Powering Arctic Observations with Marine Energy

Report to Congress
June 2023

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This report responds to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)). It is an examination of the opportunities for research and development in non-power sector applications for marine energy in conducting ocean observations. The U.S. Department of Energy transmits to Congress the following Report on Powering Arctic Observations with Marine Energy.

- **The Honorable Joe Manchin**
  Chair, Senate Committee on Energy and Natural Resources

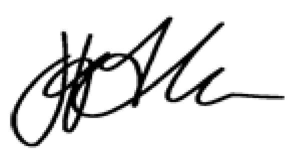
- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources
  Chair, Committee on Science, Space, and Technology

- **The Honorable Frank Lucas**
  Chair, Committee on Science, Space, and Technology

- **The Honorable Zoe Lofgren**
  Ranking Member, House Committee on Science, Space, and Technology

If you have any questions or need additional information, please contact me or Ms. Becca Ward, Deputy Assistant Secretary for Senate Affairs or Ms. Janie Thompson, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,



Jennifer M. Granholm

Executive Summary

Ship traffic and maritime use of the Arctic Ocean is expected to increase as the yearly sea ice extent decreases. Observational data such as wave heights, wind speeds, and sea ice conditions are needed to inform forecasting models, navigation, environmental research, and improve real-time situational awareness. Arctic observations are becoming increasingly valuable, but the types and frequencies of measurements are constrained by power needs. In situ power generation by marine renewable energy would increase the frequency of observations and reduce or eliminate service trips for battery replacements.

This report discusses how marine renewable energy could be developed to power instruments currently being used in the Arctic. Offshore wind, algal derived biofuels, seafloor geothermal and solar power all have potential in the Arctic but this report only discusses energy generated from water. Wave motion and tidal currents are explored as having potential to be used for energy extraction and the powering of sensors at sea. These resources are investigated for Arctic locations and recommendations are made for future studies of specific use cases.

Powering Arctic Observations with Marine Energy

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List of Abbreviations

ADCP	Acoustic doppler current profiler
APL	Applied Physics Laboratory
CO-OPS	Center for Operational Products and Services
CTD	Conductivity Temperature and Depth
FVCOM	Finite Volume Community Ocean Model
H_s	Significant wave height
IABP	International Arctic Buoy Program
LDEO	Lamont-Doherty Earth Observatory
MIZ	Marginal Ice Zone
NCEP	NOAA National Centers for Environmental Prediction
NSIDC	National Snow and Ice Data Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
PNNL	Pacific Northwest National Laboratory
T_p	Wave period
V	Volts
VIV	Vortex Induced Vibration
W	Watts
WEC	Wave energy converter
WW3	Wavewatch III

Acknowledgements

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I. Legislative Language

This report responds to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)), wherein it is stated:

''(b) STUDY OF NON-POWER SECTOR APPLICATIONS FOR ADVANCED MARINE ENERGY TECHNOLOGIES.—

(1) IN GENERAL.—The Secretary, in consultation with the Secretary of Transportation and the Secretary of Commerce, shall conduct a study to examine opportunities for research and development in advanced marine energy technologies for non-power sector applications, including applications with respect to—

> *''(A) the maritime transportation sector;*
> *''(B) associated maritime energy infrastructure, including infrastructure that serves ports, to improve system resilience and disaster recovery; and*
> *''(C) enabling scientific missions at sea and in extreme environments, including the Arctic.*

(2) REPORT.—Not later than 1 year after the date of enactment of this section, the Secretary shall submit to the Committee on Energy and Natural Resources of the Senate and the Committee on Science, Space, and Technology of the House of Representatives a report that describes the results of the study conducted under paragraph (1).''

This report discusses topic (C) shown above and was drafted in consultation with the Department of Commerce's National Oceanic and Atmospheric Administration. A separate report that addresses (A) and (B) listed above was drafted in consultation with the Department of Transportation.

II. Introduction

Collecting data at sea is challenging and scientists and researchers have developed many creative ways to collect *in-situ* data. Some environments, particularly the Arctic, are especially challenging due to their extreme conditions. The Arctic Research and Policy Act of 1984 defines the Arctic as territory north of the Arctic Circle and some areas south of the Arctic Circle as shown in Figure 1. The Bering Sea and the Aleutian Islands are the U.S. areas included in the definition that are south of the Arctic Circle. The Arctic is a critical environment to study due to its importance in climate change, unique habitats for endangered species, and wealth of natural resources. Arctic observations are increasing and will become even more valuable as the sea ice extent decreases and shipping traffic increases.

Sea ice presence in coastal regions is currently a seasonal phenomenon (Figure 2), but the Arctic is warming twice as fast as lower latitude environments and the future of sea ice throughout the region is uncertain (Overland et al. 2019, https://arctic.noaa.gov/Report-Card/Report-Card-2019/ArtMID/7916/ArticleID/835/Surface-Air-Temperature). Figure 2 shows example images of sea ice extent around Alaska at four times of the year. Above 70°N, sea ice is present along the Alaskan coastline for most of the year except late summer and early fall. Below the Arctic Circle, significant seasonal sea ice forms in the Bering Sea, the Aleutian Islands, Cook Inlet, and Prince William Sound.

Figure 1. Map of the geographic extent of the Arctic (https://www.state.gov/key-topics-office-of-ocean-and-polar-affairs/arctic/)

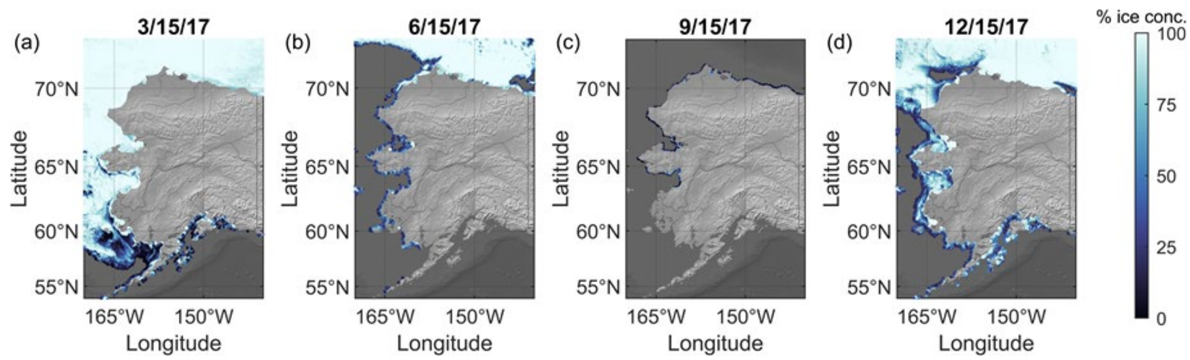

Figure 2. Sea ice concentration at four times of year in Alaska as monitored by the AMSR2 (Advanced Microwave Scanning Radiometer 2) instrument. (a) spring: March 15, 2017; (b) summer: June 15, 2017; (c) fall: September 15, 2017; (d) winter: December 15, 2017.

Arctic observations enable researchers to study this rapidly changing environment and determine the causes of changes in the sea ice. Most of these observations are made far from land and the power grid. Travel to these remote locations is very expensive due to ship time on ice breakers and chartered flights on small planes and helicopters. Many researchers use autonomous instruments that they leave in the Arctic for a year at a time. These instruments are designed to withstand extreme temperatures, high-winds, and sometimes impact or crushing from the sea ice itself as it moves. Yet, even the most robust instrument runs the risk of running out of power, and without power it cannot fulfill its data collection mission. Harvesting renewable energy from local sources, such as ocean waves, currents, wind, or solar are all viable ways to extend the operating life of these instruments. Moreover, energy harvesting at the measurement sites or on the instruments themselves would decrease the dependence on batteries and increase the amount of data collected and time between service cruises or flights. This report focuses on understanding these energy needs and how they might be met using marine energy technologies from wave or ocean current resources.

