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Technology, Performance, and Market Report of Wind-Diesel Applications for Remote and Island Communities

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TECHNOLOGY, PERFORMANCE, AND MARKET REPORT OF WIND-DIESEL APPLICATIONS FOR REMOTE AND ISLAND COMMUNITIES

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ABSTRACT

The rising cost of diesel fuel spurred on by oil costs well above $100/barrel and the environmental regulation for its transportation, use, and storage, combined with the clear impacts of carbon emissions are driving remote communities dependent on diesel fuel to look at alternative methods of providing power. During the past few years, wind energy is increasingly used to reduce diesel fuel consumption, providing economic, environmental, social, and security benefits to communities' energy supplies.

The market for wind-diesel power systems has also recently progressed from a topic discussed by researchers to many commercial operating systems. From Alaska to Chile, from Australia to Spain, from high-penetration wind-diesel plants to wind-diesel-hydro systems, the integration of wind turbines with conventional isolated generation is a commercial reality. The maturing wind industry and the advances in controls, remote monitoring, storage technologies, and diesel generators continue to spur the market for wind-diesel applications. Because of the large number of isolated diesel mini-grids, specifically in island nations such as in the Caribbean and the Pacific and the remote northern climates of Alaska and Canada, the market for wind-diesel systems is substantial. Additionally, similarities of wind-diesel applications and large grid-connected wind farms in regard to grid stability and other issues can help to develop solutions that would also benefit the implementation of wind in national grids with isolated grid characteristics.

This paper describes the current status of wind-diesel technology and its applications, the current research activities, and the remaining system technical and commercial challenges. System architectures, dispatch strategies, and operating experience from a variety of wind-diesel systems will be discussed, as well as how recent development to explore distributed energy generation solutions for wind generation can benefit from the performance experience of operating systems. The paper also includes a detailed discussion of the performance of wind-diesel applications in Alaska, where 10 wind-diesel stations are operating and additional systems are currently being implemented. Additionally, because this application represents an international opportunity, a community of interest committed to sharing technical and operating developments is being formed. The authors hope to encourage this expansion while allowing communities and nations to investigate the wind-diesel option for reducing their dependence on diesel-driven energy sources.

Keywords: Wind, Diesel, Hybrid, Remote, Power

1 Introduction

The use of diesel engines to supply power to rural communities has provided light and energy services to places where previously there has only been darkness. However, the rising cost of diesel fuel (brought on by higher oil prices and the environmental regulation for its transportation, use, and storage) combined with carbon emissions concerns is driving remote communities to look at alternative methods to supplement this power source. During the past few years, wind energy is increasingly used to reduce diesel fuel consumption, providing economic, environmental, social, and security benefits.

Systems research continues as feedback is collected from operators and plant managers about how the systems are working. This paper describes the current status of wind-diesel technology and its applications and the remaining system technical and commercial challenges. Basic system architectures, dispatch strategies, and operating experience from a variety of wind-diesel systems are discussed, as well as how recent development to explore distributed energy generation solutions for wind generation can benefit from the performance experience of operating systems. The paper also includes a detailed discussion of the performance of several wind-diesel applications.

Because of the large number of isolated diesel minigrids in both the developed and developing world, the market for retrofitting these systems is substantial. Because this market is international in scope, a community of interest has formed and is committed to sharing technical and operating experiences to expand recent successes.

2 Topography of Power Systems Combining Wind and Diesel

A wind-diesel power system can be more accurately described by the title “hybrid power system.” Such a power system can incorporate different components, including production, storage, power conditioning, and system control to supply power to an isolated load [1].

The classic hybrid system incorporates renewable technology, fossil fuel engine generator(s), a battery bank, and a power converter. In most cases, this system is based on a two-bus system: a DC bus for the battery bank and an AC bus for the engine generator and distribution.

Wind-diesel power systems differ from most smaller hybrid systems as they are traditionally larger and closely integrate the wind and diesel technology to provide consistent, high-quality AC power. Storage, if used at all, is typically provided to smooth power fluctuations, provide for short lulls in wind energy production, and enable the start of a diesel engine if one is needed. Larger systems usually contain more and larger equipment that allows for an economy of scale, and thus lower power costs.

