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Review Article

Harvesting Marine Energy – A Succinct Review

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Abstract

Many advances have been achieved in the development of facilities that can harvest marine energy. The purpose of this article is to provide a succinct review of these advances.

Keywords: Marine energy; wave energy; tidal energy; oscillating water column

Introduction

More than 70% of Earth's surface is covered by oceans that contain untapped energy. Ocean waters are influenced by the sun's heat and gravity, the moon's gravity, and planetary activities on Earth, such as plate tectonics and the interaction of the atmosphere with ocean waters. The result is the accumulation of heat in the waters, and the generation of motion in the form of waves, tides, and currents [1].

The methods summarized in Table 1 are designed to generate electrical energy from mechanical energy associated with waves, tides, and currents. Another method discussed below is the generation of electrical energy from thermal energy associated with temperature gradients. This review focuses on methods of harvesting marine energy from waves, tides, currents, and temperature gradients.

Table 1: Types of Marine Energy Harvesting Devices.

Device Type	Description [7]
Point Absorbers	Devices typically float "on or near the surface of the water, bobbing up and down with passing waves against a tether or moored component".
Attenuators	Devices "have floating segments that articulate up and down as waves pass by, capturing the relative movement of these segments against each other at the joints".
Overtoppers	Devices "operate by allowing waves to crest on top of them, letting the water flow out of the bottom by gravity through small hydroelectric turbines".
Oscillating Devices	Oscillating devices "that are fixed in place and move back and forth with the motion of waves".

Wave Energy

Wind blowing over the surface of water can amplify small disturbances into larger waves. The characteristics of the resulting waves (height, length, direction) depend on factors like wind speed, duration, water depth, underwater topography, and proximity to landmasses. Water can generate power when it moves from a high potential energy state to a low potential energy state. If the moving water is an ocean wave, we can approximate the variation of water elevation as a sinusoidal variation with time. The wave amplitude, or height of the wave relative to a calm sea, will be small during calm weather and can be very large during inclement weather such as hurricanes. By coupling appropriate technologies to wave motion, potential energy changes can be harvested and transformed into renewable power.

Wave Energy Conversion

According to Jaffe and Taylor [2], ocean waves and waves breaking on a coastline have an energy density that can range from 10 megawatts/kilometer to over 60 megawatts/kilometer. The mechanical energy of wave motion can be converted into electrical energy using floats or pitching devices to convert wave energy to electrical energy. As an example, the Pelamis Wave Power system was a wave energy converter (WEC) that consisted of a series of tubes floating on the ocean surface. The tubes were connected by joints to allow movement in all directions. The system was loosely tethered to the sea floor with an anchor line to hold it in place. Waves passing by the tubes caused the joints to move. The movement was converted into electricity by hydraulic rams driving an electrical generator. An electrical cable connected the system to subsea power lines that brought generated electricity to shore. The system was designed to function in rough weather.

Pelamis Wave Energy Converters were used in the world's first commercial wave energy project called the Agucadoura Wave Farm. It was approximately five kilometers off the Agucadoura coast in Portugal [3] and operated from 2008 to 2014. It could generate up to 2.25 megawatts.

The overtopping device is another device for harvesting wave energy. It channels water from an incident wave up a ramp and into a reservoir. The captured water drains back into the ocean through hydro turbines that transform potential energy into electrical energy. The 4 MW Wave Dragon is an example of an overtopping device.

Oscillating Water Column

The wave energy conversion devices discussed above are useful for harvesting wave energy in deep water. An oscillating water column (OWC) can be used to harvest wave energy in shallower waters along the coastline. An OWC allows tidal water to enter and exit a confined space. The rise and fall of water in the confined space drives air in and out of the top of the space. The resulting air movement drives an air-driven turbine. The amount of output power from the OWC depends on two factors: conversion of wave motion to mechanical energy, and conversion of mechanical energy to electrical energy.

The wave surge or focusing technique is another method for harnessing wave energy. Ocean waves are directed into an elevated reservoir by a tapered channel placed on a shoreline. Hydropower technology is used in conjunction with water flow out of the reservoir to generate electricity.

A Wells turbine is a low-pressure air turbine that turns in a single direction independent of the direction of air flow. It can be used in an OWC device, but it is not as efficient as an OWC device with a valve system that optimizes energy harvesting associated with the periodic reversal of airflow. The Wells turbine does have the advantage of being less expensive since it does not require a valve system.

