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DISTRIBUTED WIND LITERATURE REVIEW

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ABSTRACT

Distributed wind refers to the approach of generating wind energy on a small scale, creating a localized alternative to centralized electricity generation. The National Renewable Energy Laboratory (NREL) places wind turbines below 1 MW of electrical generation capacity into this category. Additionally, proximity to end users is a major distinction of distributed wind. The exponential growth of renewable energy (RE) has unveiled inherent limitations within our grid system regarding its capacity to meet the power demands of the future sustainably. Small-wind has gained popularity in recent years as more people move to rural, off-grid areas, creating situations more suitable for this type of turbine. This literature review attempts to assess some of the ways that small scale wind turbines can and have been used as an alternative to large, centralized power stations. By exploring the existing research, technological advancements, and case studies, insights can be provided into the potential of distributed wind energy. Areas most likely to benefit from further research and development can be identified as well.

1. DISTRIBUTED ENERGY RESOURCES

The term Distributed Energy Resources (DERs) refers to a variety of small-scale electricity generation and storage combinations, all happening close to the point of consumption. These resources can be deployed individually or aggregated, with the goal of providing energy services to homes, businesses, communities, farms, vehicles, and industrial plants. DERs can either be integrated into the electricity grid or used as an off-grid system to provide energy independence, resilience, and a clean power solution. The contribution of these systems to sustainable power development in off-grid scenarios is particularly exciting and is a focus of this literature review. Historically, grid-integrated small renewable generators have received more research attention, primarily due to the widespread presence of centralized electricity. Grid-connected DERs can also benefit from net metering arrangements, where excess energy can be sold back to the utility.

History has shown the repercussions that can arise from excessive reliance on a single source of energy production.. Research shows that distributed RE generation can provide part of the solution to modern efforts to increase and diversify electricity supply sources, reduce reliance on fossil-fuels, and avoid congestion on transmission infrastructure. NREL's Renewable Electricity Futures Study is focused on devising the least-cost energy portfolio for achieving 80% renewable electricity by 2050, and DERs play a significant role in several of those scenarios [6].

Surprisingly little research is available for evaluating the tradeoffs between centralized and distributed portfolios. DERs are small, modular, and dispersed when compared to conventional power plants entailing a distinct set of cost considerations and a nuanced comparison of the levelized cost of electricity. The "hidden value" of distributed resources may be resulting merits including avoided transmission line losses, reduced financial risk, environmental benefits, and local economic development.

Most studies fail to properly assess the implications of different future energy portfolios by not analyzing factors such as resilience in the face of natural disasters, physical or cyber attacks, and the amount of new transmission capacity that is necessary. Increased reliance on local RE generators, integrated with microgrid control systems, hold the promise of providing new ways to manage the risk of major outages.

2. DISTRIBUTED WIND RESEARCH

Distributed wind is an example of a DER also known as "*small wind"* or *wind power generated onsite* [3]. Currently, over 1 GW of distributed wind has been installed in the United States [4] which accounts for less than one-third of a percent of US renewable electricity generation capacity, and one percent of globabl wind electricity generation capacity (2021) [5].

The NREL devotes extensive research to the development of these systems, with areas of research including controls, design of deployable systems, microgrid systems, standards development and performance assessment. As researchers explore new materials, optimize turbine geometry, and develop innovative installation techniques, distributed wind systems will become more cost-effective, reliable, and accessible. The projected diffusion of distributed wind energy systems has the ability to stimulate local economies and create job opportunities [4].

2.1 The Current State of Distributed Wind

Small-wind energy systems showed increased popularity in the early 20th century. Hundreds of thousands of under-100 kW turbines have been installed worldwide for various uses. The largest expected jumps among distributed wind markets is projected for (1) the

U.S. residential grid-connected wind market and (2) the international small-scale community wind market. As a whole the Distributed Wind Turbine (DWT) market is expected to continue to show rapid growth.

Small, sub-10 kW turbines tend to lend themselves better to convenience applications, since average electric consumption for a U.S. residential utility customer is on the order of 10^0 kW even at peak consumption. For this reason, smaller wind turbines are often sufficient for meeting the energy needs of individual households, small businesses, or remote locations.

Currently, 10 kW wind turbines are being manufactured by over twenty different companies. Between 20 and 100 kW capacity, the options are limited to a handful of companies, and 100 kW capacity turbines are seldom manufactured [8].

