Renewable Energy Resources Technologies and Life Cycle Assessment

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Researchers focuse on RER-based electrical power plants as a base to achieve two different sustainable development goals, SDG7 (obtaining reasonably priced clean energy) and SDG13 (reducing climate change). These goals in turn would support other environmental, social, and economic SDG. The study is constructed based on two pillars which are technological developments and life cycle assessment (LCA) for wind, solar, biomass, and geothermal power plants. Many other essential topics are presented in brief such as fossil fuels' environmental impact, economic sustainability linkage to RER, the current contribution of RER in energy consumption worldwide and barriers and environmental effects of RER under consideration.

sustainable development | renewable energy resources | life cycle assessment | wind | solar | biomass | geothermal

1. Wind Energy

The WE[1] system has precede other types of RE systems. Also, it comes next behind hydropower energy. WE systems have been developed over years. Wind turbines are the most important parts of the WE system which have been developed over years. This is obvious through increasing size and capacity. Another indication is economically increasing generated power. Also, installation of WT in hard-to-install locations. The large growth of installed WE systems has led to more complex requirements for interconnection in order to enhance system stability [2]. The capacity of most wind turbines was 2 MW from 2005 till 2013 then, it has increased to 3/3.5 MW. Also, the tower's height increased more than two times since 1990 to 100 m and more. The blade's length and operating range (cut-in and cut-out) are not an exception, they both have increased [3]. The nacelle and tower have a great impact on a small-scale wind turbine [4]. The recent technological development in wind turbine manufacturing has led to increasing generation limits. The size of the unit has become 3.00 MW and higher. As a result, WE plays an important role in the electrical grid [5]. Large wind market earns much more strength due to governmental support while the small-scale market is still small. The growth of small-scale turbines depends on decreasing the installation cost and increasing governmental incentives [6].

Wind turbines could be classified based on the construction and orientation of the rotor shaft. WT is generally divided into two types, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The main parts are the generator, rotor shaft, gearbox, blades and tower. Each type has its own structure and characteristics. In HAWT, the rotor shaft is aligned parallel to the wind direction. All parts are mounted on the upper part of the tower. On the other side, VAWT includes a rotor shaft perpendicular to the wind direction and attached to the turbine. The generator and gearbox are installed near the base of the tower. VAWT is divided into two types, drag-based turbine and lift-based turbine. The drag-based turbine is the simplest type. It rotates more in the same direction of wind and vice versa. The lift-based turbine is not self-starting so, it starts with a powered motor. HAWT includes two types, upwind and downwind types [7].

VAWT possess many advantages: It extracts energy from the air from any direction; it has noise much lower than HAWT; it works at low wind speed; it performs better than HAWT during turbulent wind flow; it needs a small area to be installed and is easy to maintain. All these advantages make it suitable for urban areas. VAWT required an effective control strategy to produce energy efficiently. Two control techniques are usually used for VAWT, fixed and variable pitch controllers. Variable pitch control technique is more efficient and self-starting under low-speed conditions [7]. Compared to HAWT, the VAWT provides better performance in tropical and windy climates [8]. VAWT are proper for unstable wind region. So, it has a positive and negative torque. In order to operate efficiently, a wind deflector is installed to enhance positive torque and eliminate negative torque. The deflector location and direction have been reviewed to enhance the generated power [9].

Due to its ability to work at low speed and more turbulent wind, VAWT has been studied for urban applications. It has shown a good performance, more safe and negligible noise [10]. The lift-type VAWT has been reviewed based on aerodynamic design parameters. Each parameter has been studied in order to reveal pros and cons [11]. Also, it has been reviewed for onshore and offshore applications. Offshore WT is much more suitable for today's design and capacities which exceeded 10 MW; the capacity of onshore WT could be increased through increasing towers and blades [2][12]. The available techniques for improving the performance of lift-type VAWT have been reviewed based on design, flow control methods, pitch controller techniques, blade style and supporting power devices [13]. VAWT has been studied for offshore applications considering multi-criteria to investigate whether it is suitable or not [14]. VAWT output power has been supported with a duct consisting of three parts a diffuser, a nozzle and a flange. As a result, the power coefficient has increased up to 2.9 times [15]. A wind flow modifier and an involute rotor have been proposed to enhance the maximum power coefficient for urban application [16].