III. Power Usage and Requirements of Instruments Operating in the Arctic

Arctic instruments measure a variety of physical parameters at a range of spatial and temporal scales, and almost all measurements are made in remote locations where easily accessible electrical power, as from a grid, is nonexistent. The instruments are deployed on top of, at the same level as, and below the sea ice (Figures 3 and 4; Lee et al. 2012; Witte et al. 2021). Some are moored to the seabed in fixed locations and others float freely with the currents or sea ice to which they are attached. Many of the instruments are autonomous (Figure 5; Lee et al. 2017). Some instruments are part of large observational programs such as the International Arctic Buoy Program (IABP), the National Oceanic and Atmospheric Administration (NOAA)

Global Drifter Program, and the Argo float program. The deployments in the Arctic face unique challenges such as cold temperatures, high winds, and curious polar bears. Power generation systems built to supply power to these sensors need to be designed to withstand the harsh conditions and operate without intervention.

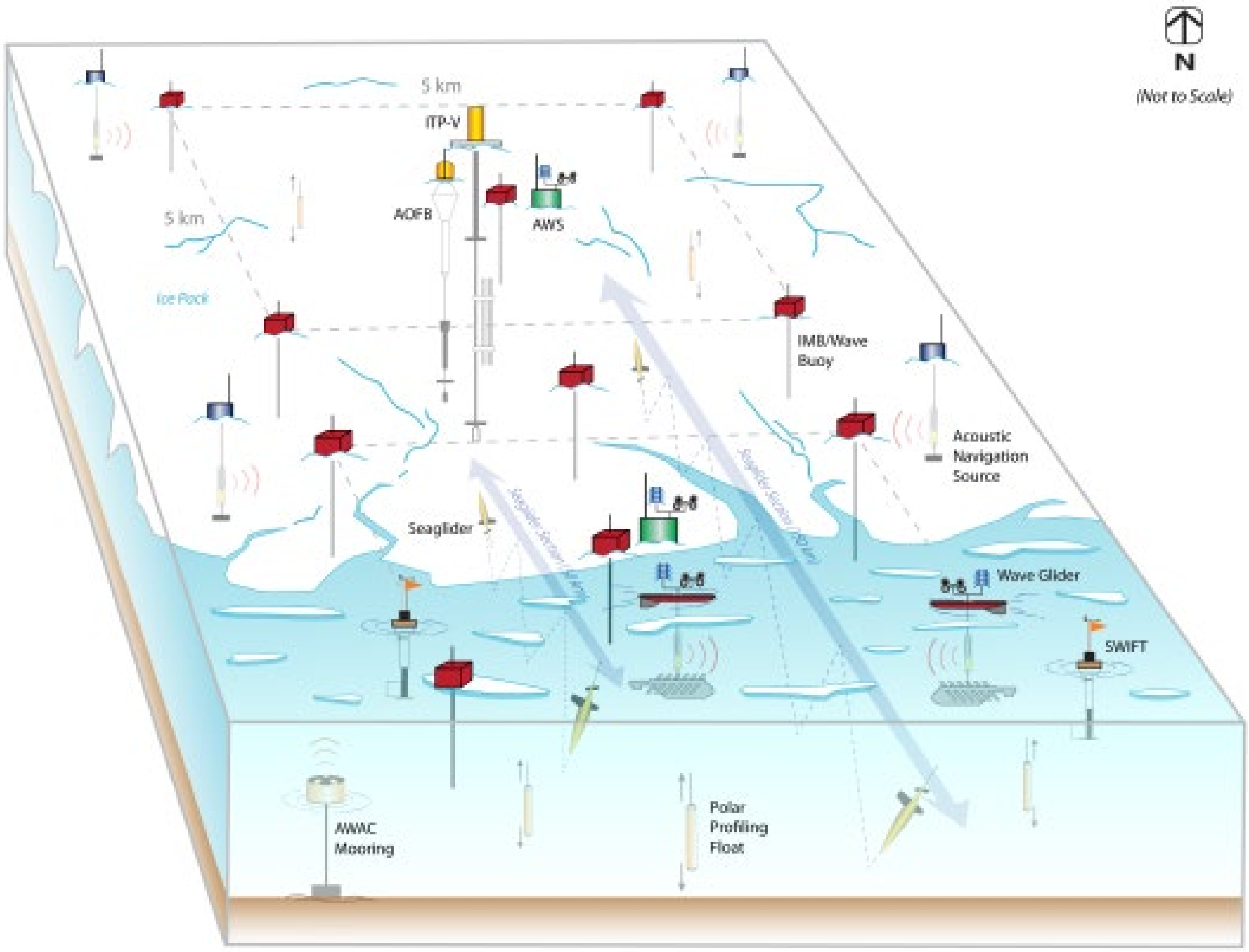

Figure 3. Instrument configuration during the Marginal Ice Zone (MIZ) Program (Lee et al. 2012).

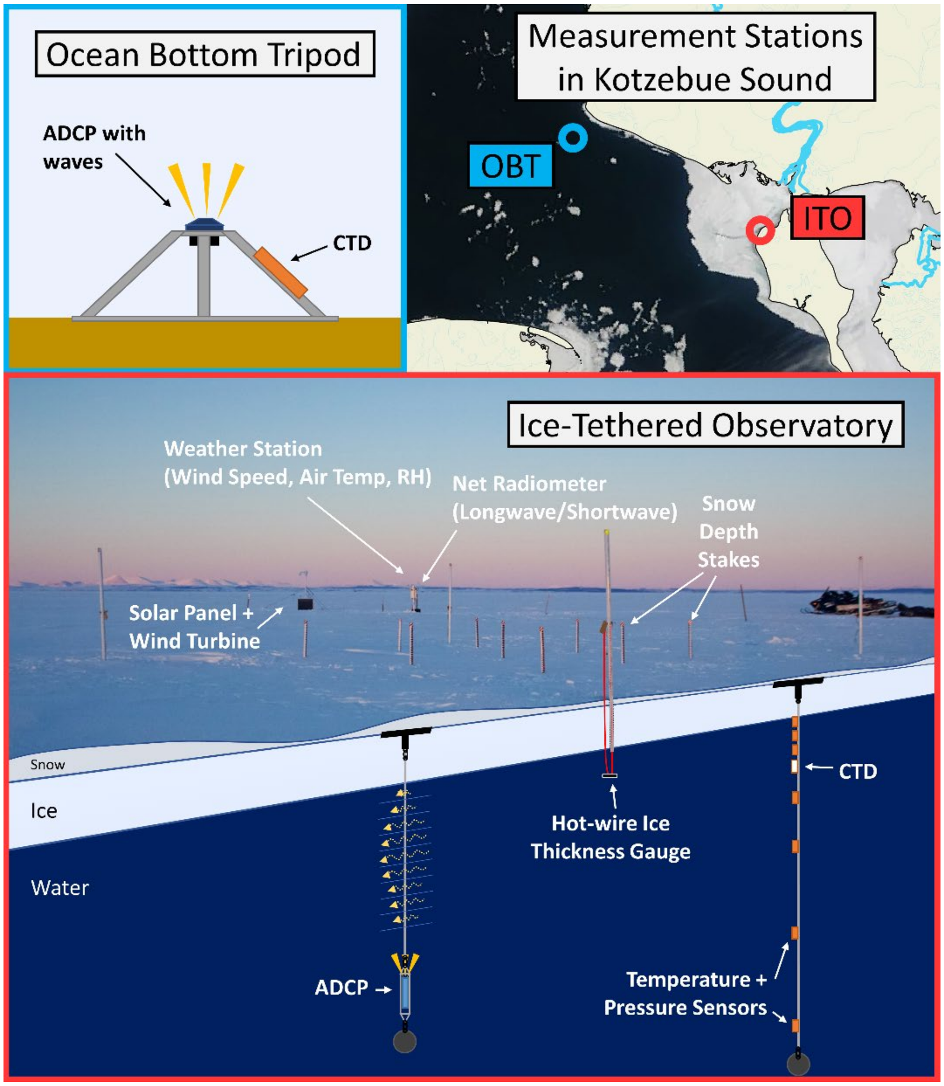

Figure 4. Ice-tethered observatory observations in Alaska (adapted from Witte et al. 2021).

