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Marine Renewable Energy Seascape

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ABSTRACT

Energy production based on fossil fuel reserves is largely responsible for carbon emissions, and hence global warming. The planet needs concerted action to reduce fossil fuel usage and to implement carbon mitigation measures. Ocean energy has huge potential, but there are major interdisciplinary problems to be overcome regarding technology, cost reduction, investment, environmental impact, governance, and so forth. This article briefly reviews ocean energy production from offshore wind, tidal stream, ocean current, tidal range, wave, thermal, salinity gradients, and biomass sources. Future areas of research and development are outlined that could make exploitation of the marine renewable energy (MRE) seascape a viable proposition; these areas include energy storage, advanced materials, robotics, and informatics. The article concludes with a sustainability perspective on the MRE seascape encompassing ethics, legislation, the regulatory environment, governance and consenting, economic, social, and environmental constraints. A new generation of engineers is needed with the ingenuity and spirit of adventure to meet the global challenge posed by MRE.

1. Introduction

Energy drove the industrial revolution in the 1800s, and drives the information technology (IT) revolution of the 21st century. Today, the world's population stands at over 7 billion. Energy usage per capita in developed countries is too high, with 4.4 t of oil equivalent used per person per annum in the Organisation for Economic Co-operation and Development (OECD) [1]; and developing countries are catching up. The present primary source of energy is fossil fuel in the forms of coal, petroleum, and natural gas. Recent oil price volatility has had a major impact on the energy sector. From mid-2014 to early 2015, the price of oil dropped from over $100 USD to less than $50 USD per barrel, lowering the market prices of natural gas and coal [2]. Although worldwide energy demand is likely to increase, the energy industry cannot continue sourcing energy from fossil fuels over the long term. A revealing statistic is that the total global carbon emissions by the energy sector over the past 27 years is equal to the total for all previous years, with fossil fuels making up more than 80% of the primary energy mix [2]. Greenhouse gas emissions have grown by about half over the past 30 years, with carbon emissions making up almost 60% of the current total greenhouse gas emissions. In 2014, coal, natural gas, and oil contributed about 44%, 20%, and 35% of energy-related carbon dioxide (CO_2) emissions, respectively, along with significant quantities of other greenhouse gases including methane and nitrous dioxide [2]. Carbon emissions from the burning of fossil fuels are hastening climate change. According to the National Oceanic and Atmospheric Administration (NOAA) [3], "The first seven months of 2015 comprised the warmest such period on record across the world's land and ocean surfaces, at 0.85 °C above the 20th century average." The statistics point toward crisis.

Worldwide, governments have initiated programs of energy production from renewable sources to mitigate anthropogenic-induced climate change, address the possible future exhaustion of fossil fuel supplies, and help ensure national energy security. Energy engineers can make a real difference. Improved energy efficiency is beneficial for both economic and environmental reasons. For example, recent improvements in internal combustion engine efficiency mean that it is possible to raise engine efficien-

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cy to almost 60% [4], well above the present peak of 40%. However, further advances must be made in predictive models and engine technology, aimed at higher efficiency and lower emissions, before such engines will roll off car production lines. Engines also need adaptation to use alternative fuels. Carbon capture and storage (CCS) is an alternative near-zero emission technology that involves separating out waste CO_2 from power stations and chemical plants, and transferring the CO_2 to suitable storage from which it cannot escape to the atmosphere. Although CCS is an expensive technology, it offers the prospect of decarbonizing energy processes in gas-turbine power stations while cutting the global cumulative emission of carbon to the atmosphere [5].

Other ways of limiting carbon, while bridging the energy gap, are to invest in nuclear energy and renewable energy technologies. Although nuclear power appears attractive as a means of producing continuous supplies of clean electricity, there are major concerns regarding radioactive waste disposal, possible accidents (such as the meltdown of three reactors that occurred at Fukushima Nuclear Power Plant in March, 2011) or sabotage, and the proliferation of nuclear arms. According to the International Energy Agency [6], "Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from sunlight, wind, oceans, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources."