Wind-diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid with a minimum of additional features, to more complex systems where advanced controls and components are required [1, 2, 3, 4, 5]. Two overlapping concepts depict the system design and required components: the amount of energy that is expected from the renewable sources (system penetration) and the methods used to control the power system depending on the level of renewable contribution. In cold climates, the use of waste energy from the diesel engines also plays a critical role in determining power system design. It should be noted that a reduction in standard diesel engine efficiency is to be expected in most cases, especially if an existing diesel system is retrofitted to allow for wind penetration. However, the displacement of diesel fuel from wind generation usually outweighs this phenomenon.

2.1 Renewable Penetration

In almost all cases, the systems control requirements increase with increasing reliance on energy from wind turbines. A method proposed but not formally published by Steve Drouilhet classifies and defines system penetration to help characterize the levels of system control complexity:

Instantaneous penetration is the product of the Wind Turbine Power Output (kW) divided by the Primary Electrical Load (kW) while the *average penetration* is a product of the Total Wind Turbine Energy Output (kWh) divided by the total Primary Electrical Load (kWh) over a given time period, typically a month or year.

Instantaneous penetration relates to the power system complexity and the required level of control to maintain acceptable power quality. Power systems with low instantaneous wind penetration require limited additional control. System control is provided by devices integrated into diesel generator hardware. As instantaneous penetrations increase, more caution is required because the variation in wind turbine output, driven by the variation of the wind resource, may overwhelm the capabilities of standard diesel control hardware. At very high levels of instantaneous penetration, where wind production is on par or even exceeds the system energy requirements, additional control must be put in place to maximize system performance and stability.

Average penetration allows an estimation of fuel savings and fuel storage needs, general system operation characteristics, and potential long-term monetary impact. Averaged over longer periods of time, it provides a record of the total amount of system energy coming from wind technology.

Drouilhet also proposed a three-level classification system for wind penetration that separates systems along power and system control needs (Table 1). The instantiations and average penetration levels provided in the table should be considered approximate and will depend greatly on the age of the diesel generator(s) and associated controls. The potential need for additional energy complicates the integration since typically space or water heating, ice production, or water purification is generated through means such as using the jacket and exhaust heat from the diesel plant.

Penetration Class	Penetration	
	Peak Instantaneous	Annual Average
Low	< 50%	< 20%
Medium	50% – 100%	20% – 50%
High	100% - 400%	50% – 150%

Table 1: Penetration class of wind-diesel systems (proposed but not published by Steve Drouilhet)

2.2 Low-Penetration Systems

Low-penetration systems are those in which the wind energy contribution to the power system is limited, requiring no special arrangements or control requirements as the energy generated by the wind turbines is seen largely as a negative load on the diesel plant. The control technology required at this level of generation is trivial, especially given the control, flexibility, and speed of modern electronically controlled and fuel-injected diesel generators and advanced wind systems. In systems incorporating older diesel engines, especially those using low-speed diesel technology, the upper limit of what is considered low penetration may shift lower. In some instances, individual wind turbines may be shut off to reduce the amount of energy from wind to prevent grid instability due to a lack of control functions in low-penetration systems. However, this rarely occurs in well-designed systems. Issues of spinning reserve (a term used to represent the availability of instantaneous system capacity to cover rapid changes in system load or energy production) are addressed by the allowable capacity of the diesel engines, which in many cases can run at 125% rated power for short periods of time with no adverse impact on the diesel or generator.

Many low-penetration systems have been installed worldwide. These vary from small to relatively large isolated grids, such as those found on several Greek islands. The power system that has operated in Kotzebue (a coastal community of more than 3,000 people in northern Alaska) for almost 10 years generally classifies as a low- to medium-penetration power system, with no additional control hardware implemented and an average penetration below 20% but the potential for instantaneous penetrations above 100% during times of high winds and low system load. [6]

2.3 Medium-Penetration Systems

Systems with larger ratios of renewable energy contribution in which some level of power system control is required fall into this category. In order to maintain minimum load levels on the diesel generators in multiple diesel plants when a larger portion of the energy is being produced by a wind source, some diesels will have to be shut off or production switched to a smaller unit. This low level of diesel generation makes it harder for the operating diesel units to tightly regulate system voltage and maintain an adequate power balance, especially with older diesel generators.

