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Exploring the Performance Extents of Hybrid Renewable Energy Systems

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Abstract: The current electricity demand has asserted the mandatory requirement of establishing renewable energy systems. This paper reviews the major contributions on practically establishing the hybrid renewable energy systems. The contributions are investigated for its practical relevance with the growing demand, exploration of various renewable energy resources and performance accomplishment. The perspectives on using various renewable energy resources are also observed to determine the viable resource. Eventually, the research gaps and the worldwide focus on hybrid renewable energy systems are summarized.

Keywords: Renewable, Wind, Photovoltaic, Power, Control.

I. INTRODUCTION

Increasing industrialization, growing population, and the mankind's craving for more and more comfort have resulted in a consistent rise in the demand for electricity. To meet this escalating demand, the number of conventional power generating stations has increased drastically, causing enormous stress on the existing infrastructure. This has led to a rapid depletion of conventional fuel reserves [26]. On the other hand, growing concerns about the harmful effects of conventional fuels on the environment have further complicated the issue and have forced mankind’s attention towards renewable energy sources, such as solar photovoltaic (PV), wind, fuel cell stack, biomass, tidal energy, etc., to meet the growing need of electric energy[27].

The use of such intermittent or variable renewable energy (VRE) sources such as wind power (WP) and Photovoltaics (PV) has been growing during the last decade and is expected to continue to grow worldwide [50]. For instance, a target of 20% mandatory renewable energy by 2020 has been set in European Union (EU), where a reduction of greenhouse gas emissions by 80% by 2050. The growing share of VRE demands increased flexibility in the power system, both in terms of transmission capacity and flexible production. Balancing of the power system is a problem on many different time scales, and the integration of VRE has a potential impact on all these time scales, from a few seconds to a year. Due to production variation, the planning of the operation and balancing the system get more complicated. The expansion of VRE is already having an impact on the economic dispatch of conventional power plants via varying electricity prices, demanding more starts and stops, part-load operation and ramping. There are some concerns that in the new market environment, the profitability of dispatched power plants will not be enough to keep plants in operation and to invest in new capacity [50].

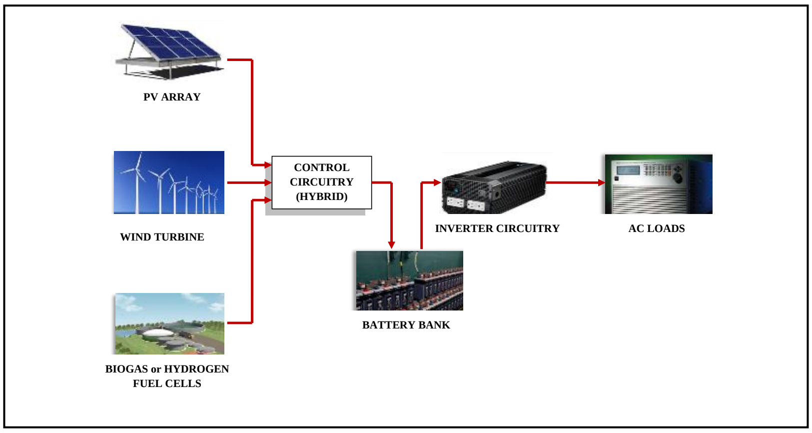

Fig. 1. **A typical HRES using PV array, wind energy, and biogas or hydrogen fuel cells**

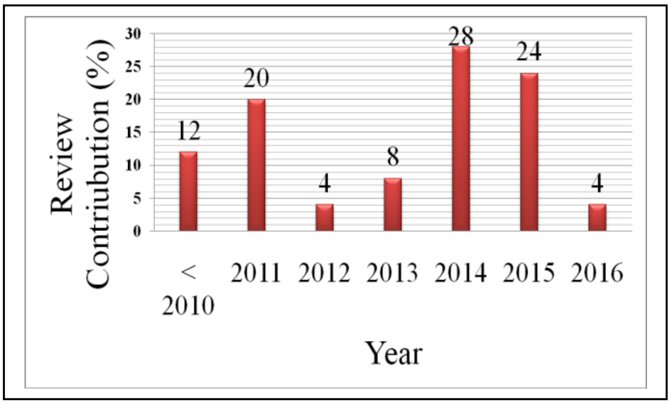

Fig. 2. **Chronological details and the contribution of the literature used in our review**