Figure 1: Bergey Windpower Excel 10

For both small scale community wind as well as residential grid-connected wind, large scale deployment will require an intense list of advancements. For small scale community wind, key market barriers include turbine availability, economics, and permitting. Similarly, grid-connected residential wind faces market barriers such as installed cost, LCOE, permitting, and connecting to the grid.

Both these DWT scenarios have technical hurdles including grid integration, optimal turbine designs, installation and maintenance, performance projections, reliability, lack of standards, and technology for low wind regimes. However the market for residential, farm and community wind projects is substantial and growing, attracting attention from policy makers and economic professionals.

The NREL is actively conducting researching in areas like advanced controls, deployable wind systems for defense and disaster applications, infrastructure for microgrid and hybrid power research, development of standards for performance and stakeholder outreach. In addition, NREL has provided financial assistance to companies who build small and mid-sized wind turbines, providing them with resources to develop, certify, and commercialize their next-generation technology.

If developed commercially, DWT technology could reduce reliance on the nation's already constrained transmission network. This monetary contribution helps manufacturers optimize their designs to optimize energy output : costs ratios, develop advanced manufacturing processes and test to certifications, with hopes of leading to large scale implementation in turn.

2.2 Cases

Bergey Windpower is an example of such a benefactor. They are the oldest and most experienced manufacturer of residential-sized wind turbines. The simple "Bergey design" has proven to provide the best reliability, performance, service life, and value. It has only three moving parts and no scheduled maintenance and has compiled a service record that no other turbine can match. Figure 1 shows a picture of this product. Further research hopes to decrease upfront costs for consumers.

In another example, competitor Primus Wind Power has developed models which feature carbon fiber blades and hub as opposed to the more popular fiber glass. Their turbines also have the reputation of being durable and reliable. While some turbines are designed to operate even in high speed situations, the Primus turbines are designed to operate most efficiently in low to mid- speeds.

Figure 2: Primus Wind Power AIR Models

Northern Power Systems' (NPS) turbines, in contrast, are designed for maximum annual energy production (AEP) and the ability to operate at high speeds. The NPS 100C-21 shown in Figure 3 is an infrequent example of a medium sized 100 kW turbine. NPS are constantly making adjustments that lead to increased AEP and reliability.

Figure 3: Norther Power Systems 100 kW turbine

In rural Colorado there sits a small dairy farm that has two NPS 100 kW turbines installed. The project demonstrates how a family farm effectively utilizes a distributed wind system to offset electricity consumption associated with energy-intensive farming. The turbines are located in an ideal site with minimal obstacles to block free flowing wind. The turbines were each expected to generate 250,000 kWh per year, and the actual productions were both within ten percent of this value. As a result, over half of the electricity needed was able to be offset. Figure 4 shows their setup.

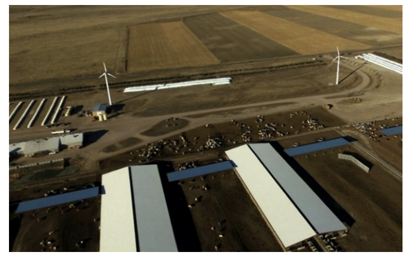
Figure 4: Two Norther Power Systems 100 kW Turbines on a dairy farm

The R&D efforts dedicated to DWTs hold great promise for the future of decentralized and sustainable energy generation. The focus now shifts to exploring the literature on the merits and demerits of Vertical Axis Wind Turbines, who have a unique ability to contribute to the evolving landscape of wing energy.

3. VERTICAL AXIS WIND TURBINES

The vertical axis wind turbine (VAWT) was the first turbine ever used to harness energy from the wind. As wind energy gained increasing recognition among modern researchers and engineers, the focus of development gravitated towards horizontal axis wind turbines (HAWTs) based on the initial belief that VAWTs were not suitable for large-scale electricity generation the initial [8].

Expectedly, wind patterns in urban environments are more turbulent. HAWTs are a relatively ineffective technology in these urban situations, and have been met with pushback due to noise, aesthetic, and public safety concerns [9]. VAWTs have been identified as a potential solution. The ability to use wind energy in urban areas would hold key merits like the generation of electricity close to or at the point of consumption, and thus elimination of dependency on grid-connectivity.