Several options exist to ensure that the high-power-quality requirements of the power system are maintained, even with 50% or more of the energy provided by renewable sources. Available options are:

a. Power reduction capabilities of the wind turbines,
b. The inclusion of secondary loads, thus increasing the overall system load,
c. Use of controlled dump loads to assist in clipping the peaks off wind variability, thus assisting in the control of frequency,
d. Use of advanced power electronics and turbine control to allow real time power specification from the wind turbine, and
e. Diesel governing electronics that allow for low-load diesel operation, enabling the diesels to a faster response time.

Maintaining the proper level of spinning reserve in medium-penetration power systems requires experience with power variability and system control but is not considered technically complex. Such spinning reserve questions should be handled on a case-by-case basis but can be solved by using advanced diesel controls, modern electronic diesel engines, and advanced plant integration.

However, even with the implementation of advanced power conditioning or power smoothing technology, diesel engines have a minimum load rating under which manufacturers state that the diesels should not be operated. Not only does operating under these levels (typically 40% to 50% of the engines' rated power for older diesels) reduce the diesel governor's ability to control frequency, reactive power and to a limited degree voltage, they force the engine to run at cooler temperatures, thus causing increased engine carbon build up, wet stacking, and higher maintenance requirements. This minimum diesel-loading requirement acts as a glass ceiling, limiting the benefit of incorporating increasing amounts of wind into a diesel power system. To allow higher penetrations of wind into small diesel systems, several companies have introduced diesel engines that can operate at very low load, generally below 10% rated power [7]. These low-load diesels maintain their ability to control frequency, voltage and reactive power at low power levels but also act as spinning reserve because of an ability to respond quickly to step changes in load.

Medium-penetration systems are more complex, which results almost invariably in increased cost. These costs must be compared against the reduction of plant diesel fuel consumption, reduced diesel engine operation, and reduced needs for fuel storage and handling, and in some cases the reduction of carbon emissions. Non-economic beneficial factors of diesel fuel reduction include reduced environmental impacts and air emissions as well as an increase in energy independence. Remote communities in Alaska value this increased energy independence, especially when semi-annual fuel barge deliveries are often threatened by weather and lately, low water levels in rivers.

It should be noted that the utility operator determines the amount of required spinning reserve. Spinning reserve requirements could be lowered if an annual system performance analysis shows that the local wind resource allows for less reserve and if the utility's diesel dispatch and operations strategy allows such measures. A reduction in spinning reserve could result in expanded diesel fuel savings.

The ability to provide high power quality in medium-penetration power systems has been demonstrated for years in a number of important locations. The most notable examples are the military diesel plants on San Clemente Island [8] and Ascension Island [9] and the power systems in Toksook Bay and Kasigluk, Alaska [6]. Several systems have also been installed using low-load diesel technology, including power systems at Coral Bay and Denham, Australia. [10] All of these systems have experienced instantaneous penetrations above 50%.

2.4 High-Penetration Systems

As instantaneous penetrations of renewable energy rises, eventually more energy can be generated than is needed by the general community load. With wind providing a large amount of the load, the ability of the diesel engines to control frequency, voltage, and reactive power is significantly reduced. Unless there is a large need for additional thermal or electrical energy, it makes financial sense to shut off as many, and preferably all, of the diesel engines when the whole load can be supplied by renewable sources (the basic hallmark of a high-penetration wind-diesel system). The operational concept behind these systems is that additional equipment is installed to ensure power system stability and power quality when the diesel engine, the device that typically controls these parameters, is shut off. In this case, any instantaneous power production over the required electrical load, an instantaneous penetration over 100%, is supplied to a variety of controllable secondary loads. In these systems, synchronous condensers, load banks, dispatchable loads, power converters, advanced system controls, and possibly storage in the form of batteries or flywheel systems are used to ensure power quality and system integrity. Additionally a well-designed demand-side load management, including load-shedding schemes, can be utilized to support grid stability and reliability. Recent designs of high-penetration wind-diesel systems in Alaska include utility-controlled residential electric heating systems with thermal storage ability that can be charged during low-load and high-wind scenarios.