Although VAWT has many advantages, it is not common such as HAWT which is suitable for large capacity and much more stable. Also, it has a large tower and taller blades. To be efficiently operated, HAWT's blades must be directed to face wind speed throughout a yaw mechanism. HAWT needs a special equipment to be installed, operated and maintained. Also, it produces more noise [7]. Large scale HAWT-based lift principle is economic, cost-effective, more efficient and much more reliable. The generated energy depends mainly on turbine capacity, hub height and rotor diameter [3]. Multi-megawatt HAWT is a growing developed technology. Improving system efficiency could be achieved through strategies. Increasing height is an effective strategy but it is limited due to structural aspects. So, designing blades have been proposed to make HAWT more efficient [17].

Small-scale HAWT design and development have been reviewed based on WT blades, diffusers, airfoil and adding winglets considering maximum power point tracking (MPPT) and environmental impact as illustrated in [18]. Also, it has been studied based on power coefficient and startup time by accurately selecting suitable airfoil [19]. The performance of small-scale HAWT has been investigated considering the effect of winglets based on power coefficient and thrust force coefficient. Different design and configuration of winglet has been studied intensively. When the winglet is exist, both power and thrust force coefficients would be increased [20]. Yaw control systems have been reviewed based on mechanical and aerodynamic pieces for large-scale HAWT. Yaw control systems could be classified based on their objectives into three types, maximizing generated power, reducing fatigue and maximizing extracted WE [21]. The yawing dynamic behavior of small-scale HAWT has been studied numerically and experimentally [22]. Unsteady Reynolds Averaged Navier-Stokes technique has been applied to study the aerodynamic characteristics of HAWT considering static and dynamic yawed conditions and start/stop yawing rotation [23].

Wind turbines also could be classified into two types, fixed and variable speed WT. Fixed speed WT consists of a squirrel cage generator connected to a multi-stage gearbox connected directly to the grid. It is simple, reliable, robust and cost-effective. It is low-performance WT characterized by fluctuating power, unstable voltage and stressed mechanically at high capacity. It is suitable for generating a capacity below 1.5 MW. Variable-speed WT consists of WT connected to the generator through a gearbox which is connected to the grid through power converters. It is characterized by, reduced mechanical stress, controllable output power, higher efficiency, improved power quality and a reduced noise level. It is suitable for higher-rated power (1.5–5 MW). Three types of generators have been used, Doubly-Fed Induction Generator (DFIG), Fixed speed Induction Generators (FSIG) and Synchronous Generators (SG). Also, to increase efficiency, MPPT techniques have to be considered [24].

Operation and maintenance costs of the current WE system are 20–25% of the total levelised cost of electricity. So, it has recently received more attention. Researchers recently pay attention towards failure analysis to minimize the probable fault occurrence which requires complex and costly maintenance [25]. People’s opinion always affects the success of any project or idea. Lack of public awareness of environmental problems and climate change may be a serious obstruction in promoting RE. For instance, SE are much accepted for cooking, water heating, and food drying but, still have less acceptance for electricity generation. Increasing awareness of RE’s importance would enhance the future of RE [26].

According to the former collected data, great efforts have been directed toward increasing WE system capacity, and efficiency and improving system performance. This could be achieved through: improving the design of towers, blades and gearboxes; enhancing the available control techniques such as yaw control mechanisms and MPPT techniques; improving Operation and maintenance systems through analyzing failures and faults; seeking for effective solutions to reduce manufacturing and installation costs and comparing between available WT technologies based on adequacy for different applications such as onshore, offshore and land-based.

