

Review

Impacts of Renewable Energy Resources on Effectiveness of Grid-Integrated Systems: Succinct Review of Current Challenges and Potential Solution Strategies

Joseph Oyekale ^{1,2,*}, Mario Petrollese ¹ , Vittorio Tola ¹ and Giorgio Cau ^{1,*} 

¹ Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, 09123 Cagliari, Italy; petrollese@unica.it (M.P.); vittorio.tola@dimcm.unica.it (V.T.)

² Department of Mechanical Engineering, Federal University of Petroleum Resources Effurun, Delta State, Nigeria

* Correspondence: oyekale.oyetola@fupre.edu.ng (J.O.); gcrau@unica.it (G.C.)

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Abstract: This study is aimed at a succinct review of practical impacts of grid integration of renewable energy systems on effectiveness of power networks, as well as often employed state-of-the-art solution strategies. The renewable energy resources focused on include solar energy, wind energy, biomass energy and geothermal energy, as well as renewable hydrogen/fuel cells, which, although not classified purely as renewable resources, are a famous energy carrier vital for future energy sustainability. Although several world energy outlooks have suggested that the renewable resources available worldwide are sufficient to satisfy global energy needs in multiples of thousands, the different challenges often associated with practical exploitation have made this assertion an illusion to date. Thus, more research efforts are required to synthesize the nature of these challenges as well as viable solution strategies, hence, the need for this review study. First, brief overviews are provided for each of the studied renewable energy sources. Next, challenges and solution strategies associated with each of them at generation phase are discussed, with reference to power grid integration. Thereafter, challenges and common solution strategies at the grid/electrical interface are discussed for each of the renewable resources. Finally, expert opinions are provided, comprising a number of aphorisms deducible from the review study, which reveal knowledge gaps in the field and potential roadmap for future research. In particular, these opinions include the essential roles that renewable hydrogen will play in future energy systems; the need for multi-sectoral coupling, specifically by promoting electric vehicle usage and integration with renewable-based power grids; the need for cheaper energy storage devices, attainable possibly by using abandoned electric vehicle batteries for electrical storage, and by further development of advanced thermal energy storage systems (overviews of state-of-the-art thermal and electrochemical energy storage are also provided); amongst others.

Keywords: concentrated solar power (CSP); photovoltaic (PV); biomass and geothermal energy; wind energy; renewable hydrogen and fuel cells; electrochemical energy storage; thermal energy storage; renewable power grid technical challenges; renewable energy vehicle-to-grid; artificial intelligence for renewable energy

1. Introduction

Global demand for energy is on the rise year by year, obviously in response to the increasing population of the world, and this trend is likely to subsist for quite a while [1]. The World Energy Outlook of the International Energy Agency (IEA) [1] reports also that about 80% of global energy generation is

still based on fossil fuels, notwithstanding the huge efforts and resources being committed to renewable energy research. However, the unsustainability of fossil-based energy plants is acknowledged widely and cannot possibly be over-emphasized. For one, emissions from these systems pose serious threats to continued sustenance of man, due to rapid degradation of health and the environment, consequences of which we already live with today. Furthermore, fossil-based energy resources are expected to become depleted someday, no matter how long, inasmuch as they are continuously exploited without any possibility for replenishment. Thus, the search for alternative and clean sources of energy should remain a critical area of research, as conspicuously captured by number 7 of the United Nation's sustainable development goals (SDGs) 2030.

As hinted above, a lot is currently being done to facilitate the development and practical deployment of renewable energy systems, albeit with limited growth in real applications due to myriads of on-field difficulties [2]. Most of the challenges hindering high penetration of renewable energy resources into modern energy systems often have their roots in the transient nature of the majority of these resources. Based on this, it is common for renewable energy systems to be characterized by low dispatchability/reliability, low conversion efficiency and high costs of operation at generation level [3]. Similarly, the transient nature of most renewable resources often leads to low power quality during integration into the electrical grid, in addition to instability of voltage and frequency, and high power losses, amongst several others [3,4]. In essence, efforts should be more intensified toward seeking and mitigating all the attendant issues that affect high penetration of renewable energy resources if the growing demand for energy can continually be satisfied in a sustainable manner.

This paper is aimed at a succinct review of the common challenges that limit the effectiveness of renewable energy systems integrated with electrical grids, as well as often employed viable state-of-the-art solution strategies. The renewable resources in focus in this paper are solar energy, wind energy, biomass energy, geothermal energy, as well as renewable hydrogen/fuel cells, which, despite not existing purely in nature as distinct renewable resources, possess strong features as an energy carrier and are thus vital to future energy sustainability. Suffice it to mention also that, although hydropower, ocean currents, tidal power and wave power (marine energy) are suitable renewable energy resources [5], they are excluded from the discussions in this paper for the sake of brevity and to avoid rowdy clustering of useful scientific information. After giving brief overviews of the different renewable energy resources in focus, the grid integration challenges and potential solution strategies are discussed in turn for each of the resources, first at the power generation stage and then during power grid integration. Following that, an expert opinion is provided, which captures some aphorisms deducible from the review study on where current research activities should be focused in order to facilitate practical and stable integration of the studied renewable energy resources with electricity networks. As a contribution to the body of knowledge, this paper provides lucid information for renewable energy researchers and practitioners on steps being taken to mitigate the different challenges often encountered in practice towards integration of renewable energy sources. Additionally, it provides a roadmap and guide on specific research topics requiring attention in this research field, all of which would ultimately contribute to increased penetration of the renewables into the modern energy systems towards the achievement of the relevant SDGs.

2. General Overview of Renewable Energy Resources of Main Interest

Renewable energy sources encompass all self-existing natural resources with one form or the other of infinitely exploitable energy contents. Generally, solar energy, wind energy, biomass energy, geothermal energy, hydropower and marine (wave and tidal) energy fall within this category. It is opined that renewable energy resources, if properly exploited, are capable of satisfying all of the global energy needs, even surpassing them in a multiple of about 3000 [6]. Although applications are growing for use of renewable resources in global energy infrastructure, a lot is left to be done to attain a world powered exclusively by renewable energy systems.

While some of the resources, such as wind and solar, rely strongly on climatic and weather conditions, others correlate strongly with geological formations of the earth's crust and aridity of lands. Solar, wind and other weather-dependent energy resources are highly intermittent in availability, although they could be exploited almost everywhere globally at varying intensity. Conversely, although biomass, geothermal and most other renewable resources that depend on nature of the earth's surface could be stable for better exploitation, they are often not universally accessible. These characteristics often pose different natures of challenges on optimal exploitation of renewable energy resources, and each resource type should be examined based on its peculiarities. This review study focuses on solar, wind, biomass and geothermal resources, as well as renewable hydrogen, which is a secondary energy carrier vital for future energy sustainability. Prior to the intended discussions on the impacts of these renewable resources on power generation and integration into distribution and transmission power grids, a brief overview is given on each of them, as highlighted hereunder.

2.1. Solar Energy

Solar energy is one renewable resource that attracts keen attention around the world today, perhaps due to its free and universal accessibility [7]. Solar irradiation could currently be exploited for power generation using either photovoltaic (PV) or concentrated solar power (CSP) technologies [8–10]. While CSP converts energy of the sun first to thermal energy by collectors and then to electrical energy by turbo-generator, PV systems are capable of converting solar light directly to electricity [11]. With regard to generation for power grid integration, CSP is an indirect technology that produces alternating current (AC) which could be applied directly [12], while PV is a simpler technology which produces direct current (DC) that must be transformed into AC by interfacial devices such as inverters [11,13]. This makes PV systems quite scalable and affordable, making them a more embraced and popular solar technology for real life applications [14]. PV plants can range from micro scale in few kilowatts [15] to mega scale in several megawatts [16], with an average thermal conversion efficiency typically of around 18% [17]. However, CSP technology is considered equally important for the generation of thermal power for use in different applications, which includes conversion to electrical power using different power cycles [18]. CSP systems are also small-to-large scale in size, ranging from hundreds of kilowatts to several megawatts, although few micro-scale plants in tens of kilowatts also exist [12]. The average solar conversion efficiency of most CSP plants is usually around 20% [8]. Thus, both PV and CSP plants are astounding solar technologies. They should play substantial roles in increasing renewable energy penetration into the future energy mix, and they are both succinctly captured in this review study.

2.1.1. Solar Photovoltaic

Solar photovoltaic systems make use of arrays of semiconductors, technically known as solar cells, to convert to electrical power the photonic effects of solar radiation. In addition to solar cells, which are assembled in small modules up to the desired size, PV systems also consist of other ancillary devices, often called balance of systems (BoS) components, which perform a range of complementary functions essential to the value chain of continuous power production and usage. Some of the auxiliary functions of PV BoS devices include mechanical assemblage and connections of solar cells into panels, chemical protection of the cells, auxiliary power generation, power inversion, electrochemical storage of electrical power as well as charge monitoring and control, etc. [13].

The science of solar cells is multidisciplinary, and there are currently extensive, diverse and progressive research activities aimed at the development of modular solar cells and PV systems in general. The different forms of solar cells include crystalline silicon (c-Si) cells; thin-film silicon cells, such as amorphous silicon (a-Si) cells, copper indium gallium di-selenide Cu(InGa)Se₂ cells, cadmium telluride (CdTe) cells as well as single-junction gallium arsenide (GaAs) cells; and high-efficiency III-V multi-junction cells and dye-sensitized or organic-based cells [11]. Shubbak [13] reported attempts by researchers to categorize these solar cells into groups based on time of development and degree

of market penetration. The c-Si are the earliest and by far the most established ones with market penetration of over 90%, generally referred to as first generation (1G) solar cells. The more recent thin-film silicon cells constitute the second generation (2G) solar cells, sharing most of the remaining market in PV systems, while the most recent and emerging multi-junction solar cells and organic-based ones constitute the third generation (3G). A lucid representation of PV system overview is shown in Figure 1.

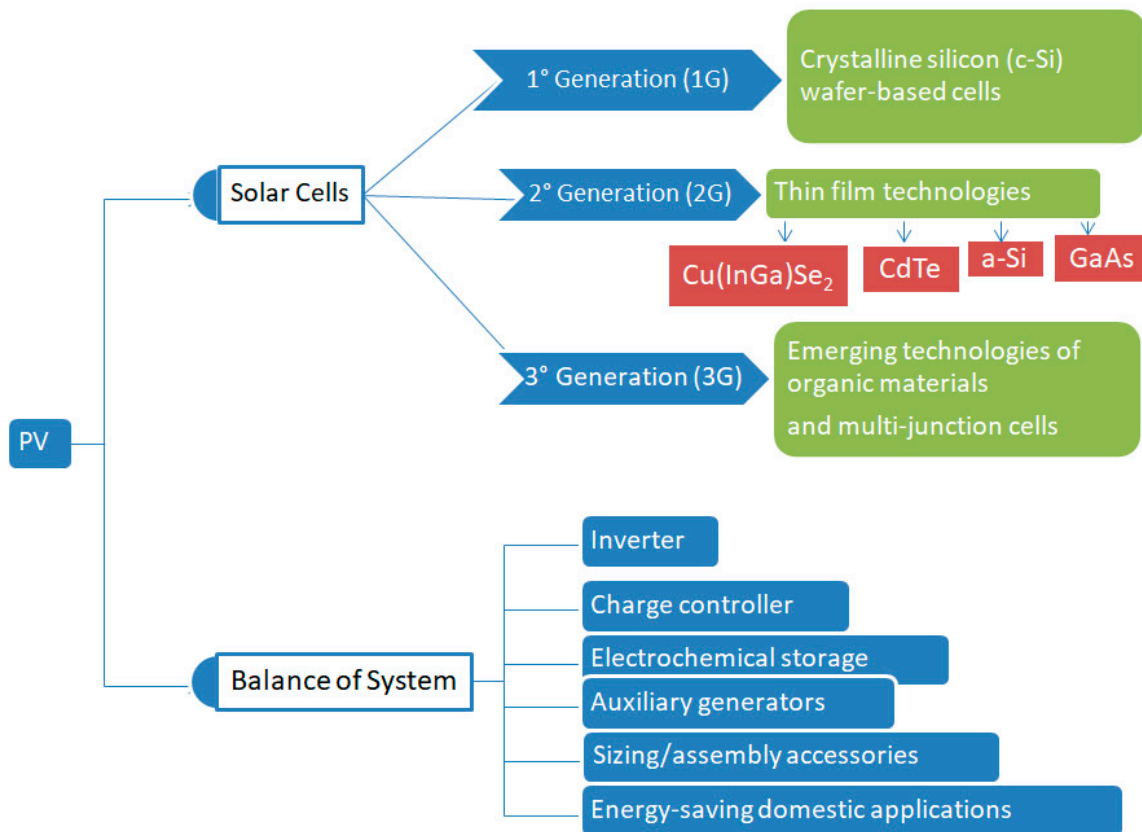


Figure 1. Photovoltaic (PV) system overview.

In order to improve economic performance of traditional PV systems where solar cells are mounted on stationary panels with large cross sectional areas of multiple cells, solar concentration and tracking mechanisms have been proposed for integration into modern PV set up. This entails the use of trackers to always position optical devices (mirrors and lenses) in the trajectory of solar radiation so as to focus sunlight on cells with smaller cross sectional area, known as concentrated photovoltaic (CPV) systems [19]. CPV systems are classified on the basis of types of optics and the adopted tracking mechanism, similar to what is obtained in the CSP systems, as elucidated in the following section. Furthermore, CPV systems are nowadays being modified to also exploit solar thermal energy in the form of hybrid CPV-thermal systems [20,21], which could be enhanced further by waste heat recovery processes [22].

Suffice it to mention here that solar PV technology is about the biggest driver of renewable energy exploitation for practical applications, with about 100 GW capacity installed globally in 2018, amounting to about 55% of new renewable energy capacity [23]. This could be attributed to advancement in technologies of PV cells and BoS, which consequently reduces costs of investment. The installed capacities of PV plants are illustrated in Figure 2 for selected countries and regions. Furthermore, large-scale PV projects now compete favorably with conventional technologies for cost-effective electricity production, especially in Chile, Mexico, Peru and UAE where new records were set in 2016 and 2017 for low-cost solar power purchase agreements [24]. Specifically, 2019 PV economic data

provided by IRENA [25] revealed that production costs are falling significantly in many countries, with the lowest levelized cost of electricity (LCOE) of about 0.04 USD/kWh obtained in India and the highest of about 0.14 USD/kWh reported in Japan. Additionally, LCOE values below 0.07 USD/kWh were reported in China, Spain and Italy.

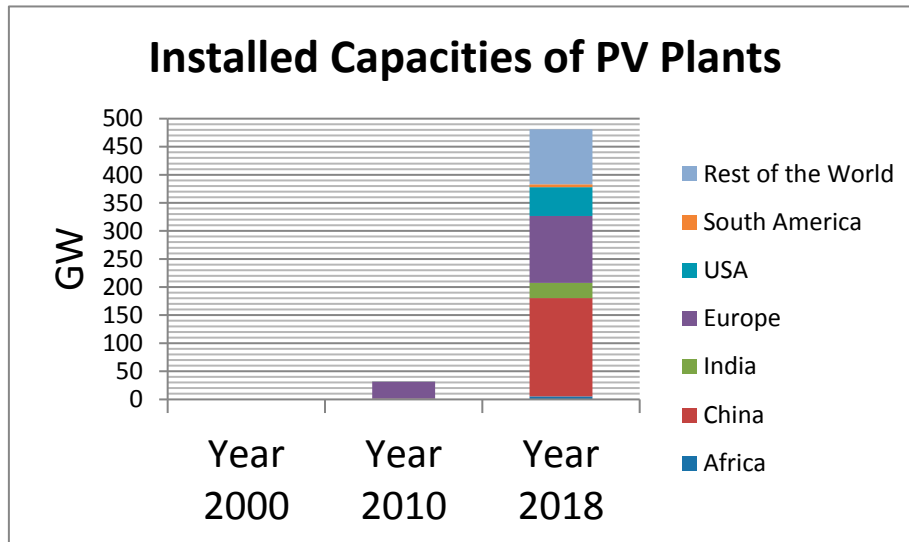


Figure 2. Installed PV capacities for selected countries and regions [26].

