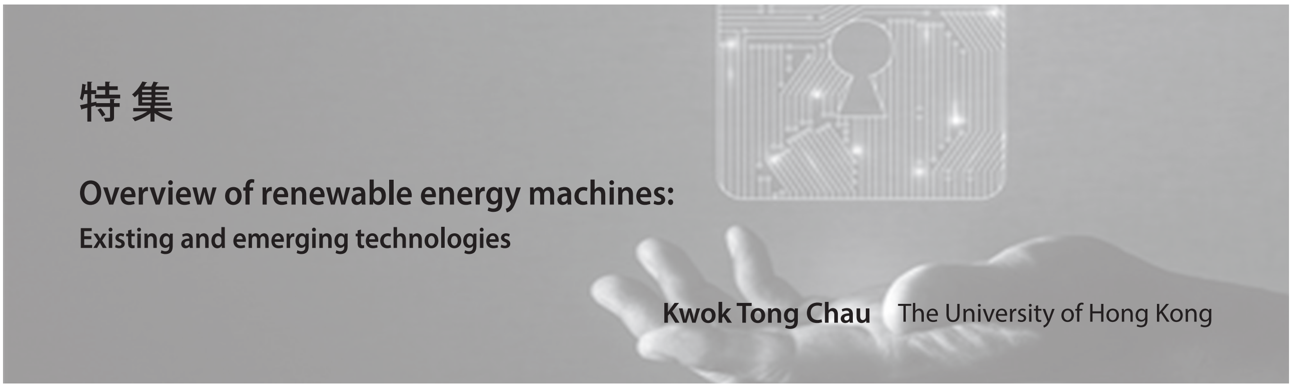

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Overview of renewable energy machines:

Existing and emerging technologies

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1. Introduction

Doubtlessly, electricity is the backbone of modern society. Where does electricity come from? Unfortunately, about two-third of electricity in the world is produced by burning fossil fuels, which inevitably brings along two most serious problems in the world today: (1) the resource of fossil fuels is finite and will be exhausted; (2) the combustion of fossil fuels creates air pollution and will worsen global warming.

Fossil fuels, including oil, coal and natural gas, currently provide about 85 % of total energy supply worldwide. These fossil fuels are finite and being depleted. The reserves-to-production ratio (R/P) is a widely used indicator to estimate the remaining amount of fossil fuels by estimating the number of years that the reserves would last if their consumption continues at the current rate. Globally, the proved reserves of oil, coal and natural gas at the end of 2015 are 1697.6 billion barrels (BB), 891.5 billion tonnes (BT) and 186.9 trillion cubic metres (Tm^3), respectively. Based on their annual production data in 2015, the global R/Ps of oil, coal and natural gas are 50.7 years, 114 years and 53.8 years, respectively (BP, 2016), which are listed in Table 1. These fossil fuel resources will get exhausted soon, probably in this generation or during our next generation.

Table 1: Reserves-to-production ratios of fossil fuels

	Reserves	Production	R/P (Years)
Oil	1697.6 BB	33.5 BB	50.7
Coal	891.5 BT	7.82 BT	114
Natural gas	186.9 Tm^3	3.54 Tm^3	52.8

Different electricity generation methods produce carbon dioxide (CO_2) emissions at different levels through construction, operation and decommissioning. For a fair comparison, the lifecycle CO_2 emissions, taking into account the construction, operation and decommissioning phases, are preferably adopted – usually dubbed as carbon footprint (WNA, 2011). The carbon footprint of primary energy for electricity generation is listed in Table 2. It can be found that the fossil fuel power plants have much higher CO_2 emissions than the renewable power plants or nuclear power plants.

Table 2: Carbon footprint of primary energy for electricity generation

	Carbon footprint (g/kWh)
Oil	733
Coal	888-1054
Natural gas	499
Renewables	26-85
Nuclear	26

Although the carbon footprint of nuclear power generation is similar to that of renewable power generation, there are many concerns on using nuclear power as an environmentally viable option. Facing with the consequence of three serious accidents of nuclear power plants in the world, namely the one at Three Mile Island in 1979, the one at Chernobyl in 1986 and the one at Fukushima-Daiichi in 2011, it is crystal clear that nuclear power generation is inherently incomparable with renewable power generation. The carbon capture and storage or called carbon capture and sequestration (CCS) technology is often cited as a promising means of mitigating CO_2 emitted from fossil fuel power plants to the atmosphere, hence combating global warming. However, the main problem is that a long-term assurance on underground or submarine storage security is hardly possible, and there is always a risk that CO_2 may leak into the atmosphere. Another key drawback is that capturing and compressing CO_2 consume a lot of energy produced by a coal-fired power plant.

