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Ocean energy: exergy analysis and conversion

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Abstract — Ocean stores energy in the form of currents, waves, tides, heat and salinity that can help to alleviate worldwide demand for power and the global climate change threat. Exergy analysis can be applied to evaluate the work potential (extractable) that a resource contains. This paper focuses on the exergy content that can be extracted from ocean reservoirs and provides a review of existing the technology installed for harvesting ocean energy.

Keywords — Ocean energy, exergy assessment, conversion, renewables

1 INTRODUCTION

Reducing greenhouse gas emissions and diversification of energy sources are pathways to achieve a sustainable development [1,2]. Environmental and strategic concerns have led to an increased interest in research and development of renewable energy technologies. Between 2000 to 2008, the renewables installed capacity increased by about 50% [2,3]. In 2008, electricity generated from renewable sources (excluding hydropower and biomass) was about 230 GW, which is nearly 5% of total global power capacity [3]. Renewables are mainly focused on the utilization of solar, wind, biomass and geothermal sources. The diversification of sources should be a target to reach in order to enlarge and vary the choice. The ocean is a major player in the Earth system. It covers more than 70% of the earth's surface and the volume of ocean water is about 1.37×10^{18} m^3 [4]. The use of this huge resource is a very contentious issue.

Ocean energy arises in a variety of forms such as hydropotential energy (ocean wave and tides), hydrokinetic energy (marine currents), and temperature and salinity gradients. Ocean circulation is very sensitive to external forcing. The wind field is a very important energy source to the ocean and can be viewed as a reservoir of atmospheric kinetic energy directly transferable into the ocean [5]. The wind work on the geostrophic circulation is a source of mechanical energy for the interior ocean [6]. Ottra and Drange [7] showed that the Atlantic meridional overturning circulation also increases (decreases) in response to lower (higher) summer solar irradiance. This effect is connected with the Arctic sea-ice volume and area. Low solar irradiance prompts less sea-ice melt (saltier Arctic Ocean), and saltier water is advected into sinking regions enhancing the intermediate and deep water formation. High solar irradiance produces an opposite response. Egbert and Ray [8] presented evidences that considerable amount of energy is transferred from tidal currents into mixing processes of the oceans. To some extent, ocean energy is the result of solar or potential energy. However, it seems that provides more available energy per square meter than either wind or solar [9] but systems developed for harvesting ocean resources were considered in general more expensive than such as for wind and solar [10]. However, last decade technological advancement and the increase of fossil fuel prices (and the expectation to stay high in the future) introduced the ocean energy in the renewable energy portfolios [10].

The European Union has adopted targets for the expanded use of ocean energy. It established the goal of reaching 3.6 GW of installed capacity by 2020, and 188 GW by 2050 [11]. The potential benefits in terms of CO2 emission are estimated in about 2.6 and 136.3 Mt/year for 2020 and 2050, respectively.

In this paper, an exergy analysis is used to study the potential of the different forms of ocean energy. Besides, it examines the technology installed for harvesting this resource.

2 EXERGY ANALYSIS

Our society is based on the use of energy resources. The assessment of these resources can be accomplished through the exergy analysis.

The connection between renewable energy sources and sustainable development was investigated in different studies [12,13]. The exergetic analysis of some renewable energy resources (solar, wind, geothermal and biomass) have been subject of several research studies. Comprehensive reviews of

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these studies are presented by Hermann [14], Dincer and Rosen [15] and Hepbasli [16]. The exergy of ocean (waves, tides and thermal gradient) was also briefly presented by [14] and [16].

2.1 Exergy analysis

Exergy is defined as the maximum work that could be obtained from a system relative to a reference state [15,17]. It defines the quality of energy in addition to the quantity.

The exergy is conventionally classified into physical and chemical. The physical exergy is the maximum useful work obtainable as the system passes from its actual state with temperature, pressure, velocity and position to a restricted equilibrium state (reference state) [15,17]

$$\psi_p = e_i - e_{i0} - T_0(s - s_0) + p\varsigma - p_0\varsigma_0 + 0.5(u - u_0)^2 + g(z - z_0) \qquad (1)$$

where ψ_p is the specific physical exergy, e_i is the internal energy, T is the temperature, P is the pressure, ζ is the specific volume, s is the specific entropy, z is the position and g is the gravity. The subscript 0 means reference state.