The use of chaotic flow to generate electricity has been a challenge faced by researchers in recent decades. However, research has revealed the following major advantages of VAWTs: VAWTs are omni-directional, accepting wind from any direction without need for a yawing mechanism. Since the VAWT design allows their generators to be located on the ground, the primary design objectives are power output and cost, as opposed to the nacelles of HAWTs which due to being placed on the tops of tall towers must consider weight as a primary design criteria.

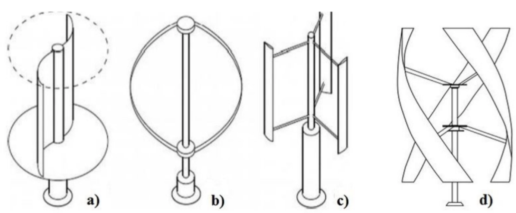

Figure 5: a) Savonius b) Darrieus c) H-rotor and d) Helical VAWT Designs

Vertical axis machines have been developed in parallel with HAWTs, but with less financial support and less interest. Figure 5 shows several design ideas for VAWTs. Turbine a) is an example of a Savonius turbine, invented in 1922 by Finnish engineer Sigurd Johannes Savonius and patented in 1926. Its rotation occurs because of drag as opposed to lift. Turbine b) is an example of a Darrieus turbine known as the "Egg-beater" design, and was invented by G.J.M. Darrieus. Both Savonius and Darrieus made tremendous contributions to the field of wind energy. Finally, turbine d) is a twisted-blade helical Darrieus turbine, and turbine c) is another lift-based Darrieus turbine with straight blades, commonly referred to as an H-rotor. Research on these designs are generally more limited compared to the extensive research that has been conducted on HAWTs.

Shortly after WWI, French aeronautical engineer Georges Jean Marie Darrieus came up with the initial design for a lift-based vertical axis wind turbine, diverging from the Savonius wind turbine which utilizes a drag-based principle. For a Darrieus turbine, one revolution of a single rotor blade generates a mean positive torque even though there are also short sections with negative torque. Darrieus turbines displayed better performance, lower construction cost, and a much simpler design than the Savonius.

During the 1970s and 1980s vertical axis machines came into focus as both Canadian and United States' governments funded several projects prototyping Darrieus turbines. These large-scale prototypes demonstrated high efficiency and reliability but VAWTs still faced challenges in the wind energy market, resulting in a decline in their development. The preference for HAWTs over VAWTs may have been coincidental rather than based on inherent superiority, as research suggests that the selection of HAWTs for large-scale development was not necessarily a clear-cut choice. The literature reveals that vertical-axis turbines can be installed much closer to each other than horizontal-axis turbines, so that the power density per square meter could be at the end considerably higher than for HAWT configurations used presently.

3.1 "Egg-beater" Darrieus

The Egg-beater, or phi (φ) rotor, design contains two or more curved blades arranged resembling arms of an egg beater. Instantaneously, wind blowing past the curved blades creates a pressure difference resulting in an unbalanced force called lift. The rotating turbine changes the angle of attack of its blades, and the airflow becomes unstable. Turbulent vortices are created, and the lift force on the blades fluctuates rapidly resulting in a phenomenon known as dynamic stall. Dynamic stall plays a crucial role in generating the net force that imparts a rotational motion.

The earliest designs of the Egg-beater Darrieus turbines exhibited minor disadvantages stemming from their complex arrangements. Early developers considered various blade geometries including troposkein (i.e. "turning rope" in Greek) blades, catenary blades, parabola shaped blades, and arc shapes [15]. Subsequent research on Darrieus turbine design has identified notable disadvantages, including high axial load on the support bearings and reliance on external power to initiate startup.

A project that exemplified the potential of Darrieus curved-blade VAWTS is the Éole project, implemented in Quebec in 1986. At a height of 96 meters and with a power rating of 3.8 MW, the Éole is the largest VAWT in the world. This massive turbine served as a prominent testament to the capabilities of VAWTs in harnessing RE. As a pioneering endeavor, it showcased Canada's pursuit of sustainable energy solutions. It produced 12 GWh in its lifetime. The machine shut down in 1993 due to failure of the bottom bearing.