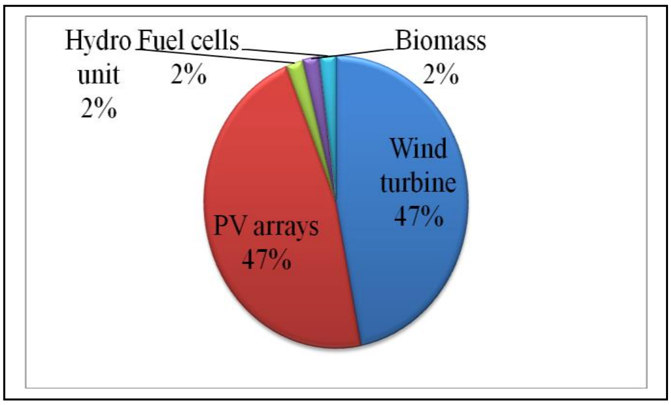

Fig. 3. **Ratio of literary contribution of various REs**

A. *Motivation*

The research ideologies and the contributions to enhance the VREs were numerous. Few contributions have been made on investigating and improving the flexibility. On the other end, integration and balancing of VRE production have also been considered by various research communities in various perspectives. In order to accomplish this, energy storage has been analyzed for its ability to regulate or balance the production deviation from the predicted power from any VRE [51] [52] [53] [54], as well as the flexibility needs in terms of the need for regulating power [55]. The Optimal sizing, design, and operation of energy storage to firm wind power has also been investigated [56] as well as the use of conventional hydropower to firm wind power both in the intra-day time scale [57], and in the seasonal time scale [58]. From a system perspective, backup power, energy storage, and transmission capacity are complementary strategies to handle balancing of VRE [59] [60]. The mix of WP and PW [61] and the amount of overcapacity in the system [62] also affect the system flexibility need.

Collectively, the literature has asserted the necessity of establishing or hybridizing multiple VREs along with conventional energy systems, since lesser probability of avoiding conventional energy systems, and the methodologies to be adopted for planning, integration and balancing the systems.

Our paper collects various notable research works carried out in the last decade, yet more from the last five years, and reviews them to understand the trending and ability in establishing hybrid renewable energy systems (HRES). The rest of the paper is organized as follows. Section II introduces the background information about the HRES and Section III discusses the key contributions in the research community, whereas Section IV reveals the performance of the system. Section V details the research gaps and challenges reside on the current HRES and Section VI concludes the paper.

II. HYBRID RENEWABLE ENERGY SYSTEM

Numerous RE sources have been reported in the literature, where wind power, solar power, hydropower, biomass energy, geothermal energy and hydrogen fuel cells have found promising positions. Unlike other REs, solar energy and wind power have recently emerged as most prominent due to its no fuel [27] [28] [29]. In addition, biomass is gaining more attention in the recent past because of its cost- effectiveness. In this paper, we present a typical HRES (in Fig. 1) with solar power, wind power, and biomass energy as the REs to supply loads.

The control circuitry consists of individual circuitry for every energy resources. A common control circuitry performs balancing and synchronization process with the conventional energy systems and other Res so that the power quality can be maintained well. A battery bank is used to regulate the power since the VREs enable uncertain deviation between the predicted power and the actual power. The inverter circuit converts the DC power for its compatibility with AC loads and long distance transmission and lossless distribution. Since the wind power and solar energy have highly contributed to the literature, more information about it is discussed in the subsequent Sections.

A. *Wind Energy Systems*

In recent years, the generation of electricity using wind energy as the main source as well as its integration with power grid has developed as a most promising and renowned technology [26]. Several applications make use of wind energy for its operation and few areas that utilize wind energy include water pumping [31] [32], street lighting, stand-alone or grid-connected generating power system [33] and much more. Wind farms with Doubly Fed Induction Generators (DFIGs) are systems that have undergone testing at various periods of time and they are well-suited for variable speed turbine systems, which depend on highly changing wind velocity [63]. A number of control techniques have been put forth in the past with the aim of improving the performance of the wind sourced DFIG systems, even when distorted grid conditions, weak area electric power system or similar other conditions exists [63] [64] [65] [66] [67]. Liu et al. [66] and Xu et al. have given eminent solutions to suppress harmonics, which occur in stator circuits, with the help of rotor side converter control. Nian et al. [68] have introduced a modified control methodology through which the entire active, as well as reactive power output of DFIG, could be smoothened out when distorted grid voltage conditions persist. Yet, utilization of wind energy is not always possible because the output power changes with changes in weather or climate [30].

