international standards on tidal and river resource assessment.
- Design documents for a data acquisition system that is deployable in a rotating current energy converter hub with no communication.

Outcomes:

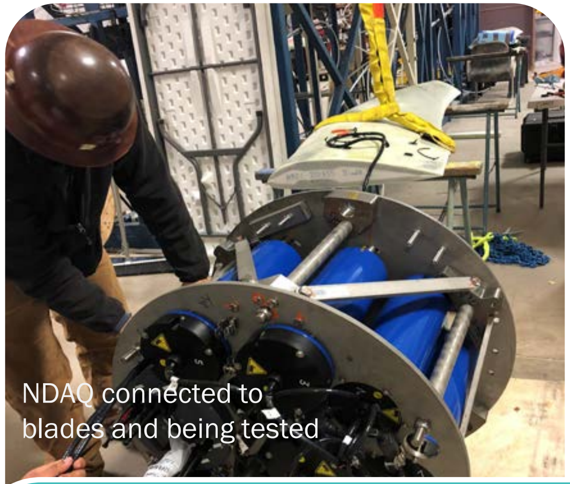
- Novel thermoplastic material will move toward commercialization, enabling better-performing and longer-lasting materials for MRE.
- Validated loads prediction tool for MRE applications can be used by industry and researchers to de-risk deployments in the future.
- The NREL DAQ design can be leveraged for future deployments to measure loads on operational turbines, increasing understanding of critical loads on blades and other structural components.
- Users will have a published step-by-step guide for how to instrument an operational tidal turbine and can use the guide to develop best practices

Project Timeline

Thermoplastic blade composite layup

FY 2019

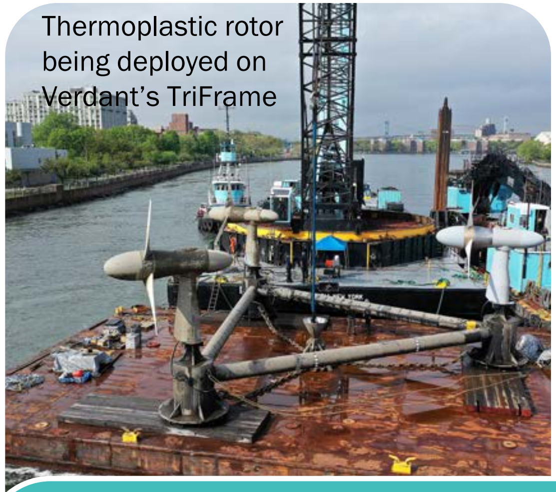
- Received blade molds and designs from Verdant
- Developed manufacturing plan and designed thermoplastic blade layup
- Validated coupons for compatibility between thermoplastic and other Verdant rotor materials.



NDAQ connected to blades and being tested

FY 2020

- Manufactured thermoplastic blades and instrumented them with strain gages
- Designed and built NDAQ to monitor loads on blades
- Validated blade instrumentation and NDAQ under water in the lab
- Go/no-go decision on deploying thermoplastic blades—go!



Thermoplastic rotor being deployed on Verdant's TriFrame

FY 2021

- Retrieved TriFrame with three epoxy rotors and replaced with the thermoplastic rotor turbine and NDAQ (issue with data)
- Deployed thermoplastic rotor for 6 months, then retrieved TriFrame
- Completed pre-deployment structural testing
- Began post-deployment structural testing.

Project Budget

Total Project Budget – Award Information		
DOE	**Cost-share**	**Total**
$3,132,870	$0	$3,132,870

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Costed**	**Total Costed**
$25,251	$1,415,562	$1,692,057	$3,132,870

- The original budget was estimated based on our best assessment of how much such a project would cost; however, **this project is the first of its kind,** and we underestimated the cost of certain areas of this work.
- **Future large-scale deployment projects should learn from this so that better budget estimates can be made early on in the project proposal process.**
    - COVID delays and additional safety measures on-site increased the cost to manufacture blades and build the DAQ, which added costs to the project (2020 cost overrun was $276,353, included in the total given above)
    - The requirement for post-deployment conditioning tanks to maintain blade saturation levels prior to testing added additional costs to the project.