Figure 6: Éole, the Largest VAWT Ever Built

Sandia National Laboratiries (SNL) is a federally funded R&D center in the United States that has extensively investigated Darrieus VAWTs. SNL found a way to improve the performance of their turbines by tailoring their airfoils. To achieve reliable turbine operation, SNL researched the effects of the tip speed ratio (TSR) which in-effect enabled a larger range of speeds before cut-off near the peak or minimum coefficient of power (C_p) condition. Airfoils by SNL also have sharp leading edge, makinf them more suitable for high TSR because of reduced flow separation and stall at higher wind speeds. The SNL airfoil design also served the purpose of providing better structural strength by allowing for more uniform propelling forces and minimizing localized edgewise bending stress. Shown in Figure 7 is the 34 meter rotor diameter Sandia turbine called "Test Bed", which achieved 500 kW rated power and a peak C_p of 0.409. Advancements like these made by SNL showcase the potential benefit of research effort on VAWT performance.

Figure 7: SNL's "Test Bed" VAWT

3.2 H-rotor

The use of straight blades with aerofoil cross-section gives a new configuration of VAWT known as a straight-bladed Darrieus, Giromill, or H-rotor design. This design can have any number of blades from one to commercially available five bladed configurations [8] [16]. A two bladed Giromill is referred to as an H-rotor. The implementation of controllable pitch angle means there is the potential to overcome the starting torque issues associated with other VAWT designs. The simple blade design means blades are much easier to manufacture than the blades of a HAWT or Darrieus turbine. A drawback is that the blades of the H-rotor are subject to large bending moments due to the large centripatal acceleration.

Experimental research has shown relatively promising results for C_p of H-rotor turbines [9]. However, a quantitative prediction of aerodynamic performance of H-rotor turbines is still very complicated, again due to the occurrence of dynamic stall on the blades.

Computational Fluid Dynamics (CFD) research for both configurations of Darrieus turbines is limited. Even with today's supercomputers, numerically exact solutions of the complete Navier-Stokes equations of turbulent flow is prohibitively expensive except for simple configurations at low Reynolds numbers [12]. However, there have been research efforts that propose CFD models for performance prediction and analysis of H-rotor turbines.

Over the last two decades, there has been significant development of analytical, computational, and experimental techniques for fluid flow analysis around an aerofoil in general and in VAWTs in particular. The use of Blade Element - Momentum (BE-M) theory has been valuable in the field of CFD analysis for turbulent flow at high Reynolds numbers. BE-M based design tools divide the airfoil blade into elements and assume the flow in each element to be two-dimensional in the plane of the airfoil section. This method has proved to be capable of accurately predicting Darrieus wind turbine performance and is the basis of most of the performance prediction tools currently used in the wind industry. Castelli et al. [13] proposed a straight-bladed VAWT performance prediction model using BE-M principles transferred to the CFD code. This type of research shows the potential of BE-M theory as it allows for more efficient calculation of aerodynamic loads on rotor blades.

Rooftop wind is not horizontal, and thus wind turbines on a roof operate in skewed flow. VAWTs are to be preferred for operation in a complex wind environment such as this. Mertens et al. [14] presents experimental data that show the increased power output of an H-rotor turbine in skewed flow, confirmed by a model based on BE-M theory that also shows this increased power output.

In the 1990s, German inventor Götz Heidelberg with his Munich-based company Heidelberg Motor started developing variable-speed 300 kW H-rotor prototypes, shown in Figure 8. Heidelberg also installed its smaller 20 kW version at a German research facility that operated for 15 years. Swedish company Vertical Wind AB erected a 200 kW variable speed H-rotor turbine in 2010 which is still operational as of 2019 (Figure 9).

Figure 8: Heidelberg Motor H-rotor prototype

Figure 9: Vertical H-rotor by Vertical Wind AB

Governments have recognized the potential of wind energy, including small-scale VAWTs, to contribute to sustainable power generation. Recently, governments have offered incentives and implemented supportive policies, aiming to encourage the adoption of wind energy technologies and accelerate the transition to cleaner sources of electricity [16].

Hover Energy, a wind power technology company based in Dallas, in the last decade has introduced its vertical axis H-rotor wind turbine as part of its microgrid system. The successful launch of this five-blade 36 kW H-rotor design marks a significant milestone in vertical axis wind turbine research.