TABLE I. FOCUS OF RESEARCHERS ON VARIOUS RES

Year	Author [Citation]	Renewable energy systems				
		Wind	*PV*	*Hydro*	*Biomass*	*Fuel cells*
2005	R. Eke, O. Kara and K. Ulgen [1]	✓	✓			
2007	Sh. I. Klychev, *et al* [2]	✓	✓			
2008	Nabil A. Ahmed, *et al* [3]		✓			
2011	L. Lakatos, *et al* [4]	✓	✓			
2011	Abd El-Shafy A. Nafeh [5]	✓	✓			
2011	K. Mousa, A. Diabat [6]	✓	✓			
2011	Pawan Sharma *et al* [7]	✓				
2011	V. V. Elistratov and Ye. S. Aronova [8]	✓	✓			
2012	Lin Ye *et al* [9]	✓	✓	✓		
2013	Lin Xu *et al* [10]	✓	✓			
2013	I. Baniasad Askari *et al* [11]	✓	✓			
2014	Jinn-Chang Wu and Chia-Wei Chou [12]		✓			
2014	Jianxiao Zoua *et al* [13]	✓	✓			
2014	Matthias Huber *et al* [14]	✓	✓			
2014	N. Mezzai *et al* [15]	✓	✓			✓
2014	Tao Ma *et al* [16]	✓	✓			
2014	Mohammad Ali Yazdanpanah Jahromi *et al* [17]	✓	✓			
2014	S.G. Malla and C.N. Bhende [18]	✓	✓			
2015	Onur Ozdal Mengi and Ismail Hakki Altas [19]	✓	✓			
2015	F.J. Santos-Alamillos *et al* [20]	✓	✓			
2015	S. Aissou *et al* [21]	✓	✓			
2015	S. Kumaravel and S. Ashoka [22]	✓	✓			
2015	Arnau González *et al* [23]	✓	✓			
2015	C. Viveiros *et al* [24]	✓				
2016	A. Perez-Navarro *et al* [25]	✓	✓		✓	

B. *PV Array Energy Systems*

The distribution power systems of the modern era are making use of solar power generation systems to a larger extent with the objective of eradicating the adverse effects of the greenhouse emissions all around the globe [34]. The solar power generation systems are growing in number due to the reduced cost associated with the solar cells or PV arrays. Hence, most of the residential applications will be benefited with even a small-capacity distributed power generated system that employs solar energy in the upcoming years. The output from a solar cell array is usually an intermittent DC power and therefore, the grid-connected solar power generation systems greatly rely on the task that the power conversion interface performs [35] [36].

III.MODELING AND CONTROL OF HRES

A. *Chronological perspective*

Before 2010, numerous contributions have been made in the literature on HRES. This paper addresses 25 research articles from leading publishers, who deal with energy systems. The acquired articles have been categorized as, articles prior 2010 and articles after 2010. The graphical illustration in Fig. 2 shows the chronological representation of the review contribution of this paper.

Prior 2010, studies have been investigated to validate the availability of the wind and solar energy generation in Energy Institute of Ege University, Izmir, Turkey, where, monthly average solar irradiation and wind speed data were measured. The measurements consisted of hourly records over an eight-year period from 1995–2002. Simple models were developed to determine the wind, solar, and hybrid power resources per unit area. Correlations between the solar and wind power data were carried out on an hourly, daily, and monthly basis [1]. In 2007, the technical and economic performance of solar and wind power plants have been investigated using a proficient model [2]. In 2008, solar photovoltaic and a wind turbine have been combined to construct a hybrid energy system [3]. A simple and cost-effective control technique has been proposed for maximum power point tracking from the photovoltaic array and wind turbine under varying climatic conditions without measuring the irradiance of the photovoltaic or the wind speed [3].

Since 2010, the research contributions have found a new path to define HRES in a feasible manner. In 2011, the detailed examination has been made of the proportion of the disability of the solar and wind energy in the course of the year. Studies have also been accelerated to understand the deviation between the simultaneous dispersibility of the two types of sources of energy with respect to seasonal changes on the monthly, hourly and daily basis [4]. Meantime, attempts have been made to optimally design the photovoltaic (PV)-wind hybrid energy home system by incorporating a storage battery. This formulation has been carried out with the purpose of arriving at a selection of the system economical components that can reliably satisfy the load demand [5]. Another possibility of optimal design of the wind and solar power has been reported in [6], where the several design parameters which are pertinent to the plant's performance are optimized, such as the number of photovoltaic modules, the wind turbine height, the number of wind turbines, and the turbine rotor diameter. An isolated hybrid power system has been developed and a reactive power control has been proposed in 2011 [7] using a proportional-integral (PI) controller with a static synchronous compensator (STATCOM). A practical method for simulating the operation and optimizing the parameters of the system for a self-contained power supply (SCPS) based on renewable energy sources has also been proposed [8].

