A Feasibility Analysis of Wind Power as an Alternative Post-mining Land Use in Surface Coal Mines in West Virginia

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Surface coal mining in West Virginia has supplied energy to the eastern coast of the United States for over a century. Over the years, the coal mining industry has been forced to adapt as societal demands regarding health, safety, and environmental impacts have changed. More recent pressure has called for another iteration of change: long-term post-mining sustainability. The research presented in this thesis investigates one potential solution—or component of a solution—to improve the sustainability of surface coal mining in West Virginia: post-mining wind power.

This thesis intends to demonstrate and explain the feasibility of synergistic mine closure and wind development. Wind conditions at three reclaimed mine sites in West Virginia were monitored in order to develop representative case studies for post-mining wind power. This report contains a summary of the literature consulted to plan the site assessments, the methodology employed to execute them, the analysis steps undertaken to derive conclusions, and a discussion of all findings.

This research has found that significant cost savings can be yielded from synergistic mine closure and wind development, as compared to greenfield wind development. Though wind conditions themselves remain the primary driver for site feasibility, post-mining wind power is a practice with significant promise for improving project economics, contributing to renewable energy development, enhancing company-community relations, providing local employment opportunities, and exemplifying sustainable business practices in Appalachia.

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As a final miscellaneous note, all photos presented in this thesis were taken by the author.

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1. Introduction

Synergistic mine closure and wind energy development offers mining companies and energy developers an opportunity to contribute to long-term community post-mining sustainability and assist in domestic renewable energy development, while simultaneously experiencing significant cost savings in their respective areas of responsibility.

In the context of long-term mining sustainability, one unavoidable issue must be addressed: all mines must, inevitably, close. From an environmental perspective, this allows the mining process to represent a temporary ecological disturbance. From a socio-economic perspective, however, mine closure has a much more profound impact in that local jobs and the resulting support of community businesses will likely both end along with the mine's production. This issue may be combated with active economic development in surrounding communities by the controlling mining corporation. Economic post-mining land uses (such as wind energy development) serve as optimal economic development opportunities since they essentially extend the economic life of the mine site and mitigate the negative effects on the community typically associated with mine closure.

One of the primary barriers to renewable energy development, especially wind and solar power, is justifying the significant capital costs associated with their construction. Although renewable energy economics are largely constrained by fixed geographic factors (i.e. wind conditions, in the case of wind energy), additional siting factors may significantly ameliorate the financial feasibility of individual projects. For example, proximity to existing power transmission infrastructure and site topography (and by extension, the amount of earthwork needed prior to equipment installation) will both profoundly influence capital costs. A reclaimed mine site would offer ideal conditions for the aforementioned factors given that basic infrastructure (water, power, and road access) has already been constructed. Furthermore, the land will have been cleared and flattened, leaving a clean slate for new development.

From the perspective of a mine operator, post-mining wind power is very attractive since it would simplify the site reclamation process by eliminating the need to perform closure activities which would contradict with wind development, such as infrastructure removal, reforestation, and earthwork to restore original topography.

At face glance, the concept of synergistic mine closure and wind development appears highly desirable, however, many questions pertaining to specific development details remain unanswered. The research discussed in this document, developed in cooperation with Alpha Natural Resources (ANR), intends to clarify these issues and make quantitatively justified recommendations pertaining to post-mining wind power.

The details of post-mining wind power feasibility will be demonstrated through the presentation of three multi-tiered case studies of separate reclaimed or partially-reclaimed mining properties controlled by ANR. Field equipment was constructed at each site to collect wind data for a period of one year. The intention of the data collection phase of the project was to emulate industry-standard practices employed by utility companies in exploring wind development opportunities. The results of this phase of the project have been utilized to simulate the electricity output of a commercial-scale wind farm. These data serve as the basis for comprehensive cash-flow analyses of all three locations, which detail multiple scenarios for each site. In addition to the quantitative elements of the case studies, more qualitative considerations such as regulatory control, public acceptance, and future renewable energy development will also be discussed. The results of the case studies, coupled with a sensitivity analysis, will form the basis for justifying the feasibility of post-mining wind power. A thorough discussion of its merits will be provided, in addition to an examination of its principal limitations and potential issues impeding its adoption as a general practice. Ultimately, this thesis serves as a guide to understanding all known facets of synergistic mine closure and wind energy development in order to provide quantitative justification for its use at viable sites.

2. Background & Literature Review

Synergistic mine closure and wind energy development represents a significant opportunity for mining and energy companies to lower their own costs while simultaneously improving the long-term economic sustainability of neighboring communities and also contributing to renewable energy development. Numerous issues will be reviewed in order to provide a foundation for the discussion of the research presented in this document. First, background information on coal mining in Appalachia will be provided, followed by a review of sustainability in mining, with an emphasis on the Appalachian region. Surface coal mining reclamation practices will also be discussed, focusing on examples of economic post-mining land uses. The basics of wind energy will also be reviewed, including details for wind assessment practices and other considerations for wind development. The literature review will conclude with a summary of the effects of wind power on local communities.

2.1. Coal Mining in Appalachia

The Appalachian Regional Commission defines Appalachia as “a 205,000-square-mile region that follows the spine of the Appalachian Mountains from southern New York to northern Mississippi” [1]. Figure 2.1 shows a map of the east coast of the U.S. with the Appalachian region highlighted.

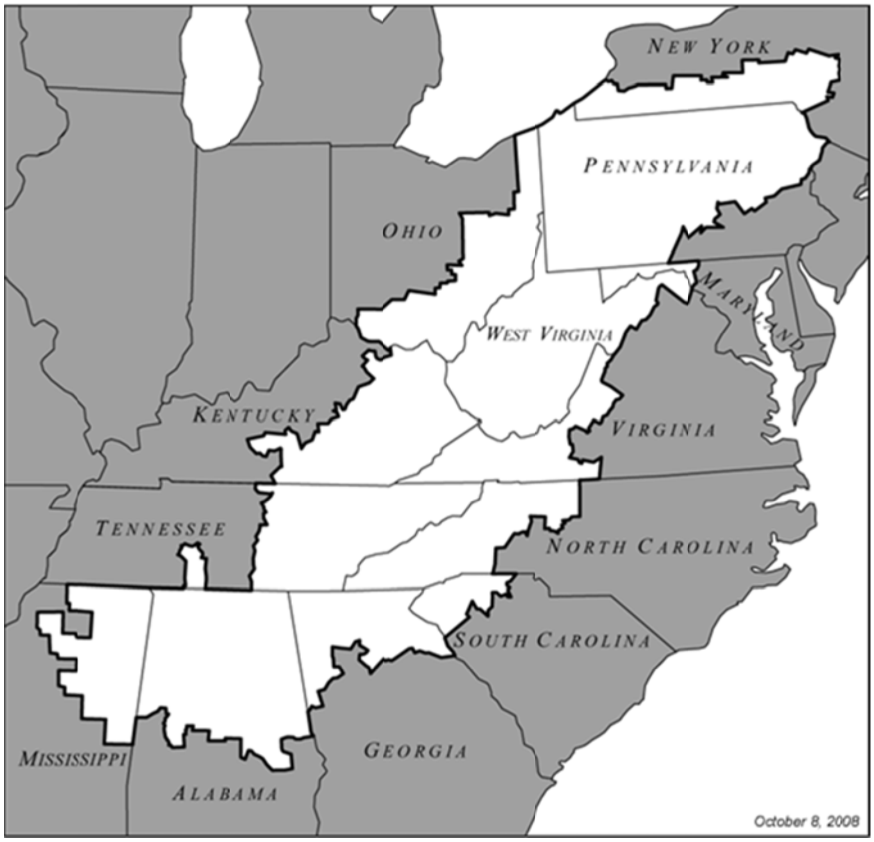

Figure 2.1 - Map of Appalachian Region, used with permission of the Appalachian Regional Commission, 2011 [Appalachian Regional Commission, *The Appalachian Region*, 2011]

Though this document will focus on West Virginia, it is important to understand the history of coal mining in the entire region. The terrain is generally mountainous with a healthy deciduous and evergreen forest cover. Slatick refers to the Central Appalachian Basin's geology as consisting of a series of small basins with a thick sequence of coal-bearing rocks, creating numerous coalfields [2]. These coalfields began to be exploited in the mid-19th century, fueling the industrial revolution in the U.S. The central and northern Appalachian coal basin continued production at a great rate, yielding approximately two-thirds of America's coal output in the 20th century. The intensity of Appalachian coal production led to many of its citizens working at mines or living near them. As such, coal mining has played a very prominent role in the history and cultural development of the Appalachian region [3]. In recent decades, American coal production has expanded westward into the Illinois and Powder River basins, reducing Appalachia's contribution to approximately one third of the national total.

Coal mining has been one of the primary economic drivers in Central Appalachia, currently directly providing around 30,000 jobs and, along with utility companies, paying approximately 65% of business taxes in West Virginia [4]. Roenker and Rose elaborate on the greater economic impacts of the coal industry, arguing that many service industries such as machine shops, construction contractors, electric services, and many others are directly and, in many cases, almost exclusively supported by the coal industry. More than 50% of the household income in many Kentucky counties is provided by coal industry jobs [5]. Rose estimates total U.S. household income contributions by the coal industry and its dependent service providers to be approximately $362 billion (2005 USD) distributed across 6.8 million jobs [6].

Although the economic contributions of coal mining have benefitted the Appalachian region, environmental damages and mine accidents have tarnished the industry's reputation. Surface coal mining—especially mountaintop removal (MTR)—in Appalachia, while having supplied millions of tons of coal, has caused more than one headache for the mining industry. Frequently depicted by the media as an archaic and environmentally-cruel profiteering tool, MTR has been at the forefront of anti-mining movements throughout Appalachia and the U.S. The arguments have escalated recently, pitting coal miners and their supporters against environmental activist groups and unhappy communities in an ongoing debate of the industry's future in the region. Davis, Fox, and Burns effectively summarize the arguments against surface coal mining with several key points: strong ties between the coal industry and the state government prevent political action and effective regulation, the environmental damages—both during and after mining—are catastrophic (and speak for themselves), coal mining does not provide an overwhelming number of jobs, and the poorest counties in the state are typically those where the most coal mining occurs [7] [8] [9].

No matter which side of the argument one agrees with, it cannot be denied that coal mining has been and continues to be—for better or for worse—a very strong component of Central Appalachia's history, economy, and culture. It is not the intention of this document to clarify the ongoing debate, but rather to establish a context in which it is clear that all sides will benefit from economic diversification and expansion, constructive mine-government communication, sustainable development, and improved community-industry relations [10].

2.2. Sustainability, Communities, and Mining

2.2.1. Sustainability Initiatives in the Mining Industry

The coal industry has reacted to societal demands in the past, having made dramatic improvements to its worker safety and environmental practices through a combination of governmental legislation and corporate initiatives. More recently, society has begun mandating overall sustainability in its industries.

The Brundtland Commission in 1987 defined sustainable development as the ability to "meet the needs of the present without compromising the ability of future generations to meet their own needs" [11]. Although many other definitions have been posited, most of them would agree that operating as a sustainable business encompasses making a combination of positive long-term <u>environmental</u>, <u>societal</u>, and <u>economic</u> contributions. Simultaneously satisfying all three categories presents a substantial challenge to any corporation. The minerals industry's difficulty is augmented by the fact that a mine is, by definition, a temporary entity which is guaranteed to disrupt the local environment and extract non-replenishable resources. Many critics have emphasized this point and argued that mining cannot ever be sustainable in a literal sense [12]. Others have indicated that, while mining and sustainability are not entirely incompatible, significant further action is needed to shift public perception [13]. Despite the challenge, mining companies all over the world have committed to sustainable practices in the interest of not only maintaining their social license to operate, but improving the welfare of the societies they serve [14]. It is also clear that, in modern society, marketing oneself as a sustainable business practitioner is a profitable enterprise (assuming, of course, that the claims are valid) [15]. Furthermore, banking institutions have begun enforcing more stringent sustainability requirements on the projects which they choose to finance [16] [17]. Ultimately, it is evident companies must continue incorporating and advancing sustainability principles in their mining practices if they are to flourish in and continue providing for our society.

