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A Review on Configurations, Control, and Future of Hybrid Renewable Energy Systems for Electric Power Generation

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Abstract - *This paper presents a review on hybrid renewable energy (RE) power generation systems focusing on energy sustainability. It highlights some important issues and challenges in the design and energy management of hybrid RE systems. System configurations, generation unit sizing, storage needs, and energy management and control are addressed. Statistics on the current status and future trend of renewable power generation, as well as some critical challenges facing the widespread deployment of RE power generation technologies and vision for future research in this area are also presented. The comprehensive list of references given at the end of the paper should be helpful to researchers working in this area.*

Key Words: Energy management, energy storage, generation unit sizing, hybrid energy systems, renewable power generation.

1.INTRODUCTION

This century is expected to witness unprecedented growth and challenges in power generation, delivery, and usage. Environmentally friendly (renewable and clean alternatives) power generation technologies will play an important role in future power supply due to increased global public awareness of the need for environmental protection and desire for less dependence on fossil fuels for energy production. These technologies include power generation from renewable energy (RE) resources, such as wind, photovoltaic (PV), micro hydro (MH), biomass, geothermal, ocean wave and tides, and clean alternative energy (AE) power generation technologies [such as fuel cells (FCs) and microturbines (MTs)]. RE/AE generation sources often come in the form of customized distributed generation (DG) systems in grid-connected or standalone configuration. FC and MT could also be considered renewable power generation sources if their input fuel is obtained from renewable sources. For instance, landfill gas has been used to fuel MT, biomass can be gasified into Syngas and used as fuel for MT and FC, or hydrogen fuel can be generated using wind- or PV-generated electricity (through an electrolyzer) for FC. Though not renewable, diesel generators and reciprocating engines are also still commonly used for a wide range of power applications, particularly in remote areas, and as backup energy sources in some standalone systems such as a power source for a remote telecommunication tower. The diesel engine's mature technology, relatively cheaper price, low fuel cost, and high fuel efficiency have kept diesel generators in the market. They are also reasonably fuel tolerant and can be considered renewable power sources when fueled by renewable fuels such as bio-fuel.

In general, the key drivers for the deployment of the above energy systems are their perceived benefits, such as reduced carbon emission, improved power quality and reliability, and in

some cases, combined heat-and-power (CHP) operation (e.g., for MT and FC), which will increase their overall system efficiency significantly. In the past half century, extensive research has been conducted in the RE/AE area worldwide, including feasibility studies, computer modeling, control, and experimental work, e.g., [1]–[5]. As a result, the use of wind and PV power generation has become a reality and extensive work is underway on other RE/AE generation technologies such as ocean wave and tides, osmotic, geothermal, FC, and MT. Much work is also needed on the more mature technologies and associated energy storage schemes to improve their operational performance and reliability. Because of the intermittent nature of many RE resources (e.g., wind, solar, ocean wave), hybrid combinations of two or more of their relevant power generation technologies, along with storage and/or AE power generation, can improve system performance. For example, wind and solar energy resources in a given area are somewhat complementary on a daily and/or seasonal basis. In general, hybrid systems convert all the resources into one form (typically electrical) and/or store the energy into some form (chemical, compressed air, thermal, mechanical flywheel, etc.), and the aggregated output is used to supply a variety of loads. Hybridization could result in increased reliability; however, proper technology selection and generation unit sizing are essential in the design of such systems for improved operational performance, and dispatch and operation control [6]–[10]. Different generation sources may also help each other to achieve higher total energy efficiency and/or improved performance. For instance, a fuel cell/microturbine combined-cycle system can better utilize the energy available in the fuel to achieve a significantly higher overall system efficiency than either source can possibly achieve [11]–[13], or the response of an energy source with slower dynamic response (e.g., wind or FC) can be enhanced by the addition of a storage device with faster dynamics (such as a battery bank, super capacitor, or flywheel) to meet different types of load requirements, e.g.,