Spinning reserve is created through the use of short-term storage or the maintenance of a consistent oversupply of renewable energy. This reserve is designed to either ride out short lulls in wind power or allow a diesel to be started to assume the load if the wind is not adequate.

Although high-penetration wind-diesel systems are being demonstrated commercially, they are not yet considered a mature technology and have not been demonstrated on systems larger than approximately a 300-kW average load. High-penetration wind-diesel power stations also require a much higher level of system integration, technology complexity, and advanced control, increasing the project cost, but reduce fuel consumption and diesel engine operation significantly.

In systems incorporating storage, the storage is used to cover short-term fluctuations in renewable power. The premise of this design is that when the renewable-based generators are supplying more power than is needed by the load, the engine generators can be shut down and the batteries charged with excess wind power. During lulls in the renewable power generation, discharging the battery bank or other storage device supplies any needed power. If the lulls are prolonged or the storage becomes discharged, an engine generator is started and takes over supplying the load. Studies have indicated that most lulls in power from the wind are of limited duration, and using storage to cover these short time periods can lead to significant reductions in the consumption of fuel, generator operational hours, and reduced generator starts [11,12].

In recent years, two types of storage have been successfully demonstrated in operational rural power systems: battery storage and flywheels. Battery storage has clearly been the most commonly used, taking advantage of the long operational history of battery technologies. Systems incorporating nickel cadmium (NiCad) batteries and rotary power converters such as those incorporated into the power system for Wales, Alaska [13] and the vanadium-based flow battery used at Kind Island, Australia [14,15] indicate that battery technology can be used to smooth out wind power fluctuations, both in small and large power systems. Although relatively proven, batteries also introduce a host of problems, most notably the use of hazardous liquids and, in many cases, limited life and a consistent maintenance requirement.

Flywheel technology is becoming more common and affordable as a method to provide short-term power storage and increase system power quality. Although flywheels provide only short-term storage, up to several minutes, they are being successfully used in systems such as Coral Bay and Flores Island [10,16]. One of the key aspects of flywheel technology is the ability of the units to supply lower levels of power for longer periods of time or short bursts of high power for very short periods of time. Although several products are on the market, the PowerStor® product from PowerCorp Australia that was used in the two aforementioned projects can provide power up to 1 MW for 15 seconds or a more reasonable 150 kW for 100 seconds. These units are also designed in a modular fashion and can be stacked to provide higher power ratings over longer storage times. Although generally still high in cost, their smaller system footprint and long operational life make them a strong candidate for future storage applications.

This type of system produces a large amount of extra energy that must be used if the project is to be economic. The power system installed on the Alaskan Island of St. Paul to supply the airport and co-located industrial complex is an example of the configuration of a high-penetration power system.

Unlike flywheels and standard batteries, hydrogen and technologies such as flow batteries can provide long-term storage. As has been found in smaller applications, longer-term storage allows the displacement of more fossil fuels by using renewable-generated energy when the renewable resource is not actually available or allow more active optimization of the power system dispatch. However, although the cost of the renewable-generated energy might be relatively low, the efficiency and cost of the storage medium is in effect competing against the incremental cost of energy from a diesel generator, which is also generally low for large power plants with defined fuel supply chains. The current cost of fuel has limited the implementation of wind systems with large storage components to technical demonstration projects such as the power system on King Island [14,15] or the first large-scale remote wind-hydrogen development on the remote

Norwegian Island of Utsira [17]. In locations with very high fuel costs, or if standard fuel costs rise sharply, longer-term storage may become attractive. A proposal to include a re-dox flow battery into an expanded wind system is currently being evaluated in Kotzebue, Alaska. The considered wind generation expansion of the exiting system in Kotzebue is contingent on the introduction of a storage device that bridges longer time periods (over the sub-minute range) due to the nature of the local wind resource and the utility requirements.

3 Operating Hybrid Power Stations

To reduce the cost of rural power generation, community vulnerability to rising fuel costs, and the environmental impact, many organizations have implemented wind-diesel hybrid power systems. The following projects provide examples of these systems.