This turbine manufacturer leverages the unique aerodynamic benefits of H-rotor designs and places them along the windward-facing edges of rooftops. Recently, the company has installed their proprietary system at HMS Eaglet Naval Base in Liverpool as part of the Ministry's broader efforts to decarbonize military bases. In the embodiment, vertical-axis wind is combined with solar PV cells, battery packs, and an integrated energy management system to provide complete energy independence.

Figure 10: Hover Energy H-rotor atop HMS Eaglet in Liverpool

This installation at HMS Eaglet shows the potential for distributed wind energy, specifically small-scale vertical axis wind turbines, to help achieve sustainable decentralized power generation. It can be revisited here that a significant portion of wind energy research focuses on the integration of wind generators into power systems, emphasizing their ability to connect to the grid. However, it is equally important to recognize the growing interest among companies that deploy small-scale wind turbines for off-grid applications. The endeavors of companies like this are extremely likely to undergo a positive impact from further research into the performance of VAWTs. However, companies like this beg for more than research into just the performance of vertical axis turbines. To be more specific, Hover Energy calls into review the overarching way we think about power.

4. ENERGY STORAGE TECHNOLOGY

The variability of wind power output poses challenges for balancing load demand. Energy storage systems (ESS) have long been recognized for their ability to decouple energy supply from energy demand. Any amount of storage would aid in periods when RE flow is just meeting or slightly under the load needs.

Most wind turbines use lead-acid battery storage (see section 4.4) [8], an outdated battery storage technology.

The 1970s saw a renewed interest in the utilization of energy conversion and storage. Research and development efforts lead to improvements in ESS. Modern research consistently points to the fact that the LCOE decreases with an increase in the duration and efficiency of the ESS in place [24].

ESSs can be categorized by storage duration, response time, and application. The location of the ESS itself can be at different levels in the networks, namely: at the production level, transmission level, or end-user level [28]. Another method of classifying ESSs is storage duration, with long-term and short-term technologies both being explored by researchers.. The most popular method is by the form of energy stored, broadly categorized into electrochemical, thermal, mechanical, chemical, and magnetic [23] batteries.

Grid-scale ESS research emphasizes the development and implementation of large scale energy storage solutions intended to support reliability of the grid. In contrast, research on distributed source energy storage systems focuses on technologies that are well-suited for smaller scale applications. This divergence allows for more efficient development of energy storage technologies allowing researchers, scientists and engineers hope to better align state-of-the-art technologies with the specific needs of energy systems.

4.1 Grid-scale ESS

Grid operators have employed load-driven techniques to maintain an instantaneous balance between total power generated by all power plants and aggregate demand for electricity. The regulation technique entails a control system monitoring load and generation which can automatically signal power stations to increase or decrease their power output. The load following technique utilizes good knowledge of wind behavior in a location to schedule other types of generation in order to meet energy demand at the lowest cost. Research on the unit commitment technique argues that consistent power can be achieved if the wind turbines are spread over a wide geographical location, essentially forwarding the argument for distributed wind. Kahn et al. excellently present the merits of this idea here [25].

Overall, research suggests that hese techniques may not be suitable for wind power variations since wind speed changes are not instant, and accurate wind forecasting is a challenging task. The resulting conclusion that researches consistently circle back to is that energy storage systems must play a crucial role in mitigating the challenges posed by wind energy variability.

For grid-scale storage systems, a significant amount of storage capacity must be provided. Various modern large-scale energy storage technologies are presented by Hasan et al. [17] and Ayodele et al. [18] and their ability to mitigate the power fluctuated onto the grid is assessed. Storage systems like compressed air energy storage (CAES), superconducting magnetic energy storage (SMES), hydrogen energy storage system (HESS), and flywheel energy storage system (FESS) as well as battery technologies all have the ability to mitigate power output fluctuations resulting from variable wind speed. Companies like Form Energy in Somerville, Massachusets look to commercialize novel battery technology. In their case, it is an iron-air battery that takes advantage of a reversible rusting reaction to store and discharge electricity.