2.1.2. Concentrated Solar Power

Concentrated solar power systems produce thermal power primarily by focusing energy contents of the sun to collecting devices [27]. Specifically, collectors are positioned using some forms of tracking mechanisms, for direct impingement of solar rays on their external surfaces. Then, the solar rays are directed onto a receiver, which encompasses the absorber where solar energy is converted to useful thermal energy, as well as the pipe network, which transports the produced thermal energy through a heat transfer fluid (HTF) [28]. Next, the HTF flows either through a heat engine for production of electrical power from the exploited solar heat, or through a thermal energy storage (TES) system where the thermal energy is accumulated for deferred usage [29]. The different components of a typical CSP system are illustrated in Figure 3.

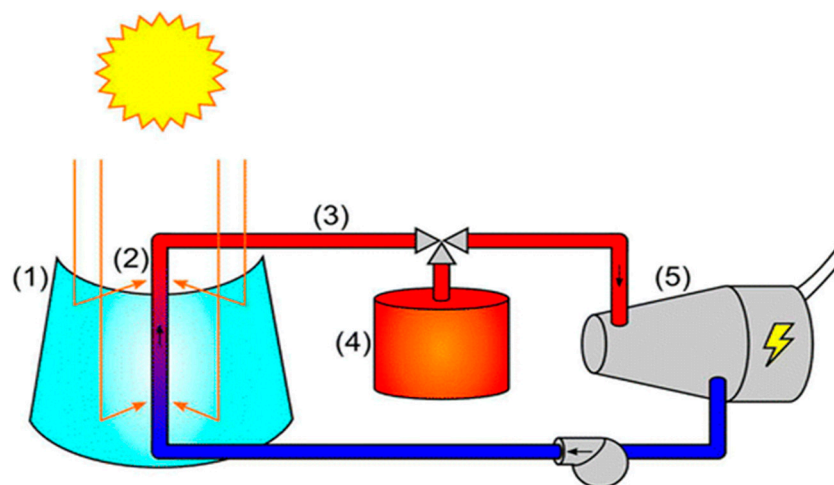


Figure 3. Basic components of a conventional concentrated solar power (CSP) system: (1) concentrator, (2) receiver, (3) heat transfer fluid (HTF), (4) thermal energy storage (TES), and (5) heat engine. Reproduced with permission from [29]. Copyright 2015 American Chemical Society.

In some instances, TES and perhaps HTF are excluded, for instance, in CSP systems where the absorber is integrated with the application device for immediate use of the exploited thermal energy. In essence, actual composition of the CSP system is case specific, depending on the intended application.

Concentrated solar technologies are often classified on the bases of the type of tracking mechanism adopted and the nature of collecting surface. Regarding the classification based on tracking mechanisms, some collectors are positioned to follow the sun's movement only on its main axis as it rotates from east to west, usually called one-axis tracking [30]. On the other hand, some other solar collectors are positioned to follow the solar movement both from east–west and north–south axes, usually referred to as two-axis tracking. The collectors adopting one-axis tracking impinge solar rays on a line, and are therefore also known as line-focus collectors. Linear Fresnel reflectors (LFR) and parabolic trough collectors (PTC) are the main solar collector technologies in this category [31]. Conversely, collectors adopting two-axis tracking mechanism impinge solar irradiation on a point, and are therefore also referred to as point-focus solar collectors. The main solar technologies in this category are the heliostatic field (often interchanged with the central solar receiver as well as the solar tower) and parabolic dish reflectors (PDR). The point-focus collectors are advantageous in that they are able to achieve higher concentration ratios relative to the line-focus collectors. However, they are equally characterized by certain disadvantages, particularly regarding the complicated technical specifications required to achieve two-axis solar tracking, which also often result in much higher costs when compared with line-focus collectors [32].

Regarding the nature of collecting surface which is the second basis of classifying CSP systems, systems exist with continuous collector surfaces, in which case the collectors are fixed to form a single unit with receiver, and they therefore move together to track solar irradiation [33]. This arrangement obliges the system the merit of very high concentration ratios, as well as a relatively simple solar tracking mechanism. The main CSP technologies in this category are PTC and PDR. On the other hand, in this respect, other systems have discrete facets collector surfaces—in which case, the receiver is stationary and is markedly dissociated from the mirrors. The advantage of this arrangement is that the collectors are less affected by wind thrust since they can be installed closer to the ground, and they can be easily accessible for maintenance. However, solar collectors based on discrete facets surfaces are often associated with low concentration ratios [34]. Main CSP technologies in this category are the heliostatic field and LFR. Based on the foregoing, it is clear that the main types of solar collectors in use are PTC, LFR, PDR and the heliostatic field. Figure 4 summarizes the aforementioned classifications of CSP technologies.

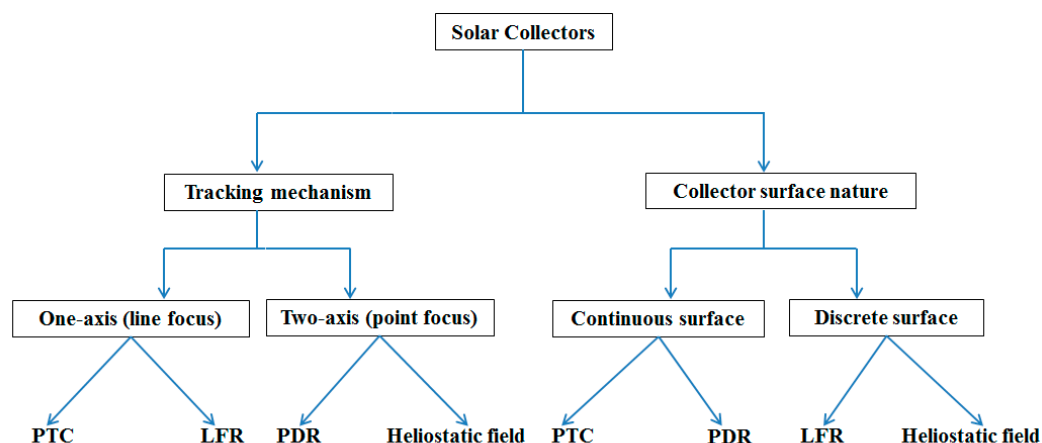


Figure 4. Classification of CSP technologies.

The most matured CSP technology is by far the PTC [35]. This can be demonstrated by the very high number of CSP projects around the world that adopt PTC today when compared to other collector types. As of August 2019, around 100 of global CSP projects make use of PTC technology; around 37 make use of heliostatic field (Solar Tower); about 15 make use of LFR; and only about 2 adopt PDR [36]. Although CSP production costs are generally high at the moment, standing between 0.15 and 0.3 USD/kWh, it is opined that the costs will continue to fall in response to ongoing developmental efforts, and the solar tower can attain LCOE of 0.09 USD/kWh by 2025 [24]. The installed capacities of CSP plants are illustrated in Figure 5 for selected countries and regions.

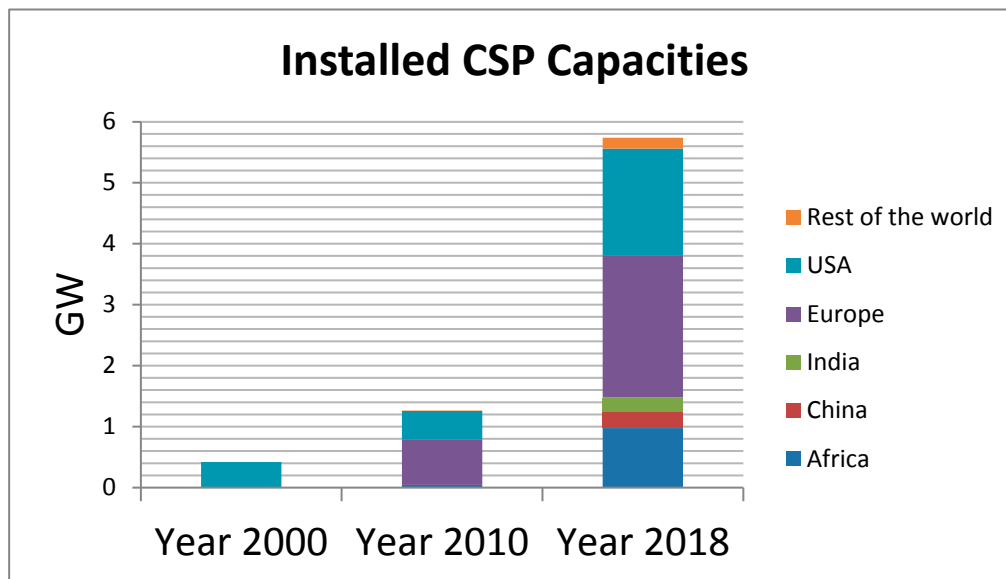


Figure 5. Installed CSP capacities for selected countries and regions [26].

Currently, researchers work assiduously to investigate new collector configurations that could improve solar collection/absorption capabilities [37]. Furthermore, a significant amount of effort is being directed at investigating viable ways of cleaning/removing dirt and film formations often deposited on collector surfaces in order to minimize efficiency losses [38], amongst others. It is a general opinion in the literature that research efforts need be intensified towards cost reduction of small-scale CSP systems [8,39]. In this case, researchers have hinted that use of water as HTF in solar collectors could be particularly viable, known technically as direct steam generation (DSG) [8]. In addition, integrated solar combined cycle systems are being investigated, where it is possible to use carbon dioxide as a heat transfer fluid in place of expensive thermal oils [40].

2.2. Wind Energy

Wind energy entails conversion of the kinetic energy of air motion into a useful form of energy, such as electricity, through a mechanical device known as wind turbine [41]. In a wind turbine, the force of wind impinges on suitably shaped blades radiating from a shaft, which encompasses an electricity generating device known as a wind turbine generator. Wind turbines can be classified according to the axis of rotation, or according to location of installation [42].

Turbines can rotate around a horizontal axis (horizontal axis wind turbines, HAWT), or on a vertical axis (vertical axis wind turbines, VAWT) [43]. HAWTs have their main rotor shaft and electric generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed to the wind by using a simple wind vane, while large ones generally use a wind sensor coupled with a servo motor. Most HAWTs have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electric generator [44]. The first generations of HAWT types were windmills introduced in the 12th century, but they have been displaced by modern multi-bladed

wind turbines. Conversely, VAWT types can more effectively exploit wind energy from any direction, and do not necessarily have to be pointed in the direction of the wind. The generator and gearbox can be placed near the ground, so the turbine tower does not need to support it, and a VAWT is thus more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may also be created when the blade rotates into the wind [45]. The main types of VAWT include the Darrieus wind turbine (including the Giromill and 'H' vertical wind turbine) and the Savonius wind turbine. The most practical wind turbine installations are those of HAWT types when compared to VAWT types [44,45]. They range in sizes from small scale of about 1 kW in distributed systems to large scale of about 3.5 MW in offshore power generation. Typically, about 50% of the wind energy transited by the turbine rotor is successfully exploited [46].

Furthermore, on the basis of installation location, wind turbines are classified into onshore and offshore types. Onshore wind turbines are those situated on firm ground or on some city shores, while those located in open seas are called offshore wind turbines. Regardless of type, single or very few wind turbines can be installed to meet certain specific energy needs, or in clusters of multiple turbines often referred to as wind farms. The different classifications of wind turbines are illustrated in Figure 6.

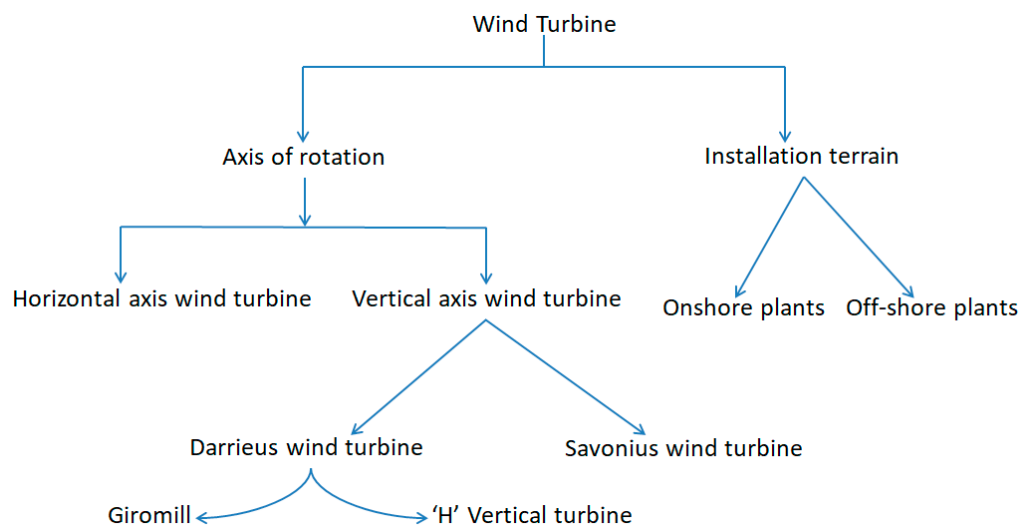


Figure 6. Wind turbine classifications.

Here too, suffice it to mention that wind power plants contribute substantially to the growth of energy generation from renewable sources, representing about 28% of new renewable energy capacity installed globally in the year 2018 [23]. Although wind energy plants are available in a few kilowatts [47], most practical systems usually range from hundreds of kilowatts to several megawatts [48]. The installed capacities of wind power plants are represented in Figure 7 for a selected parts of the world, showing a drastic increase in wind energy penetration into the global energy mix. Economically, wind power plants are improving steadily in competitive electricity generation even in the absence of financial incentives. In 2016, new onshore wind power plants recorded average LCOE in the range of 0.05–0.12 USD/kWh, while for offshore projects, slightly higher values were obtained between 0.10 and 0.21 USD/kWh [49].

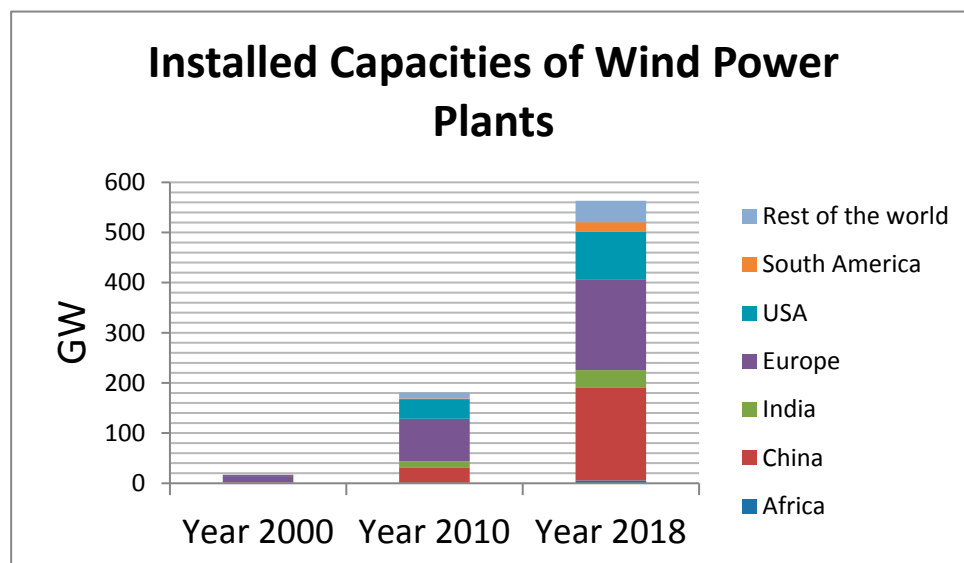


Figure 7. Installed capacities of wind power plants for selected world regions [26].