Therefore, it is an urgent need to slow down the consumption and stop the wastage of fossil fuels for electricity generation. Since renewable energy is naturally replenished and will never be exhausted, renewable power generation is the preferred way of electricity production. The purpose of this paper is to give an overview renewable energy machines for electricity production. In Section 2, the classification and features of various renewables will be discussed. Then, in Section 3, both existing and emerging technologies of renewable energy machines will be reviewed. Finally, in Section 4, a conclusion on research priorities of renewable energy machines will be drawn.

2. Renewables

What are renewables? Renewables are natural resources that are practically inexhaustible and can be naturally replenished or renewed, such as water, wind, wood and sunlight. Thus, renewable energy is generated from natural processes that are continuously replenished, such as hydroelectric power, wind power, biomass power and solar power. The fuel cells and waste-to-energy are not considered as renewables as they are not naturally replenished. Almost all types of renewable energy depend on our three planets – Sun, Moon and Earth. The classification of those well identified types of renewable energy under the effects of Sun, Moon and Earth is depicted in Figure 1. Namely, the Sun is the eternal source of solar-electric power, solar-thermal power, hydroelectric power, wind power, wave power and biomass power; the Moon and the Sun are the eternal sources of tidal power; and the Earth is the eternal source of geothermal power. Renewable energy is commonly classified as the hydroelectric power, wind power, wave power, tidal power, solar power, geothermal power and biomass power. This classification has been widely accepted because these natural resources occur spontaneously. The number of classes can readily be extended when those natural resources can be effectively harnessed for electricity generation.

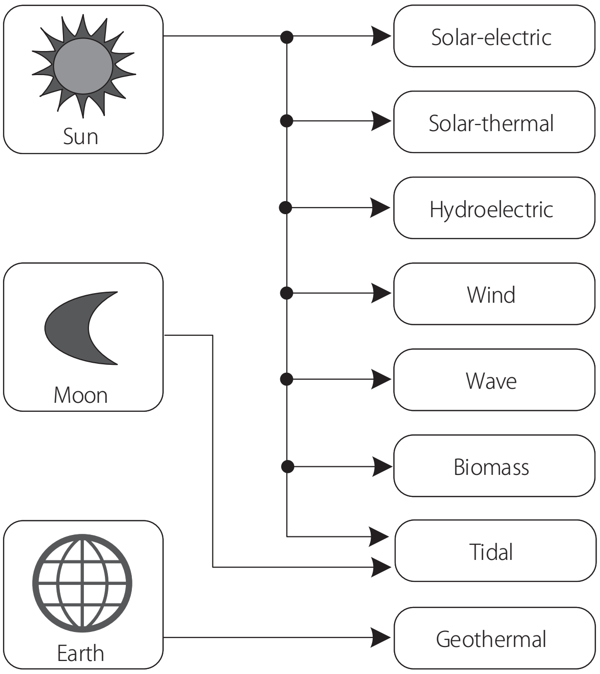

Figure 1: Eternal sources of renewables

Hydroelectric power facilities are of three main types: impoundment, run-of-river and pumped storage. Firstly, the impoundment hydro is the large hydro that everyone thinks of when they think of hydroelectric power. Essentially, there is a dam with water impounded behind, and the head difference between the water behind the dam and the water on the downstream side of the dam induces the water flowing into the intakes of the dam and then driving the water turbine which is coupled with the generator to produce electricity. Secondly, the run-of-river hydro desires small pondage or no water storage. Without pondage, the plant essentially converts the kinetic energy of water into electricity, but relies on seasonal river flows. Thus, with the use of pondage, the plant regulates the water flow at all times. Thirdly, the pumped storage hydro has the same principle of electricity generation as the impoundment hydro. The key difference is that the released water is pumped from the lower elevation reservoir back to the higher elevation reservoir during the period of low electricity demand. So, it is mainly used by the power system for load balancing, especially for those power plants with time-inflexible electricity generation such as nuclear power. On the other hand, hydroelectric power facilities can be divided into four types according to the installed capacity: large hydro (> 10 MW), small hydro (< 10 MW), micro hydro (< 100 kW) and pico hydro (< 5 kW).

Wind power facilities can be categorized into three main types: land-based, offshore and high-altitude. Firstly, the land-based wind power has been widely adopted in the world. Essentially, it consists of a group of wind turbines in the same area to produce electricity. As it generally desires a large amount of lands, it may have conflicts with land use for agricultural or industrial purposes. Secondly, the offshore wind power is becoming attractive. Due to the absence of topographic structures that affect the wind flow, the offshore wind is typically more consistent and stronger than the land-based wind. Also, it has less aesthetic impact on the landscape than the land-based one. Offshore wind power not only utilizes traditional fixed-bottom wind turbines, but may also adopt floating wind turbines at deep-water zones. However, the construction and maintenance costs are considerably higher. Thirdly, the high-altitude wind power has been proposed, but is still in the conceptual stage (Cherubini et al., 2015). Although it possesses some definite advantages that winds at higher altitudes are steadier, more persistent and of higher velocity, there are many technological challenges. Besides those large-scale wind power facilities with the capacity of 400-6000 MW, there are small-scale ones up to 50 kW which are particularly useful for isolated communities desiring low carbon footprint.