2. Marine renewable energy

Marine renewable energy (MRE) sources include offshore wind, tides, ocean currents, waves, thermal differences, salinity gradients, and biomass [7]. Krewitt et al. [8] estimated the technical potential of offshore wind energy to be ~16 000 (TW·h)·a^{-1} by 2050. Recently, Capps and Zender [9] computed the global value of offshore wind energy to be ~340 000 (TW·h)·a^{-1}. Although the global total ocean energy resource (excluding wind) has been reckoned to be over 2 million (TW·h)·a^{-1} [10], estimates as to its technical potential range from about 2000 (TW·h)·a^{-1} to 92 000 (TW·h)·a^{-1} [8,11]. Charlier and Justus [12] estimated the theoretical tidal energy potential (including both tidal stream and tidal range) to be 26 000 (TW·h)·a^{-1}, of which about 8800 (TW·h)·a^{-1} is in shallow coastal basins; though much lower technical potential is anticipated [8,11]. The theoretical wave energy potential is about 32 000 (TW·h)·a^{-1} [13], with a technical potential of about 5600 (TW·h)·a^{-1} [8]. The global resource potential of ocean thermal energy conversion (OTEC) is huge, with a theoretical potential of about 44 000 (TW·h)·a^{-1} [14]. Ocean salinity gradients have an estimated technical potential of about 1650 (TW·h)·a^{-1} [15].

The global challenge is how to extract the energy, bring it to shore, store it, and export it cost-effectively. Key aspects relate to technology, infrastructure, cost reduction, investment, environmental impact, marine governance, consenting and licensing, and legislation. The marine renewables industry is particularly sensitive to government intervention. To reduce uncertainty, new ocean data-gathering campaigns are vitally needed to provide high-quality information on seabed roughness, wave surface elevations, tidal currents, eddies, and turbulence at sites. The image of *Laminaria hyberborea* growing on the seabed off Scotland in Fig. 1 indicates just how awkward it is to characterize bed conditions [16,17]. To address barriers to development of MRE systems including device testing at full-scale, grid-connection costs, and a lack of internationally recognized standards for testing MRE technology, various multi-disciplinary MRE technology development roadmaps have been devised (e.g., Refs. [18] and [19]). Small scale tank testing is crucial to initial development and optimization of device concepts (e.g., at IH Cantabria, Spain). Ocean test sites provide scale up to pilot and full prototype conditions, examples being the European Marine Energy Centre (EMEC) in the Orkneys, Scotland (which was established in 2003, is grid connected with 14 berths, and tests wave and tidal devices in water depths 25–50 m); Wave Hub (grid-connected with 4 berths, depths 60–100 m, off Cornwall, England); the one-quarter scale test site in Galway Bay and the full-scale site at Belmullet, Ireland; the three national MRE centers funded by the US Department of Energy: Northwest National Marine Renewable Energy Center (NNMREC) with test sites off the Oregon Coast, in Puget Sound and in Lake Washington, Southwest National Marine Renewable Energy Center (SNMREC) which evaluates ocean current devices in the Florida strait, and the Hawaii National Marine Renewable Energy Center (HINMREC) which tests wave energy converters and components of ocean thermal energy conversion devices. A comprehensive list of present test centers is given by Marine Renewables Canada [20].

Fig. 1. Growths of *Laminaria hyberborea*, found in depths up to 30 m in the Pentland Firth, Scotland [16,17]. The Pentland Firth, a strait between mainland Scotland and the Orkney Isles, is one of the best locations in the world for tidal stream power, with currents that can exceed 5 m·s^{-1}.

The following sections consider different technologies for exploiting marine energy. Detailed review articles include those by Day et al. [21] concerning MRE devices, Khan et al. [22] on marine turbines, Drew et al. [23] on wave energy converters, and Adcock et al. [24] on hydrodynamic models for tidal power assessment.

2.1. Offshore wind energy

Offshore wind-turbine technology has essentially followed that of onshore wind turbines, which evolved from windmills used for electricity production (such as the 12 kW wind turbine constructed by Charles F. Brush in Cleveland, USA, depicted in Fig. 2(a)). Offshore wind turbines typically consist of three blades rotating about a hub, as shown in Fig. 2(b), and are similar to land-based wind turbines. Onshore and offshore wind technology is rapidly evolving, with the largest at the time of writing being SeaTitan™ 10 MW wind turbine of American Superconductor (AMSC) with a hub height of 125 m, rotor diameter of 190 m, rotational speed of 10 r·min^{-1}, blade-tip speed close to 100 m·s^{-1}, and rated power capacity of 10 MW [25]. It appears feasible to upscale individual wind turbines to 20 MW with 250 m rotors [26]. At such high rotor-tip speeds, problems arise from noise and