The chemical exergy is the maximum useful work defined in terms of chemical potential of the component species [15,17]

$$\psi_c = \sum_j n_j (\mu - \mu_0)_j \qquad (2)$$

Where ψ_c is the specific chemical entropy, n is the molar fraction and μ is the chemical potential (electrochemical potential in the case of electrolytes).

If the system is incompressible, the specific volume and the specific volume at reference state are similar ($\zeta \sim \zeta_0$) and, the internal energy and the specific entropy can be expressed, respectively, as

$$e = e_0 + c(T - T_0) \qquad (3)$$

$$s = s_0 + c \ln \frac{T}{T_0} \qquad (4)$$

where c is the specific heat.

The electrochemical potential of a charged component j in the liquid phase is given by

$$\mu = \mu_0 + RT \ln\left(\frac{n_j}{n_0}\right) + z_j F \Delta\phi \qquad (5)$$

where R is the gas constant, z is the valence, F is the Faraday constant, and ϕ is the electrical potential (the electrical potential term can be omitted for components with no net charge such water). The driving force behind energy harvesting is the difference in chemical potential between ocean water and freshwater. When salty water is exposed to freshwater, osmosis causes water to flow, from low salinity to high salinity. The molar fraction of pure water is 1, and for a solution of n_{solute} molar fraction of solute in water, the ratio between the vapor pressure of a solution containing a solute and the vapor pressure over the pure water is $1-n_{solute}$.

According to Eqs. (1)-(5), the total exergy, ψ, is the sum of the physical and the chemical exergy

$$\psi = c\left[T - T_0\left(1 + \ln\frac{T}{T_0}\right)\right] + \varsigma(p - p_0) + 0.5(u - u_0)^2 + + g(z - z_0) - RT\ln(1 - n_{solute}) \qquad (6)$$

The flux of exergy is given by

$$\Psi = \rho u \psi \qquad (7)$$

Here Ψ is the exergy flux density and ρ is the density.

2.2 Exergy of ocean reservoirs

The dynamics of ocean water is readily observable in the rise and fall of the tides and the continual lapping of waves. Less visible is the network of currents that constantly circulates ocean water around the globe. The hydrokinetic energy of ocean is formed by open ocean and nearshore currents and the exergy of this resource is due to kinetic energy. According to Eqs. (6) and (7)

$$\psi = 0.5u^2 \qquad (8.1)$$

and

$$\Psi = 0.5\rho u^3$$

(8.2)

where u_0 is the zero-velocity reference state. The ocean currents range between 15-300 cm/s [4,11-20].

Therefore, the specific exergy and the exergy flux density associated at this resource are 0.01-4.5 J/kg and 0.002-13.5 kW/m^2, respectively. Marine current sites with a current velocity of 2.5 m/s or more are situated in diverse places such as Gibraltar, Bosporus, English channel, Irish sea, Straits of Magellan, Gulf of Mexico, Sicily, etc.

Ocean waves and tides are examples of hydropotential energy. Ocean waves are available 80% to 90% of the time [18]. Ocean waves are caused by the wind as it blows across the sea. A wave possesses potential energy as a result of its position above the wave trough (z-z0~amplitude) which travels along the ocean.

Waves are said to be in deep water when the depth is larger than one half of their wavelength [21]. In deep water, the wave velocity does not depend on water depth and is directly proportional to the wave period, τ, ($=(g/2\pi)\tau$). Therefore

$$\psi = g(z - z_0) = gA \qquad (9.1)$$

$$\Psi = \rho g u(z - z_0) = \frac{\rho}{2\pi} g^2 \tau A \qquad (9.2)$$

The dominant period, τ, and amplitude, A, of ocean waves are typically in the range of 5-20 s and 0.3-2 m, respectively. According to Eq. (9.1) the specific exergy ranges 2.94 and 19.6 J/kg and the flux density (Eq. 9.2) is between 23 and 153 kW/m^2.

Tides result of the gravitational attraction of the moon and the sun acting upon the rotating earth, and are regular and predictable. They appear on coastlines as the regular rise and fall of the sea surface (tidal range). Tides are waves, which low tide on shore coincides with the wave trough, and high tide corresponds with the wave crest. The vertical distance between the rise and fall of the tides is associated with gravitational potential energy which creates horizontal movement of water or currents. In the open ocean is on the order of tens of centimetres but at coastlines, particularly estuaries, may create tidal ranges of up to ten meters.