In 2012, dynamic models of the main distributed generators including PV cell, wind turbine, hydro turbine as well as the equivalent power electronic interfaces, battery unit of PV and excitation system of the hydro turbine have been modeled [9]. The authors have also developed control strategies based on active power/frequency and reactive power/voltage drops for the power control of the inverters [9].

In 2013, an improved optimal sizing method for wind-solar-battery hybrid power system (WSB-HPS), considering the system working in stand-alone and grid-connected modes have been developed [10]. In [11], a hybrid (photovoltaic, PV/wind/fuel cell, FC) system comprising different combinations of PV arrays, wind turbine, hydrogen tank, an electrolyser, and FC has been investigated for stand-alone applications.

In 2014, a solar power generation system, which is composed of a DC/DC power converter and a new seven-level inverter has been reported in [12], while an active power allocation method based on multi-objective optimization technique for wind-solar-batteries hybrid system (WSBHPS) has been proposed [13]. In [14], an analysis of time series of load, wind, PV and the resulting net load in scenarios for Europe that allow quantifying flexibility requirements in future power systems with high shares of variable generation has been performed. In [15], identification and modeling of a hybrid photovoltaic/wind/fuel cells power system have been presented. In [16], the techno-economic analysis of the standalone hybrid solar–wind-pumped storage system for an isolated microgrid has been presented. In [17], a new sizing methodology has been developed by considering resource uncertainties associated with wind speed, solar irradiation, and load demand. In [18], novel control algorithms have been developed for HRES to maintain the voltage levels to its reference voltage irrespective of variations in wind speed, solar irradiance, and load.

In 2015, an intelligent energy management system (IEMS) for maintaining the energy sustainability in renewable energy systems (RES) has been reported [19]. In [20], an analysis has been done to understand the extent to which the combination of wind power and CSP can produce stable or even base load power in a particular region. In [21], another system identification and controlling method have been presented for HRES. In [22], a DC-linked stand-alone solar photovoltaic (PV)/wind/battery HRES has been introduced. Focuses have also been made on the optimal sizing of hybrid grid-connected photovoltaic–wind power systems from real hourly wind and solar irradiation data and electricity demand from a certain location [23]. An onshore variable speed wind turbine with doubly fed induction generator and under supervisory control has been presented in [24].

In 2016, reliability problems have been addressed in [25] and it has been rectified by optimal design of HRES. The HRES has included PV arrays, wind turbine and biomass gasification plant accompanying with energy storage [25].

TABLE II. Exploration of various performance investigations carried out in the literature

Authors [Citation]	Output power	Output Energy	SOC	Output voltage	Voltage change	Output current	Capacity factor	Losses	Frequency
R. Eke, O. Kara and K. Ulgen [1]		✓#							
Sh. I. Klychev, *et al* [2]									
Nabil A. Ahmed, *et al* [3]	✓								
L. Lakatos, *et al* [4]		✓#							
Abd El-Shafy A. Nafeh [5]	✓		✓						
K. Mousa, A. Diabat [6]	✓#								
Pawan Sharma *et al* [7]					✓				
V. V. Elistratov and Ye. S. Aronova [8]	✓*								
Lin Ye *et al* [9]	✓			✓					
Lin Xu *et al* [10]	✓$								
I. Baniasad Askari *et al* [11]									
Jinn-Chang Wu and Chia-Wei Chou [12]	✓								
Jianxiao Zoua *et al* [13]	✓		✓						
Matthias Huber *et al* [14]									
N. Mezzai *et al* [15]						✓			
Tao Ma *et al* [16]	✓		✓						
Mohammad Ali Yazdanpanah Jahromi *et al* [17]									
S.G. Malla and C.N. Bhende [18]	✓								
Onur Ozdal Mengi and Ismail Hakki Altas [19]	✓			✓		✓			
F.J. Santos-Alamillos *et al* [20]							✓		
S. Aissou *et al* [21]				✓					
S. Kumaravel and S. Ashoka [22]	✓								
Arnau González *et al* [23]									
C. Viveiros *et al* [24]	✓								
A. Perez-Navarro *et al* [25]								✓	✓