1.1. Environmental Impacts of Wind Energy

WE system causes many environmental impacts such as noise impact, visual impact, bird death, deforestation, lightning hit towers and electromagnetic interference.

1.2. Challenges Prevent Development of Wind Energy

Wind power emerging technologies have been studied for development achievement in the future. Based on experts' views, there are many obstacles that need to be eliminated such as [27]:

- Providing durable, lightweight and cheap manufacturing materials;
- Enabling developed control strategies;
- Providing developed substitution support structure;
- Providing a smaller energy extracting devices;
- Providing advanced power transmission techniques;
- Investments and funds for research and wind energy projects.

2. Solar Energy

The SE transmitted to earth is incredibly large. PV cell is used to absorb the photon energy in solar radiation and convert it into electricity. The main objective of technological development is to provide both economic and efficient energy sources. PV systems are divided into three generations. The first generation consists mainly of single-crystalline and multi-crystalline silicon. The second generation consists mainly of thin-film PV cells which comprise amorphous silicon, cadmium sulfide (CDS) and cadmium telluride (CDTe). The third generation comprises other silicon-free technologies such as perovskite PV cells, dye-sensitized PV cells and quantum dot PV cells [28]. This new technology is facing many challenges such as, sociotechnical barriers due to the missing data for most people which causes inappropriate use and maintenance; Management barriers due to improper financial strategy and bad after-marketing services and economic barriers due to high cost, especially for the installation. So, people moving towards the conventional source of energy and policy barriers due to missing or ineffective policies [29]. PV cells must meet some requirements in order to be commonly used, cost-effective, high efficiency, long life cycle and have available constructing materials. Crystalline-based PV cell fulfils all these requirements [30].

Bifacial PV technology is a new trend in PV solar cells. It has appeared on the scene strongly. It is expected to share in the PV market with more than 35% by 2028. Bifacial PV cell has many advantages. It absorbs solar radiation from both sides which increases the generated power. The power losses due to aluminum base removal would be eliminated. Also, it protects the cell from being bending because silicon and aluminum have different thermal expansion [31]. Bifacial crystalline PV cell technology superiors conventional PV cell technology as illustrated by authors in [32]. Bifacial PV technology field study starts in 2009. However, the available researches are quite limited. It faces some difficulties such as complex mechanisms and non-uniform rear-side irradiance. The main difference between mono-facial and bifacial PV technology is, the back surface of the PV cell. In mono-facial it contains a back surface field while in bifacial it contains antireflection coating and electrical contacts. So, bifacial

PV cells could extract radiation from both sides [33]. Bifacial PV technologies could be divided into six types as follows: passivated emitter rear contact [34][35][36], passivated emitter rear locally-diffused (PERL) [37][38][39][40], passivated emitter rear totally diffused [41][42][43], heterojunction with intrinsic thin-layer (HIT) [44][45][46][47], interdigitated back contact [48][49][50] and double-sided buried contact solar cell [51].

Another new emerging technology in PV cells is Hollow semiconductor photocatalysts. This strategy helps the cell to use light efficiently. Presently, researchers focused on the composition of oxides, nitrides, sulfides and organic semiconductors to produce high photocatalytic materials [52]. Hollow Nanostructures for Photocatalysis-based PV cells have a promising future. It provides more energy with negligible environmental effects. Photocatalysis process includes three steps, light absorption then charge splitting and transfer and finally surface reaction. The hollow nanostructure has many advantages such as, increasing light utilization through light diffusion and slow photon effects; deactivation of charge integration through decreasing charge transition distance and separation of charge carriers, and speeding up surface reactions through increasing surface area and discrimination between redox reactions. Hollow Nanostructures based Photocatalysis experience many challenges such as, Limited application, complex manufacturing process, new unclarified technology and industrial difficulties in providing large pure crystalline surface area [53]. However, this technology is new but some interesting researchers have applied this technology successfully [54][55][56][57].