Wave power facilities can generally be classified by the energy capturing mechanism: namely the point absorber, attenuator, oscillating wave surge converter, oscillating water column, overtopping device, submerged pressure differential, bulge wave, and rotating mass (EMEC, 2016). Among them, the point absorber, attenuator, oscillating wave surge and oscillating water column are most common. They can also be broadly classified by the location of these facilities: namely the shoreline, nearshore and offshore. Between them, the shoreline facilities take the advantages of easy access, low transmission losses and low investment cost, whereas the offshore facilities have the advantages of high gross wave power, more exploitable resources and less disturbance to environment. On the other hand, these facilities can be classified by their power take-off systems, which include hydraulic turbine, air turbine, pump-to-shore, hydroelectric turbine as well as rotational and linear generators (Li et al., 2009). Compared with hydroelectric and wind power facilities, the wave power facilities that have been developed are with much lower capacities, from tens of kW to a few MW only.

Tidal power facilities can generally be classified by their energy capturing mechanisms: namely the tidal barrage, tidal lagoon, tidal stream, and tidal fence (Mersey Tidal Power, 2016). Among them, the tidal barrage and tidal stream are more mature and common. Based on the types of energy to be converted into electricity, such facilities can also be divided into two classes: namely the potential energy and kinetic energy types. Between them, the potential energy is easier to be captured than the kinetic energy one, but the corresponding facilities involve higher investment cost. For those facilities converting the potential energy into electricity, the tidal lagoon power is better than the tidal barrage power because it is more flexible to be located and constructed, and has less adverse effect on our environment and ecology. For those facilities converting the kinetic energy into electricity, the tidal fence power is better than the tidal stream power because it can capture more kinetic energy from the water flowing with higher velocity, and its electric machinery is easier to maintain and repair. Compared with hydroelectric and wind power facilities, the development of tidal power is still in its infancy even though tidal power is more resourceful than hydroelectric power and tides are more predictable than wind. The amount of tidal power produced so far has been small. The installed capacities range from about 1 MW of tidal stream power to about 250 MW of tidal barrage power.

Solar power consists of two main classes: the solar-electric power and solar-thermal power. The solar-electric power includes the photovoltaic (PV) power and thermoelectric (TE) power, which are resulted from direct conversions from the Sun's light into electricity using PV panels and Sun's heat into electricity using TE modules, respectively. The solar-thermal power is the indirect conversion of Sun's heat into electricity, where mechanical energy is the transition between them and renewable energy machines play an important role. Solar-thermal power facilities are commonly classified by their sunlight collection systems: namely the parabolic trough, power tower, dish engine, and Fresnel reflector (NREL, 2016). Among them, the parabolic trough and power tower are more mature and common. Nevertheless, the dish engine exhibits the definite advantage of highest energy efficiency, while the Fresnel reflector has the merits of lower investment cost and land demand. Their installed capacities range from about 1 MW to about 400 MW. As solar power is inherently absent at night or on cloudy days, it is necessary to store the solar-thermal heat for continuous electricity generation. Available thermal storage media include the pressurized steam, typically at 50 bar and 285 °C, molten salts such as calcium nitrate, sodium nitrate and potassium nitrate, and phase change materials including organic or inorganic (Shingare, 2015). The pressurized steam is simple and low cost, but is suitable for short-term thermal storage, typically about an hour only. The molten salt is liquid at atmospheric pressure, which can provide a low-cost medium to store heat for about a week. The phase change material has a high enthalpy of fusion, which can store and release a large amount of heat energy through melting and solidifying at a certain temperature.

Geothermal power facilities can generally be classified as the dry steam, flash steam and binary cycle (Blodgett, 2014). Among them, the dry steam is simplest and most mature; the flash steam is most energy efficient; and the binary cycle is most flexible. The choice is determined by the available geothermal resource. If the water from the well is in form steam and can be directly drawn from the well, the dry steam is preferred. If the water drawn from the well is of very high temperature, a flash steam should be used; otherwise, the binary cycle should be adopted. Since there are more hot water resources than pure steam or very high temperature water resources, it is anticipated that the binary cycle will be more and more popular. Nevertheless, the binary cycle has a drawback that it involves a high initial cost so that it is not so economically attractive. Geothermal power is highly scalable: from a small power station having the installed capacity of about 5 MW to power a rural village to a geothermal complex having the installed capacity of about 1500 MW to power over a million homes. Although the initial capital cost of small-scale geothermal power plants is high, they are very attractive to serve as distributed energy resources that can be aggregated to meet regular power demand while improving the operation and security of the power system.