2.3. Biomass Energy

Biomass generally connotes organic resources produced from metabolic processes of animate and inanimate organisms [50]. Depending on origin, it is possible to classify them as forest biomass, agricultural biomass, and renewable wastes, which include municipal and industrial wastes [51]. Raw forest woods and residues are often classified under forest biomass, while agricultural biomass usually encompasses energy and rotation crops and their residues [52]. Depending on the source of generation, biomass resources can exist physically in solid, liquid or gaseous states. However, a widely acknowledged opinion holds that biomass resources exist most abundantly in solid state, and solid biomass are therefore the most commonly used ones [53].

Depending on targeted sector of application, industrial biomass products, energy biomass products and transportation biomass products are the major classes of products obtainable from different biomass processes. In the energy sector, heat is produced from processed biomass resources, which can be applied directly or further used in heat engine for production of electricity, either as a sole product or in form of combined heat and power (CHP). Vast numbers of small-scale biomass plants exist rated below 200 kW [54], while several others are much larger in tens of megawatts power ratings [55,56]. In addition, it is common to process biomass resources into fuels laden with chemical energy, including hydrogen, which could in turn be employed in myriads of applications in the energy sector. In the transportation sector, biomass resources are commonly processed into fuels in liquid and gaseous forms, which could be applied directly or indirectly to propel vehicular engines. The fuels produced from biomass resources are often referred to as biofuels [57]. Moreover, it is on record that state-of-the-art biomass resources are applicable in the production of fuels and raw materials required in certain industrial processes, among which are biochemical, bio-refining, charcoal and biomaterials [58,59]. Figure 8 represents the various sources and products obtainable from biomass.

Furthermore, based on the products intended from biomass conversion, the conversion processes are often classified into biochemical and thermochemical processes. In biochemical conversion, biomass resources undergo fermentation or digestion process to give the desired products [60]. Digestion could be aerobic if it takes place in the presence of oxygen, or anaerobic if it excludes oxygen [61]. Conversely, heat is produced directly from thermochemical biomass conversion technologies, just as the name suggests. The technologies could employ pyrolysis (encompassing liquefaction), combustion or gasification processes for biomass conversion [62]. Hydrothermal and hydrolysis processes have equally been highlighted in the literature [63,64], but these are downplayed here.

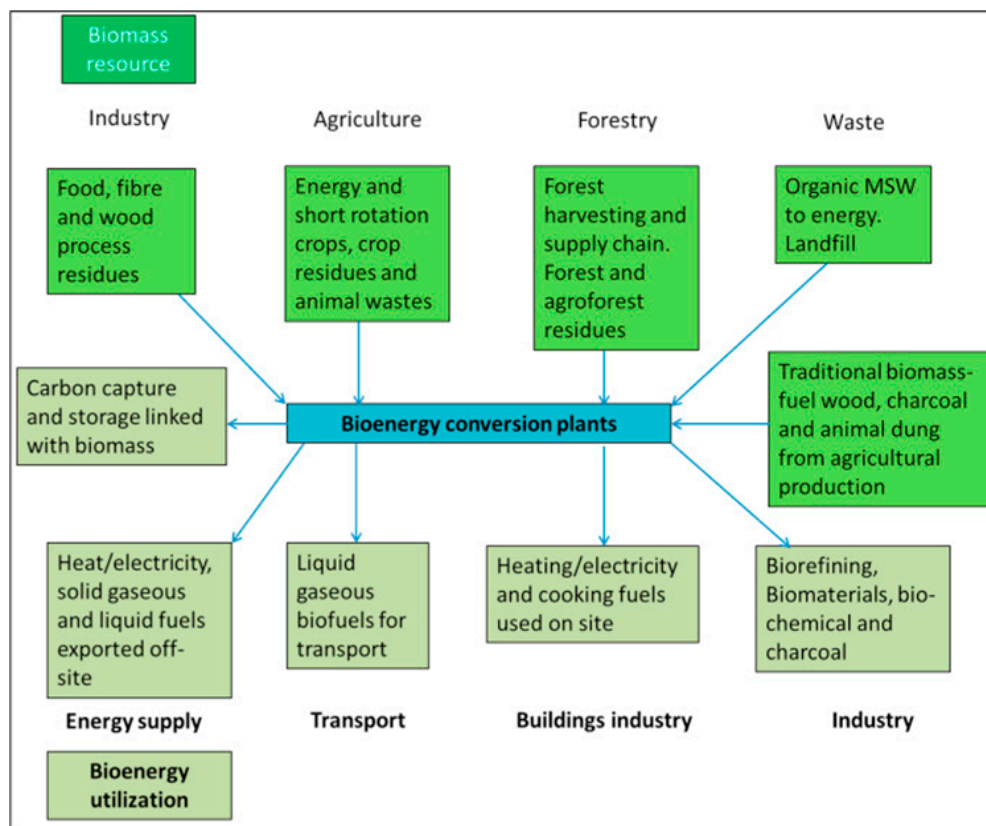


Figure 8. Overview of biomass resources and common products. Reprinted with permission from [65].

Hot combustion flue gases from the combustion process could be used directly for a desired purpose, known generally as direct combustion, or could be recovered and used in secondary heat exchange processes, for example, in steam production and generation of power, amongst others. Devices such as boilers, driers, kilns and ovens are generally applicable for biomass combustion process [66].

In the case of biomass gasification, a mixture of gases (known technically as syngas) is produced from solid biomass, which is made to change phase by the thermally driven conversion process [67]. The syngas is generally readily combustible, and it is typical to thus ignite it for production of useful heat, electricity or CHP [68]. In addition, it is possible to process the syngas obtained from biomass gasification process into fuels and chemicals, as it is obtained in bio-refineries [69]. Partial oxidation reaction or the external heat exchange process could be employed to supply heat required for the biomass gasification process [70]. Fixed and fluidized bed reactors are among the most popular technologies of biomass gasifiers, exemplified respectively by updraft/downdraft gasifiers and circulating/bubbling fluidized bed reactors [71]. Some other technologies are entrained and plasma gasifiers [71].

Next, it is possible to convert biomass simultaneously into liquid, gas and charcoal by decomposing it in the absence of oxygen. This conversion process is often referred to as pyrolysis [72]. The pyrolysis process could be influenced to favor one product over others. For instance, substantial liquid biofuels are produced, known as liquefaction process, when the fast heating rate process is employed during biomass pyrolysis, while substantial charcoal yields from the same process by employing an extremely slow heating rate process [73]. Figure 9 also captures common conversion technologies of solid biomass. Efficiencies of biomass power generation devices vary significantly by size, and for small-scale biomass power plants in the range of 1–3 kW, an average thermal efficiency of 10–12% is typical [74]. The installed capacities of bioenergy power plants are represented in Figure 10 for selected countries and regions. Depending on type of biomass fuel and location, the levelized cost of electricity (LCOE) can range typically from 0.03 to 0.14 USD/kWh, and can sometimes reach as high as 0.25 USD/kWh [75].

The weighted average stands at about 0.03 USD/kWh in India, 0.05 USD/kWh in China and about 0.085 USD/kWh in Europe and North America over the last decade [75].

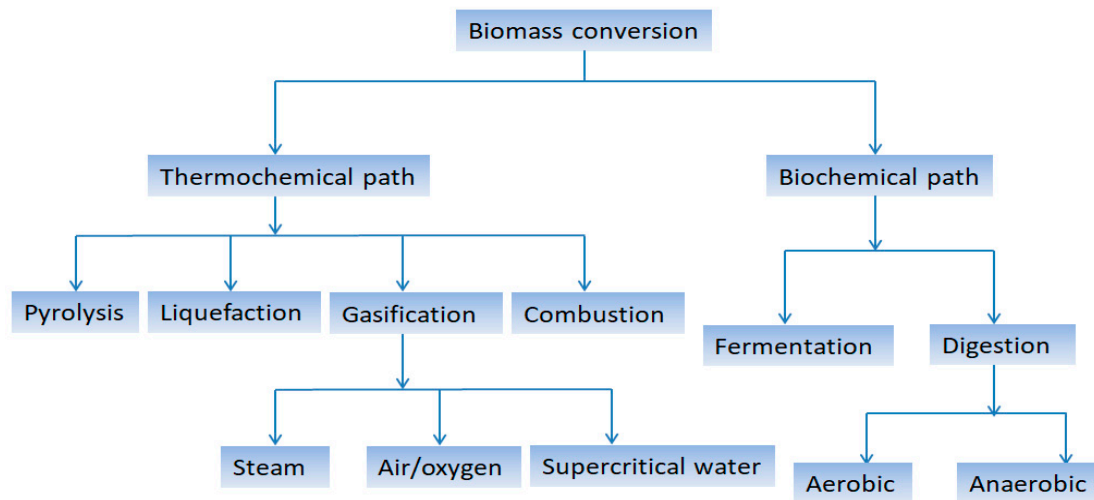


Figure 9. Overview of common biomass conversion processes. Adapted with permission from [65].

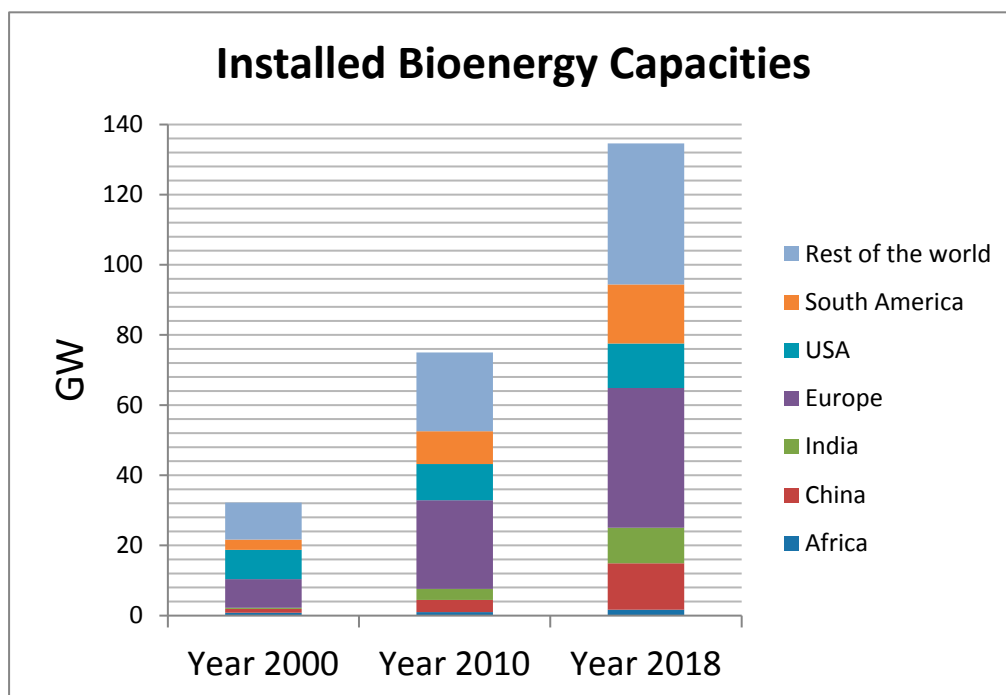


Figure 10. Installed capacities of bioenergy power plants for selected world regions [26].

Overall, current research efforts focus on improvement of techno-environmental as well as social performance indices of biomass plants, seeking specifically to enhance available conversion technologies [62]. Additionally, several studies are targeted at investigating the sustainability and suitability of different biomass resources for dedicated industrial applications. This is especially true in industries requiring high-temperature processes, for instance in steel and cement industries, etc. [63]. These efforts, if intensified, could promote areas of applications of biomass resources, with attendant reduction in use of fossil fuels, if not complete elimination.

2.4. Geothermal Energy

The term “geothermal energy” is rooted in two Greek words: geo translating to earth, and “thermal” meaning heat; thus, geothermal energy can be defined as heat form of energy produced from the earth [76]. In more detail, the geothermal reservoir, an aquifer of water with high thermal energy content, is formed from water flowing into the crust through deep faults, and is based primarily on the heat generated and stored in the mantle and core of the earth [77]. Given that the flow of heat from the depth is a natural and continuous process, geothermal resources are hardly depleted, and they are thus considered as renewable energy sources.

Geothermal energy is usually classified based on temperature range of the reservoir fluid, as well as utilization strategy. On temperature range classification basis, there are high-enthalpy geothermal energy resources (1500–2800 kJ/kg), medium-enthalpy resources (1100–1500 kJ/kg) and low-enthalpy resources (950–1100 kJ/kg) [78,79]. Regarding utilization strategies, geothermal energy is often classified into direct and indirect systems, respectively for heat and electricity generation applications [80]. Direct use of geothermal energy entails exploitation of the thermal contents of reservoir hot water in various household and industrial applications, such as agriculture crop drying, aquaculture pond and raceway heating, bathing and swimming, snow melting, as well as space heating and cooling, including district heating, with or without integration of heat pumps, amongst others [81]. In indirect applications, which is of main interest in this paper, geothermal energy is employed in a secondary thermodynamic process for electricity generation. Typically, geothermal resources with temperature higher than 150 °C are considered suitable for power generation applications. However, it is opined that the use of organic Rankine cycles in geothermal systems can allow for exploitation at lower temperature values [82].

The grid-connected geothermal power system was first built in 1914 at Larderello, Italy, about a decade after Prince P.G. Conti set up at the same location a device able to generate electricity from geothermal heat. The power system made use of a turbo alternator to generate about 250 kW of power [76,83]. In modern day, power generation from geothermal resources are based on three technologies: dry steam power plants, where high-temperature vapor from geothermal reservoir drives a turbo-generator for power production; flash steam power plants, where liquid-dominant geothermal fluid is first separated in flash vessels before vapor is channeled to drive the turbo-generator; and binary power plants, where low-temperature geothermal water is used to evaporate a different working fluid in a closed thermodynamic cycle, prior to expansion of the working fluid in turbo-generator [83]. Data from a worldwide review of global geothermal plants reported average efficiency of about 12%, with size ranging generally from hundreds of kilowatts to several megawatts [84]. Figure 11 illustrates the basic classifications of geothermal energy systems.

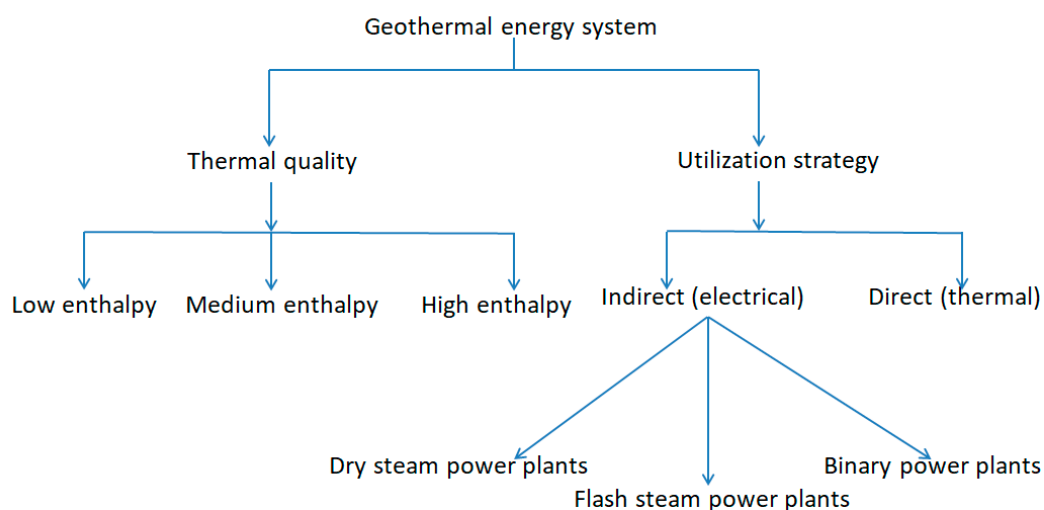


Figure 11. Classification of geothermal energy systems.