Emerging Wave Energy Converter Technology

Other wave energy converter (WEC) devices are under development. Three examples are introduced here. The first WEC is the Blue X wave energy converter developed by Mocean Energy. It consists of two hulls connected by a hinge. A generator is driven by wave motion when the hulls move about the hinge [4].

The second WEC is the PelaGen WEC developed by Marine Power Systems [5]. The PelaGen WEC has two major components: an absorber, and a nacelle. The absorber moves up and down with wave motion. A movable lever arm connects the absorber to the gearbox and generator in the nacelle. Absorber motion drives the generator in the nacelle. The PelaGen WEC can be installed at the base of a wind turbine in an offshore wind farm. This allows the WEC and wind turbine to simultaneously harness wind and wave energy.

The third WEC is the OE Wave Buoy developed by Ocean Energy [6]. It is shaped like the letter L with the shorter segment above water and the longer segment submerged in water. A chamber in the submerged segment allows water to move into and out of the chamber as passing waves cause the shorter segment to move. The shorter segment is a floating hull. When the hull moves, water enters the chamber in the longer segment and compresses air inside the chamber. Air pressure in the chamber drops and air is allowed to re-enter the chamber when water in the chamber recedes. Airflow through the chamber is used to spin a turbine in a generator.

Tidal Energy

The topography and rotation of the Earth, as well as the gravitational pull of the moon and, to a lesser extent, the sun, influence the ebb and flow of tides. Tidal energy is not available everywhere, but where it is available, it can be economically feasible. Underwater turbines can be propelled by tides in a manner that is comparable to wind-powered turbines. The installation of submerged turbines in coastal waters or rivers can generate electrical energy by harnessing the energy of moving water. Tidal stream turbines and tidal barrages are the two main types of tidal energy harnessing devices [7]. The motion of a stream caused by the motion of tides along a shoreline or channel can be harnessed by a tidal stream turbine to harness energy from the tides. Tidal barrages are usually situated across the mouth of tidal estuaries. When the tide is high, a tidal barrage collects the water and directs

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it through turbines to produce energy. More detail is provided below.

Tidal Stream Turbine

In July 2008, the first commercial scale tidal stream turbine was put into service in Strangford Lough, Northern Ireland. Developed by Marine Current Turbines (MCT), the 1.2 MW SeaGen project consisted of two 600 kW turbines. It provided approximately 5 GWh of tidal energy between July 2008 and September 2012. The SeaGen stream turbine had rotor blades that could be lowered into the water to harness tidal energy. The rotor blades could be raised above the water for maintenance and transport [8].

Open Center Turbines

An open center turbine was developed by OpenHydro [9]. The turbine could have a diameter of up to 16 meters and could provide up to 2 MW of power. The turbine shown in Figure 1 rests on the ocean floor and allows water to pass through its open core. The conical side of the turbine increases the water flow rate through the turbine. Open center turbines can be positioned at depths that minimize their impact on navigation. Submerged open center turbines cannot be seen or heard by nearby communities. Power from open center turbines can be transmitted to the coast using power lines.

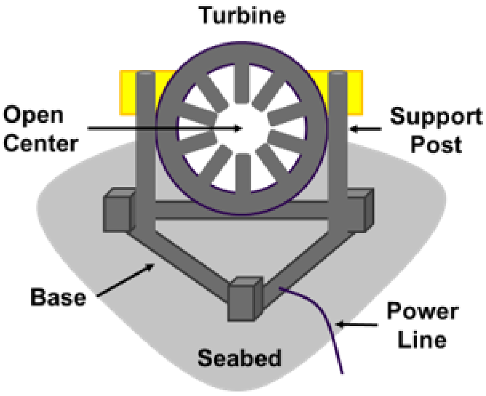

Figure 1: Sketch of an Open Center Turbine.

Tidal Energy System

Sustainable Marine Energy (SME) developed a tidal energy PLATform for Inshore energy (PLAT-I). PLAT-I consists of turbines attached to a floating platform. It can be transported to a specified location in water as shallow as two meters. The turbines are lowered into the water when the platform is in position. The platform can be oriented with the flow of water to optimize energy harvested from tidal or river currents. Turbines can be raised above the water when maintenance is required. PLAT-I is designed to be “dependable, maintainable and accessible year-round, and its modular design allows for it to be easily assembled on-site” [10].