As the previous section noted, a mining operation inherently contradicts some of the principles of sustainability for two reasons: all mining processes cause some sort of environmental disturbance and all mineral deposits will eventually be exhausted, thereby limiting the long-term economic potential of individual sites. The latter issue can be remediated in three ways. First, a company can employ a slower rate of production in order to lengthen mine life and minimize the "boom/bust" effect. Also, companies may transfer mine workers to new sites in the area after their original mine has closed. This practice is very common in Appalachia, as companies will frequently operate a large number of mines in a relatively small area and deploy the workforce as needed. The second method is to invest directly in local economic development while the mine is still active. Similarly, the third way to achieve economic and social sustainability is to create a profitable and job-providing post-mining land use, such as post-mining wind power [18].

2.2.2. Mine-Community Interactions

Though mining companies bear a responsibility to society at large, their most immediate obligation is to the communities nearest to and most affected by their operations. Many companies have made significant efforts to involve communities in the operation decision-making process, but have met with varying degrees of success [19] [20]. Similarly, participatory community development in Appalachia remains a field with substantial opportunity for improvement [21]. In any case, it is clear that successful mine-community interactions are a crucial component of the successful execution of sustainable development in a mining project [22].

In Appalachia, it is commonly perceived that companies will relinquish responsibility of their mine sites once production has ceased, taking previously available jobs elsewhere and leaving the community to deal with the environmental impacts from the site. Put simply, animosity and distrust (on both sides) frequently plague mine-community interactions. Post-mining wind power may help ameliorate these issues through the demonstration of two commitments: first, that the mining company is establishing a new job-provider for the community and second, that the mining company is not abandoning the land after reclaiming it.

2.3. Mine Reclamation

Mine reclamation is the process in which a mine site is restored to environmentally acceptable conditions. Given that a landscape represents a balance of geomorphic processes which are disrupted by mining, reclamation may be viewed as a process which returns the site to a steady state [23]. Activities to accomplish this typically include earthwork to restore approximate original contour (AOC) topography, water treatment to remove impurities, waste disposal, soil replacement and nourishment, construction of erosion controls, revegetation, reforestation, and site condition monitoring for several years after the mine has closed [24] [25]. The details of meeting acceptable conditions in the aforementioned categories are regulated at the federal level through the Surface Mining Control and Reclamation Act (SMCRA) of 1977 [26]. Kaas provides a thorough description of the general requirements of the law [27]. These tenets are enforced by the Office of Surface Mining (OSM), which has the authority to issue and revoke mining permits on the basis of their reclamation plans, among other criteria. To guarantee that reclamation activities be carried out, mining companies are, by law, required to purchase a bond valued at the total cost of reclamation [23]. This bond must be purchased prior to permit issuance and is released in stages as milestones are met in the reclamation and closure process. Should the mining company be unable to complete reclamation activities for whatever reason, the bond is instead used to fund mine reclamation and closure.

Surface coal mining in the Appalachian region typically executes reclamation activities contemporaneously with mining ones. In this case, mine *closure* is differentiated from reclamation in that it occurs exclusively after mineral extraction has been completed [28]. The research discussed in this thesis deals specifically with mine closure activities, as most reclamation tasks are inherent to the mining process and would be unaffected by the advent of post-mining wind power.

2.3.1. Post-mining Land Uses

Not all mine sites are restored to pre-mining conditions during reclamation. Although SMCRA typically mandates a return to AOC, this requirement may be waived in select cases [29]. Chief among these is the adoption of an alternative post-mining land use, which must be agreed upon by both the local community and OSM. Examples of post-mining land uses include airports, hospitals, parks, recreational lakes, schools, and commercial applications [25].

Commercial forestry is one of the most common economic post-mining land uses in Appalachia. Land owners have an opportunity to add further long-term economic value to their property, while mine operators can lower reclamation costs due to less-stringent grading requirements

[30]. Though reclamation is simplified, it is very important that land-use-specific considerations be met in order to maximize post-mining forestry potential [31]. Similarly to post-mining forestry, development of pastureland and biomass agriculture have also been explored as economic post-mining land uses [32] [33]. In all cases examined, it is evident that land preparation on behalf of the mine operator does not pose a significant expense as compared to conventional reclamation. Additionally, sources emphasize that the correct execution of land preparation activities is crucial to the success of the post-mining land use. Multiple authors have indicated that company-community cooperation and transparency with post-mining land use planning can significantly improve regional land values and economic development potential [34] [35] [36].

It should be noted that post-mining wind power will likely preclude other land uses should it be adopted. This thesis will not compare the economic and social contributions of wind power to other post-mining land uses. Rather, it is the intention of this document to demonstrate that post-mining wind power belongs in the same category as other economic land uses and bears consideration along with them. Ultimately, though, it is the responsibility of individual communities to decide what is best for their land, as some groups will inevitably weigh land use contributions differently than others.

2.3.2. Post-mining Wind Studies

While wind power has been investigated as a post-mining land use at a cursory level in the past [37], only one in-depth case study was encountered: the Coal River Mountain site [38]. This location has been a source of controversy due to the conflicts between mining developers, who wish to move forward with their already-permitted MTR plans, and environmental and community activists, who are actively advocating alternative land uses. Their chief proposal is the development of a 328 MW wind farm in conjunction with underground mining, rather than moving forward with surface mining. It is argued that MTR will severely inhibit the site's wind potential by lowering its final elevation. This concern should be limited to evaluations of MTR-type surface mines, as conventional strip mining will not significantly alter site elevation. The report also attempts to quantify the health and safety benefits of wind power vs. MTR by utilizing national-average fatality statistics for both industries. Similar tactics are employed to argue for the cumulative community benefits of wind development relative to MTR. While the report is decidedly biased, it ultimately concedes that the business advantage lies with MTR and that priorities must shift in order to induce change. In their proposed scenario of concurrent underground mining and wind power, the long-term economic contributions of this practice are repeatedly emphasized. Wind power development on reclaimed surface mine land would offer similar benefits.

2.4. Wind Energy

Wind is produced by the uneven heating of the Earth's surface by the Sun; solar energy absorbed by land or water is transferred to the atmosphere. This energy transfer heats air, changing its density and inducing flow. Wind turbines convert the kinetic energy of the wind into electrical energy. Powered by the wind, a turbine's spinning rotors drive (typically via a gearbox) electric generators housed in the nacelle. The resulting electricity is then transferred to the electric utility grid for consumption. Multiple texts offer excellent overviews of wind energy engineering basics [39] [40] [41]. Background information provided in this section has been taken from these references, whose content frequently overlaps. Specific citations are provided where concepts or theories exclusive to one reference are explained.

Humans have used wind energy as a resource for millennia. The use of wind turbines to generate electricity originated in the late nineteenth century with a 12 kW direct-current generator built by Charles Bush and Poul la Cour. After this discovery proved that wind could be used as an electricity source, wind energy research continued quietly for several decades. Serious interest did not begin until the sharp oil price increases of 1973. The first commercial-scale wind farms came into operation in the late 1970s and wind power has been rapidly expanding ever since [42]. Figure 2.2 demonstrates the stark increase in installed wind-generating capacity in the U.S; it has increased by a factor of 16 over the last ten years. To further illustrate its potential, the U.S. Department of Energy (DOE) has set a goal of providing 20% of national electricity with wind power by the year 2030 [43].

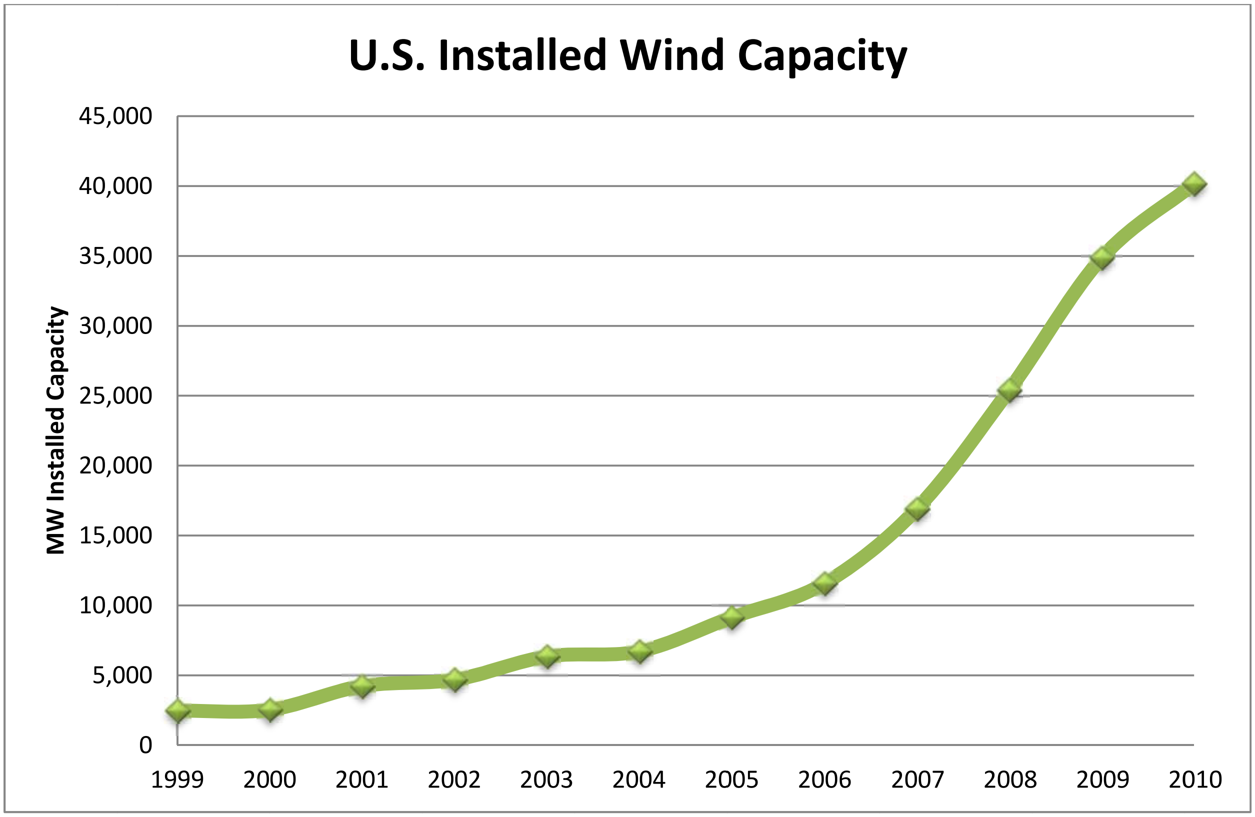

Figure 2.2 – Total U.S. Installed Wind Capacity [44]

Figure 2.3 shows the distribution of wind energy potential across the United States, while Figure 2.4 shows installed generating capacity by state. As Figure 2.3 demonstrates, a large portion of wind energy potential is distributed in the western states, though a promising area is present in eastern West Virginia.