3.1 Kotzebue, Alaska: Low- to Medium-Penetration Power System

Located above the Arctic Circle on a spit of land facing the Kotzebue Sound, the coastal community of Kotzebue has approximately 3,000 residents and serves as a regional hub for this part of northwest Alaska. The Kotzebue Electric Association (KEA) supplies power to the community, which has an average load of approximately 2.5 MW and a minimum of 700 kW. The diesel plant has an installed capacity of 11 MW. [5]

KEA initiated its wind development projects in 1997, starting with the installation of three Atlantic Orient Corporation (AOC) 15/50, 50-kW-rated wind turbines on lattice towers on a location south of the main town and airstrip. Since that time, the wind farm has grown to an installed capacity of 915 kW comprised of 17 turbines: 15 AOC 15/50 or Entegrity EW15 (50 kW); one remanufactured Vestas V17 (65 kW); and one Northern Power Systems Northwind 100/19 (100-kW) wind turbine. Although the annual average wind speed measured at the site is quite low (about 5.5 m/s based on data collected at the site between 1998 and 2004), the wind turbines generated about 667,580 kWh last year, saving an estimated 45,500 gallons of diesel fuel [18]. Specific penetration values were not available from this plant; however, based on system capacity, instantaneous penetration up to 100 are clearly possible. Currently only turbine curtailment is used to control at times of high wind output. Data collected by the U.S. Department of Energy (DOE) and the Electrical Power Research Institute through 2004 showed a relatively high system availability of 92%, including wind farm down time due to power transmission outages. Wind turbine availability is used to describe the amount of time that the turbine is in service and able to produce energy. Although more current assessments have not been published, these availability numbers have remained consistent on an annual basis [19]. This clearly demonstrates the ability for turbines to operate in remote communities with high availability, primarily due to the KEA's strong technical capabilities and dedication.

Photo 1: Kotzebue wind farm, Kotzebue Alaska, PIX16098/Ian Baring-Gould.

3.2 Toksook Bay, Alaska: Medium-Penetration Power System

The interconnected communities of Toksook, Tununak, and Nightmute have a population of approximately 1,160 people and an average load just under 370 kW. The power system is operated by the Alaska Village Electric Cooperative (AVEC) and incorporates three Northwind 100/19 100-kW wind turbines that were installed in the fall and winter of 2005/2006. The turbines are dispatched to maintain operating levels, and community heating dump loads were added to address fast overload conditions (although in recent operations, little energy has been applied to heating) [6]. The project, which was implemented as part of a complete power system upgrade, will help restrain the increased costs of electrical generation caused by rising fuel prices.

Except for some initial issues, including a blade failure, the power system is operating quite satisfactorily with a first-year turbine availability of 92.4%. The array of wind turbines experienced an average net capacity factor of 21% from September 2007 to August 2008. The average penetration for this system has been more than 23%, with average monthly penetrations more than 30% during the stronger winter wind months. In the year ending September 2008, almost 700 MWh of electricity was generated by wind, saving almost 46,000 gallons of fuel.

The cost of energy in Toksook Bay in 2007 was $0.46/kWh prior to the Power Cost Equalization Program subsidy [18], while the expected power cost (assuming a barrel of fuel at $110) would be closer to $0.77/kWh [20].

Photo 2: Northwind 100-kW wind turbines at Toksook Bay, Alaska. PIX14401/Northern Power Systems.

3.3 St. Paul, Alaska: High-Penetration Power System

The Tanadgusix Corporation (TDX), a native Alaskan corporation, needed a stand-alone power system for its facility on the island of St. Paul in the Bering Sea. The site is an airport and industrial complex with airline offices, equipment repair, and storage facilities. TDX wanted to reduce the overall energy costs for the camp's electrical and heating loads while maintaining reliable, utility-grade electrical service. In 1999, Northern Power Systems installed a high-penetration, no-storage hybrid power system that maximizes the contribution of St. Paul's abundant wind resource. The primary components of the St. Paul plant include a 225-kW Vestas V27 wind turbine, two 150-kW Volvo diesel engine generators, a synchronous condenser, a 27,000 liter (6,000 gallon) insulated hot-water tank with thermal control, and a microprocessor-based control system capable of providing fully automatic plant operation.