Research programs in the Arctic range from short month-long experiments to longer projects that monitor the environmental conditions over several years. One example of a larger monitoring project is the IABP, which maintains a network of more than 100 buoys. Figure 6 shows the positions of the IABP buoys on October 5, 2021. About half of the buoys are in the sea ice and the other half are in the open ocean. The buoys that are in the sea ice could use one type of power generation and those in the open ocean could use another type. Many buoys move from the sitting on the sea ice to floating on the open ocean, which would require the power generation system to operate in both configurations. This highlights the fact that the power requirements and marine energy power generation options vary based on the type of instrument and the type of environment in which it will be deployed.

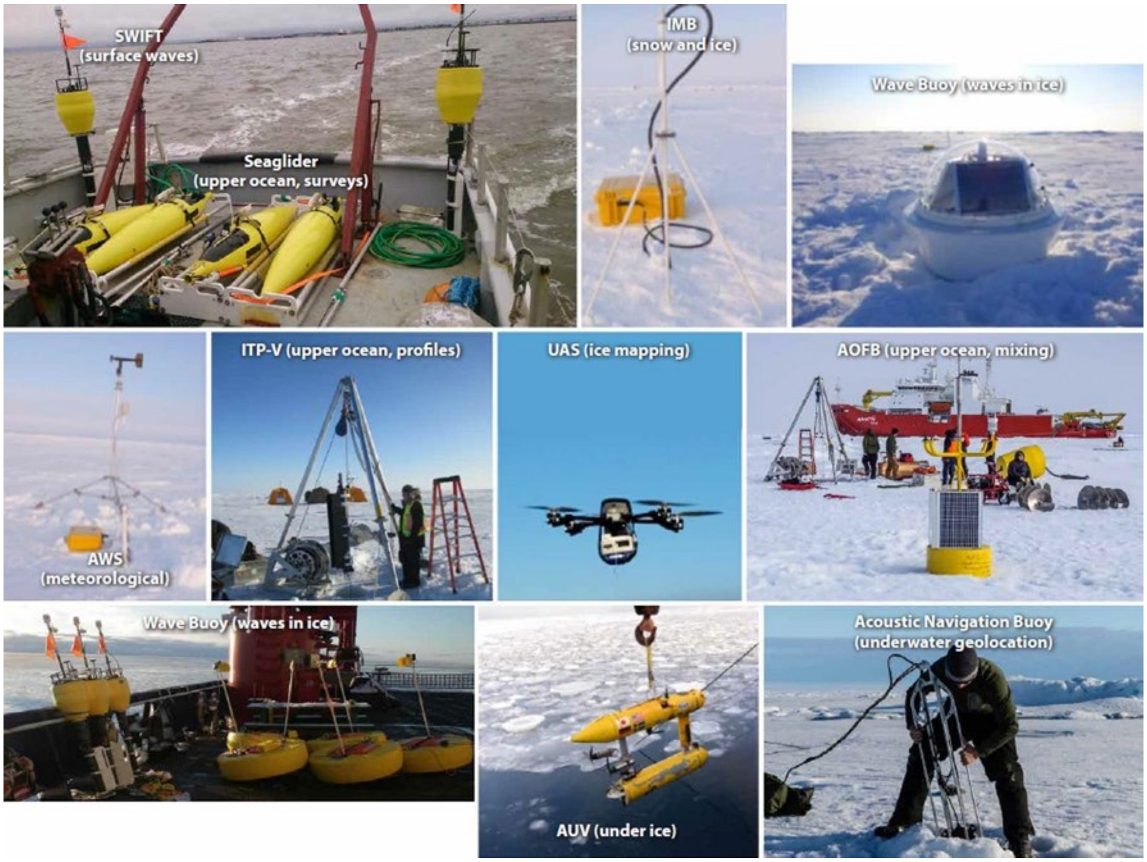

Figure 5. Autonomous platforms used in Arctic field programs (Lee et al. 2017).

Instruments used in the Arctic measure a variety of parameters such as temperature, velocity, salinity, air pressure, and sound. Many deployments require a data logger or an acoustic release if the buoy is moored to the seafloor. For real-time data monitoring, a modem is needed for transmission. Table 1 lists some instruments commonly used in the Arctic and their power requirements. The power requirements of the instruments are small (less than 10 W) yet the number of measurements taken is still power limited. Additional power supplied to these instruments would enable more frequent measurements and longer instrument lifetimes.