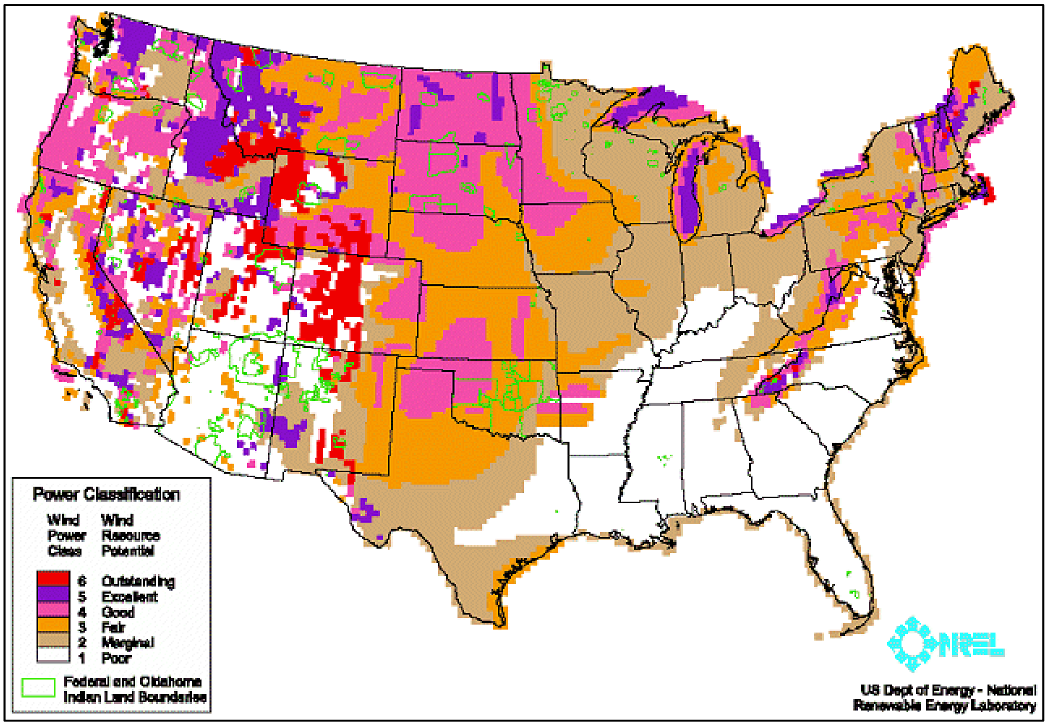

Figure 2.3 – U.S. Wind Resource Potential [45]

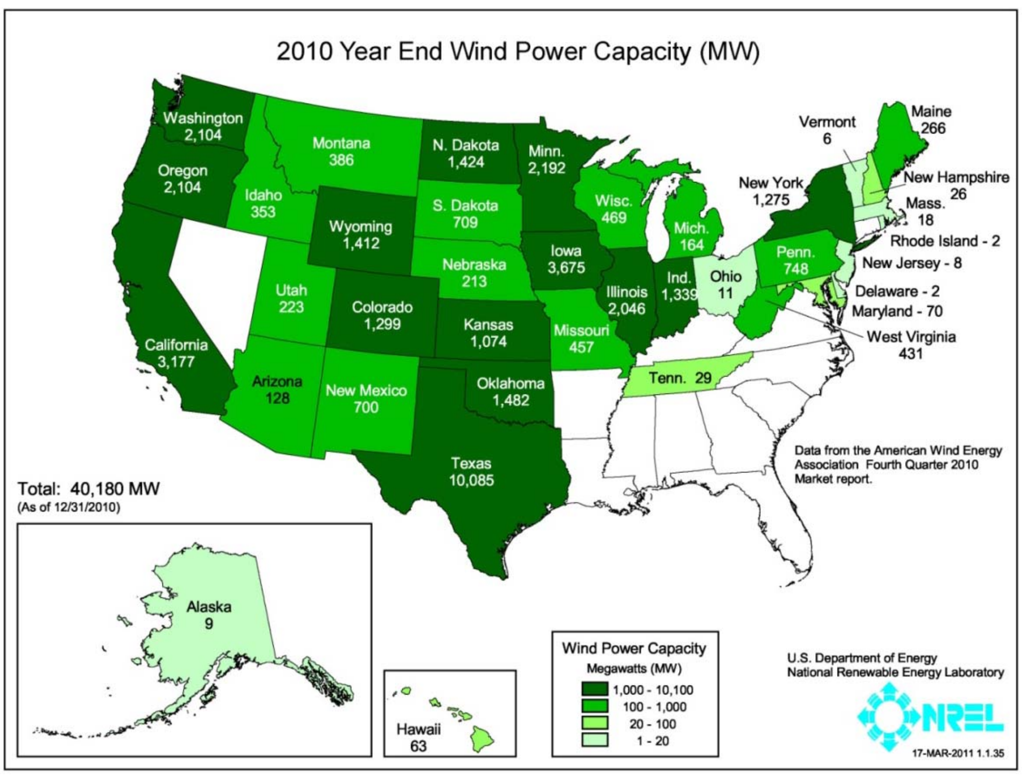

Figure 2.4 – U.S. Installed Wind Capacity by State [44]

Figure 2.5 shows West Virginia's wind resource potential in high resolution. The state of West Virginia has taken advantage of this potential with 431 MW of installed generating capacity (as of year-end 2010) at three commercial-scale facilities, with an additional 147 MW under construction [46]. The counties containing the active and under-development wind farms are highlighted in green in Figure 2.5.

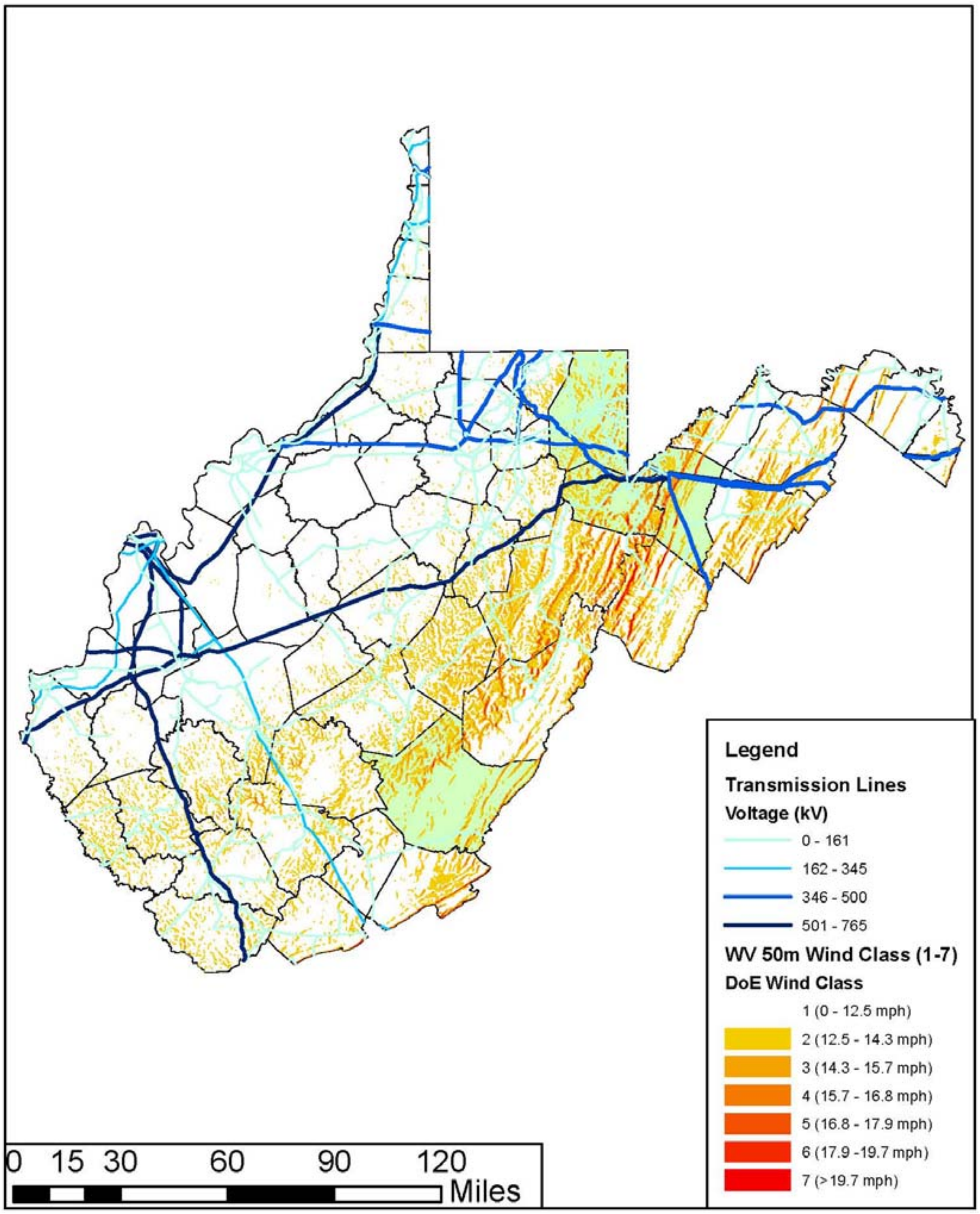

Figure 2.5 – West Virginia Wind Resource Map [47]

The instantaneous power in watts, *PD,* available from wind per square meter of cross-sectional area (wind power density) is given by the equation

$$PD = \frac{1}{2}\rho v^3 \qquad \textbf{(1)}$$

where ρ is the density of air in kg/m^3, and v is the wind speed in m/s. The wind power classes in Figure 2.3 and Figure 2.5 are based on the wind power density categories established by the DOE, which ranks wind conditions from 1-7 (poor to superb).

Wind energy has grown at such a rapid pace due to its strong set of advantages as a power source. Firstly, wind power is economically competitive with other sources when wind farms are sited properly (i.e. in excellent wind conditions). Secondly, its environmental impacts—as realized across its full life cycle—are significantly lower than most other energy sources (due to zero emissions during operation and no fuel requirement) [48]. These two factors form a very powerful combination; dual financial and environmental sustainability is a rare combination in the energy market [49].

Numerous publications debate the validity of the claim that wind power is economically competitive with conventional energy sources, arguing that government incentives disproportionately influence wind project economics [50] [51]. While these incentives (further discussed in the Policy & Legal Issues section) certainly improve project economics in all cases, many wind farms would be able to successfully operate without them. Independent of incentivization, well-sited wind power is currently the most economically-viable renewable energy source.

Despite the rapid ascent of wind energy and its associated benefits, it also possesses numerous disadvantages. Chief among these is the intermittent nature of the power delivery from wind farms. Equation 1 indicates that power output is proportional to the cube of wind speed, which fluctuate both daily and seasonally. As such, these fluctuations lead to extreme variations in electricity generation. Although large-scale energy storage would ameliorate this limitation, it is currently highly cost-prohibitive and carries with it increased environmental impacts [52] [53] [54]. Instead, other power systems must be used to fill in the gaps of electricity production from wind energy [55]. This leads to higher operating and management costs for utility companies, particularly in areas where precisely-controllable power sources (most notably, natural gas and hydropower) are not widely available.

2.4.1. Public Acceptance

Progress towards further wind development has also been hindered by issues of public acceptance [56] [57] [58]. Many rationales exist for society's hesitation to accept wind power. A primary reason is simply the visual and aesthetic impacts of a large wind farm; people don't want their views disrupted. This attitude is commonly referred to as "Not In My Back Yard" (NIMBY). Some perceive that the governmental support offered to renewable energy sources is an unfair advantage; they would prefer their tax dollars spent elsewhere. Others believe that renewable energy will always be more expensive than conventional sources and do not wish to pay more for their electricity. Finally, environmentalist groups have drawn attention to the negative effects that some wind farms have had on bird migration patterns and local bat populations [59].

In West Virginia, specifically, wind power has difficulty competing in a region dominated by coal production. Furthermore, a wind farm employs a relatively small number of people as compared to a mine. Many communities actively oppose wind development due to their loyalty to coal mining and the perceived lack of local benefits created by wind farms. On the other end of the spectrum, wind power is frequently touted as a renewable replacement for "dirty coal," with emphasis placed on MTR. Several references are provided for representative editorials, but many more are available upon searching [60] [61] [62]. Ultimately, the strong tension between coal loyalists and environmentalists has created a difficult situation for wind development in West Virginia [59] [63]. It is the intent of this research to demonstrate that coal and wind power do not need to be mutually exclusive.