Tide waves are pretty flat since their wavelengths are never less than a hundred kilometers [18,21]. Tide waves are clearly shallow water waves because the depth is much less than one twenty-fifth of their wavelength [18,21]. The range of the tide is the difference in height between low and high tide and the specific exergy associated is

$$\psi = g(z - z_0) = gH \tag{10.1}$$

The velocity of shallow water waves is (gH)$^{1/2}$ [21], and the exergy flow density associated to tide waves is given by

$$\Psi = \rho u \psi = \rho g^{3/2} H^{3/2} \tag{10.2}$$

where H is the vertical distance between the rise and fall of the tides.

The height of the tide depends strongly upon local topography. The largest tidal ranges are found in the Bay of Fundy in Canada and The Severn Estuary between England and Wales (~15 m), and the smallest tidal ranges occur in parts of the Gulf of Mexico and the Caribbean (~1m) [4,18]. The coast of Portugal has an average range of about 3 m. Therefore, the specific exergy associated at this resource (Eq. 10.1) varies between 9.8 and 147 J/kg, and the exergy flux of density (Eq. 10.2) ranges from 30 to 460 kW/m^2.

The distribution of temperature at the ocean surface tends to be zonal and ocean's layers of water have different temperatures. At surface the water temperature may reach 25 °C or more within the tropical region (mean ocean-surface temperature is ~17 °C) but deep ocean temperature may vary from 1 to 5 °C (mean temperature ~3.5°C) [4,18-21].

Based on Eqs. (6) and (7), the exergy associated to ocean's layers of water with different temperatures to drive a power-producing cycle is

$$\psi = c\left[T - T_0\left(1 + \ln\frac{T}{T_0}\right)\right] \tag{11.1}$$

$$\Psi = \rho c u\left[T - T_0\left(1 + \ln\frac{T}{T_0}\right)\right] \tag{11.2}$$

Considering the flow velocity in the 0.01-0.15 m/s range [22], and assuming ocean's layers of water with 17 °C and 3.5 °C, the average specific exergy is about 446 J/kg and the exergy flux density ranges from 4.5 and 66.8 kW/m^2.

The salinity gradients could be explored to produce energy. When salty water is exposed to freshwater, an osmotic pressure causes water to flow, from low salinity to high salinity. To sustain this process (separate the two water bodies) a membrane or an organic filter is needed to selectively blocks and filters out salt, and only water flows across the membrane, drawn toward the saltier side. Thus, the salinity of ocean water serves as the fuel for the process (salinity gradient power or osmotic power). According to Eqs. (6) and (7), the exergy associated to salinity gradients is

$$\psi = -RT\ln(1 - n_{solute}) \tag{12.1}$$

$$\Psi = -\rho u RT\ln(1 - n_{solute}) \tag{12.2}$$

The salinity of ocean water is in the range 33–37 ppt (average salinity 35 ppt) and the "osmotic energy" involves the flow of water through semi-permeable membranes or organic filters which the velocity is between 4 and 15 l/m^{2}h [23]. Therefore, the specific exergy is about 4.8 kJ/kg and the exergy flow density varies between 0.005 and 0.02 kW/m^2.

From the calculations presented above, it becomes possible to compare both the specific exergy and exergy flow density associated to the reservoirs of ocean energy resources. These results are important in order to establish priorities to explore the different reservoirs and also for the choice of technology for each specific reservoirs.

3 OCEAN ENERGY RESERVOIRS AND HARVESTING TECHNOLOGY

Like other renewable energy sources, ocean energy is used to generate electricity. Many different devices have been designed over the years to harvest this huge resource. These devices are required to operate in a harsh environment and technology development remains the critical issue for ocean energy systems. Design optimisation and materials are the focus of several underway research and will be needed going forward.

3.1 Hydrokinetic energy of oceans

Ocean current energy harvesting devices for electricity production can be separated into two categories: rotating devices (similar to wind turbines) and reciprocating devices (oscillating hydrofoil connected to a supporting arm that drives hydraulic cylinders and in turn a generator).