TABLE I

DIFFERENT RE/AE POWER GENERATION TECHNOLOGIES AND ENERGY STORAGE DEVICES

Main RE/AE Technologies	Energy Storage Types
Bio-mass	Battery
Geo-thermal	Compressed Air
Hydro/Micro-hydro	Flywheel
Ocean tidal/Wave	Hydrogen
Solar/PV	Pumped hydro
Wind	SMES
Fuel cell	Super capacitor

slowly varying loads and fast load transients [14]–[16]. Storage is an integral part of a hybrid RE/AE power generation system. Capacity-oriented energy storage technologies, such as pumped hydroelectric systems, compressed air energy storage (CAES), and hydrogen storage, generally do not have fast response time and are used for long-term energy storage/release such as managing slow load variations. On the other hand, access-oriented storage devices with fast response time, such as batteries, flywheels, super-capacitors, and superconducting magnetic energy storage (SMES), are used for responding to short time disturbances, such as fast load transients and for power quality issues. References [17] and [18] give a comprehensive explanation of the performance, purpose, and promise of different storage technologies. Table I gives a summary of different RE/AE power generation technologies and different energy storage schemes which may be used in hybrid systems. Any combination of the RE/AE power generation technologies, along with proper storage and possibly combined with a conventional generation technology, e.g., a diesel generator could form a hybrid energy system. For example, a hybrid system could have any combination of wind, PV, MH, MT, conventional diesel generator, storage battery, and FC-electrolyzer hydrogen storage in grid-connected or standalone configuration, often referred to as a microgrid. The outputs from various generation sources of a hybrid energy system need to be coordinated and controlled to realize their full benefits. Proper optimization techniques and control strategies are needed for sizing and for power dispatch from the energy sources to make the entire system sustainable to the maximum extent, while facilitating maximum reduction in environmental emissions, and at the same time minimizing cost of energy production. The optimization problem can, therefore, be multi-objective, sometimes with conflicting objectives, and, therefore, complex. In such cases, only a global optimal point, as a trade-off between several local optimal points corresponding to the different objectives, may be achieved. Such optimization problems are difficult (if not impossible) to solve using analytic techniques. Heuristic multi-objective optimization techniques [19]–[21] and goal-oriented multi-agent systems (MAS) [22]–[24] have shown potential to solve such problems. The remainder of the paper is organized as follows: Hybrid energy system configurations, unit sizing, and energy storage systems are discussed in Section II. Energy management and control are presented in Section III. Statistics on the current status and future trends of renewable power generation and sample applications of hybrid RE/AE systems and microgrids around the world are given in Section IV. Section V presents some critical challenges facing the widespread deployment of RE/AE power generation technologies and vision for future research in this area. Section VI concludes the paper.

2. HYBRIED POWER GENERATION SYSTEM CONFIGURATION

A. Integration Methods

RE/AE sources have different operating characteristics; it is, therefore, essential to have a well-defined and standardized framework/procedure for connecting them to form a hybrid system, or more widely a microgrid, where a local cluster of DG sources, energy storage, and loads are integrated together and capable of operating autonomously [25]. A robust microgrid should also have “plug-and-play” operation capability. Adapted from the concept widely used in computer science and technology, plug-and-play operation here means a device (a DG, an energy storage system, or a controllable load) capable of being added into an existing system (microgrid) without requiring system reconfiguration to perform its designed function, namely, generating power, providing energy storage capacity, or carrying out load control. A suitable system configuration and a proper interfacing circuit [also called power electronic building block (PEBB)] may be necessary to achieve the plug-and-play function of a DG system [26], [27]. There are many ways to integrate different AE power generation sources to form a hybrid system. The methods can be generally classified into three categories: dc-coupled, ac-coupled, and hybrid-coupled [28]. The ac-coupled scheme can further be classified into power frequency ac (PFAC)-coupled and high-frequency ac (HFAC)-coupled systems. These methods are briefly reviewed below.

1) DC Coupled Method

In a dc-coupled configuration, shown in Fig. 1, the different AE sources are connected to a dc bus through appropriate power electronic (PE) interfacing circuits. The dc sources may be connected to the dc bus directly if appropriate. If there are any dc loads, they can also be connected to the dc bus directly, or through dc/dc converters, to achieve appropriate dc voltage for the dc loads. The system can supply power to the ac loads (50 or 60 Hz), or be interfaced to a utility grid through an inverter, which can be designed and controlled to allow bidirectional power flow. The dc-coupling scheme is simple and no synchronization is needed to integrate the different energy sources, but it also has its own drawbacks. For instance, if the system inverter is out-of-service, then the whole system will not be able to supply ac power. To avoid this situation, it is possible to connect several inverters with lower power rating in parallel, in which case synchronization of the output voltage of the different inverters, or synchronization with the grid, if the system is grid-connected, is needed. A proper power sharing control scheme is also required to achieve a desired load distribution among the different inverters [29].