2.4.2. Wind Assessment

Wind assessment is the process in which data are collected and analyzed in order to quantify the wind conditions of a particular site. The outputs of this process may then be used to plan project development and derive economic feasibility. Multiple sources were investigated in order to understand how wind projects are evaluated and planned [39] [40] [41] [64]. Several example wind assessment projects were also referenced [65] [66] [67] [68]. The goal of this review was to establish industry-standard methodology for wind assessment.

Wind assessment typically begins with a preliminary site selection process in which regional data are reviewed. The DOE and NREL provide publically-available national wind resource maps. Additionally, several private corporations offer higher-resolution datasets derived from non-public data collection regimes and accompanying analysis. Although the primary quantity of interest in this phase of assessment is wind speed, additional considerations include proximity to power transmission infrastructure, site accessibility, and topography. The preliminary site selection process will yield a list of candidate locations where empirical data will be collected.

The data collection phase involves the construction of wind condition monitoring equipment. Two options are available for this purpose: *in situ* and remote sensing measurements. *In situ* measurements are performed with a meteorological tower (met-tower), which uses sensors to measure wind speed, wind direction, temperature, barometric pressure, and relative humidity. Remote sensing methods include SODAR and LIDAR, which are based on sound and light waves, respectively. Both rely on the Doppler shift principle to measure wind speed and direction. An example SODAR-based wind assessment effort was used to quantify wind conditions at a reclaimed surface mine site in the summer of 2010 [69]. The consulted literature elaborates on the advantages and disadvantages of these systems, noting that the three are economically comparable. SODAR and LIDAR systems are easily deployed to remote areas with minimal site preparation and construction required. While they are also able to sense wind conditions at higher resolution and to greater monitoring heights than met-towers, these systems experience losses in data quality when the atmosphere is thermally well mixed. Complex on-site calibration is required, which, if performed incorrectly, leads to error in the dataset. Moreover, no standards exist for certifying SODAR and LIDAR data. As such, these systems are generally employed as supplemental components in wind assessment campaigns and their data correlated with met-towers.

2.4.3. Wind Farm Project Development

Cost estimation techniques for wind farm development—which follows the site selection, wind assessment, and feasibility study phases—were researched from multiple sources [40] [51] [70].

Broadly, the project development phase includes the planning and permitting stage, followed by site preparation and construction.

The planning and permitting stage includes multiple steps: micrositing (i.e. placing turbines), public consultation, land and visual impact assessment, ecological assessment, and permit submission. The site preparation and construction phase may commence once a permit has been granted. Relevant tasks include infrastructure development (i.e. road and water connections), land preparation (brush and tree clearing, land leveling), turbine foundation construction, and turbine assembly. The literature consulted indicates that, while most of these tasks are common to any wind project, line-item costs will vary substantially with changes in site conditions and regional availability of wind development resources and expertise.

2.4.4. Wind Turbine Technology

Wind turbine design is a robust field of engineering with significant research and development efforts among manufacturers, universities, and governments. Though turbine design is a well-documented field, the literature on this subject was not consulted in great detail, as the purpose of this research is not to contribute to turbine design, but rather to its applications. As such, the primary information sought was which factors to consider when selecting a wind turbine [71]. The literature indicates that mechanical reliability and durability are very similar between different turbine models in the same size class. Since turbine availability (i.e. construction lead time from the manufacturer) is not considered in this research, turbines must be selected solely on the basis of their power curves.

A wind turbine power curve, an example of which is shown in Figure 2.6, plots power output versus wind speed. These curves may, therefore, be used in conjunction with measured wind data to estimate per-turbine electricity output.

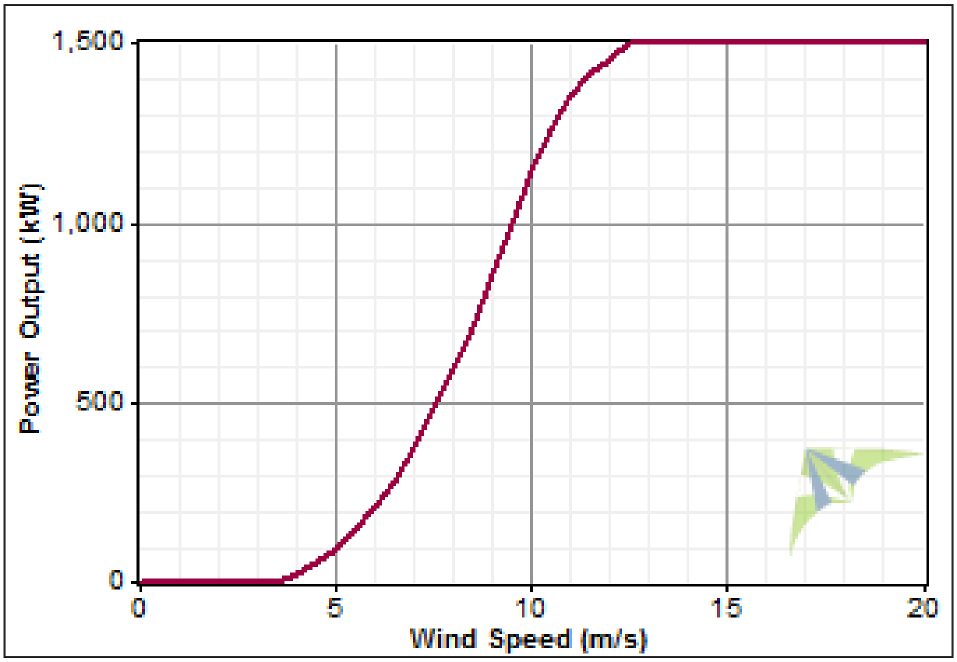

Figure 2.6 – Representative Wind Turbine Power Curve

As Figure 2.6 shows, turbines have both a cut-in and shut-off wind speed which define the operating range of the device. Smaller turbines tend to have lower cut-in speeds, allowing them to take advantage of poorer wind conditions, while larger turbines tend to have higher shut-off speeds, which correlate to higher maximum power outputs. Logically, larger turbines couple higher capital costs (both development and turbine prices) to their higher power outputs.

2.4.5. Community Economic Impacts

Multiple studies detailing the positive community-level economic impacts of wind development have been consulted [72] [73] [74] [75]. These impacts are classified as direct, indirect, and induced. NREL classifies direct impacts as those impacts that go to companies engaged in development and on-site construction and operation of wind farms. Direct beneficiaries from wind energy projects include project developers, road builders, concrete-pouring companies, construction companies, turbine erection crews, crane operators, and operations and maintenance personnel, as well as legal and engineering personnel who work on the project. Indirect impacts accrue in supporting industries and are driven by the increase in demand for goods and services from direct beneficiaries. Indirect beneficiaries include construction material and component suppliers, accountants and legal personnel who assess project feasibility and negotiate the contract agreements, banks financing the projects, wind turbine manufacturers, and manufacturers of maintenance equipment and repair parts. Finally, induced impacts result from reinvestment and spending of earnings by direct and indirect beneficiaries. These induced impacts are often associated with increased business at local restaurants and retail establishments, but also include child-care providers. In addition to the financial impact on community-based individuals and businesses, wind farms will generate tax revenues and lease-payments to land owners. Bacon effectively summarizes energy tax revenue procedures and issues [76].

The consulted literature differentiates between the construction and operations periods of community impacts, as the short-term impacts of wind farm development and construction do not persist for the life of the project. References also differentiate between benefits realized by community-owned versus privately-owned facilities. In the case of community-owned facilities, electricity generation profits (or savings, if the power is used directly) replace tax revenues and lease payments.

2.4.6. Policy & Legal Issues

Wind energy development is both driven and constrained by government laws and policy, which serve as a means to incentivize the environmental and social benefits associated with renewable energy [77] [78]. Koplow provides a thorough overview of the role of subsidization in the energy industry [79]. Also, excellent summaries of primary policy drivers in the wind industry are given by Andriano and Brown et al. [80] [81]. For the most part, public policy related to wind energy concerns itself with incentivization; permitting processes are typically regulated at a state or local level [80]. Areas of public policy affecting wind energy are discussed in individual subsections.

From a legal perspective, wind power has generated a substantial number of lawsuits. Brown and Escobar thoroughly summarize the themes of wind power in the legal system [82]. They highlight that most cases relate to lease payment disputes and local action to block wind development.

2.4.6.1. Federal Incentives

In addition to research funding, the federal government's primary means of driving wind development is through its Production Tax Credit (PTC) program, which currently pays wind utility operators a 2.1¢/kWh premium for electricity generated. This policy was enacted under the 1992 Energy Policy Act and, as of this writing, is guaranteed through 2012. Projects which commence operation prior to the PTC's closing date will qualify for the PTC for their entire production life [80]. Brown et al. notes that a production incentive alternative exists for publically-owned utilities (which are not liable for federal taxes), which subsidizes at a slightly lower rate than the PTC [81]. The PTC's future beyond 2012 is uncertain, though it should be noted that it has been up for renewal in the past and its duration has consistently been extended. The American Recovery and Reinvestment Act added an alternative 30% capital subsidization as an alternative to the PTC, but developers have, in most cases, demonstrated preference for the PTC.

2.4.6.2. State Incentives

States' primary means of driving renewable energy growth are through Renewable Portfolio Standards (RPS) programs, which Jaccard explains in detail [83]. In a basic sense, an RPS mandates that certain percentages of a state's electricity or energy be generated from renewable sources. This system may be enforced with a variety of means and "renewable energy" may be defined in different ways by different states.

RPS programs are currently in place in 29 states (21 are mandatory and eight are voluntary), including West Virginia. Some states, such as California, further incentivize wind power through state-wide zoning ordinances, loan assistance, and direct subsidization. Herzog discusses the importance of these programs and, more particularly, the effects of their withdrawal on wind development [84]. The specifics of Appalachian-region states' policies are discussed in a report prepared for the Appalachian Regional Commission [85].

In early 2011, West Virginia enacted an RPS which targets 25% alternative and renewable power by 2025 [86]. West Virginia's RPS is different from that of many other states in that it also allows for "alternative" power sources, which include variations of coal technology, coalbed methane, coal-to-liquids, synthetic gas, integrated gasification combined cycle facilities, and waste coal, among others. Though this RPS could theoretically be satisfied without the use of any truly renewable power sources (such as wind, solar, hydro, geothermal, and selected biomass), the state's generation credit system favors renewable over alternative power. Under the enacted system, one credit is awarded per MWh of electricity produced by alternative sources. Two credits are awarded per MWh of energy from renewable sources, while three credits are awarded per MWh to renewable energy produced at facilities sited on reclaimed surface mine land. Post-mining wind power qualifies for the latter designation.

2.4.6.3. Carbon Policy

A carbon tax is levied against processes which produce greenhouse gases (GHG) as a policy instrument to reduce emissions. Chupka provides a thorough overview of carbon tax basics [87], noting that multiple economists have argued in favor of carbon taxes over environmental standards policies in order to limit GHG emissions without handicapping industry. There is currently no carbon tax in place in the United States, though much speculation exists that one might be passed in the not-too-distant future. Carpenter and Hairfield elaborate on this possibility and the effects that it would have on the mining industry [88]. They also discuss the impacts of the current state of market uncertainty on technologies which would be affected by a carbon tax, if one were passed.

Although carbon taxes are currently not in place in the United States, they bear mention in that post-mining wind power would positively benefit from their inception should it ever come to pass.

2.5. Background & Literature Review Summary

This section has summarized the findings of the consulted literature on the topics of mining in Appalachia, sustainability, mine reclamation and closure, post-mining land uses, and wind energy. The intention of this discussion, beyond providing background information and technical justification for project methodology, is to establish a context in which it is clear that post-mining wind power will benefit all parties: the mining company, land owners, local communities, and wind developers. Carroll and Stanfield argue that one of the key principles of regional economic progress is the blending of new economic activity into the current economic base without destroying existing social interconnections; post-mining will do just that [89].