Tidal Barrage

A tidal barrage is a dam-like structure built across estuaries, bays, and rivers where tidal motion causes significant amounts of water to enter and exit the area. The purpose of the barrage is to harvest energy from water entering and leaving the area. To harness tidal energy, a dam with a sluice is built across the entrance to a tidal basin. The sluice is a waterway with a gate that allows you to regulate water flow. The sluice is closed when sea level is low. It is opened to allow the rising tide to flow into the basin. Because the tide rises and falls twice a day, water can pass through the gate four times a day. The elevated water in the basin is allowed to flow through a hydropower system to generate electricity.

Constructed in the 1960s and inaugurated in 1966, La Rance Tidal Barrage is located on the Rance River near St. Malo, France. A 330-meter-long dam was built in front of a 22 square kilometer basin and a power station capable of generating 240 megawatts of power using twenty-four 10 megawatt turbines was constructed [11]. The tidal range, or the difference between high and low tides, is eight meters on average and can reach up to 13.5 meters. The ecology of the tidal basin can be impacted by power plants due to diminished tidal flow and silt accumulation.

Emerging Tidal Energy Technology

Other tidal energy devices are under development. Three devices are introduced here. The first tidal energy device is the Magallanes Renovables ATIR. It consists of a floating platform with a submerged mast attached to twin rotor blades [12]. Water movement is used to compensate for tidal motion and stabilize the platform. The hollow mast provides access to a submerged powertrain that can generate up to 2 MW of electrical power. The second tidal energy device is the Orbital O2 floating tidal turbine developed by Orbital Marine Power [13]. A 72 m long tubular hull is a floating platform. Two underwater turbines are attached to nacelles supported by movable legs. The turbines are submerged during operation and can be raised to the surface for maintenance and transport. Anchors moor the floating platform so that it remains on station in a tidal stream or river current. The Orbital O2 floating tidal turbine has a capacity of up to 2 MW of electrical power and can be connected to the local electricity grid by a subsea cable.

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The third tidal energy device is the Tidal Power Tug developed by Aquantis. It harvests tidal and ocean current energy using a vertical spar buoy with a horizontal-axis, parallel-flow rotor as shown in Figure 2. The turbines are connected to a stable spar buoy moored to anchors on the seabed. The system that generates power is attached to a submerged rotor. Every system can be safely operated and maintained from the surface.

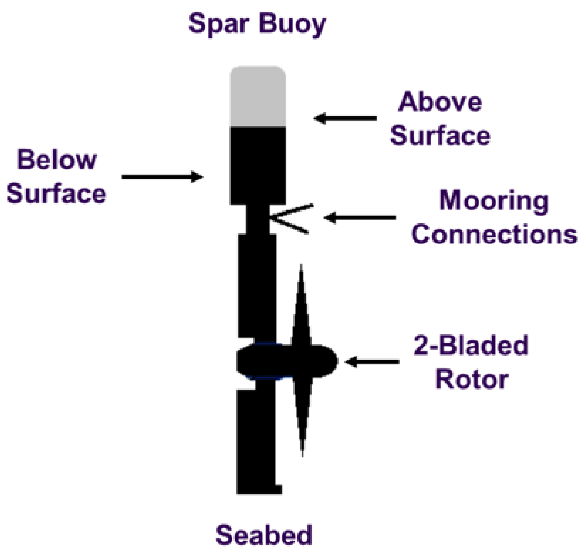

Figure 2: Sketch of a Tidal Power Tug.

Energy of Ocean Currents

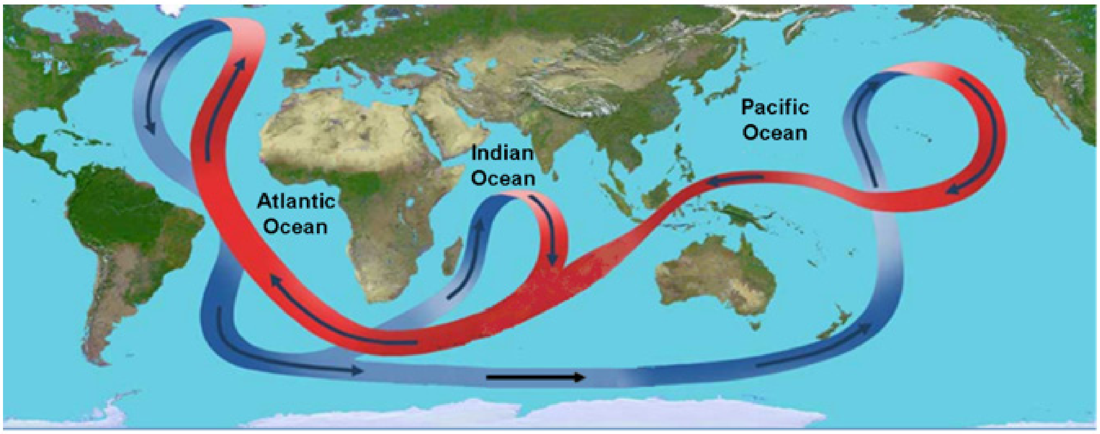

Figure 3: Great Ocean Conveyor Belt Arrows show the movement of warm surface water flow in red and cool subsurface water flow in blue [14].