Biomass power facilities can be categorized into two main groups: combustion conversion and electrochemical conversion. The combustion conversion is to burn the biomass or its derivatives to produce heat which in turn creates steam to drive a turbine for electricity generation, whereas the electrochemical conversion makes use of fuel cells to directly convert biomass or its derivatives into electricity. For the combustion conversion, it can be further divided into two types: the direct combustion and indirect combustion. The fuels for direct combustion are natural biomass, whereas the fuels for indirect combustion are those biofuels derived from biomass. There are different methods to convert biomass into biofuels, which can be classified as the thermochemical conversion, chemical conversion, and biochemical conversion. For the thermochemical conversion, depending on the availability of oxygen and variation of conversion temperatures, it makes use of the torrefaction, pyrolysis and gasification to produce the biochar, bio-oil and syngas. For the chemical conversion, it mainly uses the transesterification to produce biodiesel. For the biochemical conversion, it makes use of the anaerobic digestion and fermentation to produce the biogas and bioethanol. At present, most biomass power plants are based on direct combustion, and the installed capacities range from about 1 MW to about 100 MW. At present, co-firing biomass with fossil fuels is the most cost-effective biomass use for electricity generation, and is considered as an interim phase to fully transform fossil-fuel power plants to biomass power plants.

Almost all renewable energy harvesting systems especially those for practical power generation are based on electromechanical energy conversion: conversion from mechanical energy to electrical energy (Chau et al., 2012). Relevant renewable energy types include hydroelectric power, wind power, tidal power, wave power, solar-thermal power, biomass power, and geothermal power. The key reason is that the electromechanical energy conversion mechanism offers the following definite advantages:

- Electromechanical systems including the mechanical turbine and electric machine are mature and economical.
- Mechanical turbines can be driven by a wide variety of fluids, including water, steam, gas and air.
- Electric machines are very robust and reliable, with the capability of overloading and fault tolerance.
- Electric machines can operate over a wide speed range and a wide torque (or force) range, while maintaining high efficiency.
- Electric machines are highly scalable, providing a very wide range of power generation, from a few kilowatts to several hundred megawatts.
- Electric machines are very flexible, with the capability of adapting different motions and different orientations.

In order to capture various types of renewable energy, the mechanical turbines can be of different types: water, steam, gas and air. The water turbine is naturally adopted to harness the hydroelectric power, tidal power and wave power since they are all in the form of water. The steam turbine is used to harness the solar-thermal power, biomass power and geothermal power because they utilize their high-grade heat to produce high-temperature steam. The gas turbine is mainly used to harness those geothermal power with relatively low-grade heat. The air turbine is used to harness the wind power, and those wave power in the form of changing air pressure. Among them, the water turbine and steam turbine are dominant for utility-scale power plants. As depicted in Figure 2, all these turbines are coupled with the electric machine for conversion from mechanical energy to electrical energy.

The development trend of renewable energy has three important characteristics: technological advancement, sustainable development and synergistic collaboration. Firstly, the technological advancement focuses on increasing the conversion efficiency, improving the power density and extending the operation range of various renewable energy harvesters. Among various technologies, electric machines are the key component that attracts continual development because they are highly predominant for renewable energy harvesting. Secondly, the sustainable development aims to identify and harness those untapped renewables such as those in oceans. Thirdly, the synergistic collaboration encourages different technologies or systems collaborating together to achieve better outcome than that provided by each of them separately such as the hybridization of renewables (Liu et al., 2010) and collaboration with electric vehicles (Gao et al., 2014).

3. Renewable energy machines

While the AC machines, including synchronous generators and induction generators, have been widely accepted to work

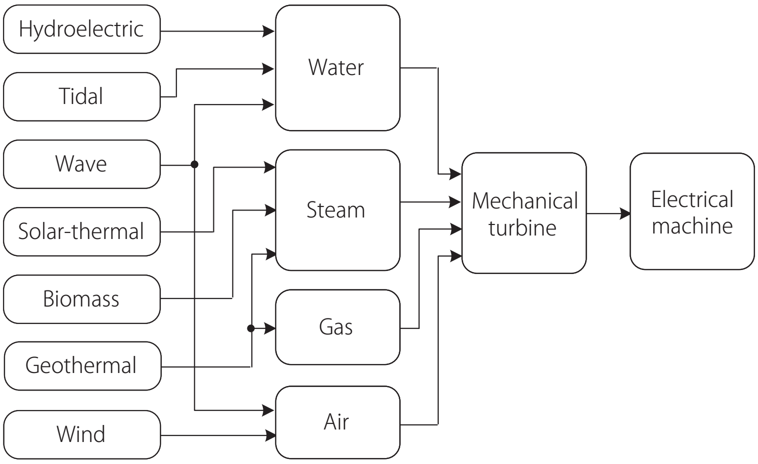

Figure 2: Electromechanical energy conversion

well for fossil-fuel power generation, why there are tremendous research activities on electric machines in recent years? The answer is the desire of new electric machine technologies to efficiently and effectively harness renewable energy – namely renewable energy machines.