An organic solar cell is an emerging technology based on organic semiconductor materials. It has two advantages over inorganic types, manufacturing cost-effective and ease of implementation on flexible substrates. The highest recent energy conversion efficiency obtained by organic, quantum dot, flexible SCs, compound semiconductor-based solar cells, DSSCs, perovskite and silicon PV cells is 13.76%, 18.05%, 15.38%,53.8%, 12.3%, 25.2% and 27.6% respectively [58].

According to the former collected data, many technologies have been studied to provide better performances and higher efficiencies. Silicon-based PV cells still dominated other technologies. Both thin film and silicon-free technologies receive considerable attention as cheap alternatives for silicon PV cells. New emerging technologies have been studied for years such as bifacial, hollow conductors and organic PV cells in order to be effectively used in future. These techniques however being applied successfully in producing electricity are still under research. The conversion efficiency is highest for silicon PV cells and lowest for organic solar cells.

2.1. Environmental Impact of Solar Power Plants

The solar PV power plant has a negligible environmental effect except for large-scale power plants. Most environmental concerns are resultant from the manufacturing process, especially heavy materials such as steel, iron, copper, silicon and aluminum which require intensive energy. For Solar TH power plants, both manufacturing and operation have the same environmental effect [59].

2.2. Challenges Facing Solar Energy Developments

Obtaining maximum benefits from solar power plants requires determining all barriers in order to be eliminated. Solar power plants, similar to all other RER, face many challenges such as [60]:

- Technological barriers linked to manufacturing, operation and maintenance
- Transparency and accountability barriers linked to corruption, lack of accountability and lack of transparency
- COVID-19 pandemic barriers which delay the installation of many plants and disrupt the development process
- Financial barriers linked to the ability to provide financial funds for development
- Policy and regulatory barriers linked to energy prices, feed-in tariffs and restrictions
- Infrastructure related to unsuitable power plant construction that would face many problems when integrating solar systems.

3. Biomass Energy

Biomass energy (BME) is one of the most confusing sources of energy according to most people. They either have no idea about the working mechanism or correlating with combustion such as conventional energy sources. It is the main source of nutrition and energy for human beings and all living creatures. BME required proper employment to be economic and clean energy with zero carbon dioxide. Biomass as a word consists of two parts bio which refers to animals and mass which refers to plants. Biomass is a carbon-neutral source of energy as the amount of carbon dioxide consumed during the photosynthesis process is the same as that released during incineration. Also, it does not produce other GHG emissions such as methane and nitrogen dioxide [61]. Biomass fuels contribute 10–14 of total consumed energy, 40% of energy production in urban areas and 90% of energy production in rural areas. Biomass is converted to different forms of energy such as electricity, thermal and transportation fuels. Various types of biofuels are produced from biomass such as bioethanol, biodiesel, biogas, bio-butanol, bio-oil and bio-hydrogen [62]. Biomass is available in three basic forms of the substance: Solid, liquid and gaseous, which in turn can be divided into primary materials and by-products [63].

Expanding the use of clean BME such as biofuels and biogas improves ecological health and accelerates human development. However, the conventional use of BME causes an adverse impact. Proper utilization of biomass is linked to technological advancement. As a result, governments should encourage investments, direct institutional researches, and regulate policies toward BME. This is to enhance biomass technological developments in order to minimize installation and running costs. For investors, site selection is a crucial issue to reduce transportation costs and guaranteed abundant sources of biomass. This would improve the BME sector and reduce GHG emissions [64][65][66].