Rotating devices consist of hydrofoilshaped blades (horizontal or vertical axis) connected to a rotor which rotate to generate electricity. The majority of the available rotating devices are horizontal axis current turbines (rotating in a plane perpendicular to the axis or rotational axis of rotor is parallel to the incoming water stream) with two or more blades (fixed pitch or variable pitch to operate in both flow directions). Horizontal-axis turbines may present an unducted or a ducted configuration [24].

The vertical turbines present a vertical rotational axis of rotor to the water surface and also orthogonal to the incoming water stream. The major issues associated with these turbines are no self-starting capabilities and high torque fluctuations with each revolution [25]. These issues can be reduced by configuring the blades in a helical set-up but efficiency is less [25].

Horizontal and vertical turbines are quite familiar to wind energy developers. There are also other comparatively new turbine-based systems that can be categorized as follows [24-27]: cross-flow turbines, Venturi systems, and gravitational-vortex systems. Non-turbine category systems are also available [24,28-30]: flutter-vane, piezoelectric, oscillating-hydrofoil, fan-belt, and paddle-wheel systems.

There already some rotating devices installed and already or very soon grid connected (for example, in Kvalsundet on the north coast of Norway (300 KW), in Verdant, USA (0.5MW) and in Strangford Lough Northern Ireland (delivery 150KW but the target is 1.2 MW)). SeaGen (Strangford Lough) ended on 2008 is the first commercial scale turbines to have been connected to the grid [31]. The horizontal turbines still regularly deliver their full rated power into the Northern Ireland grid.

Although rotating devices are in its infancy, non-turbine category systems are even less developed. To the best knowledge of the authors, only an oscillating-hydrofoil prototype was tested during few weeks in 2002 (Yell Sound, Shetland).

3.2 Hydropotential energy of oceans

Tidal range energy conversion technology already reached a mature stage. The conversion of tidal range energy into electricity is very similar to the technology used in traditional hydroelectric power plants [32]. A number of barrage schemes for power production have been suggested for various estuarial sites around the world. At present 3 tidal barrages in France (La Rance, 240 MW), Canada (Annapolis Royal, 20 MW) and China (Jiangxia, Wuyantou, 3.2 MW) operate as commercial power plants. The River Severn (UK) has a tidal range of 14 m and was proposed to tidal power generation. Although, the environmental impacts of the structures can have effects on marine life and make it unlikely that this project will ever be constructed. Tidal barrages are not considered as part of modern ocean energy [33].

The different types of wave energy converters may be classified according to their different locations (shoreline, near-shoreline and off-shore devices). Another possibility is to classify them according to their size and orientation. In 1995, Hagerman [34] identified twelve distinct wave converter devices. The main features that distinguish one concept from another are the mode of oscillation for energy absorption, type of absorber, and type of reaction point. The main generic types of wave energy harnessing schemes are:

(i) The so-called “terminator” devices are typically onshore or nearshore but also floating versions have been designed for offshore applications. Terminators are oriented perpendicular to the direction of the wave travel and capture or reflect the wave. The oscillating water column (OWC) and the overtopping devices are examples of terminators. The oscillating water column includes a partially submerged, hollow structure open to the sea below the water line. As waves come and fill the column with water, air inside is pressurized and drives a turbine. The overtopping device collects the water of incident waves in a reservoir to create a head to drive a low head turbine. The Salter's duck [35] and Wave Dragon [36] fall into the class of terminators.

(ii) Attenuators are floating structures devices oriented parallel to the direction of waves. The waves along the length of these long multisegment devices cause flexing where segments are connected and drive hydraulic rams (pumps) or other converters in the connecting sections. The Pelamis [37] (a series of long cylindrical floating devices connected to each) is an example of an attenuator.

(iii) Point absorbers devices are either floating or mounted on the sea bed and provide a heaving motion that is transformed by mechanical and/or hydraulic subsystems into linear or rotational motion to drive electric generators. AquaBuoy [38], Archimedes Wave Swing (AWS) [39] and PowerBuoy [40] are examples of point absorbers devices.