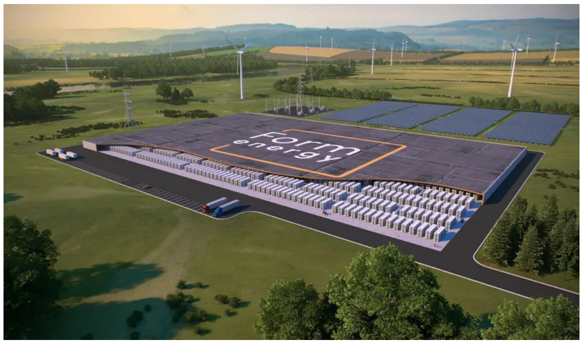

Figure 11: Form Energy Iron-Air "Reversible Rust" ESS

4.2 Small-scale ESS

For distributed wind, research shows that small wind turbines can be used in combination with other generation or with energy storage capability to feasibly meet small to medium loads. One of the largest barriers to the proliferation of distributed systems is the price of energy storage technology for small scale applications. When net metering is not available, the intermittent behavior of the wind leads to instability and unreliability, which limits the amount of wind-generated electricity that can be used without energy storage in off-grid scenarios. The added cost of electrical storage is more unavoidable for smaller off-grid applications, since a larger turbine connected to the grid can rely on the grid itself for stability. Net metered small RE projects are currently the only usage of wind energy that does not necessitate energy storage. However, these applications rely on the grid for energy stability, which in turn increases reliance on either fossil-fuels or large scale battery technologies.

Considerably less research exists on the use of small-scale ESS. However, researchers who have investigated distributed energy systems agree that small-scale ESSs are key elements for functional RES integration. As mentioned, implementation of ESSs is currently not economically feasible [26]. Economic feasibility can be achieved if the cost is decreased or a support program is implemented that economically supports ESS.

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4.3 Thermal Energy Storage (TES)

There is a growing trend to incorporate TES as a solution for multi-energy system integration. TES technology allows for temporary storage of heat in a medium that can later be used in heating, cooling, or power generation applications. TES has been explored as a potential solution for large industrial plants by providing combined heating and power (CHP). TES can be utilized in conjunction with RE sources, thermally storing excess energy generated and using it when demand exceeds generation. It is this case that pertains to the present discussion of the viability of distributed wind energy systems. TES systems are classified by their method of heat storage. In Sensible-Heat Storage, materials store thermal energy in their specific heat capacity by changing the temperature. Latent-Heat storage utilizes the energy absorbed during the phase change of a material from solid to liquid.

Antora Energy is an example of a company designing a TES system capable of converting intermittent renewable electricity into heat and power on-demand. Antora uses thermophotovoltaic (TPV) technology to convert heat from their carbon block batteries back into electricity.

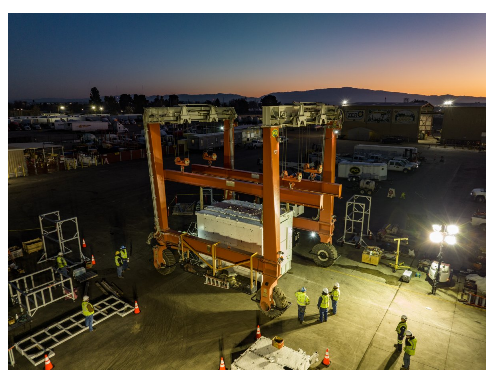

Figure 12: Antora Energy Thermal Battery Field Demonstration

Companies like Antora Energy, however, are primarily focused on decarbonizing the industrial sector, and thus the applications that they focus on are larger than small-scale distributed wind systems. However, examination of cases like these are beneficial to the present literature since they are a successful example of mitigating variable renewable electricity (VRE) in an off-grid energy scenario.

4.4 Electrochemical Energy Storage

Rechargeable (secondary) batteries are ideally suited for storing energy. The race to develop battery-powered vehicles spurred by oil embargos of the 1970s has produced major advantages in these battery technologies. Research suggests that secondary batteries are also ideally suited for electric load leveling applications. Batteries respond rapidly to load changes, provide quick-response reserves, accept third party power, and can be used to enhance system stability. Particularly challenging is the requirement that batteries exhibit attractive energy characteristic, durability, and also be low in cost. No battery meets all of the demanding requirement to make commercial energy storage applications feasible [23].

Historically, lead-acid batteries have been the most widely used electromechanical device in stationary applications. This statement applies to distributed wind energy systems. Perrin et al. [28] makes a comparison of lead-acid technology to its competitors. The combination of energy efficiency and leak-discharge, expressed as charge retention, is a determination of the amount of energy available in a storage system after a certain time. Lead-acid batteries display excellent charge retention for up to two days and are thus a satisfactory choice in applications with rest periods of several days. Technical limitations include relatively low cycle life, and relatively low power shifting (long-duration storage). Lead-acid batteries offer the most technical merits in short-duration storage applications. Economically speaking, one of the best candidates for short-duration applications are lead-acid batteries. The technology is widely avaiable in the market, and their widespread use has contributed to a mature supply chain.