Biomass is classified according to the type of vegetation and applications and there are many classifications. For instance, classifications of biomass based on types of vegetation include woody, herbaceous, animal and human waste, aquatic and mixtures [67]. Woody biomass includes barks and leaves of trees both over and underground and residue of trees and roots [68][69][70][71][72]. Herbaceous biomass is a non-woody stem plant such as agricultural waste and energy crops [73][74][75][76][77][78]. Animal and human waste biomass such as human dung, animal manure, flesh and bones are converted to fertilizers used in agriculture or converted to biogas [79][80][81]. Aquatic biomass comprises microalgae, macroalgae and plants that grow partially submerged in swamps [82][83][84][85][86][87]. Biomass mixtures are a combination of two or more substances from the former types [88][89][90][91][92].

Biomass is difficult to use in its primary form, so it is converted into another form of energy. The commonly used biomass conversion techniques are Thermochemical, biochemical and physicochemical [67]. Thermochemical conversion comprises both thermal and chemical processing and is divided into four processes such as Combustion, Pyrolysis, Gasification and Liquefaction. The combustion process is the fusing of biomass with oxygen in a high-temperature medium. This process produces heat, carbon dioxide, and water vapor. This process accounts for about 90% of the total energy provided by biomass. The pyrolysis process mainly aims to convert biomass into solid charcoal, liquid bio-oil, and gaseous combustible gas through partial combustion at different temperatures. This process includes drying, distillation, exothermic reactions and evaporation. Gasification means converting solid biomass into synthesis gas (syngas). Synthesis gas is used to generate electricity and is a basic material for the petrochemical and refining industries. Liquefaction means converting biomass into a liquid biogranulate. This process is performed in water under temperatures of 280–370 °C [67][93][94][95][96][97][98][99][100][101][102].

The biochemical conversion process uses biological species such as bacteria to break down biomass into simpler carbohydrates to convert into liquid fuels and biogas. Anaerobic digestion and fermentation are the most common biochemical conversion type. Anaerobic digestion is a biological process used to produce RE and used for waste management. The fermentation process is a series of biochemical reactions used to convert simple sugars into ethanol and CO_2 using microorganisms such as yeasts [67][103][104][105][106][107][108][109]. The physicochemical process is used to produce high-density biofuel (biodiesel) from biomass such as vegetable oils and animal fats under the esterification process [67][110][111][112][113].

According to the former collected data, most developments in the BME system are correlated to energy conversion techniques. Energy conversion techniques such as thermochemical, biochemical and physicochemical, are essential to utilize BME. Thermochemical processes especially combustion processes dominated other techniques. Biochemical and Physicochemical processes received considerable research efforts which have produced a powerful energy sources such as ethanol and biofuel which are used to generate electricity through combustion.

3.1. Environmental Impact on Biomass Energy

BME has many forms. Each type has different environmental effects based on nature construction and the surrounding area.

3.2. Challenges Facing Biomass Development

BME did not receive enough attention. This may be due to many barriers such as [114]:

- Investment risks due to uncertainty caused insufficient funds.
- Energy/space efficiency is very low.
- Transportation cost is very high.
- Skilled labor is not available.
- Research and development receive insufficient fund.
- Public awareness is very low; conversion technology is costly.
- Governments' policies are insufficient or ineffective.

4. Geothermal Energy

Geothermal energy (GTE) is an independent constant abundant energy resource. It provides a big share for power in Iceland (27%) and El Salvador (26%). It is an emerging RER extracted from earth's internal heat which comes mainly from molten magma and radioactive elements decay process. It can be categorized into shallow GTE, underground thermal water and hot dry rock resources. Shallow surface GTE is a low temperature concentrated in soil, gravel and water beneath within 200 m depth below the surface. Underground thermal water of temperature higher 25 °C within depth less than 4000 m. Hot dry rock resources is of temperature more than 150 °C buried within depth range 3–10 km [115]. GTE applied mainly for two purposes which are, electricity generation and heat production. It is expected for GTE to contribute 2–3% of total electricity generation by 2050 [116].