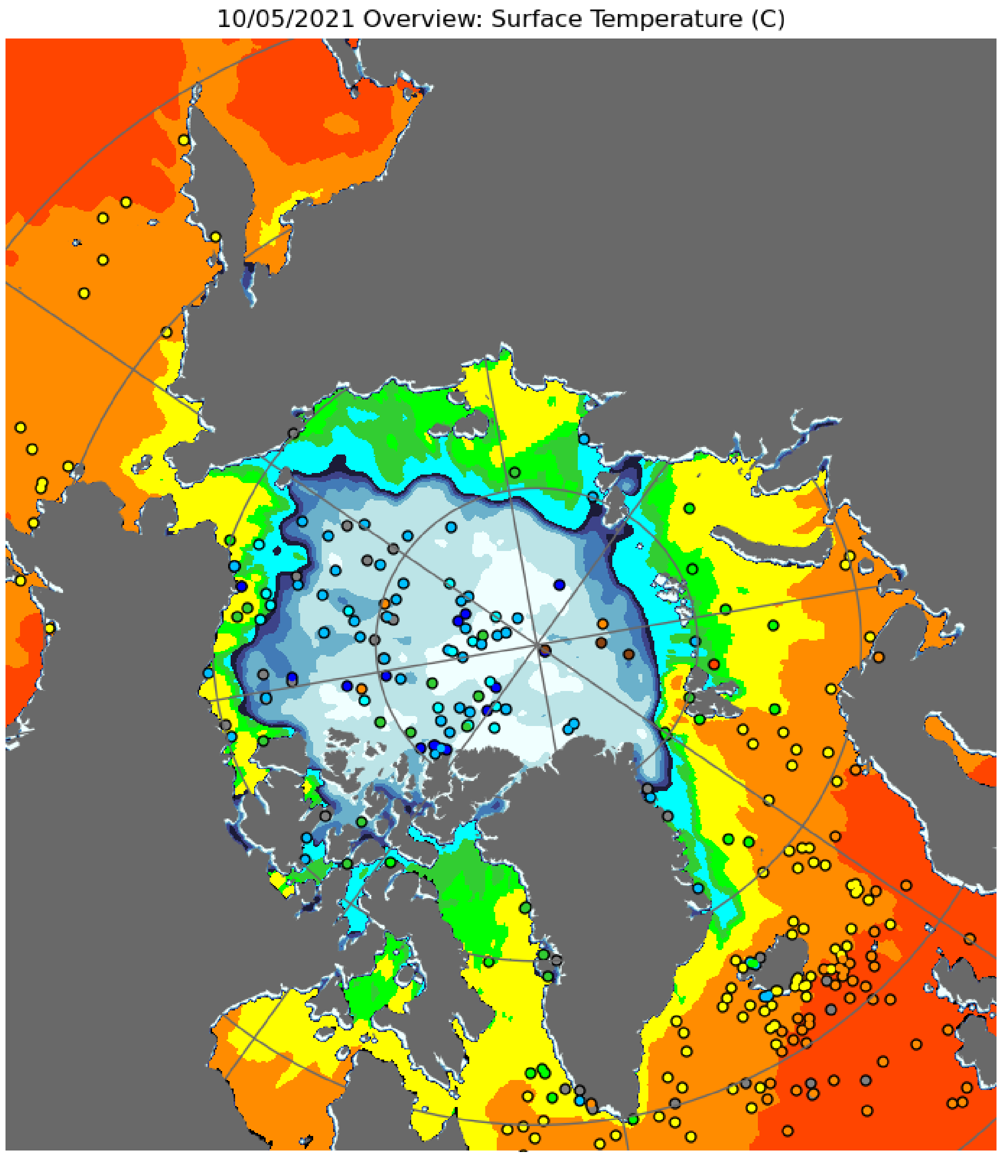

Figure 6 IABP buoy locations on October 5, 2021.

Power is currently limited on Arctic instruments by battery capacity, which drains quickly in cold temperatures. Instruments that are deployed on top of the ice can be connected to large battery packs because the weight of the batteries does not interfere with the operation of the instrument. Instrument that are floating must limit the weight of their battery packs or increase the buoyancy of the float accordingly. Lithium batteries are very difficult to transport but they are still used because they last longer than alkaline alternatives. Solar panels are sometimes used to augment battery power but they do not work well in the Arctic due to low light levels in winter and snow or frost accumulation all year round.

Table 1. Instruments used in the Arctic.

Instrument	Company	Duration	Average Power Consumption (W)
ADCP	Nortek	1 year	0.05-1.5
ADCP	Teledyne RDI	1 year	0.05-1.5
Acoustic release	Teledyne Benthos	4 years max	0.4-0.5
Acoustic release	Edgetech	2 years	0.1
CTD, 37-series	SEA-BIRD	2 year	1-2
Drifter Buoy	Pacific Gyre	1-2 years	0.1
Data Logger	Campbell Scientific	no limit	1-2
Temperature	Onset HOBO	1-2 years	0.1
CTD	RBR Concerto	1 year	0.01-1
CTD, 41-series	SEA-BIRD	1 year	0.1-0.25
Ice mass balance buoy	Cryosphere Innovation	2 years	0.1
Hydrophone	Multi-electronique	1 year	0.1-1.5
Hydrophone	Ocean Instruments	500 days	0.1
Barometer	Vaisala	N/A	0.01
Modem	Iridium	N/A	0.8
Anemometer	R. M. Young	N/A	0.05-0.1
Met station	Campbell Scientific	N/A	0.5-1

IV. Marine Energy Resources in the Arctic

Wave Resources

The wave resources in the Arctic varies seasonally and is influenced by the presence of sea ice. Wave resources can be characterized by mapping the average significant wave height. Average significant wave heights can be calculated from the NOAA National Centers for Environmental Prediction Wavewatch III (NOAA NCEP WW3) production hindcast (https://polar.ncep.noaa.gov/waves/hindcasts/prod-multi_1.php). NCEP's Arctic wave model is forced with operational NCEP winds and ice fields over a rectilinear 30 arc-minute grid. Ice is not considered to dampen, scatter, or reflect waves in this model. Model output is available from February 2005 to May 2019, but for the purpose of this report DOE retrieved only the last 10 years of available data starting with June 2009. Figure 7 shows averages of significant wave height (H_s) over the 10-year period for each of the meteorological seasons: spring (March 1 to May 31), summer (June 1 to August 31), fall (September 1 to November 30), and winter (December 1 to February 28/29). Data coverage in winter and spring is more limited than in the summer and fall because of sea ice. The most energetic wave conditions are observed in the Greenland Sea and the Barents Sea.

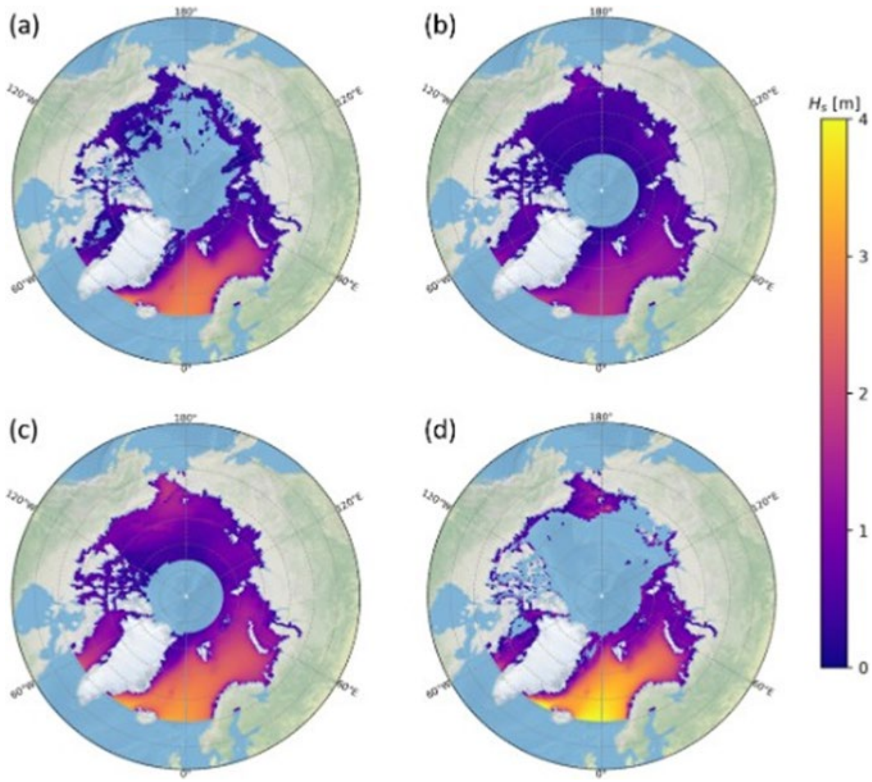

Figure 7. 10-year seasonal average of significant wave height during (a) spring, (b) summer, (c) fall and (d) winter.

The wave resource in the Arctic is increasing as the sea ice extent is decreasing. This trend is shown in Figure 8 as an increase in significant wave height, H_s, and wave period, T_p, even as the wind forcing has remained constant (Thomson et al. 2018). If the sea ice extent continues to decrease, the wave resource will continue to increase, and more wave energy will be available for electricity generation.