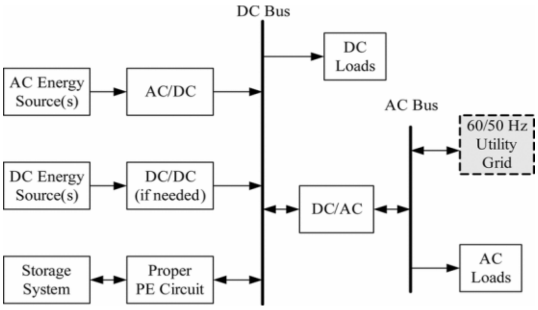

Fig. 1 DC Coupled HPS.

2) AC Coupled Method

AC coupling can be divided into two subcategories: PFAC-coupled and HFAC-coupled systems. The schematic of a PFAC-coupled system is shown in Fig. 2(a), where the different energy sources are integrated through their own power electronic interfacing circuits to a power frequency ac bus. Coupling inductors may also be needed between the power electronic circuits and the ac bus to achieve desired power flow management. The schematic of an HFAC-coupled system is shown in Fig. 2. In this scheme, the different energy sources are coupled to an HFAC bus, to which HFAC loads are connected. This configuration has been used mostly in applications with HFAC (e.g., 400 Hz) loads, such as in airplanes, vessels, submarines, and in space station applications [4]. In both PFAC and HFAC systems, dc power can be obtained through ac/dc rectification. The HFAC configuration can also include a PFAC bus and utility grid (through an ac/ac or a dc/ac converter), to which regular ac loads can be connected.

3) Hybrid Couple Method

Instead of connecting all the DG sources to just a single dc or ac bus, as discussed previously, the different DG sources can be connected to the dc or ac bus of the hybrid system. Fig. 3 shows a hybrid-coupled system, where DG resources are connected to the dc bus and/or ac bus. In this configuration, some energy sources can be integrated directly without extra interfacing circuits. As a result, the system can have higher energy efficiency and reduced cost. On the other hand, control and energy management might be more complicated than for the dc- and ac-coupled schemes. Different coupling schemes find their own appropriate applications. If major generation sources of a hybrid system generate dc power, and there are also substantial amounts of dc loads then a dc-coupled system may be a good choice. On the other and, if the main power sources generate ac (with reasonable power quality for the grid and the connected loads), then an ac-coupled system is a good option. If the major power sources of a hybrid system generate a mixture of ac and dc power, then a hybrid-coupled integration scheme may be considered. It is worth mentioning that the power electronic interfacing circuits in Figs. 2 and 3 can be made as modular building blocks, which will give the systems more flexibility and scalability.