There are many topologies of electric machines, which create various classifications. Traditionally, they were classified into two groups – DC and AC. With the advent of new machine types, this classification becomes ill-suited. Figure 3 shows the proposed classification of electric machines in which the bold types are those that have been applied to renewable power generation; meanwhile, the branches that are not viable for renewable power generation have been pruned.

Electric machines for renewable energy harvesting should not be considered as a subset of electric machines for industrial application since they have fundamental difference in requirements. The renewable energy machine should form an individual class of electric machines, which possesses the following features:

- High efficiency over wide torque (force) and speed ranges so as to increase the utilization of extractable energy;
- High power density so as to reduce the overall size and weight;
- Wide speed range so as to harness the energy at different speeds;
- High reliability so as to reduce the operational failure or fault;
- Maintenance free so as to eliminate the maintenance cost and possible outage for maintenance;
- High robustness so as to withstand harsh operating conditions and natural environment;
- Good voltage regulation so as to maintain the system voltage;
- High power factor so as to enhance the power transfer;
- Low cost so as to reduce the system cost.

3.1 Existing renewable energy machines

Among different types of electric machines, there are three main types that have been adopted for renewable power generation: namely the DC, induction and synchronous machines. They possess fundamentally different machine topologies.

For fixed-speed wind turbines, the corresponding electric machine usually adopts the synchronous machine (SM) or induction machine (IM) which can directly feed power to the grid. In order to effectively capture the wind power at different wind speeds, variable-speed wind turbine are becoming the trend of development. There are three main competing machine technologies for variable-speed wind turbines: the directly coupled IM, the power conditioned doubly fed IM (DFIM), and the power conditioned IM or permanent magnet (PM) SM (PMSM). The directly coupled IM can offer variable slip values to provide sufficient compliance to the power grid. However, the allowable speed variation is limited while an increased slip causes a significant reduction in efficiency. In order to have a wide range of speed variation, the power-conditioned DFIM is widely adopted. It incorporates two back-to-back AC-DC converters (so-called the AC-DC-AC conversion) to control the rotor current via slip rings and carbon brushes so that the output frequency can remain synchronized with the grid while the wind turbine speed varies. This arrangement of power conditioning takes the advantage that the converters need not handle the full output power of the generator, hence reducing the converter rating and cost. However, it suffers from the drawbacks of slip rings and carbon brushes such as the bulky size and need of regular maintenance. In order to provide the full operating speed range while avoiding the use of slip rings and carbon brushes, the power conditioned IM is preferable. Increasingly, in the absence of rotor copper loss, the power conditioned PMSM is becoming attractive which

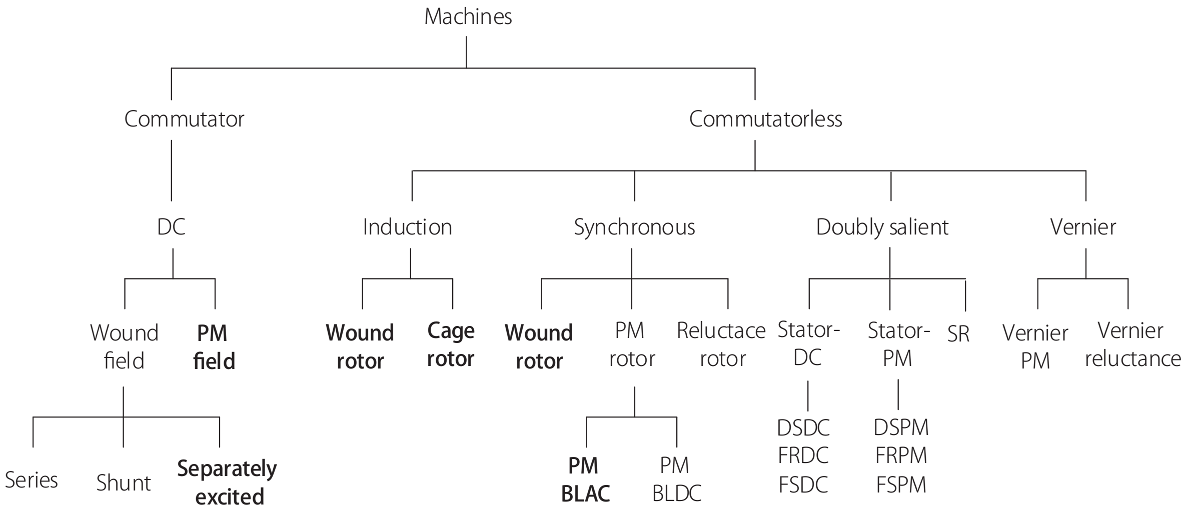

Figure 3: Classification of electric machines

takes the advantages of higher efficiency and higher power density. The key drawback of this arrangement is the need of power converters with the same rating as the generator. The key challenges of wind power generation are the intermittent production of electricity, the difficulty in harnessing low wind speeds, the need of regular maintenance if employing the SM or DFIM or using the mechanical gearbox, and the inefficient operation under time-varying wind speeds.