There exist a handful of demonstration wave power devices supplying electricity to the grid. These include:

- Pico OWC plant in Azores (Portugal) [41]: The construction of this 400 kW plant was completed in 1999, and since 2004 has been in regular trials (short periods) delivering power (intermittently) to the Azorean grid
- Wavegen Limpet OWC plant [42]: This 500 kW oscillating water-column device was installed on the Isle of Islay off Scotland in 2000
- OWC Zhelang Town plant (China) [43]: It’s 100 kW in-grid shoreline OWC wave power built in 2001
- Archimedes Wave Swing (full scale prototype): grid connected 2 MW deployed off the coast of Póvoa de Varzim (Portugal) in 2004 for few weeks
- Aguçadoura Wave Farm [44]: the first commercial wave power plant, using 3 x 750kW (2.25 MW) Pelamis devices (22.5MW total planned) started to operate offshore near Póvoa do Varzim (Portugal) in September 2008. In 2009, this pioneering project has

fallen victim to the global economic downturn after the collapse of its majority owner.

- Wave Dragon [45]: is currently under construction a full-scale 7 MW commercial demonstration unit in Pembrokeshire, Wales, with deployment and grid connection in 2012.
- Reedsport Wave Park [40]: it is currently being installed the first commercial wave park on the USA near Reedsport, Oregon. This project consists of ten PowerBuoys with a total of 1.5 MW
- Wave powered desalination plant at Vizhinjam, India [46]: OWC energy plant which yields 6–7 kW to produce 7000–8000 l/day of desalinated water.

Several projects, with different wave energy devices, are being tested under real sea conditions in the UK, Portugal, Ireland, Spain, Finland, Italy and USA, among others. Other projects have completed prototype testing and are awaiting planning permission. Descriptions of these projects can be found elsewhere [47].

3.3 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) is a way of recovering some of the solar energy stored in the upper mixed layer of ocean [48]. OTEC plants are indeed solar energy plants [49] with a solar heat collecting surface and thermal storage (in the upper layer of the ocean) and a thermal power cycle based on temperature differences. There are basically three types of OTEC cycles:

(i) Open-cycle system: the warm surface of ocean water is used itself as working fluid. The water turns to vapour in a near vacuum at surface water temperatures and drives a low-pressure turbine attached to a generator which produces electricity.

The water vaporized is fresh water and after condensed (exposed to cold water) can be used for drinking water, irrigation or aquaculture.

(ii) Closed-cycle system: uses working fluids which have very low boiling temperature (ammonia, considered currently, boils at a temperature of about 240 K at atmospheric pressure). The heat transferred from the warm surface ocean vaporizes the working fluid which drives a turbine attached to a generator and produces electricity. Cold water pumped through a second heat exchanger condenses the vapour back into a liquid.

(iii) Hybrid-cycle system: combines features of both open-cycle systems (warm ocean water is flash-evaporated into steam in a near vacuum chamber) and the closed-cycle (steam vaporizes a low-boiling-point fluid that drives a turbine to produce electricity). This cycle system also produces fresh water from seawater.

Besides energy production, the OTEC may also contributes to fresh water production (a 2 MW plant may produce about 4300 m^3 of fresh water), improvement of aquaculture (use of nutrient-rich deep waters), use of output cold water for air conditioning systems, but may also have some undesired environmental impact [50].

First experimental OTEC plants were constructed in 1930 and 1935 in Cuba and Brazil [51]. Both plants were based on an open-cycle system. Following the oil crises of 1993, 50 kW closed-cycle OTEC plant was launched in 1979 in waters off Keahole Point, Hawaii. During three months of operation generated about 50 kWh (less than 14 kW net power) [52]. In 1981, a shore-based 120 kW closed-cycle plant (freon as working fluid) in the Republic of Nauru delivered about 31.5 kWh (the cold-water conduits on the ocean floor reached a depth of 580 m) [53]. A 210 kW open-cycle OTEC plant was operated for onshore at NELHA's Keahole Point facility between 1992 and 1998 [54]. In May 1993, a 210 kW open-cycle OTEC plant at Keahole Point, Hawaii, produced about 50 kWh net energy [55]. In 1999, the Natural Energy Laboratory tested a 250 kW pilot OTEC closed-cycle plant [56]. Since then, several plants have been proposed and some have been built as pilot plants. The USA, India, Indonesia and Cuba are actively involved in the development of this technology.

3.4 Ocean salinity gradients

The concept of harvesting energy generated from the mixing of freshwater and saltwater was first reported by Pattle in 1954 [57].