The power system is designed to shut all of the diesel engines off if there is sufficient wind to cover the complete load in addition to a controllable safety margin. While the diesel engines are off, the system controller maintains a balance between the power generated by the wind turbine and total electrical consumption by adjusting power going to the thermal heaters in the water tank. The synchronous condenser is also used to provide reactive power and maintain system voltage. By conducting continuous monitoring of the load, thermal needs, and wind power output, if the controller determines there is not enough electrical headroom between the electrical load and wind production, and there is a chance that the wind power will drop below the electrical load, a diesel engine is started.

The primary electrical load for the facility averages about 70 kW, but the system also supplies the primary space heating for the facility with excess power from the generators and thermal energy from the diesel plant. Although the power system has operated well over the past 7 years, a few problems have been associated with the wind turbine (an early failure of the turbine generator, which had to be replaced completely). In 2004, for example, the wind turbine had a non-scheduled availability of 100% and a capacity factor of more than 40%.

The average penetration for this system has been almost 55%, with significant times when the system operates with both of its diesel generators off. Since January 2005, wind energy has saved an estimated 150,000 gallons of diesel fuel, about 50% of the expected consumption without wind energy.

TDX is currently working with the City of St. Paul to interconnect two additional Vestas V27 turbines installed over winter 2007 to the City of St. Paul Municipal Electric Utility. This would interconnect the industrial complex power system with 725 kW of installed wind capacity to the city's utility electric system, driven by a 2.1-MW diesel power station and having an average load of more than 600 kW. With a minimum load close to 400 kW, once interconnected the wind will be able to supply a large amount of the power for the community, and depending on the final selection of control hardware, will represent a high-penetration power system for the whole community of St. Paul [18, 21].

Photo 3: Vestas V27 at St Paul, Alaska. PIX10596/TDX Power.

3.4 Other Projects

Most wind-diesel project development currently takes place in Alaska. Ten systems are operating in rural Alaska, and an additional six are known to be in development. The recent release of the Alaska Renewable Energy fund, combined with the expected high cost of diesel fuel, provide incentives for communities to look at alternative technologies that could result in the implementation of an additional 20 projects over the next few years. The Alaska wind screening study [22] identified more than 100 communities that are considered economically and technically viable candidates for wind-diesel system development. The high-profile wind-diesel projects at the Australian Mawson Antarctic base [23], the Ross Island Wind Project [24] being implemented at the U.S. McMurdo and New Zealand Antarctic Stations, the wind project on the Galapagos island of San Cristobal [25], and the systems previously mentioned along with others completed in Western Australia and Canada exemplify the increased demand.

4 Technical and Commercial Challenges

The dominance of fossil-fueled generators to provide power to rural areas is well-justified based on a strong track record and many years of operational experience. However, as discussed, many organizations question the continued reliance on fossil fuels alone.

The incorporation of wind technologies into remote rural communities adds a host of challenges that must be considered as part of any rural energy project. Some of these items are simply symptomatic of the industry and application, while others can be solved by expanded research, development, and experience with operating power systems.

4.1 Dispatchable Loads

As more wind capacity is installed in an existing diesel plant, more excess energy will be created. For high-penetration systems, this extra energy must be used in a productive way to make projects cost-competitive. In temperate and arctic climates, this can largely be resolved by using the extra energy for space or water heating, but in tropical climates, other uses must be determined.

In some cases, this extra energy can be directed at specific loads that can be turned on or off as needed, such as electric water heaters, air conditioners, water purification/desalination systems, or to power specific devices that by their nature have embedded storage, such as pumping water or making ice. Additional controllable loads, such as electric or plug-in vehicles, could also be incorporated to use this additional peak energy when it is available.

As an additional complexity, in climates with large heating loads it is typical to extract thermal energy from the combustion cycle of the diesel plant. The inclusion of wind reduces diesel operation, thus reducing the amount of thermal energy generated. If the plant is using that thermal energy, the economics of generating that energy by other means must be taken into account when assessing the impact of incorporating wind. This is especially the case in high-penetration wind systems in which all of the diesel engines may be shut down, eliminating all thermal heat from the diesel system plant. In cases of total shut-down of diesel engines, excess wind energy might be utilized to keep the diesel engines at a certain temperature.