End-User Engagement and Dissemination

NREL and Verdant Power partnered on this project. NREL manufactured and characterized the blades, developed a data acquisition system, and performed in situ environmental site measurements. Verdant used their expertise to deploy and operate the turbine with the NREL blades installed and undertook tasks such as rotor assembly that NREL could not perform due to COVID travel restrictions. **The strengths of both partners are highly complementary, and the partnership allowed NREL and DOE to greatly leverage an already planned retrieve-and-replace operation that was previously planned and funded under a separate FOA.**

This R&D project also directly benefits the entire MRE industry by::

- Demonstrating and validating the performance of a new blade manufacturing method and material (infusible thermoplastic-fiberglass)
  - This novel thermoplastic material has the potential to provide a higher-strength, recyclable, lower-energy-consumption (during manufacturing) material for the MRE industry, ultimately resulting in lower-cost and more durable subsea structures.
- Providing the MRE industry with an open-source, free, validated static and fatigue loads prediction tool for the design and development of horizontal-axis current energy converters (HydroFAST)
  - A validated design code will enable the industry to have more confidence in their designs and move through the technology readiness levels faster, ultimately increasing efficiency and decreasing cost.

To further the impact of this work, the following publications will be released:

- Journal publication on the structural validation of pre- and post-deployed blades
- Guideline for best practices of instrumenting blades
  - Having proven that the instrumentation functioned well during the deployment, this publication will outline the steps taken, which will help future deployments have confidence in their loads measurement equipment.

Performance: Accomplishments and Progress

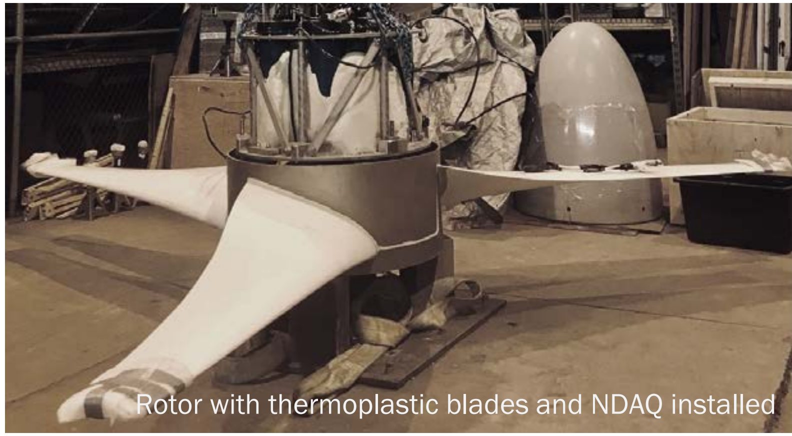
- 2.5-m epoxy blades manufactured by Composite Builders and thermoplastic blades manufactured by NREL using Elium resin
  - Fiberglass area weights for thermoplastic blades were matched to epoxy blades, and nearly identical layup was used for both blades such that the only major difference between blades is the resin and adhesive.
- Data acquisition system (NDAQ) designed to measure and record strain and position of blades with no communication during the 6-month deployment
  - 20 Nortek 15-V, 1,800-Whr lithium-ion batteries
  - Campbell Scientific CR6 acting as controller
  - FAT32 structure with 32 GB onboard storage.
- 40 internal strain gages were applied to blades prior to bonding and filling the blade skins with epoxy foam.
- NDAQ and blade instrumentation verified in the lab for 10 days with the NDAQ submerged under water.
- Blades and NDAQ shipped to Verdant Power for deployment.


NDAQ design


Thermoplastic blades being manufactured at NREL

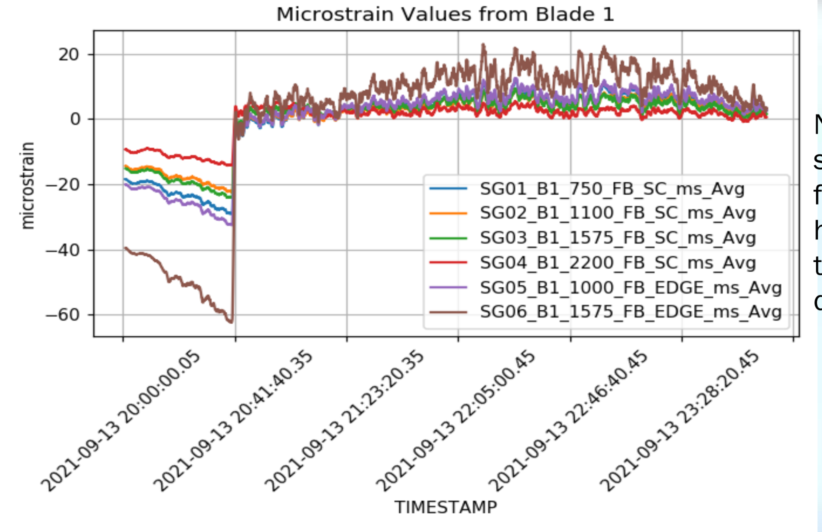

Thermoplastic blades being instrumented at NREL


Rotor with thermoplastic blades and NDAQ being installed on Verdant turbine


Rotor with thermoplastic blades and NDAQ installed

Performance: Accomplishments and Progress (cont.)