Lithium-ion batteries are considered the best choice in terms of high energy efficiency. The attention that lithium-ion technologies are attracting is based on several technical advantages: energy conversion efficiency of 95% (compared to ~80% for lead-acid [28]), long lifecycle of 3000 cycles, and energy density up to 200 Wh kg^{-1} [29]. Major problems to be considered with technologies like lead-acid and lithium-ion is availability of resources. Lithium-ion, for example, necessitates a relatively complex and energy-intensive extraction process, and commercially extracted from just five minerals. Only one active lithium mine exists in the United States as of 2022 [32].

4.5 Other Energy Storage Technologies

There are several other energy storage technologies that offer unique advantages. Compressed Air Energy Storage (CAES) uses compressed air to store and release energy. Excess electricity can be used to compress air and store it in underground caverns or pressurized vessels. This technology is particularly suitable for long-duration large-scale storage with relatively low operational costs. Superconducting Magnetic Energy Storage (SMES) is a system that relies on the phenomenon of zero electrical resistance exhibited by certain materials at low temperatures and stores energy in the form of a magnetic field created by a current flowing through superconducting coils. SMES offers high power density, rapid response times, and long cycle life. Flywheel batteries are a mechanical energy storage device that stores energy in the rotational motion of a spinning flywheel. They are popular in applications that require short-duration, high-power discharges and are a common solution to providing frequency regulation in power grids. Gravity batteries consist of a heavy mass which is lifted to a higher elevation during periods of low energy demand. Research has shown viability of gravitation energy storage for grid-scale energy storage for demanded capacities lower than 20 MW [31].

5. HYBRID RENEWABLE ENERGY SYSTEMS

The term Hybrid Renewable Energy System (HRES) encompasses power generation systems that use more than one type of RE generator, and typically includes battery storage and oftentimes fossil-fuel generators. Case studies looking to optimize wind, PV, diesel generator, and battery integration aim to find combinations that most effectively enhance system stability and improve the cost-effectriveness of renewable energy generation. Optimization studies for HRES systems, like the one conducted by Deshmukh et al. [33], model these components' performance as part of an effort to maximize power output while minimizing the LCOE as well as loss of load probability (LOLP). As a general principle, the combination of two different VRE sources creates a capacity factor greater than either of the constituent generators alone. In the case of wind and solar combinations, this benefit stems from the natural fact that high wind speeds tend to coincide with lack of sun, and vice-versa.

5.1 Microgrids

Microgrids are an example of an isolated HRES system. Microgrids are localized, independent utility systems that can operate in "island mode" or in grid-connected mode, where they draw power from RE sources and the grid when deficits in generation must be supplemented. The ability of microgrids to separate from the grid in order to feed its own islanded portion is key to the philosophy of microgrid systems and distributed power systems. This process is unsimple, however, and it has been criticized by Huaylllas et al. that "under present grid protocols, all distributed generation must be shut down during times of power outages; however, it is in this precise time when these onsite sources could offer their greatest value by providing power services to local loads" [34]. Companies like the aforementioned Hover Energy exemplify successful integration of VRE with energy storage to provide energy stability, reliability, and complete energy independence.

6. COASTAL REGIONS

Reaserch has identified favorable wind power generation conditions in coastal locations on the basis of higher average wind speeds which result form the unobstructed sea breeze. This research has further suggested that coastal regions are appropriate locations for stand-alone wind power applications.

Knowledge of historical wind speed data for a specific location allows technical and economic characteristics of the site to be conveniently determined and viabilities of different systems assessed. The NREL has been known to classify potential of a site based on forecasted power densities based on average wind speeds at specified heights with directionalities. Coastal wind data shows immense variation in wind speed at different heights, adding complications to the viability assessment since turbines of different tower heights exist and can be deployed.

Researched arguments have implied that grid-connected systems required greater power density wind characteristics than standalone systems. Wind turbine systems are a deployable technology that can be beneficial when energy independence is required for off-grid applications such as army bases or in response to natural disasters. Research arguments have suggested that coastal regions are suitable for standalone wind power applications.

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