4.2 Lack of Guidelines and Standards

A major key to success in the development and application of any new technology is proper guidelines and standards to ensure that all market players can be held accountable for products produced and advertised. As with many new markets, new organizations are quick to advertise capabilities that, in all likelihood, are outside of their experience. In the developing market for wind-diesel applications, which are generally very technically challenging, experience is the only sure indication of project success. Several organizations are developing general guidelines and/or draft standards to ensure that products advertised meet a specific set of requirements or can be designed to pass a set of specified tasks, but this is only a start and does not rise to the level of dedicated international technical standards. To ensure that improperly developed projects don't negatively impact public perception, every project developed must meet a standard of operation and quality. The above-mentioned issues are especially important in remote communities, where spare part supplies and technical support can be delayed by weather or other circumstances.

4.3 Lack of an Established Technology Track Record

Although wind-diesel applications have been operating in various applications for more than 20 years, limited documentation exists that would allow other organizations to accurately assess their operation. The only systematic data collected up to this point is from the Kotzebue wind farm (from January 1999 to July 2004). This data, however, only assessed the wind farm operation and was not correlated to diesel plant operation or output. Additionally, this analysis did not include costs for system construction, operation, and maintenance. [26]

This lack of data makes it difficult to perform more definitive assessments of technology performance and costs, a critical element in the assessment of potential future projects or to document the benefits of using wind technologies. Since many of the existing plants are relatively new, even with the limited data that are available, its focus on the first few years of project operation will skew the results, making assessments on the long-term performance and costs for system operation and maintenance speculative. The absence of data makes it easy for technology proponents to brush aside the desire to further develop wind-diesel applications, even if the best available analysis indicates that the projects provide positive benefits to everyone involved. As possible, work is ongoing to better document the performance of the existing wind-diesel applications in Alaska to clearly and accurately document their true performance.

4.4 Installation and Operation Expense

Construction projects in rural and remote areas are always more difficult and more expensive. The implementation of wind technology that typically requires the development of specialty foundations (such as permafrost designs) and the use of locally unavailable cranes to raise the turbines add to the expense. Recent studies show that the installation of wind energy projects in Alaska typically costs between $2,500 and $7,000 per kilowatt of installed wind capacity, depending on the community's size, accessibility, and differing soil conditions [26]. This is potentially four times the cost of typical wind installations in Europe or the United States. Only about 30% of these costs relate to the actual turbine and tower hardware, a basic reversal of most project development costs in which the turbine and tower make up approximately 70% of the total project costs.

The operation of these systems also poses additional challenges. Limited service capabilities, harsh climates, and expensive travel costs result in higher maintenance expenses and increased system or component down time. Advances in remote monitoring, adaptive system control and condition monitoring, and local wind technician training all help to reduce these costs and should be implemented in projects whenever possible.

5 Next Steps and Research Needs

In many locations around the world, wind-diesel applications can make financial sense (already more than 50 locations have been identified in Alaska alone) [27]. If fuel prices return to their pre-recession levels, this number will only increase. However, this will not guarantee the further development of wind-diesel applications since several policy and technical challenges remain.

5.1 Policy Challenges

Given the level of state, federal, and international funding used to supply energy (primarily through the use of diesel engines) to rural communities and research stations, policy plays a critical role in the development of new technology paradigms. The following key policy issues should be addressed:

- State policy and funding should be created or streamlined to support the development of diesel alternative systems. For example, governments in many nations will pay the entire cost of a new diesel station but require a cost share to implement wind or other renewable energy components as they are not considered critical.
- Many nations subsidize the cost of diesel fuel for power generation, which reduces the economic viability of other solutions and allows the state to be the primary benefactor of any personal reductions in fuel consumption. Fuel subsidy policy should ensure that projects that reduce fuel use should be able to capture at least a portion of the state's cost savings from that fuel reduction.
- States should mandate the consideration of the risks and impacts of investment in diesel power generation as compared to other generation solutions. For example, since fuel is considered an operational cost, power plant managers can pass any fuel-driven cost increases on to the customers. This places all risks of fuel-cost volatility on the community and removes any motivation by the plant operators, or in many cases state regulators, to support lower-risk options.
- Regional implementation approaches should be developed to support the co-development of systems in a number of communities, resulting in economies of scale for system implementation and leading to a viable operation and maintenance infrastructure (compared to funding single one-off projects that result in higher costs).
- Efforts should be continued to increase the amount of wind technology information, which will help to address the preserved risk and associated higher financial costs with the deployment of poorly understood power generation technologies.
- Permitting processes should be streamlined and different permitting agencies coordinated to reduce the time and funding necessary to develop projects.

