Renewable and Sustainable Energy Reviews 72 (2017) 590–604

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of ocean tidal, wave and thermal energy technologies

N. Khan[a,*], A. Kalair[a], N. Abas[b], A. Haider[c]

[a] Department of Electrical Engineering, Comsats Institute of Information Technology, H/Q Campus, Park Road, Islamabad, Pakistan
[b] Department of Electrical Engineering, University of Gujarat, Hafiz Hayat, Gujarat, Pakistan
[c] Department of Electrical Engineering, University of Management and Technology, Sialkot, Pakistan

ARTICLE INFO

Keywords:
Ocean energy
Tidal current
Wave converter
OTEC
OTEG
Osmotic power

ABSTRACT

Ocean tidal currents, water waves and thermal gradients are a great source of renewable energy. Ocean tidal, osmotic, wave and thermal sources have annual potentials of 800, 2,000, 8000–80,000 and 10,000–87,600 TWh, which are more than global 16,000 TWh/y electricity demand. Ocean wave generators produce relatively lower output, however, four to eleven meters tidal range stations have large power generation capacities. Abundant ocean heat energy potentially harvested using ocean thermal energy conversion (OTEC) devices and ocean thermo-electric generators (OTEG). Tidal stations may be tidal range or current types, but a wave energy converter (WEC) may be an oscillating water column (OWC), overtopping, heaving, pitching and surging devices. Ocean thermal energy can be harnessed by open, close Rankine cycles, thermo-electric generators and osmotic power plants. Large bays like Turnagain (USA), Annapolis/Minas Passage (Canada), Seven Barrages/Pentland Firth (UK), La Rance (France), Garorim (South Korea) and Mezen/Penzhin (Russia) have huge tidal current power generation capacities. Power Potential from tidal current stations is more than WEC devices which in turn is more than osmotic, OTEC and OTEG technologies. This paper reviews the current state-of-the-art of tidal, wave, OTEC and OTEG ocean energy technologies.

1. Introduction

Sun provides more than 99.99% of energy and earth contributes about 0.01% [1]. Fossil fuels are a form of antediluvian eon solar energy. All sources of energies, except geothermal and nuclear, are ultimately powered by the sun [2]. Earth radiates heat and its thermal energy come from radioactive decay (80%) and planetary accretion (20%) [3]. Oceans encompass over 70% of the earth's mass. Ocean tides are caused by earth's gravitational interaction with the moon (68%) and sun (32%). The impact of the moon is 2.6 times more than the sun due to its shorter distance from earth. Ocean waves are caused by friction of winds with the water surface. Earth has lost 17% of its rotational energy due to its slow deceleration rate of 12.19μs/y [4]. Oceans are a great form of renewable energy which is stored in the form of thermal energy (heat), kinetic energy (tides and waves), chemical energy (chemicals) and biological energies (biomass). Tidal current or wave generators harvest kinetic energies, and osmotic power plants and thermo-electric generators reap salinity and thermal gradients [5]. Up to date ocean power technologies and barriers are reported in the literature [6,7].

Climate change, S curved growths, population, energy and power crises require to explore and harvest renewable energy resources. Akin to hydropower, wind and solar energies the ocean dynamism is an ideal energy resource. The tide is a periodic rise and fall of water in the seas and oceans, twice during a lunar day (24Hr and 50 min). Ocean water remains at the maximum level for 50 min at different times on different days repeating the cycle every 19 years. Sea and ocean levels at different locations depend on their latitudes and shore. Lunar motion around the earth increases time interval between successive tides from 12 h to 12 h and 25 min. The earth, moon and sun become aligned every two weeks, at new and full moon days, to create maximum height spring tides. On waxing and waning half moon days, in the first and third quarter, the sun being at 90° creates least height neap tides. The performance of tidal and wave power plants depends on days of months and wind speeds during the years. Water waves are high in deep oceans and low near shallow shores. Wave generator performance depends on wave amplitudes which are governed by wind speeds. Water waves may become dangerous during gusts and storms. Gravity, wind and sunshine driven tidal wave and thermal power potentials were guessed earlier to be 22,000, 2000 and 87600 TWh/y [8] but recent estimates show alone wave power potential of 2985 GW [7]. Ocean temperature varies from 24 to 28 °C on surface to 4–6 °C at 1 km depths. The difference in temperature may be a basis of the ocean thermo-electric generator. Temperature differences of 20 °C are easily