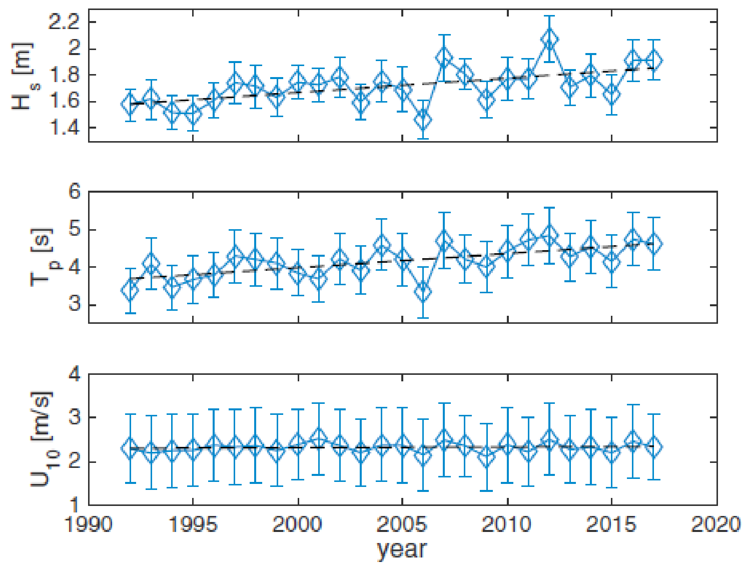

Figure 8. Trends in the wave heights, wave periods, and wind speeds over the Beaufort and Chukchi seas in autumn. Reproduced from Thomson et al. 2018.

Current Resources

Current resources in the Arctic are from ocean currents, tidal currents, or the relative current between the moving ice and the water below the ice. Ocean currents in the Arctic Ocean are not a strong resource for energy generation because their average is only about 0.2 m/s. Tidal currents are much faster than ocean currents and therefore could be considered a marine renewable energy resource in the coastal areas surrounding the Arctic Circle, including the Aleutian Islands, Baffin Island, Svalbard and Greenland (Figure 9). Cook Inlet is not technically in the Arctic, but it is affected by seasonal sea ice like the Arctic and has significant tidal currents that could be used for power generation. NOAA, the National Ocean Service (NOS), and the Center for Operational Products and Services (CO-OPS) conducted a tidal energy assessment of Cook Inlet in partnership with the Alaska Energy Authority. That modeling effort led to the existing NOS Cook Inlet Operational Forecast System. The tidal current resource has also been characterized using the numerical model Finite Volume Community Ocean Model (FVCOM) (Wang and Yang 2020). The maximum tidal power density is near 5000 watts per square meter in the Foreland region (Figure 10). The relative current between moving ice and the water below the ice has not been studied extensively as a possible energy resource. Data from an ice-tethered buoy in Alaska showed velocities as high as 1 m/s (Figure 11). A full resource assessment of the under ice velocity is needed to accurately characterize this resource.

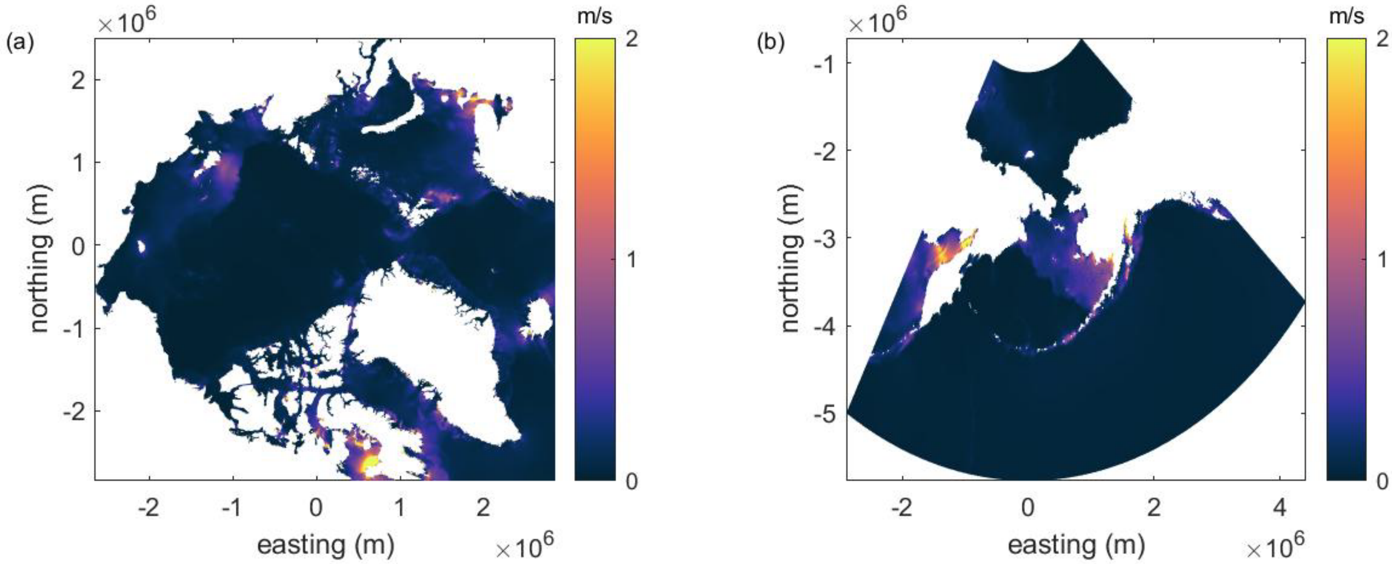

Figure 9. Peak tidal velocity in the (a) Arctic and (b) Bering Sea and Aleutian Islands.

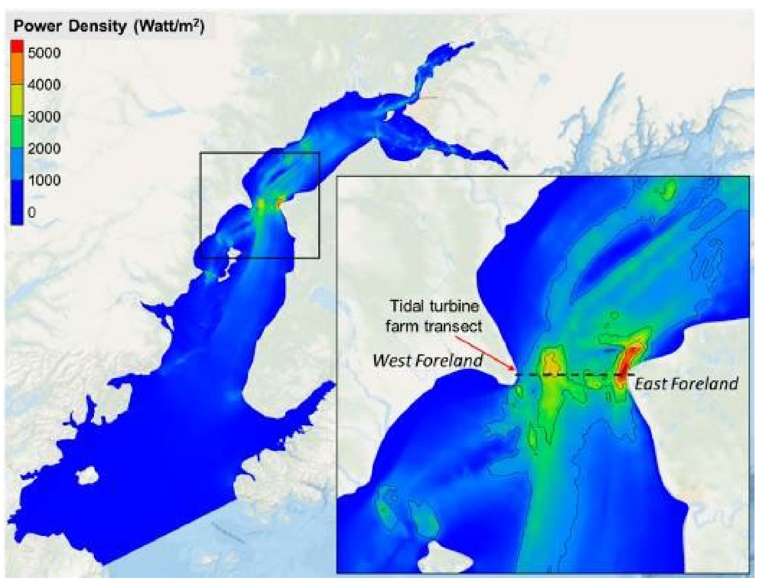

Figure 10. Average power density inside Cook Inlet (Wang and Yang 2020).

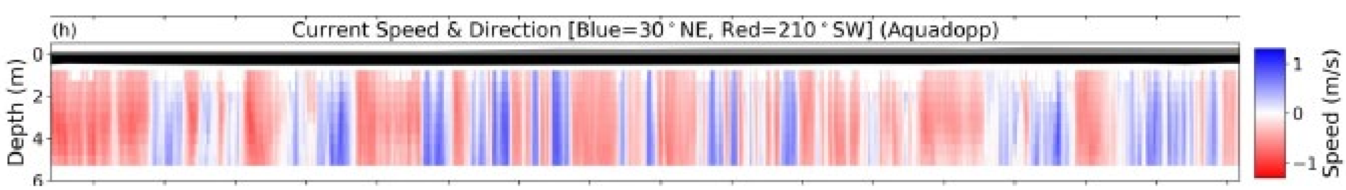

Figure 11. Current speed and direction of water under the ice-tethered observatory shown in Figure 4 (adapted from Witte et al. 2021).