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3. Materials & Methods

This section will discuss the equipment and methodology employed to assess the validity of post-mining wind power. Main topics include site selection, data collection, data processing, and financial analysis. One of the principle stipulations to ensure the validity of the feasibility study was to utilize industry-standard practices in all phases of analysis. The publications referenced to accomplish this goal are discussed in detail in the Literature Review section [39] [40] [41] [64].

3.1. Site Selection

The first phase of the wind assessment campaign was to select reclaimed or partially-reclaimed mine properties to evaluate. In the interest of only dealing with one set of state regulations, it was decided to limit the study to West Virginia. Candidate ANR sites were identified and their property boundaries entered into a Geographic Information Systems (GIS) map file using the ArcInfo GIS software suite. Wind potential and power transmission grid data were then obtained from NREL [47] and combined with the reclaimed property outlines provided by ANR engineering staff. In this way, all potential monitoring sites could be surveyed simultaneously at a basic level.

The publically-available wind potential data used in the initial GIS analysis is composed mostly of interpolations between scattered monitoring stations. A more sophisticated dataset encompassing the areas under investigation was purchased from AWS TrueWind in order to improve the quality of the study. These data are shown overlaying (and masking) the public data in all figures in this section.

The DOE classifies wind potential from Class 1-7, with 1 being poor and 7 being exceptional. These classes are based on the anticipated power density (measured in W/m^2 – see Equation 1) of an area, which is a function of wind speed and consistency. Transmission line locations are also very important due to the large costs associated with building new high voltage lines; many locations with tremendous wind conditions are not economic because of their distance from transmission infrastructure. An initial query to ANR staff indicated that 21 properties would be available for consideration for monitoring. These are shown Figure 3.1 along with wind potential and power transmission infrastructure.

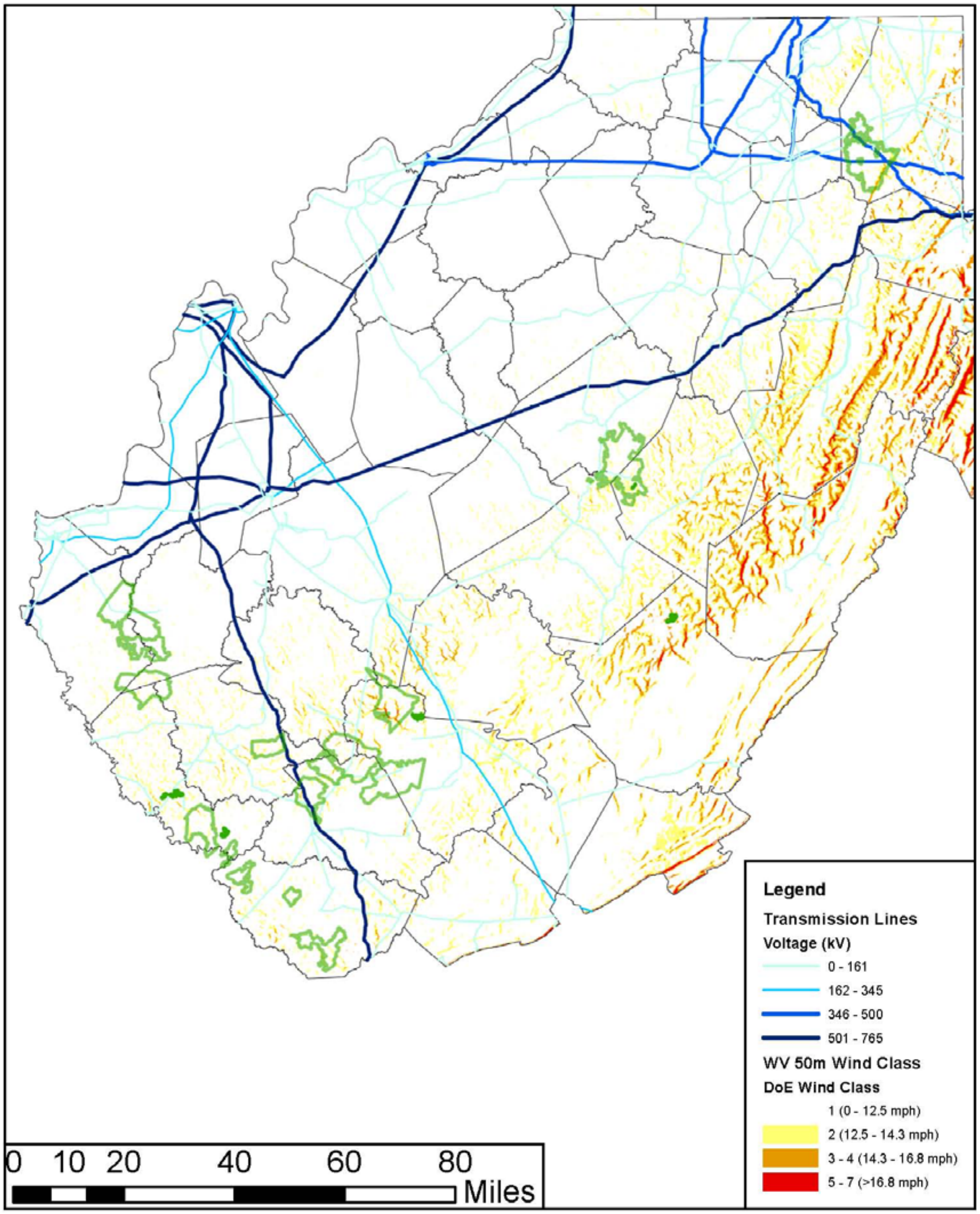

Figure 3.1 – ANR Candidate Property Locations

Many of the sites shown in Figure 3.1 were determined to be unsuitable for monitoring due to insufficient areas of reclaimed land or significant distance from desirable wind conditions. The list of candidate sites was shortened to six properties: Seven Pines, Lost Flats, Pax South, White Flame #9, White Flame #10, and Pounding Mill. Their property outlines are shown, along with wind conditions and transmission infrastructure, in Figure 3.2.

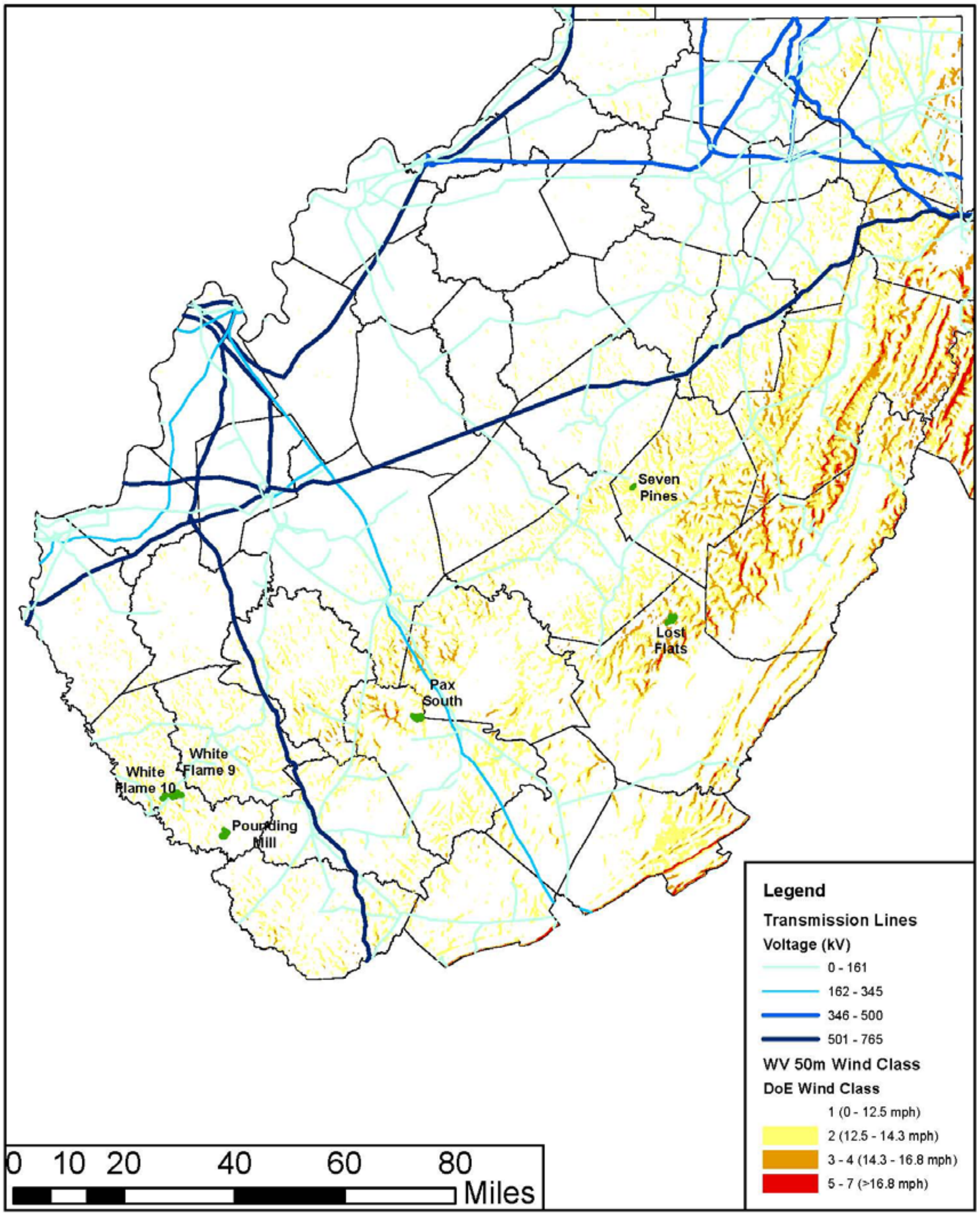

Figure 3.2 – ANR Finalist Monitoring Locations

Figure 3.3, Figure 3.4, Figure 3.5, and Figure 3.6 show zoomed-in views of all six properties. In these maps, wind conditions and property boundaries overlay a hillshade of local topography. Note that favorable wind conditions are located almost exclusively along ridgelines.