* Corresponding author.
E-mail addresses: nasrullahk@yahoo.com (N. Khan), anamkalair@gmail.com (A. Kalair), naeemkalair@uog.edu.pk (N. Abas), aun.haider@skt.umt.edu.pk (A. Haider).

http://dx.doi.org/10.1016/j.rser.2017.01.079
Received 15 October 2015; Received in revised form 7 May 2016; Accepted 15 January 2017
Available online 20 January 2017
1364-0321/

available in torrid and temperate zones between 30°S and 30°N latitudes [9,8]. Tidal potential is evenly distributed worldwide, OTEC potential is high in equatorial regions, but wave energy potential is higher in the tropic zones.

Tidal power generation sites occur naturally along the sea and oceans like coal, oil, gas, shale and mineral reserves. Worldwide tidal power generation sites explored include4,200 MW Pent land Firth (UK) [10,11] 818 to 1,320 MW Incheon and Red Tides Sihawa Bay (South Korea) [12], Kislaya Guba (Belgium) [13], 6500 MW Turnagain (USA, 2,800 MW Walcott Inlet (Australia), 5338 MW Cobequid (Canada), 7000 MW Khambat Gulf (India) and Johnstone Strait [14] and Minas Passage Bay of Fundy (Canada) [15,16]. Some estuaries and channels, like Hudson Strait (Canada), are reported to be reminiscent of half-wave resonant oscillations [16]. Ocean thermo-electric, underwater marine and surface wave generators have relatively smaller outputs, but tidal power plants give off bulk powers. Old tidal current power stations such as 3.2 MW Jiangxia Tidal Power Station (China), 20 MW Annapolis Royal Generating Station (Canada), 240 MW Rance Tidal Power Station (France) and 250 MW Sihwa Lake power Station (South Korea) have relatively low to moderate power generation capacities, but recently planned large tidal power stations such as2,200 MW Dalupiri Blue Energy Project (Philippines), 3640 MW Tugurskaya Tidal Power Station (Russia), 8640 MW Seven Barrage (UK) and12,000 MW Mezenskaya Tidal Power Station (Russia) are large power stations.. India intends to construct a 50 MW tidal power station in the Gulf of Kutch and there is unconfirmed news of 87,100 MW Penzhinskaya Tidal Power Station in Penzhin Bay Russia [17].

There are hundreds of types of marine current turbines. The British government has started an ambitious target of 200–300 MW ocean energy by 2020. Denmark started a €3 million project for wave energy in 2012 under national initiative to produce 35% of electricity from renewable energy by 2020. As of 2012 Europe produced 246.20 MW compared to 259.20 MW by Asia. Global ocean energy production was 527.70 MW by the end of 2012 which is likely increase many times by 2020 due to multiple wave energy projects worldwide. Ireland has an estimated potential of 29 GW ocean energy [18]. Ocean thermal energy potential is much more than the tidal and wave power potentials [19]. Low temperature refrigerant based heat exchangers can to some extent extract the ocean power, but ocean thermo-electric generators (OTEG) can harvest this large natural potential if low thermal gradient high figure of merit materials become available.