5.2 Technical Challenges

The current high cost of rural wind and wind-diesel development clearly indicates that technology improvements are needed to ensure expanded use for rural electrification. The following technical issues form the core of this list:

- Collection, analysis, and dissemination of wind-diesel power system performance and cost information to document a track record for the technology and provide a data set to better determine where future cost savings might be found
- Development of lower-cost turbine foundations and installation processes that don't require the use of cranes, which must be transported to rural communities
- Expanded development of packaged systems that combine all of the needed components prior to installation in a rural community. This could be developed in combination with a more flexible plug-and-play control architecture
- Expanded development of lower-cost storage technology, allowing high-penetration systems to be implemented at lower cost
- Development of standards or guidelines for wind-diesel systems and controllers, including defined commissioning procedures to ensure acceptable system operation following installation
- Availability of modern wind turbines in the appropriate size range to incorporate into wind-diesel applications
- Upgraded re-manufactured turbines with performance monitoring equipment to allow for early failure detection
- Increase remote system and health monitoring capabilities, both for diesel engines and wind turbines
- A lack of an internationally recognized and agreed-upon terminology and methodology to design, analyze, and assess wind-diesel systems.

5.3 Institutional Challenges

Institutional and social issues associated with the integration of wind technologies into existing remote power systems also introduce their own, and generally more difficult to solve, challenges. The following technical issues form the core of this list:

- Poor understanding of the technology, specifically in locations where electric power is critical to sustaining life as is the case in many arctic communities

- Lack of trained personnel and the ability to keep trained personnel in communities
- Organizations and people at all levels with a vested interest in maintaining the existing infrastructure and systems
- Environmental, siting, or other development concerns
- Requirements to work in typically small, remote communities and the potentially fractious nature of the politics of those communities.

6 Conclusions

There is a clear interest and motivation to add wind technologies into the quiver of options to provide energy services to remote communities and research installations. However, due to a lack of knowledge and documentation in many cases, the rationale for adopting wind technology is rather weak. Analytic studies indicate that in locations with good wind resources, the life-cycle cost of incorporating wind is generally positive (meaning that it will save money in the long run), but the calculations are usually based on sketchy information regarding the performance of existing wind-diesel systems, typically in different environments. However, the option of waiting for another 10 years to “see how the technology matures” just guarantees that in 10 years, hundreds of diesel plants will have been installed or upgraded without consideration of alternatives, and little new information will have been gained. The result of this course of action could be minimal (if fuel prices drop and the world decided to tackle climate change directly) or it could be catastrophic (with fuel prices doubling again and the stranding of many rural communities due to environmental change). Clearly wind, or any other technology for that matter, is not going to replace diesel technology in providing energy to rural communities in the near term, but we must decide whether to invest the resources to make sure there are multiple arrows for this quiver. These decisions are ours to make. The true question is whether we make them with an eye to the future or looking at the past.

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14. ABSTRACT *(Maximum 200 Words)*

During the past few years, wind energy is increasingly used to reduce diesel fuel consumption, providing economic, environmental, social, and security benefits to communities' energy supplies. From Alaska to Chile, from Australia to Spain, from high-penetration wind-diesel plants to wind-diesel-hydro systems, the integration of wind turbines with conventional isolated generation is a commercial reality, and the market for wind-diesel systems is substantial. This paper describes the current status of wind-diesel technology and its applications, the current research activities, and the remaining system technical and commercial challenges. System architectures, dispatch strategies, and operating experience from a variety of wind-diesel systems will be discussed, as well as how recent development to explore distributed energy generation solutions for wind generation can benefit from the performance experience of operating systems. The paper also includes a detailed discussion of the performance of wind-diesel applications in Alaska, where 10 wind-diesel stations are operating and additional systems are currently being implemented. Additionally, because this application represents an international opportunity, a community of interest committed to sharing technical and operating developments is being formed. The authors hope to encourage this expansion while allowing communities and nations to investigate the wind-diesel option for reducing their dependence on diesel-driven energy sources.

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