McNerney that it would have been extremely difficult to fix the shields had the defects not been uncovered until the reactor had been assembled.

No one has called, at least publicly, for ITER to be abandoned. Luce says he's seen no signs of any of the partners defecting. "In fact there have been positive signs," he says, one of which is that the US and India have recently paid their contribution arrears.

At the June semiannual meeting of the ITER Council in Cadarache, member nations "reaffirmed their strong belief in the value of the ITER mission, and resolved to work together to find timely solutions to facilitate ITER's success," according to a communiqué.

Even Robert Hirsch, the former head of DOE's fusion program and a longtime critic of tokamaks, says ITER should continue. "There's no question that there will be some benefit," he says. But because of their complexity, Hirsch predicts that tokamaks will never become a commercially viable energy source. "ITER never should have happened. Having said that, it is happening, and it seems to me that, practically speaking, people can't walk away from it."

Coblentz says that ITER has helped inspire the emergence of private-sector fusion companies. "We are demonstrating that these massive, precise components needed for fusion energy can be built at industrial scale, and we are developing the required new technologies as we go."

David Kramer

Tidal turbine development ebbs and flows

The renewable energy technology can benefit remote coastal communities that want to reduce carbon emissions.

ROWS OF TURBINES in the currents generated by the rise and fall of the tides offer a predictable way of producing electricity. Here, an array of 100 kW turbines sits on the Bluemull Sound seafloor off Scotland's Shetland Islands.

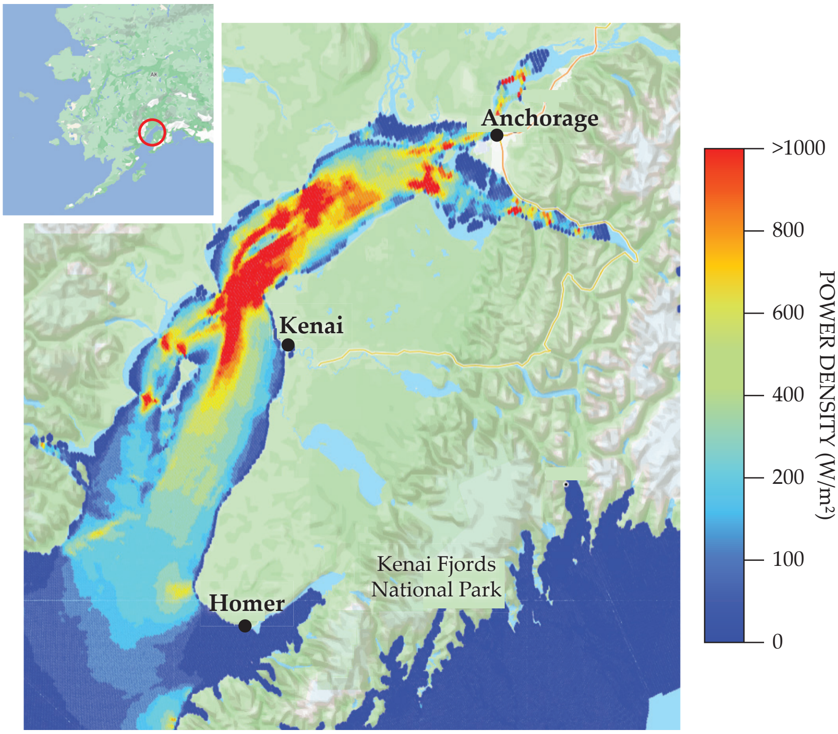
In Canada's Haida Gwaii archipelago, roughly 120 km off the northern coast of British Columbia, the north electrical grid uses more than 7 million liters of diesel to provide power to about 2500 people each year (the south grid uses roughly 3 million liters for roughly 2000 people). For long-term resident Laird Bateham, the predictability of the tides pointed to an obvious alternative. He founded Yourbrook Energy Systems in 2010 to develop a turbine for harvesting power from the local tidal currents. He and his team developed a prototype and are beginning front-end engineering of a project intended to deliver 500 kW of clean and reliable power to the isolated coastal community. That would provide for 20% of the population's average annual use. His colleague Clyde Greenough says, "We want to leave the world a better place by doing our part to slow climate change."

The twice-daily rise and fall of the tides drives powerful, predictable currents when seawater flows toward and away from Earth's coastlines. A turbine placed in the current's path can harness that power. The moving water pushes the turbines' blades, causing them to spin and drive a rotor that powers an electrical generator.

Tidal power has been harvested since the Middle Ages, when people retained incoming tidewater in storage ponds and used the outgoing flow to turn waterwheels for milling grain. In modern times, the world's largest tidal power plants are located in France and South Korea, with 240 MW and 254 MW electricity generation capacity, respectively. There, dam-like structures called barrages span ocean inlets or bays to capture incoming tidal water and generate electricity as the basin fills and empties. The installations can control flows using sluice gates, but because barrages are large scale (making them expensive to construct), they can disrupt the local ecosystem by altering lagoon salinity and animal movements.