B. METHODOLOGY

A graphical method worked on meteorological data has been used to optimize the hybrid system, which has solar and wind energy systems [1]. The pre-requisites to construct such hybrid systems have been discussed well in [2]. In [3], a simple cost-effective controlling technique has been introduced for maximum power point tracking from the photovoltaic array and wind turbine under varying climatic conditions without measuring the irradiance of the photovoltaic or the wind speed. In [5], heuristic search algorithm such as Genetic Algorithm (GA) has been exploited for the optimal design of the parameters of PV array and wind turbine so that the system cost has been reduced significantly over the individual systems. In [6], the complementary nature of the wind and solar energy resources has been characterized for optimal design of HRES. In contrast to the earlier contribution, authors of [7] have worked on introducing STATCOM with PI controller for reactive power control of their HRES. Methods have been proposed to simulate and optimize the system parameters of the self-contained power supply (SCPS) using renewable energy sources [8]. In addition, simulations based on the dynamic models for various REs have been reported along with the necessary control strategies based on the active power or frequency and reactive power/ voltage drops [9]. In [10], an improved optimal sizing method for the wind solar-battery hybrid power system has been proposed. An optimization tool from NREL, termed as HOMER, has been used by researchers [11] to perform techno-economic analysis of stand-alone hybrid (PV/wind/FC) energy systems to supply the load requirements of a typical residential apartment.

A typical solar power generation system composed of a DC/DC power converter and a seven-level inverter has been introduced in [12]. The seven-level inverter of [12] contains only six power electronic switches, which has simplified the circuit configuration. A power allocation method introduced in [13] has been formulated as a multi-objective optimization problem and solved using a pattern search algorithm. A time series analysis has been employed in [14] to estimate the deterministic flexibility of the HRES, whereas a techno-economic analysis and sensitivity analysis have been presented in [16], for a standalone hybrid solar–wind-pumped storage system of an isolated Microgrid.

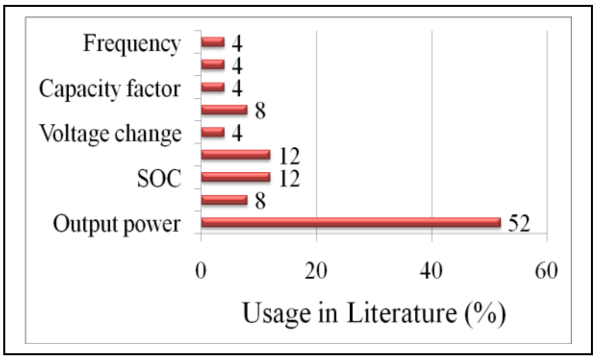

Fig. 4. **Ratio of literary contribution of various performance metrics**

In [15], a global control and system identification methodology have been presented. The authors in [17] have developed a sizing methodology to handle the multi-objective function that considers inequality coefficient, correlation coefficient, and annualized system cost. The line voltages of the HRES have been balanced at the point of common coupling (PCC) has been accomplished by the controlling strategy introduced in [18]. The IEMS [19] have maintained the energy sustainability and the PMA have gathered the power from REs. The maximum usability of the wind power has been investigated in [20] by determining the spatial variability of wind power and CSP capacity factors, whereas a system model and its controlling operation has been successfully presented in [21]. An HRES model based on wind and PV sources have been simulated in MATLAB/Simulink platform for which the performance investigation has been carried out in [22]. An optimization algorithm that calculates the optimum sizing for a grid-connected HRES according to a given electricity demand has been developed in [23]. In [24], an event – based supervisor deployment for supervision level and two distinct controllers for the execution level have been proposed for an onshore WECS with DFIG, using simulations in Matlab/Simulink to determine the performance of the proposed controllers. The supervisory control has determined the operational state according to with the data from the wind and generator speed and sends the state to the controllers in the execution level. The fuzzy PI and discrete adaptive LQ controllers have regulated the VSWT blades to maintain the generated power around the rated power. Overall, the fuzzy PI controller has allowed a smoother closed loop response at the expense of large variations of the pitch angle and frequent switches between regions while LQ controller has presented larger consumption of control and oscillatory closed loop response. According to [25], a laboratory, termed as LADDER, has been constructed to investigate the feasibility of HRES at specific instants.