V. Power Generation

Wave Energy for Power Generation

Wave energy was first used in the Arctic more than 10 years ago for propulsion of Wave Gliders by NOAA and university research groups (Lee et al. 2012; Wood et al. 2013). Wave glider-powered research continues in the Arctic, as can be seen in the photo in Figure 12, which was taken north of Alaska in September 2018. As the sea ice extent decreases and the wave energy increases the use of wave energy is expected to increase in the Arctic and wave energy convertors might be used to power instruments or remote coastal communities.

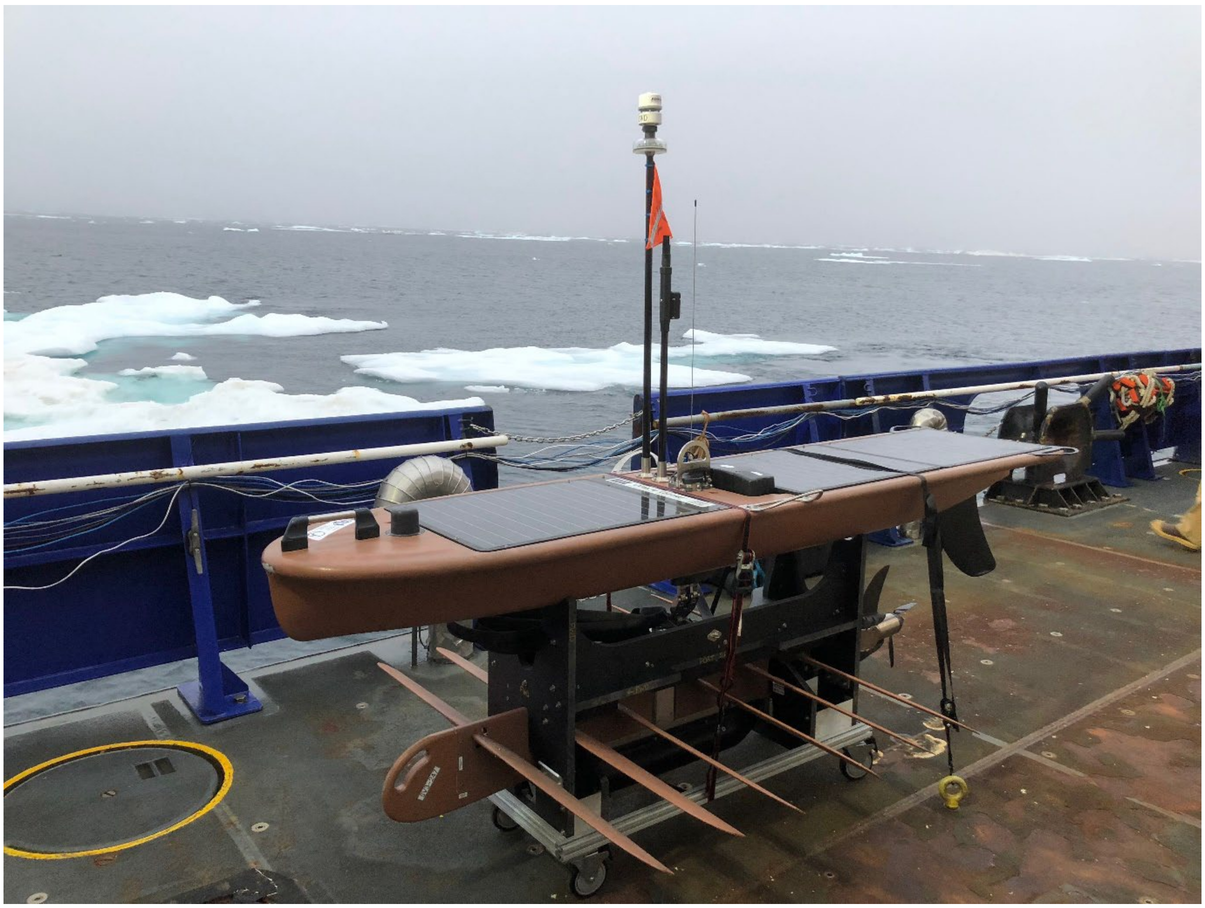

Figure 12. Wave glider in the Arctic for the Stratified Ocean Dynamics of the Arctic program cruise (2018). Photo by J. Thomson APL-UW.

Wave energy converter (WEC) development is an active area of research. Large-scale WECs could be used in the Arctic during the ice-free season or if they are built to operate below the sea ice. Small-scale WECs could be used to power instruments such as thermistors and hydrophones. A list of 143 companies developing WECs can be found here: https://theliquidgrid.com/marine-clean-technology/wave-energy-converters/. No small-scale WECs are currently available for purchase. Ten types of WECs are listed along with their maximum rated power and depth of operation. Most of the companies are developing WECs for large grid-scale applications. WITT Energy is the listed company that is developing the smallest maximum rated power WEC. WITT does not currently have a WEC unit for sale but testing of the unit is under way. Once a small-scale WEC is developed it could be anchored as a power source in a fixed location or it could generate power from wave motion as it floats freely in a buoy.

Wave energy can also be harvested on a much smaller scale by piezoelectric or triboelectric nanogenerators. This technology development is being driven by the market for self-powered wearable electronics, but the electricity generated by motion could be used to power instruments such as small temperature or salinity sensors (Wang et al. 2017; Dahiya et al. 2018; Wu et al. 2018). As ship traffic increases in the Arctic, more buoys will be needed for operational awareness such as the current ice conditions. A network of small, disposable, environmentally friendly buoys could be used for that purpose. Those buoys may rely on new technologies such as piezoelectric or triboelectric nanogeneration for their power needs.

Current Energy for Power Generation

Current energy resources from ocean currents, tidal currents, and the relative ice/water currents are small in the Arctic, but the power requirements of most instruments are also small. Small-scale portable turbines have been developed for charging USB devices such as phones and tablets in the field. Two that are currently available for purchase are the ENOMAD and the WaterLily turbines. The ENOMAD turbine (Figure 13a) can generate 5 W in 1.2 m/s flow (http://www.energynomad.com/). The turbine charges a 5600 mAh lithium-ion battery and users charge their devices from the battery using a USB cable.