In the past decade, motivated by advances in turbine technology and an increased urgency to find energy alternatives to fossil fuels, researchers have worked to generate electrical power by placing small numbers of turbines in strong tidal currents.

Projects like Yourbrook Energy are on



NREL MARINE ENERGY ATLAS

MAPS OF TIDAL RANGES, buoy measurements, and seafloor topographies have led to hydrodynamic models of depth-averaged tidal currents where turbines may be valuable for generating energy. Shown here is the distribution of tidal power density, developed from model simulations, in Alaska's Cook Inlet.

the rise. Tidal turbines could be valuable in helping small coastal communities meet their energy needs. Months-long turbine demonstrations are showing where technical difficulties remain. Scaling up brings challenges related to cost and corrosion and to maintenance of components that are hard to access underwater. The turbines' rotating blades can threaten marine life, and the seafloor platforms that support the turbines can alter flow and induce erosion. In addition, suitable sites are often privately owned, making access difficult. But researchers are coming up with creative technical designs, and turbine developers are finding appropriate sites for testing and installing their technologies.

Predictable, but how practical?

In May 2023, the US Department of Energy announced a $45 million funding opportunity for the development of tidal energy projects. An assessment conducted in 2021 by DOE's National Renewable Energy Laboratory (NREL) determined that the total energy available in the US from tidal currents in the country was 220 TWh/yr. That amount represents roughly 5% of the electricity generated in the US in 2019. The assessment, based on coastal ocean dynamics modeling, estimated that the resource could power 21 million homes. Energy available from all marine resources—including tidal currents, river currents, ocean waves, and ocean thermal gradients—amounts to 2300 TWh/yr, according to the assessment.

The National Research Council in 2013 looked at an earlier set of assessments produced by DOE and raised concerns that are still relevant. For example, the committee that conducted the review suggested that the theoretically available power could be a significant overestimation of the practically available resource. "There's a tendency for proponents to exaggerate the potential and not look at the practical side," says Chris Garrett, an oceanographer emeritus at the University of Victoria and a member of the National Academies review committee. Many evaluations that make a site look appealing for a tidal array based on available resources ignore the impact on marine life and channel erosion. "Things that sound green in principle are green in a small-scale situation," he says. "But even if large scale is feasible, it may not be green."

Garrett's calculations also indicate that proponents overestimate the power potential of tidal turbines. Introducing turbines to a channel slows the water flow. "At some point, adding one more turbine produces less additional power than is lost by the reduced output of the other turbines," Garrett explains. According to a simple study that he and Patrick Cummins published in 2008, the maximum attainable power from an array of turbines in a channel is associated with a 42% reduction in current speed.

Similar studies by researchers across the globe have mapped tidal flow patterns and speeds in specific channels and calculated the power that could be captured by one or more turbines. The sites that can deliver the most power have large tidal ranges, have strong currents, and are located along narrow tidal channels. High-resolution simulations of the sites with the highest tidal power densities can evaluate how energy extraction might affect flow behavior far from a turbine array. Such studies could help to guide site selection and turbine placement.

A 2019 DOE overview of marine renewable energy estimated that tidal energy costs \$130–\$280/MWh. An NREL technology baseline report published in 2023 said that in 2021, onshore wind energy cost as little as \$30/MWh, and utility-scale solar \$39/MWh. The cost of any renewable energy technology, however, tends to decrease as the technology improves, mass production increases, and the supporting industry matures.

Where tidal energy excels is its predictability. Unlike wind and solar, tidal currents are "incredibly reliable," says Levi Kilcher, a marine energy researcher at the NREL and coauthor on the 2021 assessment for DOE. "Operating the grid with highly variable renewables is a massive problem." Still, he says, harnessing just 10% of the US's tidal energy resources could be an optimistic goal even as the technology matures.

Rising tides

The first commercially licensed US-based tidal turbine, Verdant Power's Roosevelt Island Tidal Energy (RITE) project, operated for nine months in 2020 and 2021. Three turbines, fixed to a platform on the river bottom, were installed at a depth of 10 m in the tidal strait of the East River, which connects Long Island Sound with Upper New York Bay. The turbines generated electricity when the water flow velocity exceeded 1.0 m/s, a total of 4.5 hours each day. They delivered more than 312 MWh to the electricity grid, enough to supply 40 homes, which on average use 900 kWh in a month. During the demonstration, Verdant Power honed its maintenance capabilities. "Showing they could extract and replace a turbine and nailing down what the costs would be for the operation was a big success," says Kilcher.

BEN LOEFFLER/ALASKA CENTER FOR ENERGY AND POWER

DRIFTWOOD AND PLANT MATTER can jam tidal turbine blades. Researchers at the Tanana River Hydrokinetic Test Site in Alaska are working on designs that minimize debris fouling.