C. *Research Claims*

The hybrid system [1] can be applied for the efficient and economic utilization of these resources. The cost of the hybrid system for the Solar Energy Institute building was found to be less than those of the individual PV and wind systems [1]. In [3], it has been claimed that their hybrid system was simple, easy to control and cost – effective. Though the hybrid system is established well, lack of knowledge about the energy sources will lead to failure. A positive analysis has been made in [4] to overcome such effects. According to [4], such hybrid systems can be expanded only when both the temporal and spatial relevance of the energy sources are studied. In [5], hybrid wind and solar power systems, which are optimally designed by the contributors, have incurred lesser cost than individual wind or solar power system. Using the parametric optimization in [5], the authors have claimed that their optimized HRES can reliably deliver energy throughout the year, to meet variable seasonal demand, by taking advantage of the complementary nature of sources.

Apart from them, usage of STATCOM devices, as recommended in [7], have claimed to adjust the power output depending upon the condition of wind either at constant or at variable slips and will absorb or generate reactive power as per the requirement of the system. As the increase in input wind power has claimed to change the induction generator slip, thereby the reactive power requirement has changed [7]. The total costs incurred to set the optimized HRES [8] have been proved to be lesser than the conventional engine – driven power generation systems. Similar cost-based analysis have been done on the HRES [11] in which their system has incurred lesser cost than the traditional systems. In addition to the cost analysis, reduced energy storage has been asserted in [16], while using HRES. According to [23], 25 years of exploiting their HRES may lead to 40% of cost reduction over the traditional energy generation units.

The performance of HRES has been ensured even under the varying composition of REs [17]. The optimal sizing method introduced in [10] has ensured high reliability on the power supply as well as less fluctuation on the power to be injected. The attempts to reduce the fluctuation and to improve the power output have also succeeded in [13]. The reduced fluctuation on HRES has also been reported in [20]. The system reliability has also been ensured in [22], where DC-link storage system has been developed for HRES. According to [14], 20-30% of expandable or flexible energy can be met by their HRES. The seven-level inverter introduced in [12] has been tested and succeeded for its low switching power loss and improved power efficiency. The control strategy adopted in [21] has been claimed for its simplicity. A smooth controlling operation has been ensured by fuzzified PI control, as per [24]. The THD analysis performed in [18] has ensured that their hybrid system is has reduced THD of just about 5%. The IEMS has been claimed to be suitable to the environment, where the availability of REs and the demand are uncertain [9].

IV. EXPLORATION OF RENEWABLE ENERGY RESOURCES

A. *Ratio of Usage of Renewable Energy Resources*

In literature, numerous renewable resources have been examined to investigate the suitability in terms of both meetings the growing electricity demand as well as the resources availability. As per our literary collection, the majority of the researchers have focused on wind energy or solar energy or the combination of both or its combination with other energy resources, which can be either renewable or conventional. The summary of its contribution in the literature is given in Table I and Fig. 3, in the perspective of the impact on research and the renewable energy resources, respectively. Based on the literary summary, the interestingness among the researchers on the renewable energy resources can be interpreted well. It reveals that 23 out of the total research articles have worked on wind energy and solar energy, which is extremely than the usage of other resources such as hydro unit, biomass, and hydrogen fuel cells. It interprets that 92% of the research articles have referred wind energy and solar energy, whereas only 4% of the articles have worked on the other energy resources. These can be well summarized by Fig. 3 in which ratio of usage (in percentage) are plotted in pie-chart. Out of the total usage, solar and wind energy have contributed equally by 47%.

TABLE III. EXPLORATION OF VARIOUS PERFORMANCE INVESTIGATIONS CARRIED OUT IN THE LITERATURE

Year	Author [Citation]	Various REs			
		PV Array	*Wind Turbine*	*Miscellaneous REs*	*Total Power (in case of HRES*
2005	R. Eke et al [1]				
2007	Sh. I. Klychev et al [2]				
2008	Nabil A. Ahmed et al [3]	750 W	1750 W/1000 W		1750 W
2011	L. Lakatos et al [4]				
2011	Abd El-Shafy A. Nafeh [5]	5900 W	$2.45x10^2$ W		$3.1 x10^2$ W
2011	K. Mousa, A. Diabat [6]				
2011	Pawan Sharma et al [7]				
2011	V. V. Elistratov and Ye. S. Aronova [8]				
2012	Lin Ye et al [9]				
2013	Lin Xu et al [10]				350 kW
2013	I. Baniasad Askari et al [11]				
2014	Jinn-Chang Wu, and Chia-Wei Chou [12]	400 W			
2014	Jianxiao Zoua et al [13]				9000 kW/9000 kW/12000 kW
2014	Matthias Huber et al [14]				
2014	N. Mezzai et al [15]				
2014	Tao Ma et al [16]	22.5k W	4 kW		
2014	Mohammad Ali Yazdanpanah Jahromi et al [17]				
2014	S.G. Malla and C.N. Bhende [18]	4100.002 W	2399.998W	8916.665W	
2015	Onur Ozdal Mengi and Ismail Hakki Altas [19]	1100 W/750W	500W/750W		
2015	F.J. Santos-Alamillos et al [20]		2MW/3MW		
2015	S. Aissou, D. et al [21]		900 W		
2015	S. Kumaravel and S. Ashoka [22]	75 W	5 KW		
2015	Arnau González et al [23]		200 KW		
2015	C. Viveiros et al [24]		5 MW		
2016	A. Perez-Navarro et al [25]	1100W/1500 W	2500 W	5300 W/5000 W	4100 W