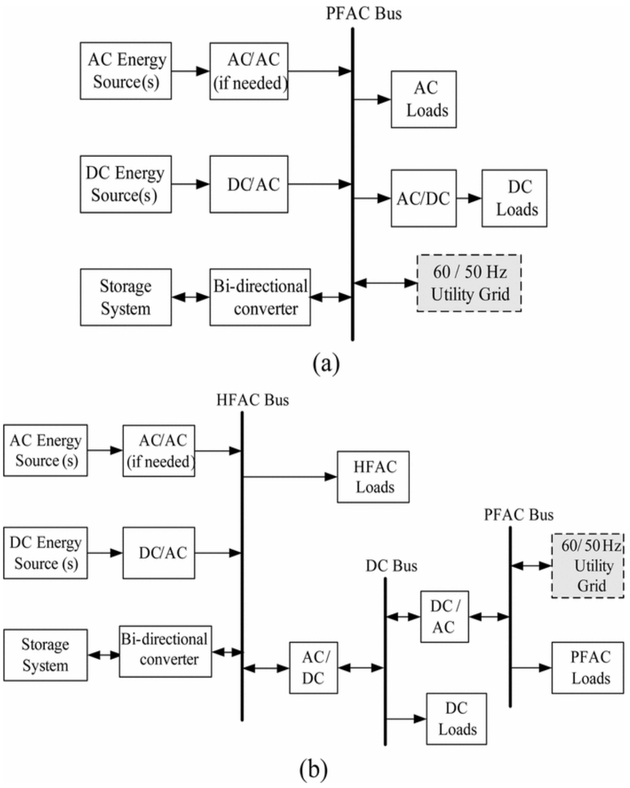

Fig.2. AC Coupled HPS

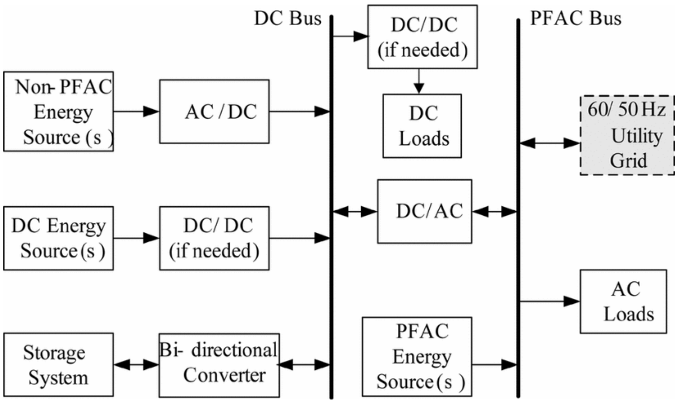

Fig.3 Hybrid coupled HPS

B. Unit Sizing and Technology Selection

The Component sizing of hybrid RE/AE systems is important and has been studied extensively, e.g., [7], [11], and [30]. Selection of the most suitable generation technologies (i.e., suitable mix of RE/AE/conventional sources) for a particular application is also equally important. Available application software can be used to properly select generation technologies. and their sizes for specific applications. For example, with the aid of HOMER software, developed at the National Renewable Energy Laboratory (NREL) [31], a hybrid RE/AE system can be designed; and with the aid of the Distributed Energy Resource-Customer Adaption Model (DER-CAM) software, developed at Lawrence Berkeley National Laboratory (LBL) optimal technology selection for hybrid systems (to operate as independent microgrids) can be achieved. Unit sizing and technology selection can sometimes be as straightforward as meeting certain simple requirements such as using the available generation technology and not exceeding the equipment power rating, or it can be as complex as satisfying several constraints and achieving several objectives to maximum extent at the same time. Normally, based on available statistical information about generation, load, financial parameters (e.g., interest rate), geographic factors, desired system reliability, cost requirements, and other case-specific information, generation technologies and their sizes can be optimized to satisfy specific objective functions, such as minimizing environmental impact, installation and operating costs, payback periods on investment, and/or maximizing reliability. Power system optimization methods such as linear programming (LP) [32], interior-point-method (IPM) [33], and heuristic methods such as genetic algorithms and particle swarm optimization (PSO) can be used for component sizing and energy management of hybrid RE/AE systems. These techniques are especially attractive when multiple objectives are to be met, some of which may be conflicting, e.g., minimizing cost, maximizing system availability and efficiency, and minimizing carbon emission.

C. Storage

1) Storage Diversity: Storage technology is critical for ensuring high levels of power quality and energy management of stationary hybrid RE systems. The ideal storage technology would offer fast access to power whenever needed, provide high capacity of energy, have a long life expectancy, and is available at a competitive cost. However, there is no energy storage technology currently available that can meet all these desirable characteristics simultaneously. In this section, the different types of energy storage devices and systems are covered without going into the details of operation of any specific device. The operational performance and applications of energy storage devices for advanced power applications (also, equally suited for hybrid RE/AE power generation system applications) are, for example, discussed in [17] and [18].

2) Storage Types: In analogy to data storage in computer engineering, a classification in terms of access and capacity orientation may also be considered for energy storage. Among the different types of storage given in Table I, supercapacitors, flywheels, and SMES offer fast access to the stored energy, have a very high cycle life of charge and discharge operations, and very high round-trip efficiency on the order of 95%. However, the cost per unit of stored energy is also very high. Therefore, all three technologies can be classified as access-oriented and support power quality. The usage of SMES can here only be economically justified for applications involving comparatively high levels of power. Batteries could also be classified as high-power and/or high-energy types depending on their design. However, in general, their cycle life of charge/discharge is shorter than the high-access energy storage devices explained above. A promising capacity-oriented energy storage technology is the flow battery. In conventional batteries, chemical energy is stored in reactants, placed near the electrodes inside the battery cell, but in flow batteries, chemical energy is stored in the electrolyte solutions stored in two tanks outside the battery cell stacks. As the solution is pumped to circulate from on storage tank, through a cell stack, to the second tank, ion exchange takes place through the cell porous membrane, and electrons flow through the load to generate electrical power. Several different flow battery chemistries have been developed for MW/MWh-level utility applications [34], [35]. The available electrolyte chemistries include zinc-bromine flow batteries (ZBFB) and vanadium redox batteries (VRB). Other chemistries are under development. An advantage of flow batteries is that their power and energy capacity can be designed independently. A battery power rating can be increased by increasing the cell area where energy conversion takes place, i.e., by increasing the number of cell stacks, while its energy capacity can be increased by using larger volume of electrolyte solutions in larger tanks. Furthermore, flow batteries can be stored and shipped completely discharged as the reaction only takes place when the electrolyte circulation pumps are turned ON. Conventional lead-acid batteries are the least expensive for hybrid energy system applications, but they suffer from a low cycle life. Nickel metal hydride (Ni-MH) batteries and those with sodium sulfur (NaS) chemistry offer significant improvements over lead-acid batteries. Popular commercial applications for Ni-MH batteries have included usage in hybrid electric vehicles (HEVs) and distributed RE systems. NaS batteries have been used in Japan in distributed energy systems and to firm up wind energy in the grid on a large scale, up to 34 MW of power and 245 MWh of energy. The operating temperature of NaS batteries is of the order of 300 C to 350 C, which does not make them attractive for mobile applications. This is in contrast with zinc–bromine batteries that operate near ambient temperature. With increasing interest in electric vehicles, the development of lithium–ion batteries has received a significant boost. They can be well designed as high-power or high-energy batteries. While this is also possible for other battery chemistries, the Li–ion type allows reaching particularly high power-to-weight or high energy-to-weight densities. Compared with other commercially available batteries, conventional Li–ion batteries excel in performance with the exception of cost and life expectancy. Since the cost is relatively high, the main interest relates to mobile applications. Through the vehicle-to-grid (V2G) concept, Li–ion batteries are expected to appear as active resources in distribution networks. Hydrogen can serve as an energy carrier for capacity-oriented energy storage. Hydrogen may be produced through electrolysis, where water is split into its component parts of hydrogen and oxygen. The electrolysis can be powered from renewable