The movement of large volumes of water along a predictable path in the ocean is known as an ocean current. The Great Ocean Conveyor Belt is shown in Figure 3 [14]. The motion of warmer water transfers heat from equatorial regions to the poles, while cooler water moves from the poles to equatorial regions. Ocean currents influence the climates of coastal regions. Some ocean currents move water along the surface of the ocean, while others move water at depths below tidal streams. Ocean topography can influence the flow rate of an ocean current. The Gulf Stream is an example of an ocean current that is constricted when it passes from the Gulf of Mexico through the Florida Straits. Marine energy harvesting technology such as submerged turbines can be used to harvest energy contained in the current.

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Ocean Thermal

Lakes, seas, and oceans receive warmth from solar radiation. The temperature of water close to the surface can be significantly warmer than the temperature of water in deep oceans and seas. The difference in temperature from one position to another is referred to as a temperature gradient. Temperature gradients can be found near underwater volcanoes and geothermal vents in the ocean floor. Warmer water is found near the heat source and cools as it moves away from the heat source. Ocean thermal energy conversion (OTEC) power plants can be used to produce electricity from temperature gradients if they are sufficiently large. Optimum temperature gradients for OTEC systems are found in deep waters between 20° North and 20° South latitude [15]. The Caribbean Sea, Gulf of Mexico, Atlantic, Pacific, Indian, and Arabian Seas are within this region. Warm surface water and cooler deep water can differ in temperature by more than 20°C (about 40°F). Here we consider three types of OTEC systems [16]: closed-cycle plants, open-cycle plants, and hybrid plants. A closed-cycle plant uses a closed system to circulate a heat transfer fluid with a low boiling point, such as ammonia.

Warm seawater heats the fluid until it flashes to the vapor phase. After passing through a turbine, heat exchangers can use cooler seawater to condense the vapor phase to the liquid phase. An open-cycle plant uses changes in pressure to convert warm seawater to vapor. The vapor is then used to rotate a turbine and generate electricity. As an example, liquid water at atmospheric pressure can undergo a phase transition to the vapor phase when placed in a vacuum chamber. An open-cycle plant combined with a heat transfer fluid is called a hybrid plant. If the heat transfer fluid is seawater, the seawater is vaporized to steam. A closed-cycle plant can be implemented by circulating the vaporized heat transfer fluid in a closed system.

An ocean thermal energy conversion (OTEC) system can be built on land near a coast, installed near the shore on a continental shelf, or mounted on floating structures for use offshore. Flashed seawater can be condensed as fresh, desalinated water by removing salt and other contaminants. The production of desalinated water is a desirable byproduct of an OTEC system in some parts of the world, such as the Middle East. Salt from the desalination process must be disposed of in an environmentally acceptable manner.

Offshore Opportunities and Challenges

Offshore or coastal facilities have the advantage of being well-suited for distributed generation. The facilities can be built to scale to serve nearby communities, including large coastal populations. A study by the European Union Tidal Stream Industry Energizer (TIGER) pointed out that a significant cost reduction could be achieved in the tidal market by 2035 if installed capacity is significantly increased in the next ten years [17].

There are some common problems associated with the building of offshore energy harvesting facilities. For example, rough seas can cause damage to facilities, particularly during storms. Electrical and mechanical equipment can sustain damage from corrosive seawater and sea spray. Scale accumulation can harm moving parts. Considerations for facility placement include disrupting established sea lanes, creating sound waves that could harm marine life, building a structure that the surrounding communities find unsightly, and interfering with electromagnetic communication. Marine energy harvesting facilities can encounter legal issues that are unique to the offshore environment. For instance, legal jurisdiction over a facility may be ambiguous, particularly in international waterways or places where certain aspects of the facility—like electricity lines—may cross international borders. Facilities may be subjected to competing and overlapping regulatory bodies even when the legal jurisdiction is unambiguous. Regulators may speak for federal, state, or municipal government agencies.

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