B. *Performance Review*

Though the HRES has been built under varying the experimental setup and environment, it is found to be essential to understand its performance. Many metrics have been reported in the literature for evaluating the HRES, its modeling and controlling methodologies that include electrical components such as storage batteries, etc. Most of such metrics have been temporally analyzed. In other words, the output power or voltage or energy exhibited by the HRES with respect to time or month or days has been investigated. In addition to the power and voltage, few other metrics have also been considered by the researchers. In Table II, such metrics have been acquired and summarized for our better understanding.

It refers only to the renowned metrics to determine the metrics that has gained significant attention from the researchers. In Table II, the superscripts such as *, # and $ refer to the temporal parameters such as time slot, month and combination of time and month, respectively. The absence of such symbols refers to time. According to the contribution of the researchers, the output power has been converged as the interesting metrics to define the performance of HRES, since it has been exploited by 52 % of the collected literary works. Frequency, losses, capacity factor and change in voltage with respect to time or time slot or month have been used by only 4% of the researchers. Output current and energy have been exploited by 8% of the researchers, whereas 12% of the researchers have used output voltage and SOC to demonstrate the system performance.

The relative usage of output power with respect to the least used metrics such as frequency, losses, capacity factor and change in voltage gains higher margin, i.e., the researchers who have used output power to demonstrate the performance is 92% more than those who have used the metrics such as frequency, losses, capacity factor and change in voltage. Similarly, 77% more researchers have focused on the output power than the researchers who have focused on the second frequently used metrics such as output voltage and SOC. The margin between these two levels does not show a big difference. In other words, the next highly contribution metrics and the least contributed metrics are far behind the contribution of output power. Hence, we can identify that the output power with respect to the temporal variation remains as a promising metrics to define the performance of the HRES. Though it has been widely used, the methodologies that have not been examined under such metrics remains uncertain. Since the further investigation is required on understanding such HRES, it can be considered as the open challenge among the researchers.

The 52% of the research contributions have been further subjected to review in terms of quality. Though the environmental conditions, geographical information, and meteorological nature vary among the works, we consider them under the same platform to determine the characteristic of the HRES. In Table III, we have presented the achieved output power versus time by various HRES, its modeling and controlling scenarios. The given results are approximated from the results published in the literature. The precision of the results remains uncertain as the experimental setup and the environment vary to each other. The results are collected from the literature at any of the instants, yet we maintained to acquire the maximum achieved power.

V. PRACTICAL IMPLICATIONS AND CHALLENGES

A. *Global Plans on Establishing HRES*

Most of the power systems of near future are believed to use renewable energy for its operation to a larger extent. In particular, the variable renewable energy (VRE) sources, namely, the wind and the solar PV are thought to grab a great share in the upcoming years [37]. The future market trends, the elevated growth rates of the present day, ambitious policy targets and support policies, scenario outcomes, and many other factors serve as the evidence for the considerable growth in the utilization of VRE sources. The "Renewables global status reports" of 2013 and 2014 reveals that variable renewable electricity is being quickly spread all around the globe and in addition, the wind and the solar PV are observed to exhibit a worldwide annual growth rate of 21% and 55% in order, especially from late 2008 to 2013. The power generating capacity of the renewables have already crossed the power generating capacity of the conventional fuels, like nuclear and fossil fuels in 2012. Denmark, Germany, and Spain have owned about 56%, 25% and 42% renewable electricity generation shares in a respective way. In all the three countries, the majority of the renewable electricity generation shares were from the wind as well as the solar energy. The future policy makers have fixed the renewable energy targets in 138 countries. In addition, they have also implemented support schemes to render targets that mitigate climate-change with improved energy security and for lessening the externalities like air pollution. For instance, by 2050, about 100% renewables have been targeted in Denmark in their final energy consumption and about 80% renewables have been planned to be utilized in the power sector in Germany. In 2030, the European Council has set to implement an EU-wide binding target of not less than 27% renewables in final energy. The 'Energy Roadmap 2050' states that the share of renewables can be imagined to grow massively in almost all decarbonisation circumstances and thereby, the European commission have targeted to use not less than 55% of renewables in final energy. Most of the states in the US have hiked the shares on renewable electricity in their standards. For instance, 30% and 33% increased targets by 2030 have been set by Colorado and California, respectively [37].