- Verdant turbine with NREL-made blades was successfully deployed in May 2021 and produced 31.8 MWh of power into the NYC grid
  - Turbine with thermoplastic blades produced 5% more power when compared with the previous epoxy blade turbine in the same position and adjusted for flow velocities.
- NDAQ hardware performed well and successfully *measured* data for more than 5 months.
- Blades and NDAQ structure appeared to have no damage upon retrieval, and all strain gages were still operational upon retrieval.
- **Only 4 hours of data were *recorded* by the NDAQ system due to a software error.** Result: No blade loads data.
  - NDAQ measured 3.7 billion data points total over 5.5 months, but data was overwritten every 4 hours due to software failure.
  - After the code was tested and verified, a last-minute code change was made, and the change was not sufficiently tested and verified.
- NREL is rigorously working to improve QA/QC systems to ensure this does not happen again and is being transparent with industry to help de-risk future deployments by encouraging others to learn from this mistake.



NDAQ blade strain data from last 4 hours of turbine deployment

Rotor with thermoplastic blades and NDAQ being deployed on Verdant TriFrame

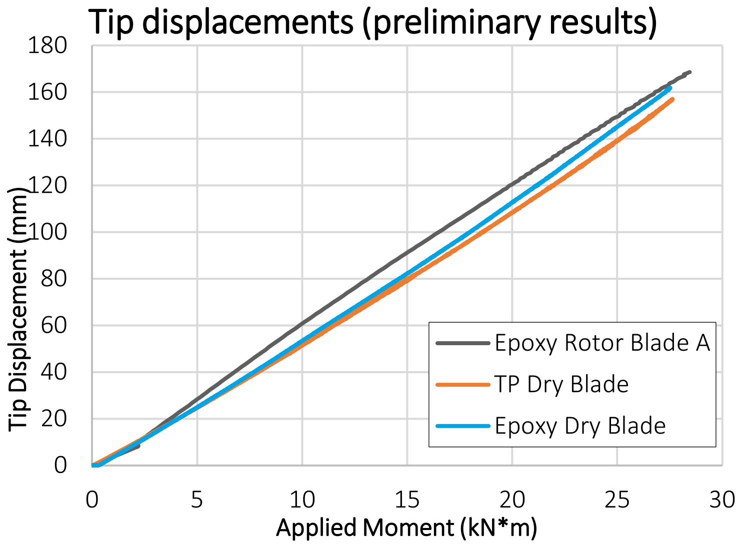
Performance: Accomplishments and Progress (cont.)

- Characterization after 6-month deployment of both blade types allows us to quantify how each material performed in seawater at scale.
- Epoxy and thermoplastic blades loaded to 50% of maximum expected static load (fatigue testing ongoing)
  - Pre-deployment **thermoplastic blades were 6% stiffer** than dry epoxy blades
  - Have not completed post-deployment testing, but preliminary results thus far suggest post-deployed epoxy blades are slightly less stiff than dry blades.
- Based on modal testing, the thermoplastic blades had **significantly more damping** than the epoxy blades
  - Positive knock-on effects by decreasing the loads transferred to the rest of the down-stream components.


Pre-deployment dry thermoplastic blade being tested at NREL


Post-deployment epoxy rotor and blade being tested at NREL

	Thermoplastic Blade		Epoxy Blade		Comparison	
Mode #	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
1	28.8	0.537	27.4	0.135	105%	398%
2	69.7	0.803	66.9	0.334	104%	240%
3	113	0.825	114	0.153	99%	539%



Future Work

- Complete post-deployment structural testing
  - NREL's post-deployment structural testing will quantify how well each blade type—thermoplastic vs. epoxy—performed during the 6-month deployment. This data can help build confidence in this new, lower-cost, recyclable material and move the technology closer to commercial adoption.
  - Testing will go into the start of FY23 so that the thermoplastic rotor can be conditioned in the soak tank for the same length of time as the epoxy rotor.

- Publications to be completed and submitted
  - Publications on thermoplastic blade structural performance and instrumentation best practices will ensure the marine energy industry can incorporate this promising new material into their own technology.

- Marine hydrokinetic materials task will take specimens from the post-deployed blades after structural testing is complete to try to better understand the effects of seawater ingress at a microscopic scale.

Note: All photos in this presentation either by Ryan Beach, Robynne Murray or David Dawkins, NREL

Thank you!

NREL and Verdant Power RMC project team

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