Furthermore, geothermal energy is being considered in hybridization with other intermittent renewable resources, such as solar energy, and this has been purported to be a viable way of improving performance [85]. The installed capacities of geothermal power plants are represented in Figure 12 for selected countries and regions. Depending on whether the geothermal project is from a virgin field or based on secondary field development, LCOE can range from 0.04 to 0.14 USD/kWh [86].

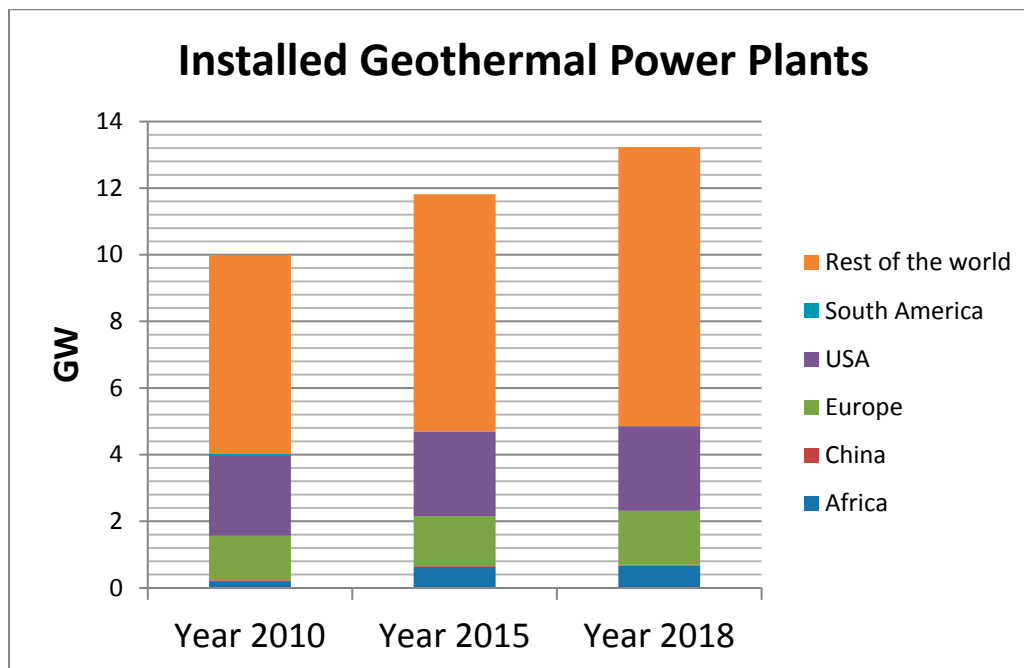


Figure 12. Installed capacities of geothermal power plants for selected world regions [26].

In sum, Table 1 highlights the global electricity generation from different renewable energy resources, including projections up to the year 2040 based on stated policies committed to be put in place by different stakeholders.

Table 1. Global renewable energy consumption for electricity generation [1].

Generation by Resource Type	2000	2018	2030	2040
Hydro	2613	4203	5255	6098
Bioenergy	164	636	1085	1459
Wind	31	1265	3317	5226
Solar PV	1	592	2562	4705
Geothermal	52	90	182	316
CSP	1	12	67	196
Marine	1	1	10	49
Renewable electricity generation (TWh)	2863	6799	12,479	18,049
Share of total electricity generation	19%	26%	37%	44%

2.5. Renewable Hydrogen and Fuel Cell

Hydrogen is the most frequently occurring element in the universe, appearing on earth bounded to other elements, as it appears in water, hydrocarbons, etc. Although it has found applications for decades in chemical and petrochemical industries, its exploitation as a viable energy carrier is more recent, and extensive research as well as practical demonstrations are ongoing globally [87]. Applications of hydrogen in the energy industry are diverse and varied, but they can be classified into three main categories. First, hydrogen could be employed as sustainable electricity storage medium in systems based on other transient renewable resources, based on its amenability to power-to-X-to-power

conversion processes, X being gas, liquid or solid [88,89]. Second, hydrogen could undergo clean and direct conversion processes to produce power, heat or electricity [87,90,91]. Third, hydrogen could be employed alongside fuel cells in power units to complement storage and direct power production applications [92–94]. These are the main motivations for including hydrogen in this study, coupled with its future potentials to compete favorably well with natural gas as a final source of energy for different applications. In fact, the supposed world's first industrial-scale integrated power-to-X-to-power hydrogen gas turbine demonstrator is currently being developed under the HyflexPower project, a consortium made up of Engie Solutions (Paris, France), Siemens Gas and Power GmbH & Co. KG (Munich, Germany), Centrax Ltd. (Abbot, England), Arttic, German Aerospace Center (DLR; Cologne, Germany) and four European universities [95].

As aforementioned, water and hydrocarbons, such as fossil fuels and biomass, are the main sources of hydrogen. It is reported that hydrogen production from hydrocarbon by steam reforming process is by far the most matured process at the moment, with fossil fuels being the most exploited sources with market share of about 96–98% of total production as at 2017 [87,96,97]. However, enormous research efforts are underway aimed at promoting the use of biomass and other renewable sources in place of fossil fuels, which is the focus here [98,99]. Similarly, partial oxidation is being researched and promoted as a viable process of producing hydrogen from hydrocarbons, as well as production from electrolysis, thermochemical and photo-catalytic processes [100,101]. These renewable hydrogen production sources and processes are summarized in Figure 13.

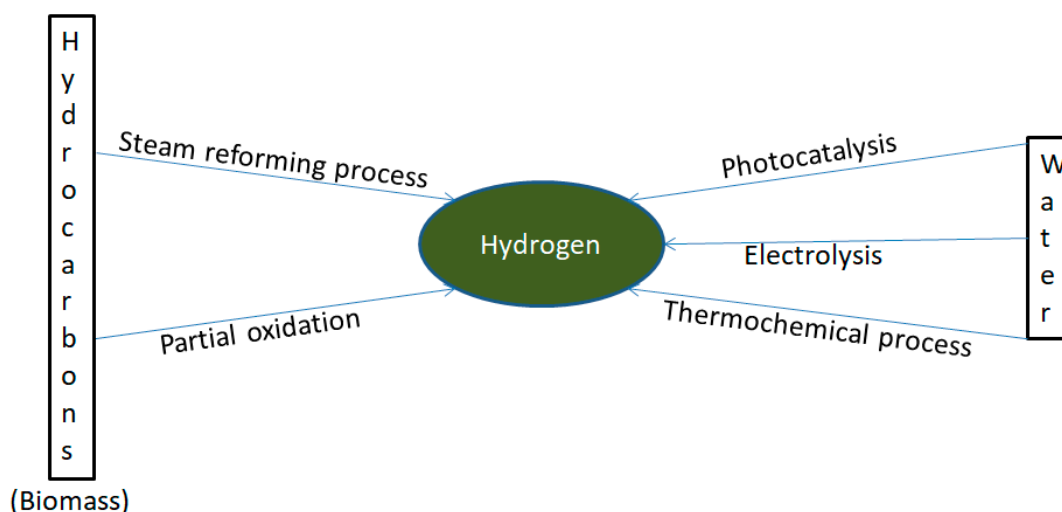


Figure 13. Sources of renewable hydrogen and production processes.

Fuel cells are generally regarded as compact energy conversion systems used for production of electricity and heat from chemical energy. A cell consists of an anode and a cathode on either side, separated by an ion-conducting and electron-blocking device known as an electrolyte. Although a good number of fuels would suffice for use in fuel cells, those allowing for application of hydrogen are highly desirable, owing to the high efficiency that they provide the system with [87]. Fuel cells are often classified based on the electrolytes adopted and range of temperature required. The most prominent types include the proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC) and molten carbonate fuel cell (MCFC), all using different kinds of electrolytes. Amongst these fuel cell types, PEMFC and AFC require relatively low temperatures (typically below 100 °C) for their electrolytes to conduct ions, while PAFC, MCFC and SOFC operate with 205 °C, 650 °C and in the range 600–1000 °C, respectively [87,102,103]. The classification basis and types of fuel cells are succinctly illustrated in Figure 14. A similar classification suffices even for electrolyzers.

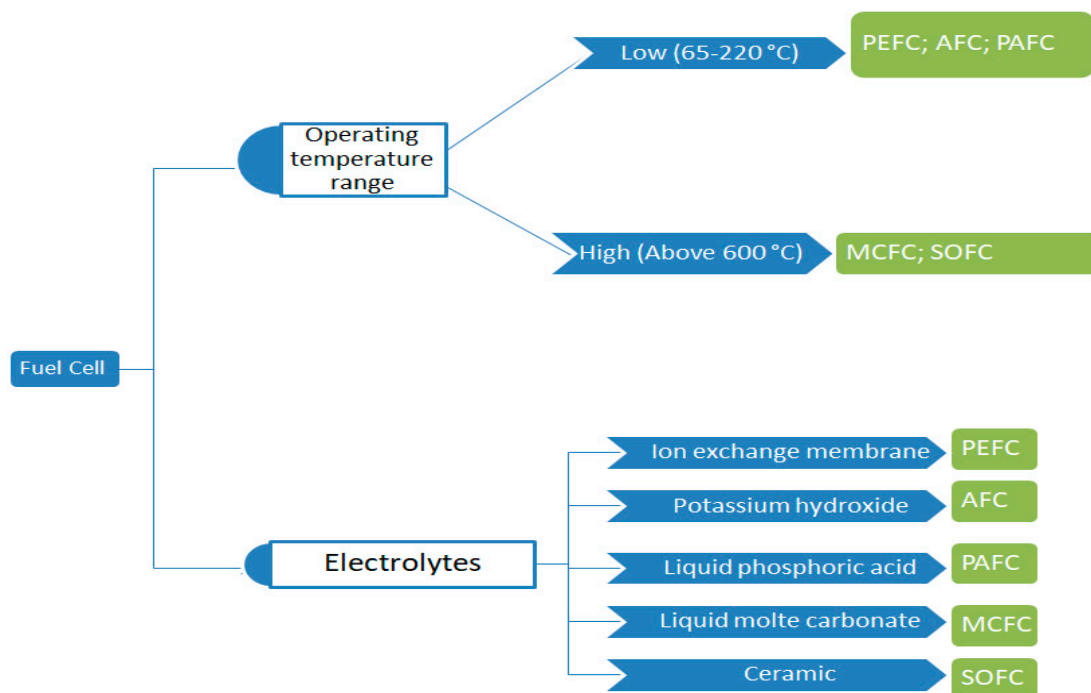


Figure 14. Classifications of fuel cells.

Regarding the economics of hydrogen-based power generation systems, a recent study by Hydrogen Council [104] suggests that hydrogen-based heavy duty turbines for grid-integrated power generation can assume LCOE value of about 0.14 USD/kWh, with an assumed hydrogen import cost of 3 USD/kg. For electricity generation using the hydrogen-based fuel cell, LCOE value of 0.433 EUR/kWh was reported for a 10 MW PEM electrolyzer type in 2013, with projection of dramatic reduction to about 0.056 EUR/kWh by the year 2030 [105].

3. Challenges at Power Generation Phase

The common effects of power generation from renewable resources on grid-integrated energy systems are discussed in this section. The renewable resources in focus are analyzed in turn, and viable strategies that have been applied in the literature to mitigate the respective peculiar challenges are succinctly highlighted.

3.1. Solar Energy

The current extensive interest in solar energy exploitation is generally due to the huge potential it portends, as with all clean and renewable energy sources, to amply reduce the impacts of carbon emissions resulting from fossil fuels combustions in conventional systems. Moreover, some studies have highlighted that integration of solar systems, especially based on PV, to power grids can portend economically feasible option in some cases, as exemplified in [106] for the case of grid integration of solar PV systems in Burkina Faso, replacing existing diesel generators. However, such integration is known generally to be associated with diverse challenges, especially due to the transient nature of solar irradiation, and this has led to myriad of studies for the discussion of these challenges in their diverse faces.

Solar energy availability correlates strongly with environmental conditions, which makes it extremely difficult to profile adequately the power generation and supply in tandem with user demand. Some impacts of ambient conditions, such as solar-irradiation and air temperatures, on stability of grid-integrated large-scale solar plants are reported in [107] for a Nordic system operating long term. As reiterated in this study, dispatchability of solar-based systems is quite low, making them somewhat

unreliable for practical applications. In particular, parameters such as azimuth and tilt angles have been found to play indispensable roles in dispatchability and stability of solar-based energy systems, with poor positioning leading always to an under-performing system. This challenge was the focus of the study presented by Laveyne et al. [108], with reference to a solar-based grid-integrated distributed power system for residential applications. Specifically, real irradiation data and parameters of an existing distribution grid were employed to investigate the effects of PV panels' inclinations and azimuth angles on power output and stability of a low-voltage residential distribution grid. Results showed that azimuth and tilt angles of PV panels influence greatly the total power output. For the Belgium data used in the study, the authors identified that southward orientations (azimuth of 0°) and tilt angle of about 34.5° optimize PV output, albeit at the expense of grid losses and those due to over-voltage power curtailment. Furthermore, the authors reported that PV orientation had negligibly insignificant effects on voltage unbalance factors. The intensity of impacts of tilt and azimuth angles on PV generation was equally reiterated by Awad et al. [109] in a study of the long-term performance of small-scale grid-tied solar PV systems for residential buildings in northern latitudes. In fact, they reported that these PV orientations are of more importance than the locations of PV installations with respect to steady and reliable system operations. The findings in these studies suggest that adequate multi-objective optimization tools should be integrated into the design of grid-integrated solar PV systems for the selection of orientation angles of PV panels in practical installations. Furthermore, fluctuating power output due to transient weather conditions often necessitates power balancing measures such as energy storage to ensure steady satisfaction of user energy demands.

Another obvious solution strategy lies with accurate forecast of environmental parameters, amongst other similar measures [110]. Thus, extensive studies are progressive aimed at developing accurate forecast models. For solar PV systems, Ahmed et al. [111] reviewed the recent forecast models being employed for improved grid integration. The authors reported that weather classification and cloud motion are important factors in models since PV production correlates strongly with solar irradiation. Moreover, following the discussion of other key factors that are essential for adequacy of forecast models, the authors concluded that hybridizing artificial neural networks and evolutionary algorithms is optimum. In addition, Theocharides et al. [112] sought to improve the accuracy of day-ahead solar forecast, which led to proposition of a comprehensive model that combined machine learning (ANN) and post-processing linear regression correction methods that could enhance performance. The authors applied the proposed models to PV systems in hot as well as cold semi-arid regions, and results showed high forecasting accuracy and stability. In a similar effort, Sun et al. [113] proposed a probabilistic approach for enhanced forecast of solar parameters that would positively impact overall performance of grid-integrated solar systems. The proposed method is based on a machine learning multi-model approach, where interplay between predicted and observed weather variables leads to the generation of a probabilistic power weather forecast scenario. Based on application to seven different solar farms from the 2000-bus synthetic grid system in Texas, the authors reported that the proposed forecast method could improve the pinball loss metric score by up to 140% compared to conventional forecast models, which are mostly based on the deterministic approach.