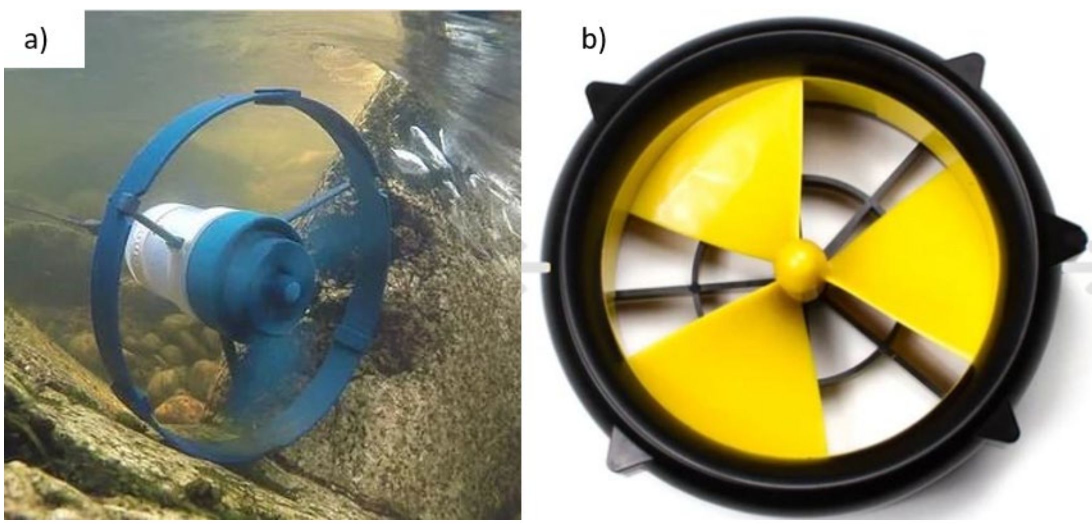

Figure 13. Small turbines: (a) ENOMAD (http://www.energynomad.com/) (b) WaterLily (https://www.waterlilyturbine.com/).

The WaterLily turbine (Figure 13b) has a maximum rated power output of 15 W, but multiple turbines can be connected to generate more power (https://www.waterlilyturbine.com/). It can be purchased with a USB connector or a 12 V connector. The USB version outputs 5 V of regulated power up to 3 A, and the 12 V version outputs 14.6 V DC up to 2 A. The minimum flow speed required is 0.3 m/s and the flow speed needed for the peak power output is 3.2 m/s. The WaterLily is rated for a maximum flow speed of 4 m/s.

Both the ENOMAD and WaterLily turbines show potential for very small-scale marine renewable energy applications, but they have not yet been integrated with ocean observation sensors or shown to work for that purpose. One concern with these types of turbines would be clogging issues due to woody debris or seaweed. Woody debris and seaweed may not be a problem offshore in the Arctic, but they would need to be considered for coastal installations or in areas of the ocean where sargassum grows.

Another type of technology that shows potential for Arctic applications is vortex-induced vibration (VIV). Traditional rotating turbines have a minimum flow velocity of 0.5 m/s, but VIV is a technology that can generate power at flows down to 0.2 m/s. VIV instruments also have fewer external moving parts that might get clogged with woody debris. Figure 14 shows two VIV instruments that are currently being developed. The WITT system (Figure 14a) was described previously in this report as a WEC, but it can also be used as a VIV if it is mounted for that purpose. The WITT instrument is not yet available off the shelf, but the company plans to produce a range of sizes from 80 mm units that produce 5 W to 2 m units that produce 500 W. The power production depends not only on the size of the instrument but also on the velocity of the current. The VIVACE instrument (Figure 14b) is also not yet available for purchase but has been extensively tested in the field. It is much larger than the WITT and could be used to meet greater power needs. Both the WITT and the VIVACE can generate more power when deployed as arrays. Another advantage of a VIV instrument is its low noise production. Quiet power generation is necessary for applications such as powering hydrophones and echosounders to limit interference of the power generation with the signal being measured.

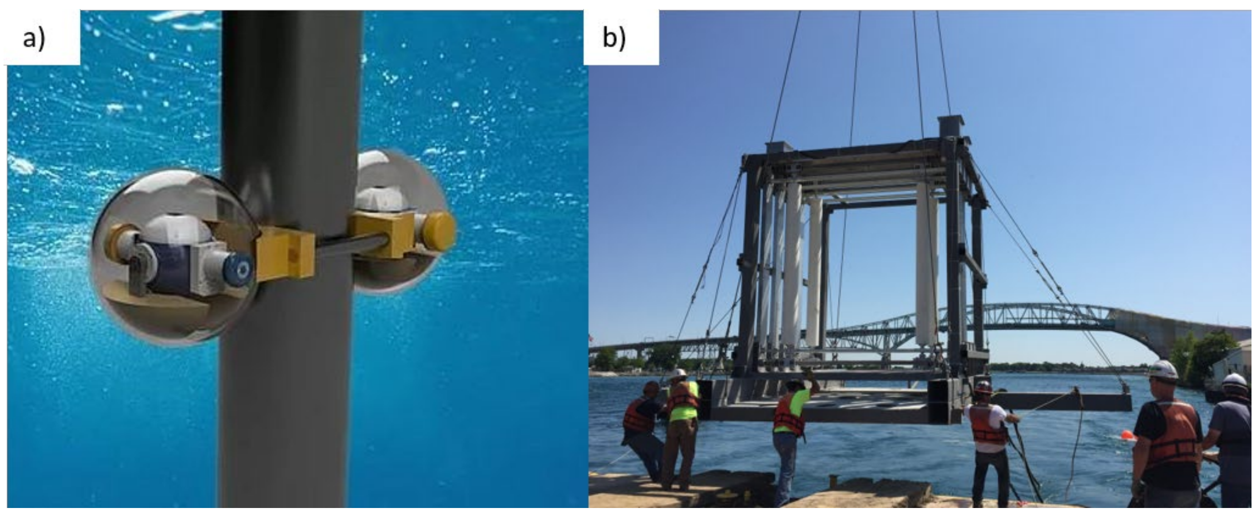

Figure 14. Vortex Induced Vibration Instruments: (a) WITT (https://www.witt-energy.com/sub-sea) (b) VIVACE (https://www.vortexhydroenergy.com/)

VI. Opportunities

Wave and current resources are small in the Arctic but the power usage of most currently operated instruments is also small. Future small-scale WECs, turbines, and VIV instruments will be able to power small devices such as thermistors, acoustic releases, and hydrophones.

The first recommendation is to encourage the development of small-scale WECs, turbines, and VIV instruments to be used for stationary ocean observations. Initial case studies will include the use of WECs or turbines to power remote tide gauges and hydrophones. NOAA operates tide gauges and hydrophones in remote locations of Alaska where grid power is not available (Figure 15). The five NOAA tide gauges that operate without grid power run intermittently, fueled by solar, diesel, and wind (Figure 15a). Wave power could be used to operate these instruments. Two NOAA hydrophones in remote Alaskan locations could be powered by tidal currents in Unimak and by waves at Gambell (Figure 15b).