Working principle for geothermal power plant: extracting earth's internal thermal energy through injecting hydrothermal fluid such as water, this hot water produce pressurized steam that rotate the turbine which connected to generators. Three common power plants are used: dry steam, flash steam and binary cycle. In dry steam power plant, a hydrothermal fluid injected deep in earth to acquire thermal energy. Then it converted to steam used to rotate turbine to generate electricity. Then the steam would be condensed and injected again to the well. Flash steam power plant comprises the same former process except that, the lifted steam directed to a steam separator filled with high temperature hydrothermal fluid which converted to steam and separated. This separated steam used to rotate the turbine. This plant requires temperature more than 182 °C to be operated. In Binary cycle power, the extracted heat is transferred to another lower boiling point hydrothermal fluid converting it to steam directed to rotate the turbine to generate electricity [117].

Five technologies have been utilized to convert bio thermal energy into electricity. These power plants are dry steam, single and double steam, binary cycle and other advanced conversion systems which comprises hybridization between different technologies [118]. GTE can be applied directly in many applications. For instance, it could be used for heat pumps, Space heating and thermal Industrial processes. Also it can be used for drying crops and Greenhouses. For residential applications it could be used for space heating and cooling; Bathing and swimming and snow melting [119]. Heating and cooling of residential buildings has received more attention. New technologies have been developed to reach deeper layers to obtain higher thermal energy. Another direction towards utilizing lower temperature at smaller depth has been appeared to reduce heat losses and contaminated substances passes to the system [120]. Applying GTE to produce hydrogen is a promising field of research. Producing hydrogen based on geothermal power plant has been investigated considering thermodynamic analysis, techno-economic analysis and environmental effects [121]. Different geothermal power plants have been compared to select an efficient technology to produce hydrogen. Flash-steam combined cycle and binary cycle show better efficiency [122].

To obtain sufficient temperatures for large projects, more depth are required. Utilization of deep GTE required some advanced techniques such as hot dry rock (HDR), U-tube single-well, open loop single-well and closed loop single-well [123]. Enhanced geothermal power plant is a very common plant utilize the hot deep dry rock of temperature 120 °C to 220 °C to utilize GTE efficiently. The working principle comprises transferring the heat concentrated in hot dry rock to the injected water which converted into steam to generate electricity. The discharge fluid is injected again forming a circulating loop [124]. Strategies and Barriers for installing enhanced GTE plants has been introduced by the authors [125][126][127]. GTE not concentrated only inside soil, underground water, and deep hot rock but, hydrocarbon reservoirs also contains GTE [128]. As a result oil fields GTE has recently attracts many researchers [129][130][131][132][133].

According to the former collected data: GTE systems available data are still scarce and requires more research efforts; GTE is costly and dangerous; applications of GTE for electricity generation are concentrated in developed countries due to having special advanced technologies; Oil fields recently received a considerable attention as a source of GTE to produce electricity in oil field sites and the expected contribution of GTE in electricity generation could not exceed 3% by 2050. It would be better to concentrate on other RER systems.

4.1. Environmental Impact of Geothermal Energy

According to environmental effect, GTE is not a preferred energy source compared to other RE systems. But it is still an environment friendly source compared to conventional fossil fuels energy. GTE comprises different environmental impacts. There are surface and subsurface environmental effect, hydrological effect, geological effect, microbiological effect and air environmental effect.

4.2. Barriers Affecting Utilization of Geothermal Energy

Utilization of GTE is facing many obstacles as follows [134]:

- Geological risk such as seismicity; land drop, landslip related to fluid circulation and decreasing water level
- Noise resultant from drilling

- Underwater pollution
- High investment cost due to discovering, construction equipment and drilling cost and threating public health and safety.

5. Comparing between Environmental Impact for Different RER under Considerations

According to the preceding data, a comparison between environmental effect for wind, solar, biomass and geothermal RER could be held.

Solar and wind RER have the least environmental impact compared to biomass and geothermal RER. Geothermal RER has the worst environmental effect and surrounding by many risks and hazards. Biomass energy environmental impact depends on conversion methods. Most of these environmental effects could be treated in future if there is a true will.

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