As a case in point of application of weather forecast studies to promote grid integration of solar systems, Pierro et al. [114] studied a real scenario of massive penetration of PV systems into the Italian energy sector, where they proposed two strategies to enhance power imbalance mitigations in power grids. The first strategy concerns improving forecast accuracy as well as enlarging the controlled grid, while the second deals with transformation of unconstrained PV plants into flexible ones that can be controlled remotely together with installed battery energy storage systems. The authors showed that the two strategies could provide an economically viable approach, and when combined in a single application, possess the propensity to completely eliminate imbalances in Italian transmission grids based on PV penetration, thereby raising the confidence and returns on investment of transmission system operators (TSO). Furthermore, the benefits in using accurate weather forecast data in home PV systems equipped with a battery bank and characterized by a certain share of deferrable loads were

proven by Petrollese et al. [115], with the aim of increasing the self-consumption ratio of the systems. Results demonstrated that by means of reliable weather forecast data together with the implementations of optimized energy management strategies, which take into account also the uncertainty of the forecast data, the achievable self-sufficiency rates of home PV systems can be maximized. In particular, the optimal allocation of deferrable loads as well as the optimal dispatch of the battery system can be obtained, with the subsequent minimization of the impact of the PV system in the grid in terms of balancing the surplus/deficit in power production relative to load demands.

Towards the optimization of costs associated with grid-integrated solar systems which is also often negatively impacted by varying weather conditions, Goransson et al. [116] proposed a multi-sectoral approach where transient renewables are utilized not only in electrical networks, but also for power generation in electricity-intensive industries such as the steel industry, the electrified transport sector (passenger electric vehicles) and residential heat supply. Using the case study of northern Europe, the authors reported that this approach could lead to an 8% reduction in total system costs, as well as up to a 20% reduction in the annual market price of electricity.

Similar to PV systems, a lot of effort is being made to facilitate grid integration of CSP plants. However, the aforementioned adverse effects of transient nature of solar irradiation and associated environmental parameters are much more pronounced in these systems, leading often to inefficient, unreliable and costly power generation systems. Two strategies are commonly deployed for mitigating these challenges at system level: hybridization with other renewable energy systems, such as biomass, and inclusion of thermal energy storage (TES) systems. Several theoretical and optimization studies have demonstrated the substantial thermo-economic improvements obtainable by hybridizing CSP systems with biomass [82,117–124]. Moreover, regarding TES inclusion in CSP systems, the current research space is quite wide, and a short review of current progress is thus provided below following that of electrochemical energy storage. The hybridization with a dispatchable source and/or the addition of TES system allows CSP plants to generate electricity during little or no solar irradiance, and to schedule production following the demand curve all-day long. The possibility of scheduling the electricity production (also called self-scheduling) encourages CSP plants to participate in electricity markets, where the aim of electricity producers is to maximize profits from the sale of energy. The optimal scheduling of CSP plant is usually expressed as a mixed-integer linear programming (MILP) problem. Forecasts of weather and electricity price must be considered, because in electricity markets, power plant owners have to offer a daily schedule ahead of time [125]. Consequently, different approaches were proposed in literature for dealing with this potential source of uncertainty. The adoption of a deterministic approach to maximize the profitability without considering any uncertainty was proposed in [126,127]. However, the accuracy of the Direct Normal Irradiation (DNI) forecasts limits the predictability of the actual solar field energy production. This could lead to overestimation of the potential day-ahead electricity production of the CSP plants, with a subsequent risk of being penalized when participating in day-ahead electricity markets for deviating from the committed generation schedule. For this reason, robust and stochastic approaches were proposed to deal with the uncertainty of CSP production and energy price forecasts in the CSP scheduling problem. Dominguez et al. [128] proposed a robust optimization for the CSP plant optimal offering curve, taking into account uncertainties in the solar energy availability and market prices by means of confidence intervals. A similar approach was applied by Pousinho et al. both for the optimal offering strategy of a hybrid CSP-fossil fuel plant [129] and for the day-ahead schedule harmonization between wind power plants and CSP plants [130]. In both cases, improvements of profits were demonstrated compared to the use of a deterministic approach. A stochastic approach centered on the generation of several scenarios based on the probability distribution function of the DNI error was proposed by Petrollese et al. [131] and compared with robust and deterministic optimization approaches. The results demonstrated that the convenience of using a stochastic approach instead of a robust one largely depends on the accuracy of the weather forecast service and on the distribution of the DNI errors. Another alternative approach was proposed by Vassallo et al. [132] where a generation rescheduling mechanism based

on a model-based predictive control (MPC) approach was proposed and studied. All the above-cited papers reveal the important role of CSP plants as semi-dispatchable power generation systems, since they are able to provide a reliable output of electricity taking advantage of their TES section, but using an intermittent source of energy. This peculiarity is fundamental for improving the RES penetration into the existing electrical grid and for reducing non-renewable power reserve.

3.2. Wind Energy

The main concerns of wind turbine systems at the generation level regard the transient nature of wind availability and speed, making it extremely challenging to always close the gaps between energy demand and availability for supply, and vice versa. This concern is often aggravated by instantaneous turbulence of air movement, making it all the more difficult for wind turbines to follow the dynamics of the system, thereby badly affecting system inertia. For instance, Jonaitis et al. [133] demonstrated based on a real experience in Lithuania that low inertia of wind power plants is usually associated with issues bothering on frequency stability, voltage stability, and power quality, amongst other measures of instabilities due to fast system dynamics. These impacts were equally amongst those highlighted in [134], where the authors reported several technical, socio-economic and environmental impacts of grid integration of wind energy. To mitigate these challenges at generation level, it is essential to always predict correctly the profile of wind availability and speed on wind farms, as this guarantees knowledge of quantitative energy producible from the system per time. On the other hand, accurate information is needed on the trend of energy demand from users. These two pieces of information would reveal the flow of energy deficit or surplus in the system towards the realization of technical steps necessary for smoothening output power. In addition to unbalanced supply and smoothening challenges, renewable plant investors/operators are most times required to transmit wind power over a long range of distance, resulting in high losses and weak grids. Thus, various techniques often adopted for mitigating these challenges in grid applications of wind energy plants are discussed in this section.

The art of sustainable operation of grid-integrated wind power plants is believed to have its roots at the pre-design stage, where suitable reliability studies are required for the identification of an adequate location for minimized transmission losses. In this respect, Hoseinzadeh and Blaabjerg [135] presented an approach to pre-identify the feasibility of specific wind power plant projects based on steady state analysis. The method uses basic grid characteristics often required by transmission system operators to identify the potential weak grid connections, maximum active power transferable to the grid as well as reactive power compensation that would ensure a stable and reliable system. The authors affirmed short circuit ratio (SCR) and reactive over reactance (XoR), respectively, as the first and second determinant factors affecting grid connection feasibility of wind power plants. In addition, adequate planning of wind integration into electrical network would ordinarily be required for sustainable and optimal energy production and supply to the demand side. This has made essential the development and application of planning models to grid-integrated wind power plants. In this regard, Zhang et al. [136] proposed a robust model for planning of grid-integrated wind energy conversion system, combining the operations of a wind farm, energy storage and a power transmission network. The proposed model reportedly took into account the imbalanced power, unit ramp capacity and incentive mechanism. Furthermore, optimal transmission switching (OTS) and unit commitment (UC) were incorporated to enhance performance by reducing transmission congestion and increasing wind energy utilization. Moreover, following the design of a linear tie-line model to bridge presumed limitations of the co-planning approach, a decentralized decomposition algorithm based on parallel analytical target cascading (ATC) was adapted for solving the proposed model. It was affirmed that the combination of OTS and UC in a single co-planning model as executed in the paper was the first of its kind, and its better performance over conventional models was demonstrated using a modified IEEE 48-bus test system.

With respect to the essentiality of accurate prediction of dynamic wind characteristics at wind farms, substantial efforts are in progress aimed at developing robust forecast models and methodologies [137].

Kosovic et al. [138] reported an enhanced wind power forecasting system based on a synergistic combination of numerical weather prediction and machine-learning methods. Better than what is obtained in most forecasting systems in practical applications, the enhanced system facilitates short-time forecasting for unit commitment and economic dispatch by blending a variational Doppler radar analysis system with an observation-based expert system; probabilistic forecasting to quantify uncertainties in wind speed prediction based on an analog ensemble approach; as well as prediction of extreme events like icing by the combination of numerical weather prediction with a fuzzy logic artificial intelligence system. The enhanced forecast system was reported to represent an improved approach to data quality control. In addition, Archer et al. [139] dedicated a study to the development of error forecast model which could be adapted to other real forecast models for easy grid integration of wind energy. The model data were used as obtained from a real 186 GW off-shore wind farm in the USA. The study was motivated by the impediments that forecast errors were imposing on grid integration of wind energy systems in the US, which was illustrated further by detailed simulation of electricity market operations in the second part [140].

Furthermore, the solution strategy being deployed for improved energy management lies with optimum control of practical wind power plants, and a considerable number of studies have been devoted to it, a handful of which are highlighted here. Qais et al. [141] demonstrated an application for smoothening of wind power plants output, using a continuous mixed p-norm (CMPN) algorithm to self-tune all proportional integral (PI) controllers in a superconducting magnetic energy storage (SMES). Specifically, the authors investigated the viabilities of the proposed CMPN self-tuned PI algorithm to sufficiently minimize fluctuating effects of ambient conditions on grid-integrated wind power plants. Applying the proposed algorithm for the control of these electronic circuits and juxtaposing the outcomes with those obtained with optimal genetic algorithm-based PI-controlled SMES units, the effectiveness of the proposed algorithm was reportedly validated. In furtherance to studies on optimal control of wind energy conversion systems, Araghi et al. [142] recently presented a supposedly advanced control approach for the improvement of exploitation of wind energy in irregular windy situations, which would also enhance performance and operational life of wind turbines. In particular, the proposed approach implements wind forecasting by aggregating the dynamic control equations of economic nonlinear model predictive control (ENMPC) with artificial neural networks (ANN). In addition, Guo et al. [143] proposed a so-called new approach that uses hybrid energy storage system made up of batteries and super-capacitors for smoothening of wind power plants. Specifically, the proposed approach entails decomposition of wind power time series into optimized wavelet parameters, while preserving technical strictures for power injections, state of charge of the hybrid storages and permissible charge/discharge depth. In addition, the proposed measure took into account the potentials for erroneous prediction of wind speed, and by applying to realistic wind data and comparing with existing smoothening methods, it was concluded to better facilitate stability of grid-integrated renewable energy systems.

While battery storage integration could provide an improved wind power system due to ability to mitigate to some extent the forecast errors and attendant stability issues, it also adds to system costs, thereby ultimately reducing profitability. In order to improve profitability, Zhan et al. [144] suggested that retired batteries of electric vehicle (EV) could be used, since they most often still have high re-use capacity and of course should be much cheaper than new batteries. Specifically, to scientifically verify their claim, the authors proposed a robust two-stage optimization approach for integration of a retired EV battery as a storage device in a wind energy conversion system. A 21 MW wind farm was used to investigate the economic benefits of the scheme, concluding that, with either optimistic or pessimistic assumptions of initial costs of retired EV batteries, the proposed measure would significantly increase profitability of the wind energy system.

3.3. Biomass Energy

Biomass represents one of the few renewable energy resources capable of operating with a high level of stability. This makes it suitable for application not only in electrical transmission and distribution networks, but also in isolated systems, for instance in steel and cement industries where high-temperature thermal energy is highly required for production processes. In particular, biomass gasification plants have been reported to be capable of taking the place of fossil-based systems in national energy scenarios, especially at the distributed level [54,145]. It would in fact not be an overstatement to state that increased grid integration of biomass energy would play indispensable roles towards the achievement of a fully renewable energy economy. This is especially true owing to the possibility of hybridizing with biomass, transient solar and wind energy systems to improve dispatchability and stability, as aforementioned. However, for grid-integrated systems, it is reported in [146] based on Indian case study that stand-alone biomass systems benefits more in economic terms than hybrid configurations. A similar conclusion is reported for a Columbian case study in [147], stating particularly that grid integration of biomass plants based on wood wastes would reduce investment costs by about 10.5%, compared to reduction of about 8.6% that could be achieved with biogas systems.

The above-highlighted benefits notwithstanding, grid integration of biomass energy systems equally poses some challenges at the generation phase. An example to justify this is a 100 kW biomass gasification power plant in Karnataka, India, which was able to provide only about 70 h of grid output after a cumulative operation of over 1000 h [148]. A combination of factors is usually responsible, one of which is difficulty in regulating generation to suit demand from the grid, thereby leading to energy losses. Similar to solar and wind energy-based systems, this challenge is solved mainly by an efficient control system. In this regard, Glinsky et al. [149] developed a control scheme for a biomass-based micro combined heat and power (mCHP) plant generally for peak shaving purposes. Specifically, the proposed control scheme employed actual demand profiles at different seasons of the year to moderate production of heat and power in the mCHP device. At times when power is over-produced due to low demand, excess power is re-channeled for production of heat, and vice-versa. The authors concluded that the proposed scheme satisfactorily reduced peak energy demands at the local (household) level. In a similar study, Schorghuber et al. [150] presented a model-based controller for biomass grate boilers. The proposed control strategy possessed just three parameters for tuning, which substantially reduced technical complexities often associated with control mechanisms of biomass boilers. By implementing the proposed approach to a biomass grate boiler rated at 180 kW, the authors affirmed that it aided the biomass boiler much better than other model-based control strategies, allowing it to operate with all load ranges with no compromise to high efficiency and low pollutant emissions.

Furthermore, biomass combustion plants are generally regarded to be lower in carbon emissions, and in fact the emitted ones are believed to be re-captured by growing biomass plants, which leaves the systems with zero (sometimes negative, with a carbon capture device incorporated) net emission of CO₂. However, combustion of biomass produces other pollutants as well, especially due to incomplete combustion process, which leads to production of soot that pose hazard to human health and the environment. In order to ameliorate this challenge, it is common for biomass plant operators to install some forms of filters, which technically sieve and clean the emitted gases so as to minimize their impacts on environmental degradation. One type of such filters is a bubble-column scrubber, which was reported to operate with removal efficiency up to 95% based on a lab-scale 25 kW biomass plant [151]. Other types of filters include electrostatic precipitators, sleeve filters and wet scrubbers, which have reached advanced technological states and are currently applied widely in medium to large-scale plants, as well as open-cell ceramic foams, which are relatively new but offer high techno-economic potential [152].

Other technical challenges impeding growth of biomass as a viable source of grid-integrated renewable energy system regard inefficient supply chains, burdensome logistic issues (transportation

and storage), as well as other ancillary technical hitches often encountered during biomass conversion processes [153,154]. The use of different types of biomass in other sectors of the economy is the main cause of inefficient supply chain for energy applications. For instance, in place of using oil palm fronds, trunks and empty fruit bunches as potential solid biomass fuels in combustion process for power generation, they are now being processed for mulching process within the same agriculture (palm oil) industry [155]. The use of biomass as a mulching material has been associated with enhanced soil pH and the nutrient recycling process [156], as well as minimized soil erosion [157]. Similarly, pyrolysis ash has been discovered as a good source of fertilizer, which would be expected to diminish usage for energy generation purposes [158]. This poses a threat to the availability of feedstock needed for energy generation from biomass, especially in large-scale grid-integrated biomass plants where large stocks of biomass fuel are required for continuous operation [54]. A potential solution to this is consideration of biogenic technologies to complement other assets for optimal performance of power grids [159].