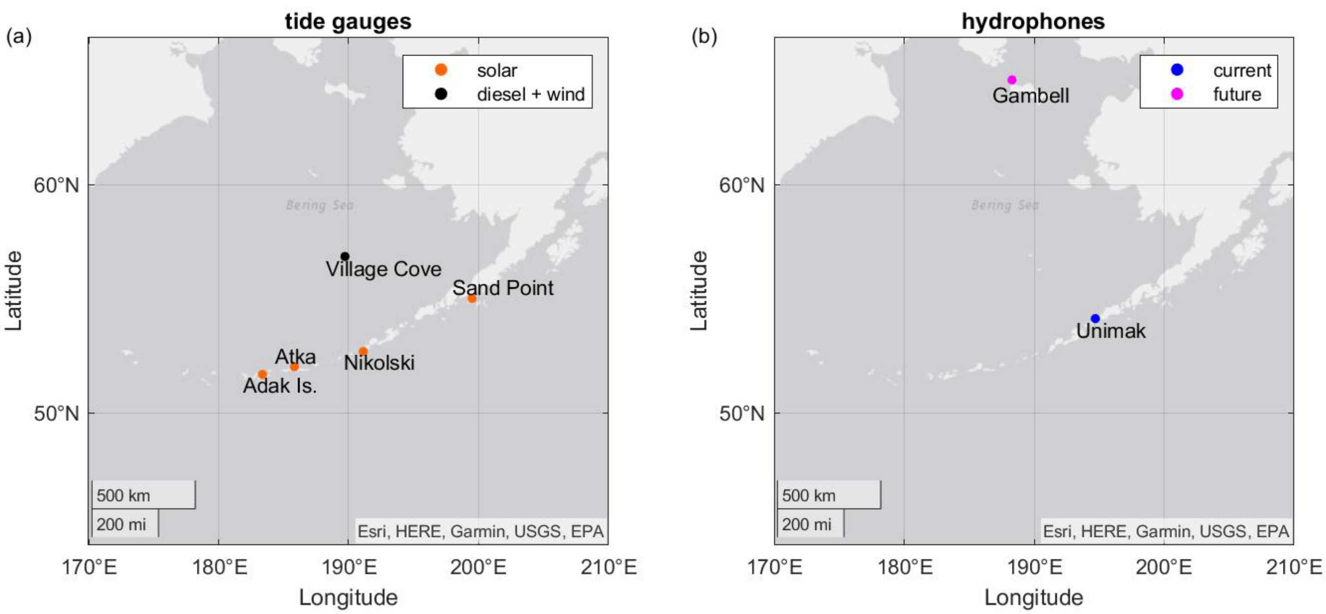

Figure 15. Locations of remote NOAA instruments: (a) tide gauges that operate without grid power and currently rely on solar, diesel, or wind; and (b) current and future locations of hydrophone buoys in Unimak and Gambell.

The second recommendation is to encourage the development of freely floating buoys that are partially powered by WECs. Batteries on the buoys would be recharged when the buoys encounter regions of higher wave energy. The power-generation device on the buoys could be triboelectric or mechanical. Figure 16 shows the drift track of a buoy in the IABP on top of the sea ice concentration from August 22, 2020. August 22 was the date when the acceleration measured by the inertial motion unit on the buoy detected a large increase in motion. The acceleration measured by the buoy greatly increased when the buoy drifted out of the ice and continued south. The magenta part of the drift track is the time when the buoy experienced large accelerations due to waves and a WEC could be used to generate power.

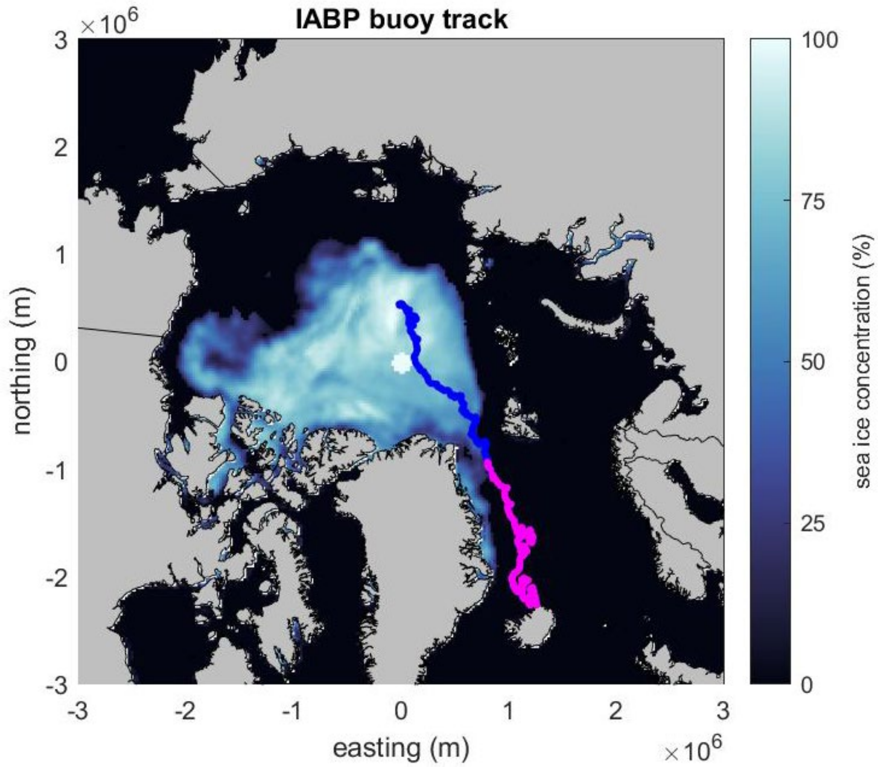

Figure 16. Sea ice concentration on 8/22/20 and an International Arctic Buoy Program buoy track shown in blue when the buoy acceleration was <10,000 and magenta when it was >10,000. Sea ice data from the National Snow and Ice Data Center and buoy data from IABP.

Our third recommendation is to encourage the development of a power-generation device mounted on the ice that drifts with the ice and takes advantage of the relative velocity between the ice and the water it is floating on. This would power instruments that make measurements on, in, or directly below the ice. Data from the ice-tethered observatory pictured in Figure 4 shows water velocities up to 1 m/s (Figure 11). A full resource assessment needs to be performed for this velocity resource in the Arctic. The ocean currents are slow in the Arctic, but the wind pushes the ice and if the resulting relative velocity is greater than 0.2 m/s, then it could be used for power generation. Many researchers, including NOAA (Figure 17), mount instruments on the ice and would benefit from this technology.

Figure 17. NOAA Arctic StarDot NetCam #2 Mon Jul 05 07:34:49 2010 UTC. Image © NOAA/PMEL.

The last recommendation is to encourage collaborations with NOAA, IABP, and university researchers to deploy new small scale WECs, turbines, and VIV instruments in the Arctic. These collaborations have already begun to explore use cases such as those in Figures 15 and 16. NOAA Sea Grant and the Department of Energy are working together to find shared benefits through partner-based efforts. Many discussions are still in the exploratory phase, but realized partnerships include a shared position for the Sea Grant Knauss Fellowship, a co-funded competitive research competition, and a National Liaison position.

This report does not make any recommendations about marine energy power generation solutions for autonomous vehicles. Autonomous vehicles may be able to derive energy from motion, but the amount of energy would be small unless they were near the surface with strong wave conditions. In the future, autonomous vehicle charging stations may be available that are powered by either wave or current motion.

VII. Conclusions

This report is a response to legislative language set forth in section 3001(a) of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Title III, codified at 42 U.S.C. § 17214(b)) requesting the U.S. Department of Energy's Water Power Technologies Office to study the research and development opportunities in advanced marine energy technologies to enable scientific missions at sea and in the Arctic. While there are many research and development opportunities in marine energy technologies for scientific missions at sea, this report focused on those related to the Arctic since it is experiencing high rates of change and as is considered one of the most important environments for climate modeling. Most of the technologies investigated would be applicable to scientific missions at sea globally after they have been developed for the Arctic.

Arctic observations are increasingly needed to improve navigation and inform weather and climate forecasting models. The observational instruments are power limited and marine renewable energy has the potential to power them, but the energy-generation technology is in the early stages of development. Improved energy generation technology to power Arctic observations would enable longer deployments and more frequent measurements, which would assist navigation, improve forecasting, and improve our understanding of Arctic processes.

Marine renewable energy resources are small in the Arctic but large enough to power the small instruments that are currently being used for observations. The technology needed to use marine renewable energy to power small instruments is still in the development phase. Once the technology is developed it will enable distributed and persistent observing networks that are not dependent on battery power. The small turbine, WEC, and VIV technologies being developed for the Arctic will be applicable to power ocean observations globally and will improve maritime awareness and oceanographic studies worldwide.

VIII. References

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