B. *Research Gaps*

1) *System Integration Costs:* Both long-term and bottom-up resource assessment studies have ensured the significant role of renewable energy in accomplishing the climatic stability targets [38] [39] [40]. Along with the global agreements on exploiting the renewable energy, the individual policies to mitigate the climatic changes had led to the contribution of renewable energy can be achieved as 30-80% of the total energy consumption by mid of the century. This is a massive increase from the current contribution, which is just 13%.

   However, the range of accomplishment is huge that is because of the uncertainties forecasted about the compliments for renewable energies. According to the investigations carried out in [41], 50% of the forecast models have asserted that more than 59% of contribution in the total energy can be made by renewables, whereas a specific model has asserted for just 35% or sometimes greater than it. Yet, even such minimal contribution can make significant mitigation of the climatic change. Under such circumstances, the renewable energy systems should be integrated with the global energy systems. However, the integration finds difficulties in characteristic differences between the renewable and conventional energy systems. Though such difficulties will not remain as a barrier for integration, they introduce system level costs, which are called as integration costs [42]. The costs remain and open-ended challenge because it highly relies on the unavoidable characteristics such as uncertainty, spatial and temporal variabilities.

2) *Output Uncertainty:* The wind speed and solar irradiation are naturally varying over and they are not precisely predictable. Lack of methods to ensure precise prediction of such natural variations often leads to poor predictability of output power. This makes the VRE output always uncertain. This uncertainty can be handled by short-term balancing services and introduce operating reserve capacity. According to [43], [45], [46], the balancing services incur 10% of the generation costs. It can be reduced further by introducing precise forecasting techniques [37]. Though the balancing costs are relatively less and the

option to reduce it further, the current literature lags in having such forecasting techniques or reducing balancing costs constraints.

3) *Spatial Variability:* Since the wind speed and the solar irradiation varies with respect to location, their output remains spatially varying. Unlike nuclear or fossil fuels, these renewable energy resources are non-transportable. Moreover, the demand is also varying with respect to location and as a result, there is huge need to transmit the generated power from one end to another end. This can introduce a considerable transmission cost to the renewable energy system. The problem becomes more complex, because of lack of methodologies to estimate the grid costs precisely. According to the grid cost estimation by Germany's power sector [47], National Renewable Energy Laboratory (NREL) of US [48] and other European models for wind energy integration [43], the transmission grid costs are found as relatively higher than balancing and smaller than generation costs. Despite it is asserted as smaller than the generation costs, huge exploitation and transmission of the energy may make the role of the transmission costs significant.

4) *Temporal Variability:* The solar and wind energy availabilities are varying over time. This can have two impacts on the output performance. The first impact is on ramping and cycling of the conventional plants, where they should be increased further. Yet, the studies [46] [47] [48] have compromised on it, because of its relatively lesser cost and the negligibility while increasing the contribution of renewable energy. The second impact is on meeting the demand, which also temporally varies and cannot be matched with the output profile. The price inelasticity and lack of provision to storing the generated power make the second impact more significant. The current literature has not provided much attention on considering this impact while concentrating on balancing, grid transmission, ramping and cycling. Few economic studies have ensured acute cost reduction from 110% to 50-80%, while the wind energy contributes 30% of the total electricity consumption [44] [49]. Though it remains positive, the said measure is from economic analysis, which lags in the technical viabilities to attain them.

CONCLUSION

The devastating reduction in the availability of conventional resources and their costs has increased the necessity to find suitable renewable energy resources. This has gained considerable attention by the researchers, especially in the last five years. The research works have led to the feasibility of using renewable energy resources such as solar energy, wind energy, etc. Significant contributions have also been made to introduce precise modeling and robust control of HRES to improve the productivity of the electrical energy. The review of such contributions has revealed the current status of the contributions, their viabilities and the performance extent. The research challenges and the global focus on the REs remain useful for future research works.

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