Regarding the logistics issues, it is common for biomass transportation and storage to attract very high costs due to high moisture contents (hydrophilicity) of most biomass fuels, as well as sparse availability in diverse locations [160]. Other similar biomass properties are also contributory, such as low mass and energy density, poor grindability and poor ash manageability. The approach adopted in Germany and other European countries to ameliorate this challenge is by integrating several intermediate processes such as drying, briquetting and palletizing, so as to enhance energy density of feedstock prior to transportation, storage and eventual field application [161]. Torrefaction is another intermediate process that has been affirmed to possess high potential of enhancing biomass utilization [162], however, it is at the moment economically inefficient and complex, and more research effort is required for technical and economic optimization [163].

In the case of ancillary challenges, such as energy and cost-intensive pre-treatment and conversion processes, and complex catalytic requirements for efficient conversion to desired products, amongst others [164], research gaps exist, as more innovative ways of ameliorating these challenges are still required for enhanced commercialization of biomass power plants [153]. Specifically, for biomass gasification plants, advanced systems with efficient gas-conditioning technologies are still needed to improve market penetration [165].

3.4. Geothermal Energy

Similar to biomass, geothermal resources constitute another category of renewable energy systems capable of power dispatchability, and this makes them vital to future energy and environmental sustainability. This fact is especially true, considering the rapid growth of hybridization schemes where geothermal energy is used to complement transient renewable energy systems, for improved reliability and performance [85]. In addition, exploitations of geothermal resources for grid-connected power production can sometimes be achieved at optimal thermo-economic conditions, for instance, in cases where exploration wells already exist, particularly through re-use of abandoned crude oil wells [166].

The main technical challenges affecting grid-integrated geothermal energy systems concern sustainability of reservoirs, for instance, due to fluctuations of thermodynamic properties, such as temperature and mass flow rates, of re-injected reservoir fluid, as well as impurities in geothermal fluid often resulting to clogging [5,167]. Furthermore, reservoir sustainability is often threatened by tectonic of geothermal well sites (due to constraints regarding suitability of locations) as well as availability of facilities for cooling [5], which often require huge costs relating to planning and feasibility studies. Most often, geothermal wells are far from load demand, thereby necessitating power transportation over a long distance alongside its attendant losses. To ameliorate these challenges, enhancement of geothermal energy has been proposed [168], and this has been affirmed capable of increasing widespread usability and sustainability of geothermal resources when compared to conventional systems.

In addition, it was highlighted in [169] that geothermal resource dynamics play vital roles in the techno-economic sustainability of geothermal power plants. Thus, it is required to take into account

potential off-design behaviors right from design stage of grid-integrated geothermal systems for overall efficient performance.

3.5. Renewable Hydrogen and Fuel Cells

In this section, the challenges and potential solutions associated with production of power from hydrogen and vice versa are succinctly discussed within the context of power grid networks. The majority of the challenges being studied towards grid integration of hydrogen and fuel cell systems focus on power quality and control schemes for power conditioning [170], due especially to the indispensable use of power electronic converters. Although these power quality challenges, such as low-frequency current ripples, often impose considerable effects on the generating system, including overheating, cathode surface slow response, high fuel consumption, nuisance tripping due to overload, and hardware damages [171], etc.; they are commonly idealized in grid-integrated fuel cell studies [172]. In addition, studies on grid integration of hydrogen and fuel cell systems often exclude detailed considerations of generating stack features, such as gas manifold, thermodynamics of mixtures and compressor dynamics [173,174]. However, real distributed power grids operate on constant power basis, and the intricacies of the aforementioned stack features play indispensable roles on stable performance of the entire power system. As a solution strategy, a robust control system that would enhance grid integration of fuel cell systems should include detailed models of the stack components as well as a realistic electrical interface with the power grid.

To contribute to overcoming the above-stated challenge of over simplification of fuel cell controllers for grid integration purposes, Sun et al. [172] developed a so-called innovative approach to couple the interaction between the operations of the stack in a proton exchange fuel cell, the compressor and the inverter. The aim was to investigate the real relationship between the voltage and current in a grid-integrated fuel cell system, as well as that between the compressor and stack. To achieve this, the authors proposed algorithms to determine state variables for handling various computational couplings. Additionally, the constant power operation mode was activated to reveal the static oxygen excess ratio as well as dynamic initial reference in the oxygen excess ratio step response. By implementing the proposed model, the author found that coupling between the inverter and stack imposes safety limitations on stack voltage, necessitating a need for subsequent modification of the oxygen excess ratio optimal reference. Similarly, the coupling between the compressor and stack revealed the effect on potential instability of the system in the absence of a robust controller that incorporates the mechanical, electrochemical and electrical aspects of the system. In a similar study, Nayana and Chakrasali [175] demonstrated recently that introduction of an ultra-capacitor in a grid-connected fuel cell is capable of expediting a quick thermodynamic response of the generator to load variations.

As can be seen, a knowledge gap exists on incorporating fuel cell mechanical features into electrical control models. Going forward, improved controllers that would capture all these aspects are needed for grid-integrated hydrogen and fuel cell systems, as they are currently lacking in the state-of-the-art technology.

The common technical challenges and potential solutions discussed for grid-integrated renewable energy sources are summarized in Table 2.

Table 2. Common challenges of grid-integrated renewable energy sources at power generation phase.

Renewable Resource	Challenges	Potential Solutions
Solar energy	- Low dispatchability/reliability - Inefficient cost	- Adequate orientation of solar panels (proper design for azimuth and tilt angles) [108,109] - Installation of low-cost energy storage devices [176] - Hybridization with dispatchable renewable energy sources such as biomass, renewable hydrogen and geothermal energy [117,177] - Development of robust weather forecast models for accurate predictions of energy production. Data-driven (artificial intelligence (AI)) methods could be helpful [111,115] - Multi-sectoral coupling, e.g., Electric vehicle (EV) in power grids [116]
	- High transmission losses due to long-distant installations	- Development of robust planning models incorporating optimal transmission switching (OTS) and unit commitment (UC), to ensure adequate short circuit ratio and reactive over-reactance [135,136]
Wind energy	- Low dispatchability/reliability	- Installation of low-cost energy storage devices [143,178] - Hybridization with dispatchable renewable energy sources such as biomass, renewable hydrogen and geothermal energy - Development of robust weather forecast models for accurate predictions of energy production. Data-driven (AI) methods could be helpful [138,142] - Multi-sectoral coupling e.g., EV in power grids [144]
	- Inefficient conversion processes and high energy losses	- Development of model-based control schemes [149,150] - Deployment of advanced systems with efficient gas conditioning technologies [165]
Biomass energy	- Emissions of obnoxious gases	- Installation of advanced filtering devices [151,152]
	- Inefficient supply chain	- Improvement of biogenic technologies [159]
	- Burdensome logistic issues (transportation and storage)	- Advancement of current intermediate processes, such as briquetting, drying, palletising and torrefaction [161,162]

Table 2. Cont.

Renewable Resource	Challenges	Potential Solutions
Geothermal energy	<ul style="list-style-type: none"> - Fluctuating properties of re-injected reservoir fluid - Tectonic and inadequate cooling facilities - Impurities in geothermal fluid leading to clogging 	<ul style="list-style-type: none"> - Enhancement of geothermal systems [168] - Treatment of geothermal fluid with acid solution as well as frequent scrubbing [169]
Hydrogen and fuel cells	<ul style="list-style-type: none"> - Stack overheating - Cathode surface slow response - High fuel consumption - Frequent tripping - Hardware damages 	<ul style="list-style-type: none"> - Advanced control schemes to incorporate detailed mechanical/operating features of the stack components [172,175]

4. The Roles of Energy Storage Systems

As aforementioned, energy storage systems are widely acknowledged to play key roles in efficient operation of renewable-based electricity grids. In particular, storage systems accumulating electrical energy are essential at grid/user interface, whether in distribution or a transmission grid, while systems accumulating thermal energy are useful at the generation/grid interface of the network. A brief overview of different kinds of electrochemical and thermal energy storage systems are discussed in this section, as well as their areas of applications in green energy grids.

4.1. Electrochemical Energy Storage Systems (Batteries)

Grid integration of transient renewable energy sources, typical of solar and wind energy, often necessitates adequate power control on electrical grid networks, which might be positive or negative depending on the required direction of power flow [179]. Thus, very fast response devices are quite vital for balancing flow of electrical energy in green grids, and this has positioned electrochemical energy storage systems at the center of the discourse under review [180].

Electrochemical energy storage systems are employed for storing excess electricity available on the grid (by conversion to chemical energy) for delivery of the same to end users or for ancillary services within the grid network at a later time. The devices are basically batteries, often referred to technically as a battery energy storage system (BESS). During discharging process, electric current is generated through chemical reactions in a battery cell, based on flow of electrons triggered by load connected to the cell [181]. In some cases, BESS is an integral part of the power system, and independent design of the storage device is unattainable. In some other cases, BESS is a distinct sub-unit which is designed and sized independent of the power system. Redox flow batteries fall within this category [180]. More generally, the different BESS often applied in transient power grids include the lead–acid battery, the nickel–cadmium battery, the lithium-ion battery, the sodium–nickel battery, the vanadium redox flow battery, the and zinc–bromine flow battery [181]. All the aforementioned battery technologies are characterized by given ranges of capacity, storage power, response time, discharge time, life time, efficiency, cycle life, and maturity. These characteristics reveal the suitability or otherwise of such storage systems for different applications. For instance, lithium-ion batteries are mostly preferred for small-scale renewable energy integration applications, due to their fast response time, great stability in calendar and cycle time and high roundtrip efficiency, but they are unsuitable for applications where large storage capacity is required, such as energy arbitrage in large grids.

In addition, Krivik and Baca [182] attempted to group commercial batteries based on the electrochemical system employed. Specifically, the authors classified lead-acid and Ni-Cd as standard batteries; Ni-MH, Li-ion and Li-pol as modern batteries; Ag-Zn and Ni-H₂ as special batteries; Br₂-Zn and vanadium redox as flow batteries; and Na-S and Na-metal chloride as high-temperature

batteries. The chemistry and other technical details of the different categories have been discussed extensively by experts in the field [183], and are thus not repeated in this paper.

Furthermore, capacities of practical BESS in green grids today range from small scale of rated power in few kW [184] to large scale in several MW [185]. In addition, apart from peak shaving of power on electrical grids, BESS are further employed for performing other key functions on the grid, such as arbitrage, which by extension reduces power curtailment due to the fluctuating renewable energy source; transmission and distribution upgrade deferrals; as well as black start, which entails using energy stored in the grid to warm up big generating plants at start-up prior to the onset of power generation [186]. Depending on the actual functions required of specific BESS, it could be sited in different locations on the power grid, including in the transmission network, in the distribution network near load centers, as well as amongst the variable renewable energy generators [186].

Extensive research activities are ongoing to reduce costs of modern and redox flow batteries for improved market penetration. Generally, it is opined that ongoing efforts could lead to reduction in costs of electricity storage up to 66% by 2030 [187]. Further research attention should be focused on enhancement of data and analysis capabilities aimed at improving confidence of investors in the technology, which is still somewhat new when compared to conventional energy systems. In addition, technical and environmental optimizations of existing and new battery technologies are highly essential to improve the confidence of policy makers as well as the general public.

4.2. Thermal Energy Storage Systems

Energy technologies capable of accumulating thermal energy from a source, retaining the stored heat over a period of time, and making same available subsequently for deferred usage are generally referred to as thermal energy storage (TES) systems. Specifically, in more technical terms, the heat accumulation stage in TES systems is often called the charging phase; the retaining process is referred to as storage; and the releasing stage is known as the discharging phase [188]. In the context of this study, TES systems are applicable for improving reliability and competitiveness of systems that exploit transient renewable energy resources, such as solar energy. Specifically, TES systems are often used to interface the renewable sources and application ends, aimed mainly at improving dispatchability of the energy system, and this also helps to shift loads for a synchronous energy production and demand curves in domestic applications [176]. In fact, it is widely believed that TES is intricately aligned with future advancement of CSP plants and practical applications [12].

For CSP applications, TES systems are commonly classified on two distinct bases. The first is the mode of thermal energy storage adopted, while the second bothers on the concept of integration to CSP unit. Based on the mode of storage, TES systems are of the types sensible heat, latent heat and thermochemical systems [189]. A sensible heat system operates by increasing temperature of the storage medium during the accumulation phase, as well as decreasing the same during the discharging phase, precluding a change in phase of the storage medium [189]. Storage media are often in solid or liquid phase, and they are generally required to possess adequate properties characterized by good thermal conductivity, density, diffusivity and specific heat, amongst others [190]. One identified disadvantage of sensible heat TES system is low energy density of the most popular storage media, which often necessitates installation of large TES systems alongside the consequent large volume/space requirements. With the view of addressing this challenge, research effort is underway, aimed at enhancing energy densities of solid sensible heat TES materials through integration of encapsulated materials [191] or nanoparticles [192]. The sensible heat TES system is the most commonly used technology today, based on the majority of the currently installed CSP-TES plants [193].

In the latent heat TES system, thermal energy is stored by isothermal phase change in the storage material during charging and discharging phases [194]. Specifically, the phase change material (PCM) undergoes a physical transformation as heat transfer processes progress, and this can take the form as solid–liquid, solid–gas, or liquid–gas phase change [194]. It is reported that the solid–liquid phase change process is the most effective with respect to volumetric change. These TES

system types are characterized by higher storage density compared to the sensible heat systems, and lower installed volume is thus usually required [195]. However, potential PCM often require very stringent properties, which often impact negatively the technical risks and economic performance of latent heat TES systems when compared to their sensible heat counterparts [196]. Moreover, very high charge/discharge durations are required for PCMs, since they often possess low thermal conductivities [197]. Investigations of adequate additives and new schemes viable for improving heat transfer characteristics of PCMs are thus common research themes currently studied in the literature [198].

In thermochemical TES systems, thermal energy is stored through combination or decomposition of molecular structures of reactants, using reversible chemical reactions [199]. During the accumulation process, heat energy produced by CSP is used in an endothermic reaction for storage, while during the discharge process, the process is reversed, in which case an exothermic reaction releases heat from the system [199]. Advantages of this type of storage include possibility of low-temperature charge/discharge processes, as well as possible elongation of storage duration. Others include high energy density of commonly used reactants when compared to what is obtained in latent heat TES systems, which literarily connotes much lower storage costs [200]. The details of materials and reactions often employed in thermochemical TES systems are available in the literature [200], and suffice it to mention here that they are quite diverse and different in features. Very slow heat transfer as well as reduced mass transfer processes constitute the main demerits of thermochemical TES systems, which are attributed respectively to poor thermal conductivity and low permeability typical of thermochemical storage materials [201]. Thus, the state-of-the-art technology is replete with many developmental techniques [202], which have been proposed as potential ways of improving mass and heat transfer characteristics during decomposition and combination of reactants, and huge efforts are currently underway [203].

Regarding the classification based on the concept of integration to CSP units, there are active and passive TES types. In active TES systems, forced convection heat transfer process is employed to drive the storage medium, as it flows during charging and discharging processes to interact with thermal source and sink, respectively. In some cases, the HTF flowing through the solar collectors is the same as the TES storage medium, often referred to as direct active TES systems. In some other instances, HTF circulating the CSP is distinctly different from storage medium, usually called indirect active TES. There could be a 2-tank TES system, when cold and hot storage media are stored in separate tanks, or a 1-tank TES system, when cold and hot storage materials are accumulated in a single tank separated by temperature stratification, usually reinforced with filler materials to improve the dividing zone between the two regions, called thermocline [204], and to prevent mass transition from one region to the other [205]. Adequate filler materials are essential, and state-of-the-art encapsulated PCMs are assiduously being investigated, alongside other innovative solutions [206]. Conversely, the storage medium is usually stationary in passive TES systems, often in solid state, and thermal energy is accumulated or discharged through circulation of different HTF from/to solar collectors [207]. Figure 15 summarizes the different classifications of TES systems.