sources. Hydrogen may also be derived through steam reforming from methane or natural gas. The amount of power that can be provided from hydrogen depends on the size of the fuel cell stacks. Hydrogen is flexible in that it can be stored in tanks without disturbing self-discharging effects and can also be used to fill the tanks of fuel cell cars quickly. In stationary applications that use electrolyzers to produce hydrogen and fuel cells to generate electric power, the comparatively low round-trip efficiency is known to be a disadvantage. Very popular in large-scale power systems is the usage of pumped hydro energy storage. It relies on the availability of a suitable geology and is, therefore, not considered further here. Compressed air energy storage is also not considered for the same reasons. In Table II, the storage types that can be considered for hybrid energy systems and have been discussed above are classified. None of the technologies rely on local geology. Whether a battery is designed for high-power or high-energy depends on its intended application.

3) Multilevel Storage: In computer systems, the access-oriented storage serves as a cache for the capacity-oriented storage. This type of integration has allowed creating a storage system that offers fast and frequent access to the stored medium through the cache while also offering a high capacity of storage at a low cost. The concept of cache control can also be designed for the benefit of power and energy systems. For the purpose of illustration, a multilevel energy storage consisting of an access oriented storage serving as the cache for the parallel-connected capacity-oriented. To make sure that the access-oriented storage deals with fast fluctuations of power, the cache control can be realized through filtering to separate the high-frequency power fluctuations from the slowly varying and steady-state power spectrum. Alternatively, knowledge-based control has been proposed for this purpose. The knowledge-based system uses two neural networks to capture a set of rules. While the system integration shown in Fig. 4 offers a high level of performance in the design of hybrid energy systems, it has been common practice to use just one storage technology. Normally, batteries are used and designed for the intended usage. For smaller-scale applications, as in single residential hybrid energy systems, the Ni-MH battery technology would be an appropriate candidate. For larger-scale applications involving the compensation of power from wind farms or multiple residences, flow batteries or NaS batteries have shown to be practical in Japan. V2G concepts are most interesting with Li–ion batteries [36]. 1) Storage Diversity: Storage technology is critical for ensuring high levels of power quality and energy management of stationary hybrid RE systems. The ideal storage technology would offer fast access to power whenever needed, provide high capacity of energy, have a long life expectancy, and is available at a competitive cost. However, there is no energy storage technology currently available that can meet all these desirable characteristics simultaneously. In this section, the different types of energy storage devices and systems are covered without going into the details of operation of any specific device. The operational performance and applications of energy storage devices for advanced power applications (also, equally suited for hybrid RE/AE power generation system applications) are, for example, discussed in [17] and [18].