Similar to the existing wind power generation, the SM, IM, DFIM, PMSM are applicable for the existing wave power generation adopting rotational turbines or hydraulic mechanisms. In order to directly capture the linear reciprocating wave motion, the linear PMSM (LPMSM) is preferable since the linear versions of SM, IM and DFIM are relatively bulky, heavy and inefficient. The key challenges of wave power generation are the intermittent electricity production, the difficulty in capturing slow linear reciprocating wave motion, the need of regular maintenance if employing the SM or DFIM, the mechanical problems of gearbox or linear-to-rotary mechanisms and the harsh and corrosive operating environment.

There are various machine technologies for the existing hydroelectric power generation. For large hydroelectric power stations, the water flow via the dam is nearly constant so that the SM is almost exclusively used. Although this SM takes the definite merit of mature technology with very high power ratings, it has the drawbacks of the inevitable power loss in the field circuit and the need of regular maintenance for the slip rings and carbon brushes. Thus, its key challenge is how to get rid of the field circuit and the corresponding slip rings and carbon brushes while maintaining such high power ratings. On the other hand, for small hydroelectric power stations, especially the run-of-river hydro, there is a large variation in water flow while the generated power level is not very high. So, the IM or PMSM with power conditioning is preferred to the SM. The corresponding challenges are how to handle the varying flow of river, the difficulty in harnessing slow water motion and the need of regular maintenance if using the mechanical gearbox.

Similar to the large hydro, the tidal barrage produces nearly constant water flow for high power generation so that the SM is almost exclusively used. Meanwhile, similar to the run-of-river hydro, the tidal stream involves time-varying water flow for up to a few megawatts only. So, the IM or PMSM with power conditioning is preferred to the SM. On top of the challenges similar to that for the large hydro and run-of-river hydro, the electric machines for tidal power generation inevitably suffer from the challenge in providing adequate corrosion protection against sea water.

Alike the traditional thermal power plants, the solar-thermal power generation is based on steam turbines so that the SM is widely used. Meanwhile, for small-scale solar-thermal installations, the IM takes the advantages of low cost and maintenance-free operation. The key challenge on solar-thermal generation is how to effectively and efficiently store the thermal energy obtained from sunlight so that electricity generation can be maintained during the cloudy days or night periods. Other challenges on electric machines are how to get rid of the field circuit and the corresponding slip rings and carbon brushes of the SM, and how to improve the efficiency, power density and power factor of the IM.

The geothermal power generation and biomass power generation are based on steam or gas turbines so that the SM or IM can be adopted. Of course, the SM takes the advantages of higher efficiency and higher power rating, whereas the IM takes the merits of more robust, lower cost and maintenance-free operation. However, the drawbacks of using the SM and IM are still challenges to be solved. Although the biomass fuels are very resourceful with a very low raw material cost, the key challenge of biomass power generation is the transportation cost of feedstock. Thus, grid-connected small- or micro-scale biomass power stations are becoming attractive, which have sufficient amounts of feedstock on site. While the SM and IM have their own shortcomings, it is challenging to develop a new breed of electric machines for this small- or micro-scale biomass power generation.

Based on the aforementioned renewable power generation systems, the existing types of renewable energy machines and the corresponding requirements of power conditioning are compared as compared in Table 3. It can be observed that the machines and power conditioners are the same between wind and wave power generations in which the linear wave motion is first transformed into rotational motion, the same between large hydro and tidal barrage power generations, the same between small or run-of-river hydro and tidal stream power generations, the same between solar-thermal, geothermal and biomass-thermal power generations because they have similar characteristics, respectively. Of course, the electric machine for direct-drive wave power generation is unique.