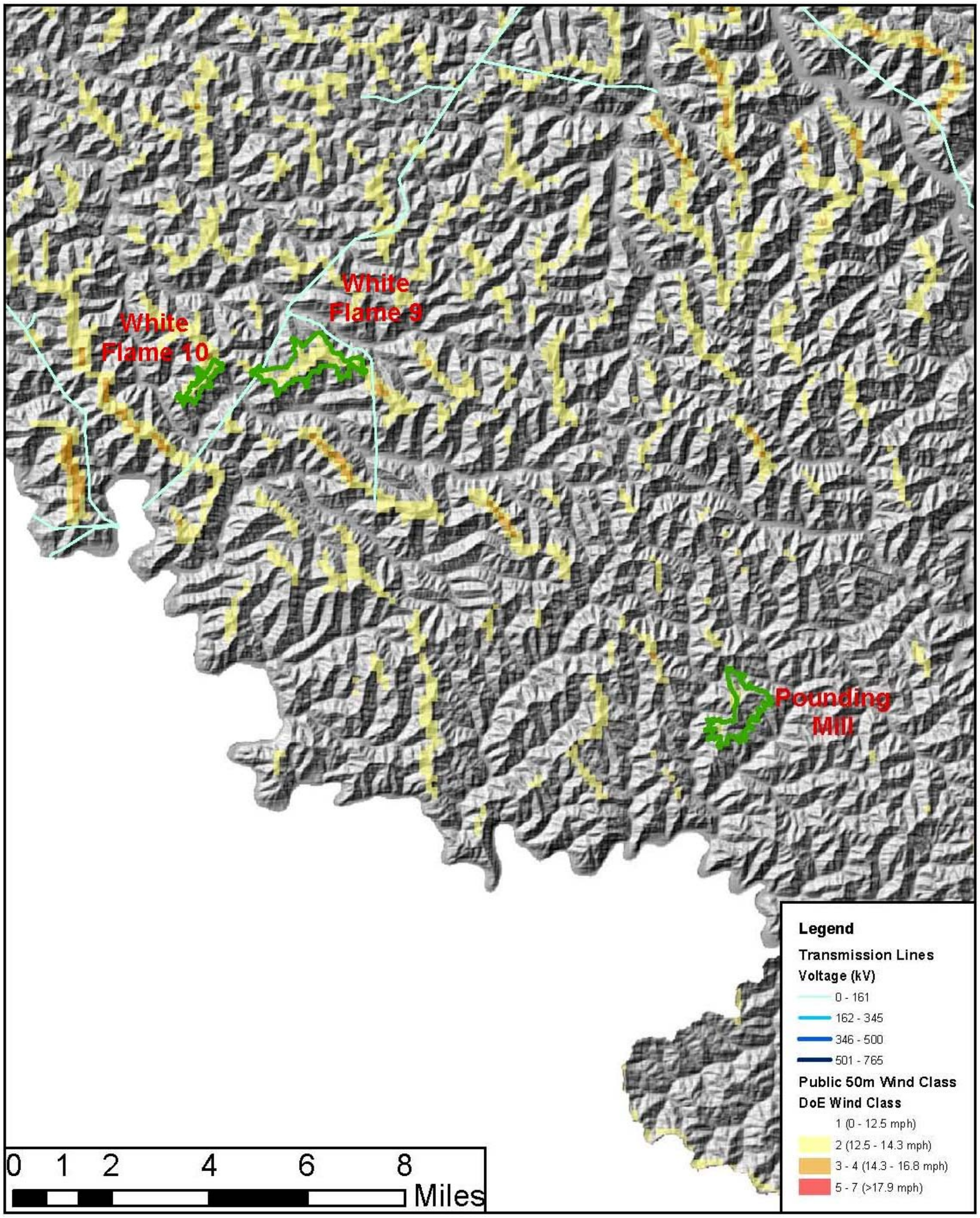

Figure 3.3 – Callaway Properties Map

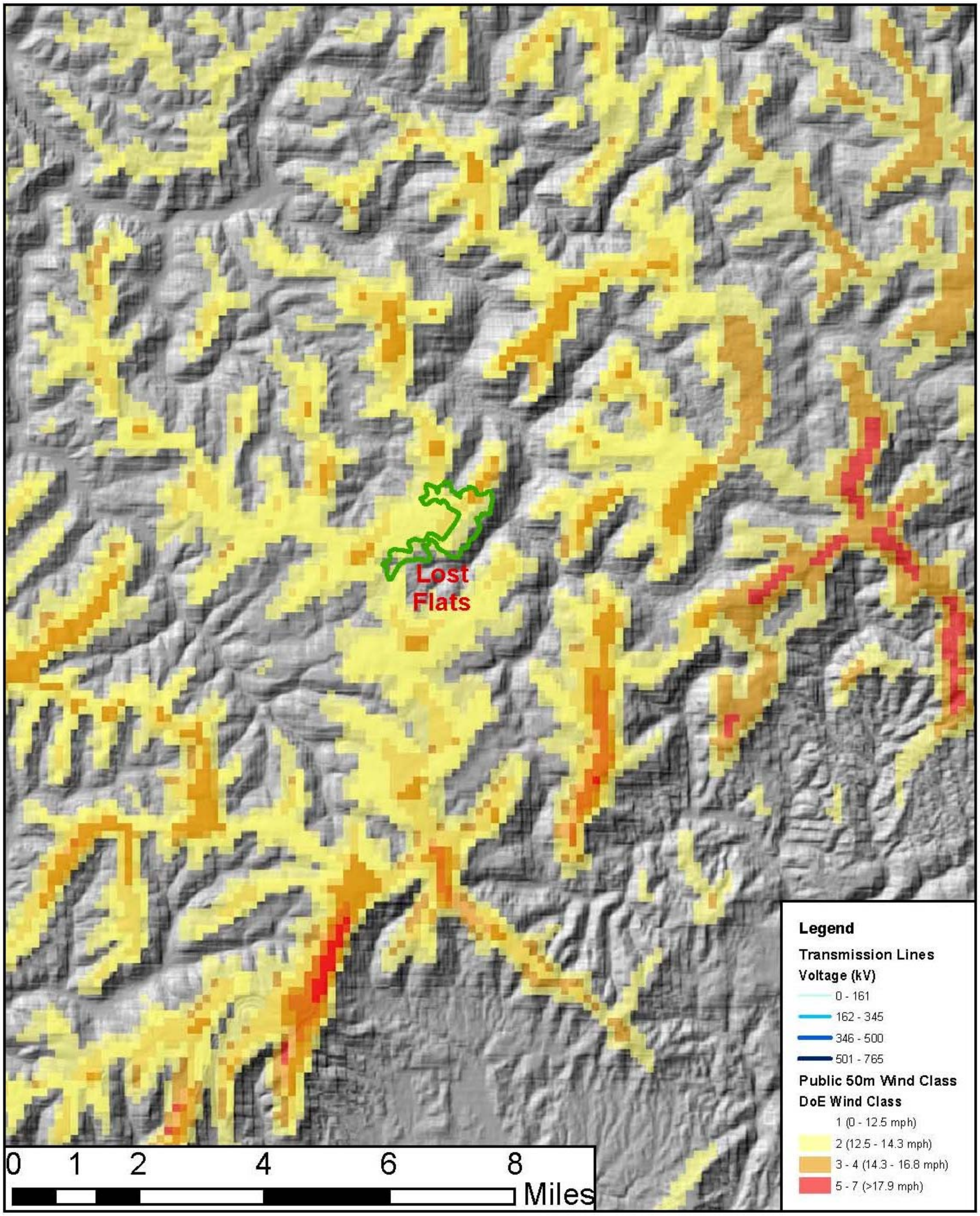

Figure 3.4 – Lost Flats Map

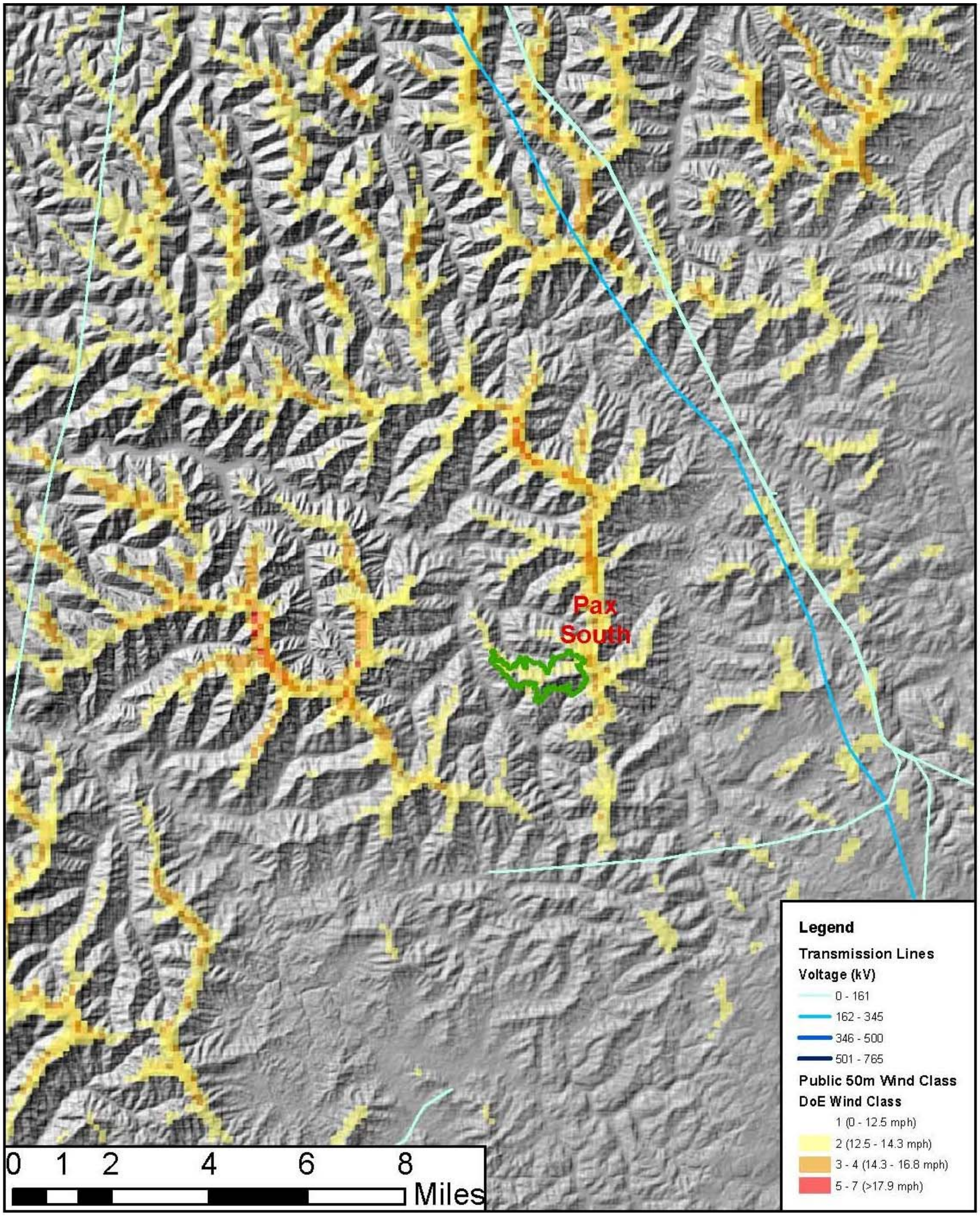

Figure 3.5 – Pax South Map

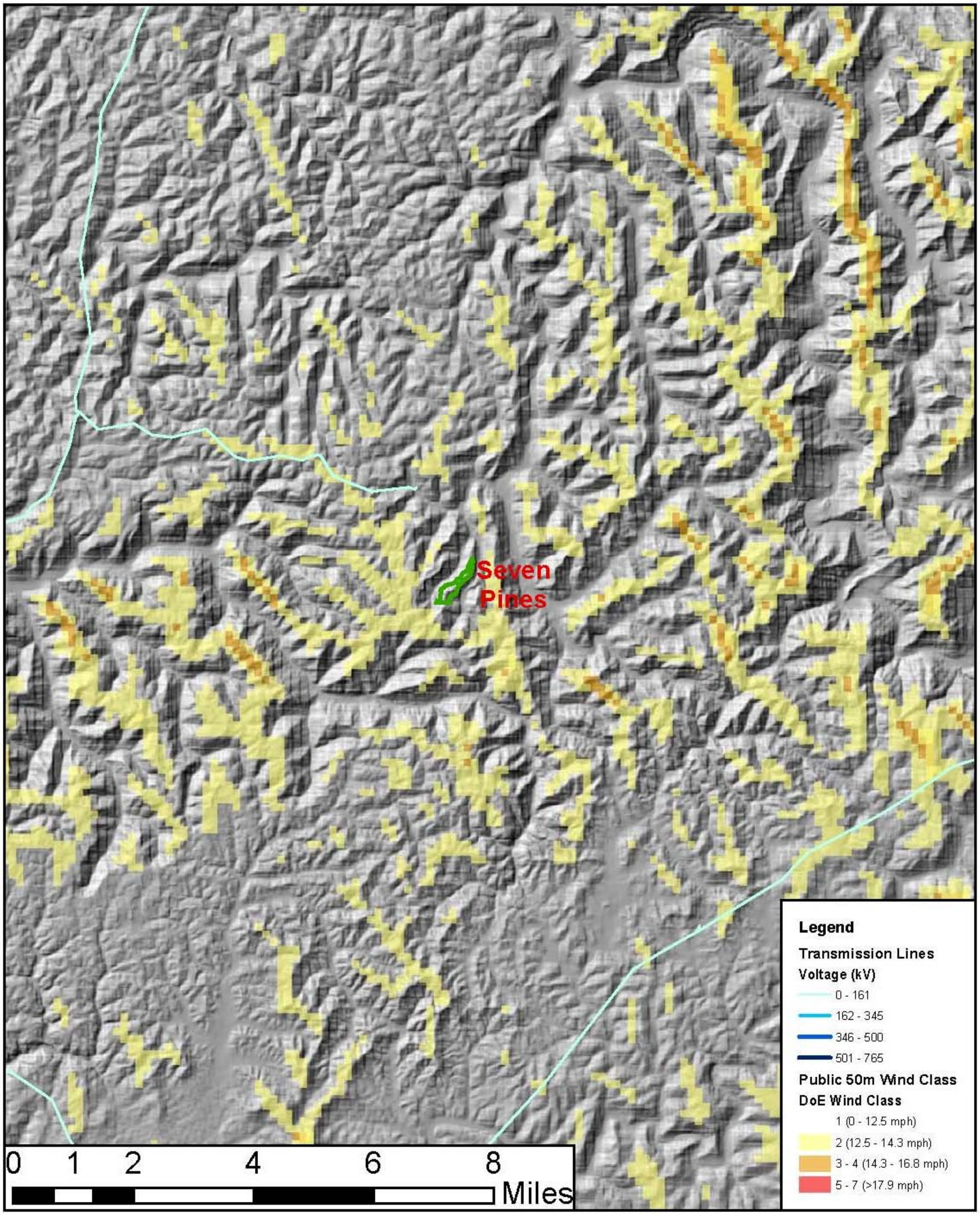

Figure 3.6 – Seven Pines Map

It should be stressed again that these data are the result of interpolation and numerical modeling based on scattered monitoring stations – not on comprehensive surveys. As such, areas shown as Class 2 may have sections of Class 3 or 4 (or vice-versa). The true conditions of a site cannot be known definitively until they have been measured directly. However, this general data can adequately serve as the basis for selecting the sites to be monitored.

All six candidate sites were visited in person and evaluated subjectively. Based on these considerations, site wind potential, and proximity to transmission infrastructure, the Lost Flats, Pax South, and White Flame #10 sites were chosen for monitoring. These locations are pictured in Figure 3.7, Figure 3.8, and Figure 3.9, respectively.

Figure 3.7 – Lost Flats Photo

Figure 3.8 – Pax South Photo

Figure 3.9 – White Flame #10 Photo

With monitoring locations selected, the wind assessment campaign could commence.

3.2. Data Collection – Wind Assessment Campaign

The purpose of the wind assessment campaign was to empirically collect data characterizing wind conditions at each of the three selected monitoring locations. This section will explain the details of the monitoring equipment selected and how it performs its intended functions.

3.2.1. Monitoring Equipment

Three options exist for data collection: met-towers, SODAR, and LIDAR (see Literature Review for additional details). Met-towers were selected due to their proven success rate and the industry-wide acceptance of met-tower data.

Industry-standard practices call for the measurement of three properties at any given monitoring location: wind speed, wind direction, and air temperature. Wind speed data are utilized for predicting turbine electrical output, directional data are used in siting and orienting turbines, and temperature data are used in the calculation of air density. All quantities are to be sampled at 2.0 Hz and logged at time-stamped 10-minute intervals which include average, maximum, minimum, and standard deviation values. Except for wind direction, the average value is defined as the mean for all samples. For wind direction, the average is a unit vector. These data must be collected for a period of at least 12 months in order to properly quantify the seasonal variations in wind conditions, though additional time is preferable.

After a detailed review of multiple monitoring solutions, a preferred equipment system was identified in the NRG Systems 60m XHD. The package contains a 60m (197ft) thin-wall steel tube tilt-up tower, six pre-calibrated cup anemometers, two directional vane sensors, temperature sensor, barometric pressure sensor, data logger, solar panels, satellite uplink (for data transmission), and all assembly tools and instructions. In addition to precisely following industry-standard methodology, the system is self-powered and able to transmit data under any conditions. Two anemometers are present at each monitoring height of 60, 50, and 38m; directional sensors are located at 60 and 50m; and the temperature and pressure sensors are placed at the base of the tower at a height of 2m.

Three NRG 60m XHD units were purchased and assembled at the Lost Flats, Pax South, and White Flame #10 locations. The towers were assembled on the ground and then tilted up using a hydraulic winch and gin pole. The tensions in a series of guy wires were adjusted during the lift and are used to stabilize the structure after it reaches a vertical orientation. The White Flame installation was completed on April 30th, 2010; the Pax South installation was completed on August 12th, 2010; and the Lost Flats installation was completed on August 20th, 2010. Figure 3.10, Figure 3.11, and Figure 3.12 depict the White Flame #10 tower being lifted into its final position.

Figure 3.10 – White Flame #10 Tower Installation I

Figure 3.11 – White Flame #10 Tower Installation II

Figure 3.12 – White Flame #10 Tower Installation III

The data collected from these towers were then used to quantify site wind conditions.

3.3. Data Processing

3.3.1. Wind Condition Quantification

The data gathered from the three monitoring locations were processed using the Professional Edition of the Windographer software, developed by Mistaya Engineering. Several quantities must be calculated from the raw data in order to conduct a site feasibility study. Wind speed and wind direction data are typically organized into bins and plotted as histograms. The Weibull probability density is then calculated from these data, given by the equation

$$\mathrm{pd}(v) = (\mathrm{k/A})\ (\mathrm{v/A})^{k-1}\ e^{-(v/A)^k} \text{ for } v > 0 \qquad \textbf{(2)}$$