Current research activities focus mainly on enhancement of heat transfer and ancillary characteristics of different storage materials [208,209]. Moreover, researchers are working hard to develop TES materials that could function effectively at higher ranges of temperature when compared to what is currently obtainable [210]. In this respect, the combination of two or more thermal storage modes are being investigated in a state-of-the-art form of hybrid TES systems [211–213]. In addition, researchers are assiduously investigating viable and cost-effective measures of minimizing thermal inertial in TES systems and of improving control of HTF temperature as it flows through the system. In this regard, system cascading has been proposed, particularly by designing and producing TES systems in smaller units, in place of the current practice which often combine all the processes in one single unit [214–216]. Furthermore, researchers are newly investigating application of granular particles both as storage media

and HTF, in which case, mechanical devices are adopted for circulation of solid materials [217,218]. Again, further research efforts are required in this respect.

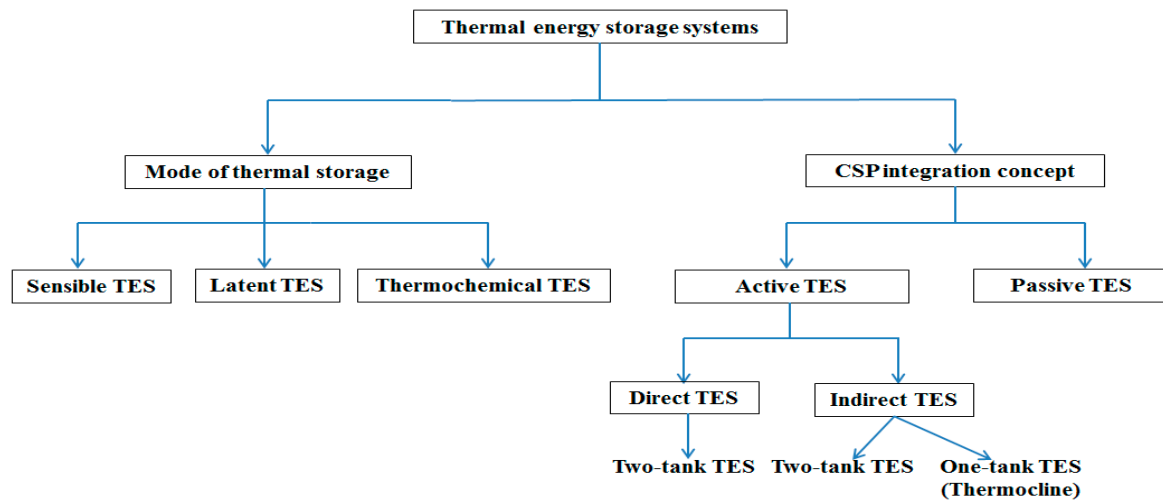


Figure 15. Classification of thermal energy storage systems for CSP applications.

5. Challenges with Grid Integration for Distribution and Transmission Networks

Generally, technical challenges with grid integration of renewable energy systems are more pronounced at the electrical supply phase, and they often attract huge attention from electrical engineers. Whether for small-scale distributed power networks or transmission ones, the transient nature of most renewable energy resources as well as dynamic operations of equipment from user ends often trigger power flow irregularities. Some of the challenges commonly studied in this respect include harmonics, voltage imbalances (voltage dips, over-voltage), frequency imbalances (over-frequency and under-frequency), pulse voltage, flickers, and power cuts, etc. Viable ways of solving these challenges are progressively being sought, which has led to the development and popularity of smart grids [219]. Practical implementation of smart grids and hybridization of renewable power plants are particularly highlighted in [220] as some of the paradigm shifts needed to ameliorate the aforementioned challenges, which are expected to exacerbate as integration of renewable energy systems further matures. This section discusses the specific challenges and prospective solutions relating to grid integration of each of the different renewable energy resources under discussion.

5.1. Solar Energy

Integration of solar systems to grids is often associated with technical challenges at transmission and distribution phases, including voltage fluctuations, frequency fluctuations, grid instability, flickering as well as coordination and control difficulties, amongst others [221]. The effects that some of these technical challenges would have depend largely on size, since small-scale solar systems tend to be compatible with distribution networks, while their large-scale counterparts are often targeted at transmission grids. For small-scale PV systems in distribution power grids, for instance, it is generally opined that issues of voltage regulation are the most critical technical challenges [222]. Several notable studies that investigated some of these challenges and applied solution strategies are discussed here.

When users connect loads higher in voltage than what is supplied by solar systems, voltage rise occurs, posing challenges to grid stability. Alquthami et al. [223] investigated some measures adequate for mitigation of voltage rise due to high PV penetration in distribution network of Saudi Arabia. In particular, the authors investigated the effectiveness of active power curtailment, reactive power rejection and hybrid of the two techniques to adequately manage feeder over-voltage in distribution power grid due to PV penetrations. In the active power curtailment technique, the upper limit of user-defined voltage is monitored, above which the active power output from the system is curtailed,

thereby limiting the overall power output. In the case of the reactive power rejection technique, the target is to maintain a specified voltage by automatically modifying the output reactive power into inductive or capacitive forms. It is typical to decrease voltage drop by offsetting the reactive power demand from the load using inverters. In essence, the effectiveness of this technique depends strongly on the size of inverter as well as the PV output. The authors investigated the viability of these techniques using data from a typical distribution grid in Saudi Arabia based on steady state and dynamic analyses at various loading conditions. Results showed that a hybrid of active power curtailment and reactive power injection techniques was found to best mitigate the effects of the voltage rise on grid performance. Furthermore, Cabrera-Tobar [224] proposed an enhanced local controller of active and reactive power in grid-integrated PV systems, which would facilitate compliance with new grid codes set by transmission system operators. Specifically, the new controller takes into consideration the PV generator instantaneous capability curves, which depend on solar irradiance, temperature, DC voltage as well as modulation index. Based on results of PV generator model executed in the DigSILENT Power Factory, the authors concluded that the proposed controller is capable of adequately modifying the active and reactive power at different irradiation and ambient conditions.

Within the same context, Anbarasu et al. [225] sought to address the issue of power loss and instabilities in solar-integrated electrical network using a fractional order proportional integral Derivative (FOPID) controller to track maximum power point in the grid based on adaptive neuro fuzzy inference system (ANFIS). The authors reported, based on comparative MATLAB simulations, a better performance of the proposed controller relative to conventional ones often employed in grid-integrated solar systems.

Regarding frequency imbalances, Yap et al. [226] sought to increase frequency stability in a grid-integrated PV system by applying a new machine learning (ML) approach to synthesize virtual inertia (VI) in synchronverter topology. Specifically, the proposed approach decoupled active and reactive power control, which when combined with capability for flexible changes in moment of inertia, facilitated higher frequency stability and fast transient response relative to the traditional PI and fuzzy logic controllers. In numeric terms, the authors reported succinctly that, based on several case studies simulated in MATLAB/Simulink, the proposed controller reduced the maximum frequency deviation from the nominal value by 0.1 Hz, the settling time to reach quasi-steady-state frequency by 35% and steady-state error by 27%.

Furthermore, from a very practical perspective, Bayer et al. [227] investigated the popular approaches applied in Germany by distribution system operators (DSOs) for real integration of rooftop PV solar energy into low-voltage distribution grids, based on technical interviews. In order to maintain voltage range, several measures were applied, classified generally into the classic grid expansion, intelligent equipment and grip optimization interventions. Specifically, under grid expansion measures, it was typical for DSOs to replace local distribution transformers in order to segment local grids when maximum voltage requirement would be exceeded, to lay parallel cables and to increase conductor cross-sections. For measures under intelligent equipment measures, DSOs were installing voltage regulators as well as voltage-regulated distribution transformers, which are based on advanced automatic control processes. Additionally, individual tap changing of the distribution transformer, wide-area control, reactive power feed-in and grid topology adjustments are the major measures being employed for grid optimization. In addition, measures such as replacement of local distribution transformers, segmentation of local grids as well as adjustment of grid topology equally served the purpose of avoiding thermal overload of transformers. To avoid thermal overload of power lines due to PV penetration, replacement of grid topology, segmentation of local grids, installation of parallel cables and increases in conductor cross-sections were the measures mostly deployed by DSOs in Germany. For mitigation of voltage-related issues, wide-area control, reactive power feed-in and installation of parallel cables are highly deployed by most DSOs; individual tap changing of distribution transformers is averagely deployed, while installations of voltage-regulated distribution transformers and voltage

regulators, segmentation of local grid, increase in conductor cross-section, and change of grid topology were reported to have a low level of application in this respect.

Wang et al. [228] equally reiterated the limitations imposed by the issues of voltage regulation on practical integration of small-scale PV systems to low-voltage distribution grids, with emphasis on unbalanced voltage across phases. The authors opined that most traditional methods of mitigating overvoltage across phases, such as the power factor droop control strategy, sometimes trigger unplanned voltage-reactive power responses across phases due to line coupling, which ultimately limits their effectiveness. In this regard, the authors proposed a supposed new joint centralized–decentralized approach aimed at overcoming PV voltage regulation issues due to imbalances across phases. In particular, the approach involves adaptive scheduling of the reactive power response of the inverter to intermittent and variable power in different phases, mainly to downplay the effects of inter-phase voltage-reactive power responses on voltage regulation due to grid integration of PV systems. Robust dynamic simulations were employed to investigate the effectiveness of the proposed method when compared to the traditional ones, using a real-life low-voltage distribution system and recorded data in Australia. It was concluded that the new method is capable of controlling the system voltage within the allowable range, with no case of disconnection of PV power, a feat unattainable hitherto by traditional methods.

In addition, regarding the new trend of facilitating grid integration of solar systems through the use of transformer-less PV inverters, especially in residential installations, it is widely acknowledged that this topology has enhanced PV systems for reduced cost and size, as well as improved energy performance [229]. However, with regard to integration to distribution power grids, single-phase transformer-less PV inverters equally possess a number of challenges that must be overcome, such as current leakage. Although a considerable amount of studies has been conducted to ameliorate this challenge and to generally improve performance of such systems [229], substantial research efforts are still required for enhanced market penetration. Moreover, the role of smart grids in facilitating grid integration of solar-based renewable energy systems is underscored in [4], where the authors reiterated specifically the importance of combining the real power grid with multiple micro-grids for optimal exploitation of solar energy and accompanying energy storage units. The authors reported also that integration of energy storage devices is as important in maintaining system stability in the smart grid architecture as it is in conventional power grids. Overall, substantial research efforts are also required to facilitate optimal performance of smart grids for increased market penetration.

5.2. Wind Energy

The doubly fed induction generator (DFIG) is a prominent conversion system used in many real wind turbine systems integrated to power grid networks [230,231]. This is particularly due to its ability to prevent delivery of disturbances to electrical networks by decoupling production between active and reactive power [232]. However, due to the voltage irregularities typical of renewable-integrated power networks, continued and optimal performance of wind turbine using DFIG is often a cause of concern, especially at a penetration rate beyond 50% where the stator angle is no longer stable [232]. Whenever there is a voltage dip in the power grid, connoting essentially a sudden and transient drop in amplitude of the RMS voltage affecting certain phases at some points in the power network, effects on DFIG performance often lead to the entire system being shut down as well as a potential damage to the generator. The damage is due mainly to the rotor side converter that would exceed electric current limits, as voltage dip would ordinarily lead to an extreme surge in currents on stator and rotor circuits for a specified power flow. To ameliorate these undesirable effects on grid-integrated wind turbine systems, several studies are in progress aimed at developing viable control systems [233]. In this regard, Mensou et al. [234] proposed a direct power control method based on the backstepping controller, aimed at mitigating the spike in electric currents on rotor and stator circuits as well as restoring the voltage level to nominal value. These bi-objectives of the proposed method were achieved by controlling the stator active and reactive power, respectively. Based on the results obtained from

modelling and dynamic simulation of a DFIG rated at 1.5 kW, the authors reported that the proposed method satisfactorily mitigated the adverse consequences of voltage dip in a grid-integrated wind turbine system. Similarly, for control of direct torque in a grid-integrated wind turbine system using DFIG, it is typical to have a minimum of two current sensors each for the stator and rotor, as well as a rotor position sensor. In order to enhance hardware reliability in a DFIG grid system, Prasad and Mulla [235] proposed a direct torque control mechanism that excludes the rotor position and rotor current sensors, using measurable stator quantities to determine the rotor flux vector magnitude and torque. The authors reported that the direct torque control scheme proposed is quite viable on the basis of simulations results of a 2 MW DFIG-based wind energy conversion system.

Furthermore, generally for different wind turbine generators, Sayahi et al. [236] demonstrated the suitability of a static synchronous compensator (STATCOM) control strategy, based on direct power control, for improving voltage stability and to reduce undesired effects on generators due to voltage dip and other grid faults. Following theoretical analysis based on computer simulations, a hardware prototype was built for experimentation purposes, and the results obtained reportedly validated the effectiveness of the studied control method for practical grid-integrated wind power plants. Similarly, Ashok Kumar and Indragandhi [237] combined a battery energy storage system (BESS) with STATCOM for enhanced grid integration of the wind energy system. A so-called novel controller was implemented in the study, which facilitated provision of reactive power support. These findings correlate quite well with those reported by Adetokun et al. [238], where active power-voltage analysis was carried out to investigate the effects of increasing penetration of DFIG-based wind power plants on voltage stability in electrical networks. It was discovered also in the latter study that effective line enhancement and adoption of flexible AC transmission system (FACTS) devices are essential to stabilize voltage in a power grid with increased penetration of wind power plants.

One new and innovative way in which the stability of grid networks based on renewable energy systems is being realized is by integrating electric vehicles (EV), either on a vehicle to grid (V2G) or a grid to vehicle (G2V) basis. This approach is particularly beneficial for economical operations of both renewable energy-based micro-grids and EV, as it can reliably address the challenge of peak shaving in micro-grids. However, the concept does not entirely erase the challenges associated with uncertainties in the system, and, in fact, integration of EV to the power grid often expands the degree of freedom of system dynamics, thereby necessitating stricter prediction and control measures for optimal performance. As a result of this, research interests are growing in this field. Shi et al. [239] proposed a way of improving economy and security of micro-grids based on integration of a V2G network. Specifically, the authors focused on a wind power based micro-grid, and they matched the uncertainties relating to wind power to those of EV's state of charge (SOC) and modelled them as a predictive set. The scheduling model introduced is multi-objective in nature, with considerations to technical, economic and environmental optimization of the hybrid power grid–EV system. It was sufficed in the study that the proposed model and multi-objective optimization procedures revealed the potentials of EVs to facilitate two-way delivery of energy, leading to improvement of the peak-shaving effect and exploitation of wind energy, amongst others. In a similar study, Zhang et al. [240] proposed a short-time forecasting model for a wind energy conversion system integrating EV, which uses an innovative information fusion approach to combine the Back Propagation (BP) neural network, the wavelet neural network and the relevance vector machine (RVM). The uncertainty in the forecasting process was equally taken into consideration using the Gaussian cloud model. The authors reported that, based on measured data of two units, the proposed combined model out-performed any single forecasting method based on its ability to minimize prediction errors. This reportedly enhanced the power grid to guide EV in its charging dynamics based on power curves as well as wind power availability, which ultimately improved techno-economic performance of the wind–EV system.

5.3. Biomass Energy

Biomass power plants are typically capable of interfacing the grid and end-user demands in a dispatchable manner, which makes them more suitable for grid integration than most other renewable energy resources. In fact, it is common to see biomass power plants being used for balancing electrical power networks in cases where other transient energy sources are integrated [241]. In essence, biomass systems can be operated to have similar characteristics that most conventional energy systems have on electrical networks. However, cases exist when supply chain and ancillary issues would affect continuous operation of the biomass plant at generation level, and this might equally portend instability effects on the electrical grid. For this purpose, Munoz et al. [242] attempted to mitigate frequency instability in a micro-grid based on integration of a biomass gasification system. Following the modelling and simulation of different sections of the gasifier achieved in MATLAB/Simulink, the authors proposed a cascaded PI controller to moderate frequency of the micro-grid for minimized settling time and frequency overshoot. The focal point of the proposed controller was to maintain valve points at different levels for level of load, while maintaining the blower frequency at its nominal condition. Based on the application to a real micro-grid in Nececli, Colombia, the authors reported a satisfactory performance of the proposed frequency controller at steady state.