European projects are more advanced because they attracted investment earlier. The first grid-connected tidal array was installed off Scotland's Shetland Islands in 2016 by Nova Innovation, which added a sixth turbine in January, making the array the largest in the world. Each turbine provides enough electricity for 72 homes and is cost-competitive with diesel generation, according to CEO Simon Forrest. In thousands of hours of underwater video footage, the company recorded fish feeding around the structures at slack tide, moving away when the current began to flow, and disappearing from the area when the turbine blades picked up speed. An independent Scotland environmental regulator determined that there were "no negative impacts," says Forrest. In Shetland, tidal energy is "still more expensive than solar or wind, but prices are coming down, and we believe that we'll be competitive with nuclear energy," he says.

Curran Crawford codirects the Pacific Regional Institute for Marine Energy Discovery (PRIMED) at the University of Victoria. In April the institute won Can\$2 million from British Columbia to continue work on supporting remote communities, many of which are First Nations, through marine renewables including tidal energy. PRIMED is now working to implement a tidal turbine testing facility in a channel along the British Columbia coast at the family-owned Blind Channel Resort, which welcomes the idea of demonstrating a tidal turbine. The tidal turbine will be integrated into the resort's microgrid along with batteries to reduce diesel usage. The researchers plan to deploy a resident turbine capable of producing approximately 50 kW at maximum current, and want to host other turbines over time to prove out operations in British Columbia waters. First Nation communities in similar settings are intrigued about switching to a climate-friendly energy source, but they are still wary of the technology and want to see demonstrated success, Crawford says.

Small fossil-fuel-dependent communities along rivers also benefit from turbine technologies and can provide lessons for tidal installations. In Alaska, turbines deployed in the Yukon River at the towns of Eagle and Ruby highlighted a problem in 2013. Their blades frequently got jammed with logs, detritus, silt, and other debris, says Ben Loeffler, who leads the hydrokinetic research group at the Alaska Center for Energy and Power. To help develop technologies that avoid such jamming, he and his colleagues work at a test site on the Tanana River, where facilities let researchers quantify debris loading and make changes to turbine designs. What they learn could benefit future offshore projects: South-central Alaska's Cook Inlet is home to one of the most powerful tidal energy sites in the US. "We're translating our river turbine experience and knowledge to the Cook Inlet now that it is being looked at seriously for tidal energy," says Loeffler.

Technical creativity

New approaches are improving turbine efficiency and reducing blade damage. Some lessons can be learned from waterwheels that have their support structures above water and can be accessed from the land or a boat, in contrast to the seafloor foundations that support bladed turbines. But there are drawbacks. "Waterwheels are simple and cost-effective, they don't have blades that could damage fish and marine mammals, but until you find a way to increase the flow, they're not efficient," says Gerald Muller, an associate professor of engineering and the environment at the UK's University of Southampton.

Some researchers in the tidal energy community believe waterwheels can be refined to provide the functionality of a turbine and may provide some advantages. Working with Muller as a scientific adviser, Halifax-based BigMoon Power designed a floating, flow-augmented waterwheel. Inclined plates create a low-pressure zone on the wheel's downflow side; the zone lowers the water level in the wheel's channel and increases flow velocity by 50%. Because the kinetic power of a fluid is a cubic function of the flow velocity, the available power is increased by a factor of 3.4. The floating platform is anchored with removable concrete blocks, keeping all mechanical and electrical parts above water for easy maintenance while avoiding the leakage and condensation that plague turbine electronics.

"In the offshore business, it's a rule that everything that can break will break. You want to keep it as simple as possible," says Muller.

BigMoon Power has secured a license to operate eight of its 500 kW tidal energy generators in the Bay of Fundy, which separates New Brunswick from Nova Scotia and has the highest tides in the world. The team is installing a second-generation version of their 12.6-m-diameter device that will connect to Nova Scotia's grid this summer.

The debris in Alaska's Yukon River led Loeffler's colleagues to create a design that could harvest energy from turbulent flow at sites they had previously considered untenable. The researchers developed a vertical oscillator system that draws energy from a pipe placed transverse to the currents. Although the device turned out not to be economical and was discontinued, other companies are developing similar systems for river and tidal currents. Another design deployed and tested by Oregon's BladeRunner Energy in the Tanana River keeps a rotor submerged at the end of a large flexible driveshaft. The rotor transmits torque while floating at the end of a cable in the water. That design is on course for a pilot project in an Alaskan community in 2025. "Their 5 kW system could power five homes in the summertime," says Loeffler.

Economic viability

Efforts to deploy megawatt-scale tidal turbines "have been challenged by getting enough capital together," says Crawford. "If something goes wrong, you sink the company." In the near to medium term, he says, the most promising market segment is smaller turbines for decarbonizing remote communities. They are a necessary step to multi-megawatt-scale versions. "Sidestepping small device development introduces risk," says Crawford.

According to Kilcher, the energy sector considers a project that is robust and reliable for 20–30 years to be economically viable. "In wind turbines, this lifetime is the standard," he says, "and it's where we need to be for tidal turbines."

Rachel Berkowitz PT