Table 3: Existing renewable energy machines

	Machine	Power conditioning
Wind	SM, IM, DFIM, PMSM	Optional, AC-DC-AC
Wave (rotational)	SM, IM, DFIM, PMSM	Optional, AC-DC-AC
Wave (linear)	LPMSM	AC-DC-AC
Large hydro	SM	NA
Small hydro	IM, PMSM	AC-DC-AC
Tidal barrage	SM	NA
Tidal stream	IM, PMSM	AC-DC-AC
Solar-thermal	SM, IM	NA
Geothermal	SM, IM	NA
Biomass	SM, IM	NA

3.2 Emerging renewable energy machines

The latest development of renewable energy machines is focused on three directions: the stator-PM machines aiming to achieve high reliability and high robustness; the direct-drive PM machines aiming to directly harness the renewable energy without any transmission mechanism; and the magnetless machines aiming to avoid using expensive rare-earth PMs.

The stator-PM machines are with PMs located in the stator, and generally with salient poles in both the stator and the rotor (Liu et al., 2008). Since the rotor has neither PMs nor windings, this class of machines is mechanically simple and robust. Hence, they are very suitable for renewable energy harvesting which is intermittent in nature. According to the location of the PMs, it can be split into the doubly salient PM (DSPM), flux-reversal PM (FRPM) and flux-switching PM (FSPM) types. Among them, the DSPM machine is relatively the most mature one (Cheng et al., 2001). This machine takes the definite advantages of high reliability and high robustness for wind power generation (Fan et al., 2006a). The FRPM machine exhibits the feature of bipolar flux linkage variation (Deodhar et al., 1997). Since the bipolar flux linkage variation can have better utilization of iron core than the unipolar counterpart, the FRPM machine inherently offers higher power density than the DSPM machine. However, since the PMs are attached on the surface of stator teeth, they are more prone to partial demagnetization. Also, significant eddy current loss in the PMs may be resulted. The FSPM machine has the topology that each stator tooth consists of two adjacent laminated segments and a PM, and each of these segments is sandwiched by two circumferentially magnetized PMs, thus enabling flux focusing (Zhu et al., 2010). It also has less armature reaction, hence offering higher electric loading. Since its back EMF waveform is essentially sinusoidal, this machine is more suitable for the BLAC operation (Yu et al., 2016).

Most of the renewable energy harvesting devices, such as the hydroelectric turbine, wind turbine and wave turbine, inherently operate at low speeds. In order to directly convert this low-speed motion into electricity, this low-speed machine has to be designed with many poles, leading to be bulky and heavy. So, the turbine speed is usually stepped up by a gearbox before feeding into a high-speed machine. However, the use of mechanical gear inevitably involves transmission loss, acoustic noise and regular lubrication. To solve these problems, magnetic gears are becoming attractive, since they inherently offer the merits of high efficiency, reduced acoustic noise, and maintenance free (Jian et al., 2009a; Chen et al., 2014).

By artfully integrating the magnetic gear into the PM synchronous machine, the low-speed direct-drive requirement and the high-speed machine design can be achieved simultaneously. This magnetic-geared machine not only offers reduced size and weight, but also eliminates all the drawbacks due to the mechanical gear (Jian et al., 2009b). Nevertheless, this magnetic-geared machine may suffer from the drawback of manufacturing difficulty due to the presence of three air-gaps and two rotors. Based on the modulation function of the toothed-pole structure, the vernier PM (VPM) machine can directly offer the low-speed high-torque feature for direct-drive applications (Li et al., 2015). Namely, each stator tooth is split into small teeth at the end, termed flux-modulation poles, so that a small movement of the PM rotor can cause a large movement of flux-linkage in the stator armature winding. This is the so-called magnetic gearing effect or vernier effect (Li et al., 2010). It offers the definite merit of only one air-gap and one rotor as compared with the magnetic-geared counterpart (Li et al., 2011a). Furthermore, based on the same principle of operation, the VPM machine allow the PMs located in the stator so as to improve the mechanical integrity of the rotor.

For wave energy harvesting, the linear machine is preferred to the rotational machine because the wave motion is inherently linear. Also, the rotational machine inevitably desires a bulky and inefficient linear-to-rotary transmission mechanism which should be eliminated. Because of the low-speed nature of reciprocating wave motion (typically 0.5 m/s), the linear direct-drive PM machine is highly desirable. Borrowing the concept of coaxial magnetic gears, the linear magnetic gears can readily be used to amplify the linear motion (Li et al., 2011b; Li et al., 2017a). Hence, the linear magnetic-geared PM synchronous machine can offer the low-speed direct-drive operation for wave power generation and the high-speed machine design for maximizing power density (Li et al., 2013). Meanwhile, the rotational VPM machine can also be extended to form the linear VPM machine, which exhibits the low-speed high-force feature for directly harnessing wave energy (Du et al., 2015).

With ever increasing popularity of PM machines for renewable power generation, the demand of rare-earth PM materials such as neodymium-iron-born is drastically soaring. The price of the rare-earth element neodymium is the determining factor in pricing these PM machines. In recent decade, both the absolute value and volatility of the neodymium price severely add uncertainty to the development of PM machines, and stimulate the research of advanced magnetless machines (Lee et al., 2013).