5.4. Geothermal Energy

As aforementioned, geothermal energy systems are dispatchable and are among the most suitable renewable energy systems for grid integration. In addition, in the likeness of biomass systems, geothermal plants are applicable for balancing electrical power networks, especially for integration of solar energy. In essence, geothermal systems can be operated to have similar characteristics that most conventional energy systems have on electrical networks. However, inconsistent load-side demands common with all grid-integrated energy systems could lead to challenges of excess or shortage power availability in some instances. Thus, energy storage systems and robust control schemes are equally of high importance towards optimal performance of grid-integrated geothermal systems. In this respect, Erdiansyah et al. [243] investigated the demand response management in a geothermal power plant in Indonesia by implementing a hybrid energy storage device in a three-phase system with an adaptive PQ controller. Specifically, the control-based hybrid energy storage system interfaces the geothermal plant with a transmission grid for regulating demand-side load requirement in agreement with power plant production. Based on real load demand data of Java-Bali, Indonesia, the energy management system built in MATLAB/Simulink was affirmed suitable for optimal performance of grid-integrated geothermal power plants.

5.5. Renewable Hydrogen and Fuel Cells

Renewable hydrogen and fuel cells are increasingly used for peak shaving and balancing of electrical grids nowadays, especially in grid-integrated systems based on transient renewable energy sources such as solar and wind [244–248]. This is because of the easier amenability of hydrogen-based and fuel cell systems to improve dispatchability in the electricity grid [249]. For instance, the role of hydrogen in the balancing of large-scale electrical grid is illustrated in [250] for the case of Spain. Conversely, instances of grid integration of sole hydrogen-based fuel cells are also on the rise, especially in small-scale applications [251]. In fact, the world's first electricity grid using hydrogen as baseload has been developed recently by Joi Scientific and NB Power [252], reiterating the possibility of future reliance on hydrogen as primary energy carrier in place of fossil fuels. The negative impacts of such grid integration instances of hydrogen and fuel cells on power networks are discussed here, together with potential state-of-the-art solutions that are being proposed.

One such challenge is unplanned islanding, which is a condition in which the power source does not stop to supply electric load even when the utility grid is already disconnected. This situation poses challenges not only to the fuel cell and other electrical appliances, but also to operators. One way of

ameliorating this challenge is through timely detection, in which case, robust detection mechanisms are essential. Although a good number of studies have proposed different approaches to detect islanding in distribution power grids, most of them are often associated with one form of deficiency or the other, such as the presence of a non-detective zone or a high implementation cost, amongst others [253]. For the fuel cell power grid, Bayrak and Cebeci [254] proposed a hybrid method that would exclude non-detective zones to promptly detect and signal unplanned islanding in the network. The communication-based approach, as reported in the study, is capable of disconnecting the fuel cell power source from the utility grid within three–four cycles of operation with the islanding condition, claimed by the authors to be faster than other available methods at the time. The effectiveness of the proposed method was validated using a comparison between simulation and experimental results.

In addition, fuel cell-distributed generators also interface the grid using electronic converters and similar devices in the likeness of systems based on transient renewable energy resources. Thus, it is typical for fuel cell systems to equally be associated with power quality challenges such as voltage sag and swell, current harmonics, under-voltage and over-voltage, under-frequency and over-frequency, as well as noise and disturbances, amongst others. As a solution strategy, it is common to implement adequate control schemes for system optimization, so as to maintain quality operations devoid of these unwanted effects [255]. In this regard, several studies have proposed different control strategies for smooth integration of fuel cell-based generators to distribution power grid. Sabir [256] presented a control strategy able to add low-voltage ride-through to a grid-connected fuel cell system under unbalanced conditions. In particular, the proposed strategy is based on uncertainty and the disturbance estimation controller and repetitive controller for dc–dc-side and grid-side currents, respectively. According to the author, simulation case studies realized with the SimPowerSystems™ toolbox in the MATLAB/Simulink environment affirmed the robustness, fast transient response and disturbance rejection ability of the control scheme, also based on digital implementation on an economical micro controller. Ro and Rahman [257] developed a controller that generates switching signals to the DC–AC inverter for grid stability of fuel cell systems. Computer model-based analysis of the proposed controller and corresponding test affirmed its effectiveness in distributed networks, as claimed by the authors. Thammasirioj et al. [258] presented a so-called innovative approach for the control of power supply distribution in a fuel cell generator based on a multiphase interleaved converter. The control scheme involves a non-linear single-loop feedback scheme, unlike linear multiple-loop feedback usually employed in traditional DC electrical output controllers in converters. A prototypical lab-scale fuel cell power converter was constructed, with which the proposed control approach was validated using a dSPACE 1104 controller card. The authors reported excellent performance of the controller for all of the steady-state and dynamic responses, as well as in terms of control robustness, when used with an experimental 1.2 kW Nexa Ballard polymer electrolyte fuel cell. Furthermore, Wu et al. [259] illustrated the superiority of an active disturbance rejection control (ADRC) approach over the conventional proportional-integral (PI) controller for grid current control in a fuel cell-based electrical network. Specifically, the proposed ADRC stabilizes the DC link voltage in the DC–DC converter section of the power conditioning system, while in the DC–AC converter section, it eliminates steady-state error. The authors reported that, regardless of variations in the load demand and network parameters, the output current controlled by the proposed ADRC did not at any time possess total harmonic distortions up to 5%. Mosaad and Ramadan [260] investigated the applicability of three evolutionary methods for optimized tuning in power quality management and control of a grid-integrated fuel cell system based on PI controllers. The authors reported that, when implemented in MATLAB environment, the investigated harmony search, modified flower pollination algorithm and electromagnetic field optimization performed better than the particle swarm optimization technique with respect to voltage profile, power quality and execution time.

Another challenge common with grid integration of fuel cells is deterioration of the utility grid power factor due to generation of reactive power from local reactive loads connected to the system, leading to losses and overloading, amongst other undesirable effects. The active and reactive power of

the fuel cell system have to be adequately interfaced with the utility grid, which is the main function of inverters. In essence, proper control signals must be generated for adequate functioning of inverter and system stability, which often necessitates implementation of feasible active/reactive control mechanisms. The main solution being deployed lies with development of robust energy control and management strategies such that reactive energy consumption is eliminated from the utility grid, leading to reduced electrical demand [261,262].

Furthermore, researchers have long ago suggested online production of hydrogen in grid-integrated fuel cell power plants for potential system economic optimization [263]. More recently and in the same vein, fuel cell electric vehicle (FCEV) application in grid-integrated electric vehicle (V2G) systems has been opined to be one of the key areas that could enhance market penetration of hydrogen and fuel cell-based energy systems. However, the use of FCEV increases complexities and economic burdens of V2G systems, thereby necessitating implementation of robust optimization models to realize highly-efficient and cost-effective systems, such as that proposed in [264]. Robledo et al. [265] demonstrated the technical viability of such a system as part of the Car as Power Plant project at The Green Village in the Netherlands, and the mutual techno-economic benefits to electricity and mobility sectors were affirmed quantitatively. In another similar study aimed at investigating the possibility of integrating the electric vehicle to the electricity network to power an industrial building by using excess power to produce hydrogen for storage and consequent conversion to electricity in the fuel cell, a slightly contrary opinion was expressed, reporting that such arrangement led to an economically and technically feasible approach for promoting real applications of the renewables in a reliable and flexible manner [266].

The main technical challenges and potential solutions commonly associated with the studied renewable energy sources at the electrical grid interface are highlighted in Table 3.

Table 3. Common challenges of renewable energy sources at the electrical grid interface.

Renewable Resource	Challenges	Potential Solutions
Solar energy	- Voltage irregularities (dip, rise, sag, swell, pulse voltage)	- Advanced control mechanisms for active power curtailment and reactive power rejection Methods hybridizing active power curtailment and reactive power rejection in the same controller could be particularly viable to minimize low power quality [223,224]
	- Frequency imbalances (over-frequency, under-frequency)	- Control schemes based on machine learning (AI) could proffer better solution than those based on proportional integral and fuzzy logic approaches [226]
	- Current harmonics	- Development of viable schemes for demand-side management [227,228]
	- Flickering	- Online grid expansion and optimization [227]
	- Power cuts/power losses	- Further improvement and deployment of transformer-less inverters, especially for distributed grids based on PV [229]
		- Further improvement and deployment of smart grids [4]

Table 3. Cont.

Renewable Resource	Challenges	Potential Solutions
Wind energy	- As mentioned above for solar-based grids	- As mentioned above for solar-based grids - Advanced controllers integrating battery energy storage system with STATCOM, and those based on FACTS devices could be particularly viable for wind-based grid operations [236–238] - Integration of EV (V2G or G2V) [239,240]
Biomass energy	- Power quality fluctuations generally due to poor control of the generating system at the grid interface	- Development of advanced model-based control schemes [242]
Geothermal energy	- High tendencies for poor demand-side management	- Integration of cost-effective energy storage systems and control strategies [243]
Renewable hydrogen and fuel cell	- Unplanned islanding	- Development of advanced communication-based approaches for instant detection of islanding [254]
	- Low voltage	- Advancement of control strategies for compliance with a low-voltage ride-through requirement under unbalanced grid conditions [256,258,259]
	- Current harmonics	- Further development and deployment of an active disturbance rejection control (ADRC) approach [259]
	- Frequency imbalances	- Development of robust evolutionary-based controllers [260]
	- Deterioration of utility grid power factor	- Development of viable energy control and management strategies [265]

6. Expert Opinions on Existing Research Gaps

Based on the foregoing, some aphorisms are highlighted here which could guide interested researchers on areas of interest in regard to which future research themes could be focused on. The statements encompass open challenges needing more attentions both at generation and grid integration stages, as follows:

- Development of improved weather forecast models aimed at minimizing errors. Applications of artificial intelligence methods, in isolation or in combination with robust evolutionary methods, need be further explored towards accurate prediction of real-time weather data and towards increased penetration of transient energy resources such as solar and wind;
- Improvement of cleaning technologies for solar mirrors and cells, for reduced efficiency losses due to formations and soil particles. This could further enhance the practical deployment of PV systems, due to further reduction in costs, while also having significant impact on the economic viability of CSP systems;

- Further development of compactness and cost efficiency of thermal and electrical energy storage devices. For electrical storage, sustainability of the use of abandoned EV batteries should be investigated, as this could provide an effective cost-saving measure for grid integration of transient renewable resources;
- Development of detailed control models of grid-integrated fuel cell systems that would incorporate stack characteristics, in addition to adequate representation of real operations on the grid which is based on constant power;
- Incorporation of multi-sectoral application potentials in the design of grid-integrated renewable energy systems. As a specific example, integration of EV into renewable-based power grid could benefit both the energy and transportation sectors, as EV could provide a form of peak-shaving function for the grid in the framework of V2G and G2V applications;
- The role of renewable hydrogen is very vital for attaining energy sustainability in the future. This is because hydrogen can serve as direct fuel for power generators, and as an energy storage medium due to its amenability to power-to-X-to-power conversion useful for peak shaving in renewable-based power grids;
- Further development of robust energy management and control schemes, which has become imperative for smooth running of grid-integrated energy systems due to unavoidable incorporation of power electronic devices (inverters/converters) as the interface between generators and power grids. This is particularly essential to mitigate the main technical challenges often associated with renewable-based power grids, such as low power quality as well as unstable voltage, frequency, current harmonics, etc. Here too, the applications of AI methods should be well researched, in isolation or as a hybrid to existing PI and evolutionary control methods.

7. Conclusions

The technical challenges associated with integration of renewable energy resources into power grid, and common solution strategies, are succinctly reviewed in this paper. The renewable resources focused on include solar energy, wind energy, biomass energy, geothermal energy, as well as renewable hydrogen/fuel cells, which, although not classified purely as renewable resources, are a famous energy carrier vital for future energy sustainability.

Following a brief but comprehensive overview provided for each of these renewable resources, the impacts on effectiveness of power grid were discussed for power generation from each of the renewable energy resources. For transient ones such as solar and wind, the challenge of accurate weather forecast impacts negatively the market penetration due to low system dispatchability and reliability, leading also to high costs. To mitigate these effects, state-of-the-art robust weather forecasts models are being developed, but more efforts are required in this respect, especially by exploiting the vast potentials of AI-based prediction and optimization methods. Furthermore, hybridization of renewable sources as well as deployment of energy storage devices are being explored to improve dispatchability. In the case of biomass energy, challenges at the generation phase are related to the issues of inefficient conversion processes, as well as insufficient supply chain and complex logistic processes. It is common to find application of model-based control systems to improve energy conversion processes, while development of intermediate processes such as drying, briquetting, palletizing and torrefaction are being explored to reduce logistics issues, amongst others. For geothermal energy, fluctuations of thermodynamic properties of re-injected reservoir fluid, tectonic of well sites and impurities in geothermal fluid often pose threats to sustainable power generation. Various enhancement processes are being deployed as solution strategies. For hydrogen/fuel cell systems, substantial efforts are required to incorporate thermodynamic and mechanical features of the stack into system control models, as this is often neglected at the moment, often leading to frequent damages and shorter life of the system.

Furthermore, the impacts of each of the studied renewable resources at grid (electrical) integration phase were discussed, where the need is underscored to use power electronic devices, such as inverters

and converters for interfacing the generators with power grids. Furthermore, it was gleaned from the review study that these devices are the main reasons for low power quality and power control issues usually associated with renewable-based power grids, and substantial efforts are ongoing to develop robust power control schemes to ameliorate these challenges. Here too, more efforts are required for further development of improved control models, and the vast potentials of AI-based and hybrid control schemes need be explored.

Finally, expert opinions were provided, comprising a number of aphorisms on knowledge gaps requiring research attention in this field for guidance in the choice of future research themes.

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Nomenclature

Letter Symbols and Abbreviations:

1G	first generation
2G	second generation
3G	third generation
AC	alternating current
AFC	alkaline fuel cell
AI	artificial intelligence
a-Si	amorphous silicon
BESS	battery energy storage system
BoS	balance of system
CdTe	cadmium telluride
CHP	combined heat and power
CPV	concentrated photovoltaic
c-Si	crystalline silicon
CSP	concentrated solar power
Cu(InGa)	Se ₂ copper indium gallium di-selenide
DC	direct current
DSO	distribution system operators
EV	electric vehicle
FACTS	flexible AC transmission systems
FCEV	fuel cell electric vehicle
G2V	grid to vehicle
GaAs	single-junction gallium arsenide
HAWT	horizontal axis wind turbine
HTF	heat transfer fluid
IEA	International energy agency
LCOE	Levelized cost of electricity
LFR	linear Fresnel reflector
MCFC	molten carbonate fuel cell
MFC	microbial fuel cell
OTS	optimal transmission switching
PAFC	phosphoric acid fuel cell
PDR	parabolic dish reflector
PEMFC	proton exchange membrane fuel cell

PTC	parabolic trough collector
PV	photovoltaic
SDGs	sustainable development goals
SOC	state of charge
SOFC	solid oxide fuel cell
STATCOM	static synchronous compensator
TES	thermal energy storage
TSO	transmission system operators
UC	unit commitment
V2G	vehicle to grid
VAWT	vertical axis wind turbine
VSC	voltage source converter

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