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3. CONTROL AND ENERGY MANAGEMENT

In a centralized control paradigm, the measurement signals of all energy units in a group, i.e., a microgrid, are sent to a centralized controller, as shown in Fig. 5. The centralized controller acts as an energy supervisor [37] and makes decisions on control actions based on all measured signals and a set of predetermined constraints and objectives. It will prioritize and manage energy utilization among the various energy sources of the microgrid. The objective functions could be conflicting; for example, minimizing system operation and maintenance costs and environmental impact (carbon footprint), and maximizing system efficiency at the same time may be competing objectives and could make solving the problem even more difficult. Often, multi-objective problems do not have a single solution but a complete non-dominated or Pareto set, which includes the alternatives representing potential compromise solutions among the objectives. This could make a range of choices available to decision makers and provide them with the trade-off information among the multiple objectives effectively [38]. The control signals are then sent to the corresponding energy sources to output proper power. The advantage of this control structure is that the multi-objective energy management system can achieve global optimization based on all available information. However, the scheme suffers from heavy computation burden and is subject to single-point failures [7].

4. CHALLENGES AND FUTRUE OF RE/AE POWER GENERATION TECHNOLOGIES

In this section, a partial list of challenges facing the widespread deployment of RE/AE power generation technologies and future visionary research areas are presented.

A. Challenges

Despite their significant benefits to the environment and great long-term potential for sustainable energy development, hybrid RE/AE systems are currently in an economic disadvantage position because of their high installation costs compared with traditional electricity generation technologies. In the majority of cases, the incentives from federal and state governments and local utilities are necessary to make a hybrid system economically viable, which, in turn, makes the incentive policies so critical to the widespread deployment of such systems. Energy storage is necessary for standalone hybrid RE/AE systems to have continuous, reliable power supply with desired power quality. Energy storage is also one of the enabling technologies to accommodate grid-scale renewable generation sources into power systems at high penetration. Among the different energy storage techniques discussed in Section II-C, only pumped hydroelectric storage and underground CAES are the two technologies which can provide a competitive system cost . However, they are heavily geographically constrained and only suitable for large grid-scale energy storage applications. On the other hand, batteries are the most common energy storage technologies for distributed hybrid RE/AE systems. Though the requirement of energy density and specific energy are not so critical to stationary energy storage applications, system cost and durability are still the key barriers for battery storage systems. Moreover, it is a very challenging task to accurately gauge and estimate the state of charge (SOC) and state of health (SOH) of batteries, in particular, as electric vehicles are being put on the road around the world. Therefore, new battery technologies deserve more research attention and efforts to improve their durability and performance, and lower their cost.

B. Vision for the Future

A partial list of the future research topic areas, which can impact RE/AE power generation and management, is given below:

1) Energy Management and Standardization: As the deployment of hybrid RE/AE systems in the form of independent microgrid increases, the need for real-time energy management of such systems, and robust communication between the individual energy sources of the microgrid, become important tasks and, therefore, deserve further attention. Furthermore, systematic approaches and standardization, e.g., IEEE Standard 1547 [39] and IEC 61850 [40], are needed for efficient and safe deployment of such systems.

2) DC Distribution: With the development of modern equipment and household appliances that use dc voltage, several researchers have explored the virtue of dc Microgrid for localized loads and the idea of completely rewiring homes to run on dc. This venue deserves further attention to explore its technical and economic feasibility.

3) New Semiconductor Devices: The rugged electronic power switching technology using silicon carbide and gallium nitride semiconductors is rapidly advancing [41]. Devices made out of these materials can be operated at much higher frequencies, and such operations can lead to compact inverters, choppers, and other interface systems, which can enhance the overall performance of hybrid RE/AE systems. As these devices become available, research efforts are needed to integrate them into the evolving hybrid systems.

4) Excitonic Solar Cells: This class of solar cells uses Titania nanotube arrays [42] shows considerable promise to harness a larger fraction of the solar spectrum. The availability of this class of devices should be closely monitored for potential use in RE/AE systems.

5) Nanotechnology: In general, the application of nanotechnology to improve various components of hybrid systems should be a constant topic of research and investigation.

6) Hydrogen: Last but not least, the production of hydrogen and hydrogen economy should be a constant future research topic. A breakthrough in this area could revolutionize the way we live.

5. CONCLUSIONS

This paper provides a summary of available approaches and those currently under research for optimal design of hybrid RE/AE energy systems. Different approaches for system configuration, unit sizing, and control and energy management of hybrid systems are presented. Current status and future trends of RE Power Generation, the challenges facing the widespread deployment of RE/AE systems, and research vision for the future of RE/AE power generation technologies have been discussed. The comprehensive list of references at the end of the paper is aimed to help interested researchers in the design and power management of hybrid RE/AE energy systems with focus on energy sustainability.

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