where v is the wind speed, k is the shape factor, and A is the scale factor.

A modified version of Equation 1, which calculates power density, PD, in W/m^2 is shown below for use with the bin method.

$$PD = \left(\sum_{i=1}^{N} \rho_i {v_i}^3\right)/2 \qquad \textbf{(3)}$$

In Equation 3, N is the number of measurements, ρ_i is air density at time i, and v_i is wind speed at time i. Air density, ρ, in kg/m^3 is calculated with the equation

$$\rho = RH * 610.78 * 10^{\frac{7.5T_C}{237.3+T_C}} \qquad \textbf{(4)}$$

where RH is the relative humidity and T_C is the temperature in degrees Celsius.

Wind shear, which is quantified as an exponential function, is defined as the change in horizontal wind speed relative to a change in height. The vertical wind shear exponent, γ, is calculated with the equation

$$\gamma_{1,2} = \frac{\log(v_1/v_2)}{\log(h_1/h_2)} \qquad \textbf{(5)}$$

where v_1 is the wind speed at height h_1 and v_2 is the wind speed at height h_2.

Turbulence has a very specific meaning when describing wind conditions; it is the standard deviation of horizontal wind speed, vertical wind speed, and wind direction around the ten-minute average. Turbulence intensity, *TI*, is defined as the ratio of standard deviation to the average. In wind projects, the horizontal wind speed turbulence intensity is most commonly used. The horizontal wind speed turbulence intensity is given by the equation

$$TI = \frac{\sigma}{v_{avg}} \qquad \textbf{(6)}$$

where σ is the standard deviation of wind speed and v_{avg} is the average horizontal wind speed.

The Windographer software automatically processes the raw data to generate these quantities and plots relevant data in order to represent site wind conditions.

3.3.2. Electricity Output Estimation

The Windographer software is able to estimate the annual energy production (AEP) by correlating the recorded wind conditions with a turbine model's power curve. The AEP of a specific turbine is given by the equation

$$\text{AEP} = \frac{\sum_{i=1}^{N} PC(v_i)}{N/52{,}560} \qquad \textbf{(7)}$$

where $PC(v_i)$ is the power curve's electric output at v_i and N is the number of ten-minute interval data points in the time series.

The turbine model used in the analysis—the General Electric 1.5s—was chosen for the commercial-scale wind farm analyses because it is the most common wind turbine in the world. It has a hub height of 64.7m, a rotor diameter of 70.5m, and a rated output of 1500 kW. The GE's power curve is shown in Figure 3.13.

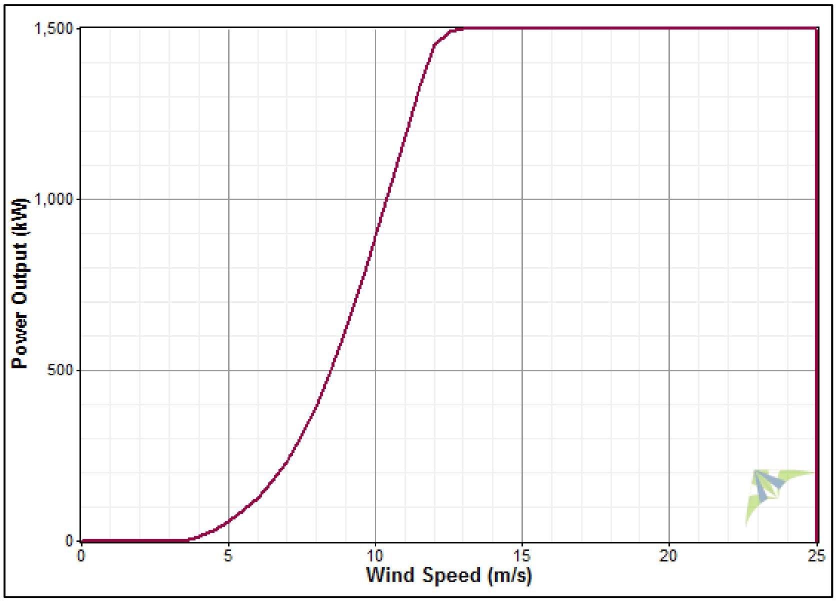

Figure 3.13 – General Electric 1.5s Turbine Power Curve

3.3.3. Data Uncertainty

Due to the dramatic influence of wind condition variations on wind farms' power outputs, a data uncertainty analysis should be performed with all wind assessment campaigns. Typical sources of uncertainty include [39]:

1) Sensors
2) Shear model
3) Spatial distribution model
4) Long-term climate adjustment
5) Plant loss uncertainty

Sensor uncertainty refers to instrument, calibration, and setup errors which skew readouts from individual sensors. Shear model uncertainty refers to errors incurred during the extrapolation of wind conditions from sensor heights to turbine hub heights. Spatial distribution model uncertainty refers to the error present when wind data is translated from measured locations to turbine locations. Long-term climate adjustment uncertainty refers to the error in the predictions of long-term wind conditions from short-term datasets. Finally, plant loss uncertainty refers to the error in estimating turbine power output losses relative to the AEP values calculated in Equation 7. Uncertainty quantities are typically calculated for each category and then combined into a total uncertainty factor. Assuming that individual components are uncorrelated, the total uncertainty is found by taking the square root of the sum of the squares of the individual uncertainties.

Since the focus of this thesis is on discussing the benefits of post-mining wind power, advanced uncertainty calculations were not performed. Baseline values for uncertainty were, however, incorporated into the sensitivity analysis presented in Chapter 5.

3.4. Financial Analysis Methodology

This subsection will explain the methodology employed to evaluate the economic potential of post-mining wind power at the monitored locations. The basic approach of this analysis is to produce discounted cash flows of multiple post-mining wind power scenarios and compare them to a reference case. Discounted cash flow methodology has been adopted from Stermole and Stermole [90]. Wind industry-specific considerations were referenced from Jain [39].

Each cash flow will be comprised of wind development capital costs, annual revenue (i.e. electricity sold), annual operating expenses, and taxation. Mine closure costs will be presented separately. Representative cash flows will be developed for post-mining wind scenarios by manipulating mine closure costs, wind development capital costs, and taxation benefits.