2. Tidal current power

Tidal power generation depends on the rise and fall of sea and ocean waters. About 4–12 m range spring and neap tides have an estimated potential of 1–10 MW/km along the seashores. Terrestrial and celestial gravitational variations predictably affect power generation capacities. Spring tides (high tides) occur on new as well as full moons and neap tides (low tides) occur in waxing or waning half moons due to misalignment of the earth with the moon and the sun. The Earth rotates on its axis at speed of 16,500 km/h and revolves around the sun at a speed of 107,000 km/y. Earth completes one rotation in one day (24 h) but moon completes one revolution around the earth in 29.53 days. A solar month has 30 days in a month, whereas lunar month has 29 days and 10 min, so the solar month is 50 min longer than lunar month. In a solar month earth and moon twice become aligned to exert a maximum gravity pull on ocean waters to create spring tides. A range of water springs may be as high as 11.4 m (Penzhinsk, Russia) to 12.4 m (Cobequid, Canada). Ocean waters bulge out by lunar and solar gravitational forces at new moon and full moon as shown in Fig. 1.

Tidal power generation potential may be estimated by considering an estuary on sea shore. If the spring tide water level is R meters over the sea datum line, then energy potential is given by

$$E = \rho g \int_{h=0}^{h=R} hA dh \tag{1}$$

where ρ is sea water density (kg/m^2) and g is gravitational constant (9.81 m/s^2). The energy associated with a fixed area estuary may be given by

$$E = \frac{1}{2}\rho g A R^2 \tag{2}$$

Taking P=E/t, the average power (in kW) comes out to be

$$\overline{P} = \frac{\frac{1}{2}\rho g R^2}{time} = 1025 \times 9.81 \times A \times \frac{R^2}{44700} = 225AR^2 \tag{3}$$

Where 44,700 are seconds in 6 h and 12.5 min. In case of a double cycle tidal station producing electricity in forward and reverse directions of water flows then the power potential increases to 450AR^2 kW twice of the single cycle station. If the tidal range equal to difference of maximum and minimum levels in the basin, then at an average water discharge rate (Q =AH/t) through the turbine the work done by falling water through h height is given by

$$P = \rho Q h \tag{4}$$

Power generation potential for 705 tidal cycles by an ηefficiency turbine in a year is

$$P_{year} = \int_0^t Pdt = \int_0^t \frac{\rho\eta Qh}{75} \times 0.736 \times 705 dt P_{year} = 7092.3\eta \int_0^t Qhdt \tag{5}$$

Tidal power generation capacity increases with tidal range and minimum barrage, dam or dyke. A suitable storage may be achieved with an estuary, creek, channel, rut or runnel close to sea shore. Important components of tidal power stations are barrage to form a basin or estuary, sluice gates to fill or empty basins, turbines to convert kinetic energy into mechanical energy which can be converted to electricity by coupling generator. The dyke crest and slopes are constructed of rock filling to withstand water waves. The sluices are equipped with local as well as remote controlled gates. Sluice gates may be fabricated out of steel to withstand salty water.

Akin to run of river and dammed hydropower plants the ocean tidal power stations may be categorized as tidal range and tidal current stations. Depending upon the situation the tidal power stations are classified as single basin single operation, single basin double operation, double basin with the link's basin operation and double basin with paired basin operation as shown in Fig. 2.

Single operation sluice opens during high tides, but remains closed during emptying process. Tidal power turbine functions only during emptying process. Single operation turbine generation period is 3.5 h. Double operation reversible turbine and sluice function during high tide, but sluice remains closed during emptying process. Output of double operation tidal plant is not twice, instead just 15% more than the single operation turbine. Typical example of a double operation turbine is 240 MW tidal station La Rance (France). Sluice of the high basin linked barrage opens during high tide for filling and low basin sluice opens during emptying process. The turbine is placed on Tied barrage. In the case of double paired barrages upper sluice opens during filling and lower sluice during emptying process. The tidal power stations are suitable for intermediate demands between base and peak loads. Tidal current turbines may be horizontal or vertical axis types like horizontal (HAWT) and vertical (VAWT) axis wind turbines.

Horizontal axis turbines were installed in the Bristol Channel between England and Wales, and vertical axis turbines are installed in Strait of Messina between Sicily and Italy. Marine current horizontal axis turbines include 1–2 MW Tidal Stream, Lunar energy, TidEL, Hydrovision, Sea Flow and Seagen (UK), 0.75–1 MW Blue Tide (Norway) and1MW HydroHelix (France). Vertical axis marine current