Ocean salinity gradient energy harnessing schemes can be divided into two groups, with and without a membrane. Vapour-pressure difference [58] exploits differences in vapour pressure of water and ocean water to obtain power from the gradient in salinity without the need of a membrane. Basically, freshwater is evaporated under vacuum conditions and condensed in ocean water, and the resulting vapour flow is utilised to generate electrical power in a turbine (analogous to the open-cycle OTEC system). Another technique, called hydrocratic generator, freshwater enters in direct contact with high salinity water (enclosed in a chamber) through one or more openings. Contacting the higher salinity water causes entrainment into and upwelling of the mixture within the chamber and electrical power is generated by an underwater turbine. This technique is described into detail elsewhere [59]. Another possibility is the mechanochemical engine of Katchalsky and co-authors [60,61] that used local ionic conditions to control a cycle of entropic contraction and expansion of collagen fibers (i.e., contraction of collagen fibers in a salt solution and the expansion in fresh water).

Membrane based harnessing schemes are pressure-retarded osmosis and reverse electrodialysis. In a pressure-retarded osmosis [62] two solutions of different salinity are brought into contact by a semi-permeable membrane which allows the solvent (water) to permeate and retains the solute (salt). The water flow is due to chemical potential difference between the solutions. In case of hydrostatic pressure applied to the concentrated solution, the water flow will be partly retarded. The water flow from the low-pressure diluted solution to the high-pressure concentrated solution results in a pressurization of the volume of transported water. This pressurized volume of water may be used to generate electrical power in a turbine.

In the reverse electrodialysis [57,62] a number of cation and anion exchange membranes are stacked in an alternating pattern between a cathode and an anode (i.e., it requires two types of membranes namely one that is selectively permeable for cation and another for anion). The compartments between the membranes are alternately filled with a concentrated salt solution and a diluted salt solution, and the salinity gradient results in a potential difference over each membrane (membrane potential) which can be converted into electricity.

The major handicap in energy harnessing schemes without a membrane is the size of turbines required. Besides, vapor pressure difference technique requires a large area of surface evaporation and the maintenance of the vacuum in a continuous process will require much energy. On the other hand, the cost of membranes is the major obstacle to progress in harnessing schemes based on membranes. Over the last two decades, membrane technology has become essential desalination and water treatment/decontamination areas resulting in a great reduction in prices, despite few number of membrane manufacturers in the world.

Membranes used for freshwater production by reverse osmosis are used in an installation for producing electricity by pressure-retarded osmosis under investigation in Norway. Statkraft has proved this concept at a prototype plant opened in November 2009 in Tofte, Norway [63]. Reverse electrodialysis technique was used in USA and Israel in 50's and 70's, respectively. In 2002, Netherlands revived the investigation under the brand name "Blue Energy", focused on membrane development, and currently operates a small scale plant in Harlingen, Netherlands [64].

Both Tofte and Harlingen plants that yield 2-5 kW are able to generate about 1W per square meter of membrane but are steadily in the rise (projects will be cost-effective at about 5 W/m^2).

According to Charlier and Finkl [65] Lockheed built a 180MW experimental reverse electrodialysis plant. According to the authors the system consumes an important part of the produced current to operate the system (i.e., pump water). NASA is developing osmosis primarily for water treatment on spacecraft but is also interested in its electricity outcome.

4 FINAL REMARKS

The ocean has a great potential for energy extraction, as it contains a large amount of energy. Its potential is crucial for future power. In this study, exergy analysis is performed to point out the potential of the different forms of ocean energy, such as hydrokinetic, hydropotential, thermal and salinity gradients. It is found that the highest availability comes with ocean hydropotential energy that has an exergy flux range of 23-153 kW/m^2 which is followed by thermal energy (4.5-66.8 kW/m^2). Though hydrokinetic and energy driven by salinity gradients seem to be less significant with ranges of 0.002-13.5kW/m2, 0.005-0.02 kW/m2 , respectively, This may not be underestimated due to huge surface areas of oceans. This paper also lists different technologies installed for harvesting the ocean energy in many countries, such as France, Canada, China, Portugal, UK, USA and India. Although the significant contributions have been done, there is enough room for further technological developments and improvements.

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