The switched reluctance (SR) machine is a kind of doubly salient machines, and also a kind of advanced magnetless machines. The stator of this SR machine is a simple iron core with salient poles wound with the concentrated armature winding, while the rotor is simply an iron core with salient poles having no windings or PMs. Its operating principle is simply based on the ‘minimum reluctance’ rule. So, it offers the definite advantages of simple construction, high robustness, low manufacturing cost and low moment of inertia. Because of these advantages, this SR machine is becoming attractive for wind power generation (Cárdenas et al., 2005). Nevertheless, it suffers from the problem of no self-excitation capability. To overcome this problem, some researchers have made use of an external DC power source to create magnetic field around the armature winding so that electricity can be generated when the rotor moves.

The stator-DC machines are a class of emerging magnetless machines, which are actually derived from the class of stator-PM machines. A basic type of SDC machines is the doubly salient DC (DSDC) machine (Fan et al., 2006b). It adopts the same rotor structure as the SR machine, namely the solid iron with salient poles. Differing from the SR machine, the DSDC machine has two types of windings on the stator – the 3-phase armature winding and the DC field winding. Since the current flowing through the field winding is independently controlled, this machine can retain the inherent merit of higher power density than the SR machine while enjoying the additional merit of controllable air-gap flux density. Consequently, when the generated output voltage deviates from the preset value, the DC field current can be controlled in such a way that the output voltage is kept constant. Also, based on the measured mechanical input power and electrical output power, the DC field current can be tuned in such a way that the system efficiency is maximized. These two features are highly desirable for wind power generation. In recent years, the FRPM machine and FSPM machine have also extended to derive the flux-reversal DC (FRDC) machine (Lee et al., 2015a) and flux-switching DC (FSDC) machine (Lee et al., 2015b), respectively. Both of them can offer higher power density than the DSDC machine, and better cost effectiveness than their PM counterparts.

Because of the merits of high efficiency, high power density and maintenance-free operation, the PMSM and stator-PM machine (SPMM) will be the most preferable machines for most kinds of renewable energy harvesting in near term. With ever increasing concern on the supply of rare-earth materials and volatility of their price, the SR machine (SRM) will be equally important. For wave energy extraction, their linear versions, namely the LPMSM, LSPMM and LSRM, will be preferable. Nevertheless, for hydroelectric power with very high power ratings, the traditional SM can maintain its attraction in near term due to its maturity. In long term, the VPM machine (VPMM) will be more attractive than the PMSM or SPMM for those renewable energies with slow intermittent motion, whereas the PMSM and SPMM will still be preferable for the large hydro or those renewable energies in thermal nature. The stator-DC machine (SDCM) will supersede the SRM in long term. Of course, the linear VPMM (LVPMM) and linear SDCM (LSDCM) will be preferred for wave energy. The near-term and long-term potentialities of these representative renewable energy machines are summarized in Table 4.

Table 4: Representative renewable energy machines

	Near-term	Long-term
Wind	PMSM, SPMM, SRM	VPMM, SDCM
Wave	LPMSM, LSPMM, LSRM	LVPMM, LSDCM
Hydro	SM, PMSM, SPMM, SRM	PMSM, SPMM, VPMM, SDCM
Tidal	PMSM, SPMM, SRM	VPMM, SDCM
Solar-thermal	PMSM, SPMM, SRM	PMSM, SPMM, SDCM
Geothermal	PMSM, SPMM, SRM	PMSM, SPMM, SDCM
Biomass	PMSM, SPMM, SRM	PMSM, SPMM, SDCM

It should be noted that the acceptability of advanced magnetless machines depends on the price and abundance of future PM materials. If there are new PM alloys without using any rare-earth elements while offering similar magnetic properties as the neodymium-iron-boron, the magnetless machines will not be so attractive. Moreover, there are many factors, such as new machine materials, affecting the long-term preference of electric machines for renewable energy harvesting. For instance, high temperature superconducting (HTS) materials have potentials to change the long-term development of renewable energy machines (Li et al., 2017b; Li et al., 2017c).

4. Conclusion

In this paper, a comprehensive overview of renewable energy machines has been presented, with emphasis on their emerging research activities. Among them, the SPMM technology is most preferable for renewable energy harvesting in near term, which should enjoy the highest research priority. Its linear version, namely the LSPMM, is particularly attractive for wave energy extraction. For those renewable energies involving slow intermittent motion, the VPMM and LVPMM are very promising technology, which should have high research priority. Meanwhile, the advanced magnetless machine technology, namely the SDCM and LSDCM, should also be actively researched, which can significantly increase the system cost effectiveness. Finally, the advancement of HTS materials should not be ignored as it is anticipated that the HTS machine will have a great impact for high power renewable energy harvesting in future.

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