Mine closure costs are summarized in Table 3.1 and wind development costs are presented in Table 3.2.

Table 3.1 – Mine Closure Unit Costs

Item	Cost
Revegetation	$ 500.00 /acre
Drainage	$ 50,000.00 (lump sum)
Tree Planting	$ 1,500.00 /acre
Regrade & Topsoil	$ 3,000.00 /acre
Road Removal	$ 36.00 /ft
Power Line Removal	$ 14.77 /ft

Table 3.2 – Wind Development Unit Costs

Item	Cost
Tree Removal	$ 2,500.00 /acre
Site Grading	$ 5,000.00 /acre
Road Construction	$ 60.00 /ft
Electrical	$ 2,000,000.00 (lump sum)
Transmission	$ 25.00 /ft
Turbine Foundations	$ 150,000.00 /turbine
Turbine Construction	$ 100,000.00 /turbine
Engn. & QC	$ 2,000,000.00 (lump sum)
Turbines	$ 1,500,000.00 /unit

Operating costs include turbine maintenance, site maintenance, fees and licenses, utilities, insurance, consumables, and turbine replacement parts inventory. Lease payments are made to landowners as a percentage of revenue generated from turbines placed on their land. Revenues are earned from the sale of this electricity and, in select scenarios, the sale of RPS and carbon credits. Taxation considerations include federal taxes, West Virginia state taxes, and the PTC.

In the reference case, mine closure and wind development occur independently; all costs are incurred. In the synergistic development scenario, redundant mine closure and wind development costs are removed. Further details are divulged in the Analysis & Discussion section.

Four financial metrics will be used to compare the development scenarios: net present value (NPV), internal rate of return (IRR), levelized cost of electricity (LCOE), and payback period (PBB). The NPV is calculated with the equation

$$\mathrm{NPV} = \sum_{i=0}^{L} \mathrm{cf(i)}/(1+r)^{i} \quad \textbf{(8)}$$

where L is the life of the project in years, i is the year index, r is the discount rate, $i = 0$ is the year when investment is made, $i = 1$ is the year when project starts producing energy, and cf(0) = total installed cost (TIC). The IRR is the discount rate which yields an NPV of zero. The LCOE is the value of energy that yields an NPV of zero. This industry-standard metric takes into account the total lifecycle cost of electrical power sources, including capital, operating, and financing costs. Assuming that all capital costs are incurred in year zero, LCOE is given by the equation

$$\mathrm{LCOE} = \left(\sum_{i=1}^{L} \mathrm{rc}(i)/(1+r)^{i} + \mathrm{TIC} \right) \bigg/ \sum_{i=1}^{L} \mathrm{AEP}(i)/(1+r)^{i} \qquad \textbf{(9)}$$

where rc(i) is the recurring cost in year *i*. Finally, PBB is a measure of the number of years it takes for a project to repay its total investment, as determined by comparing the sum of net after-tax cash flow to the TIC.

4. Results

This section will present the results obtained from the wind assessment campaign for the Pax South, White Flame #10, and Lost Flats monitored locations. All plots presented in this section were created using the Windographer software.

4.1. White Flame #10

This subsection will present the data collected at the White Flame #10 site. Figure 4.1 shows the plot of mean monthly wind speeds.

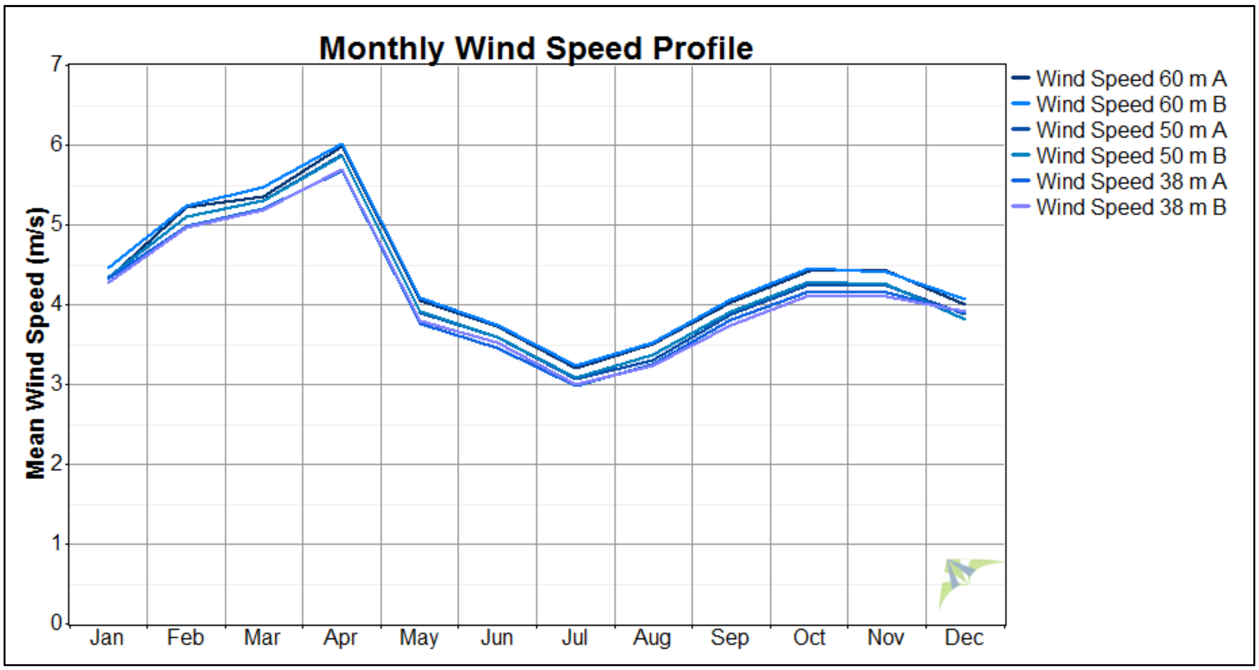

Figure 4.1 – White Flame #10 Monthly Mean Wind Speed

Figure 4.2 shows the plot of hourly mean wind speeds. Cumulatively, these describe the diurnal wind speed fluctuations at the site.

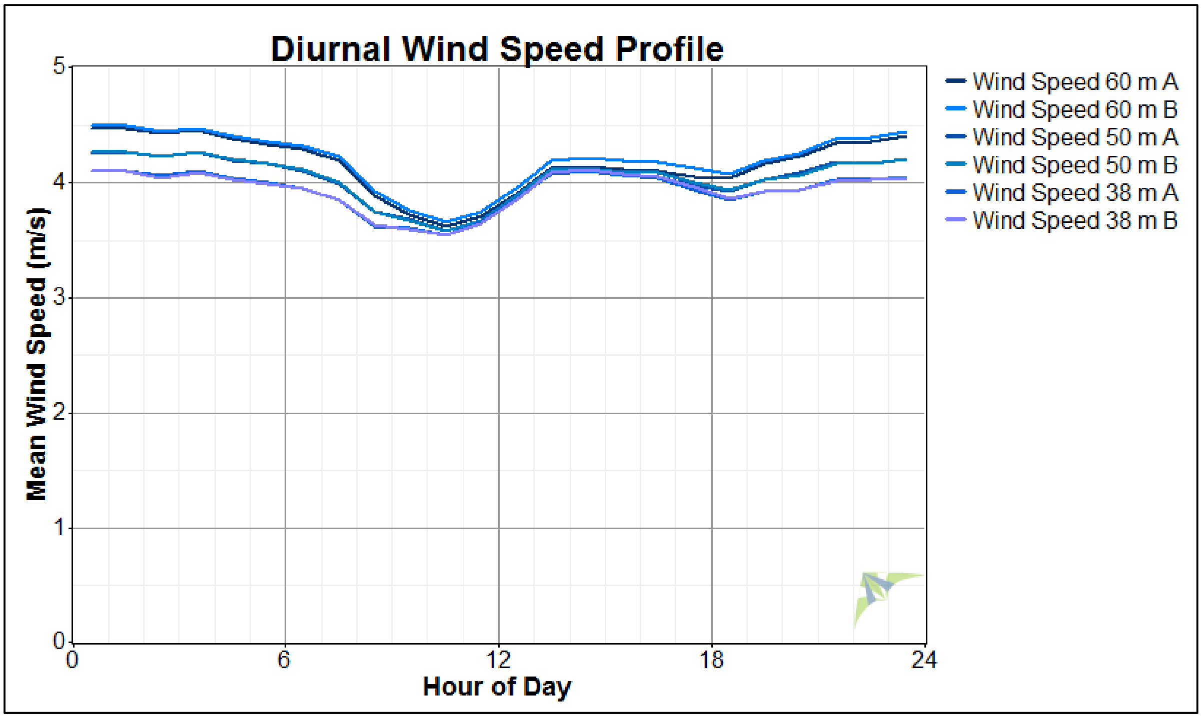

Figure 4.2 – White Flame #10 Diurnal Wind Speed Profile

Figure 4.3 shows the vertical wind shear profile, which is used along with mean wind speed to determine turbine electrical output.

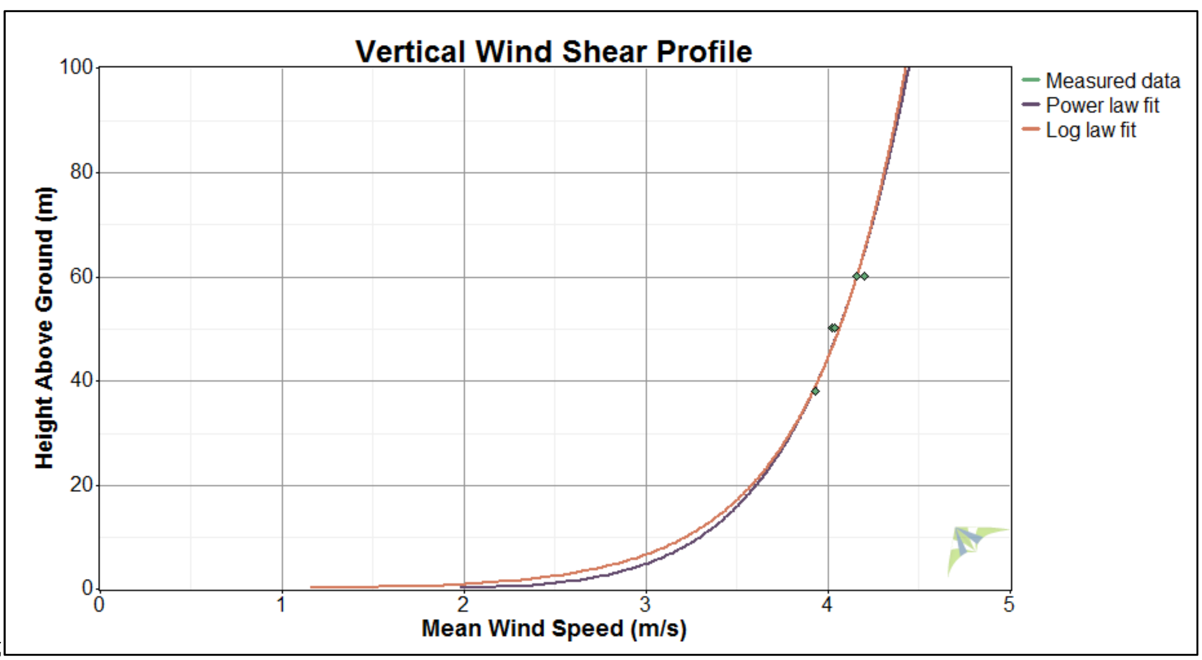

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Figure 4.3 – White Flame #10 Vertical Wind Shear Profile

Figure 4.4 and Figure 4.5 show the directional frequency of wind at the site, indicating that winds at White Flame trend in a range between the northwest and south directions.

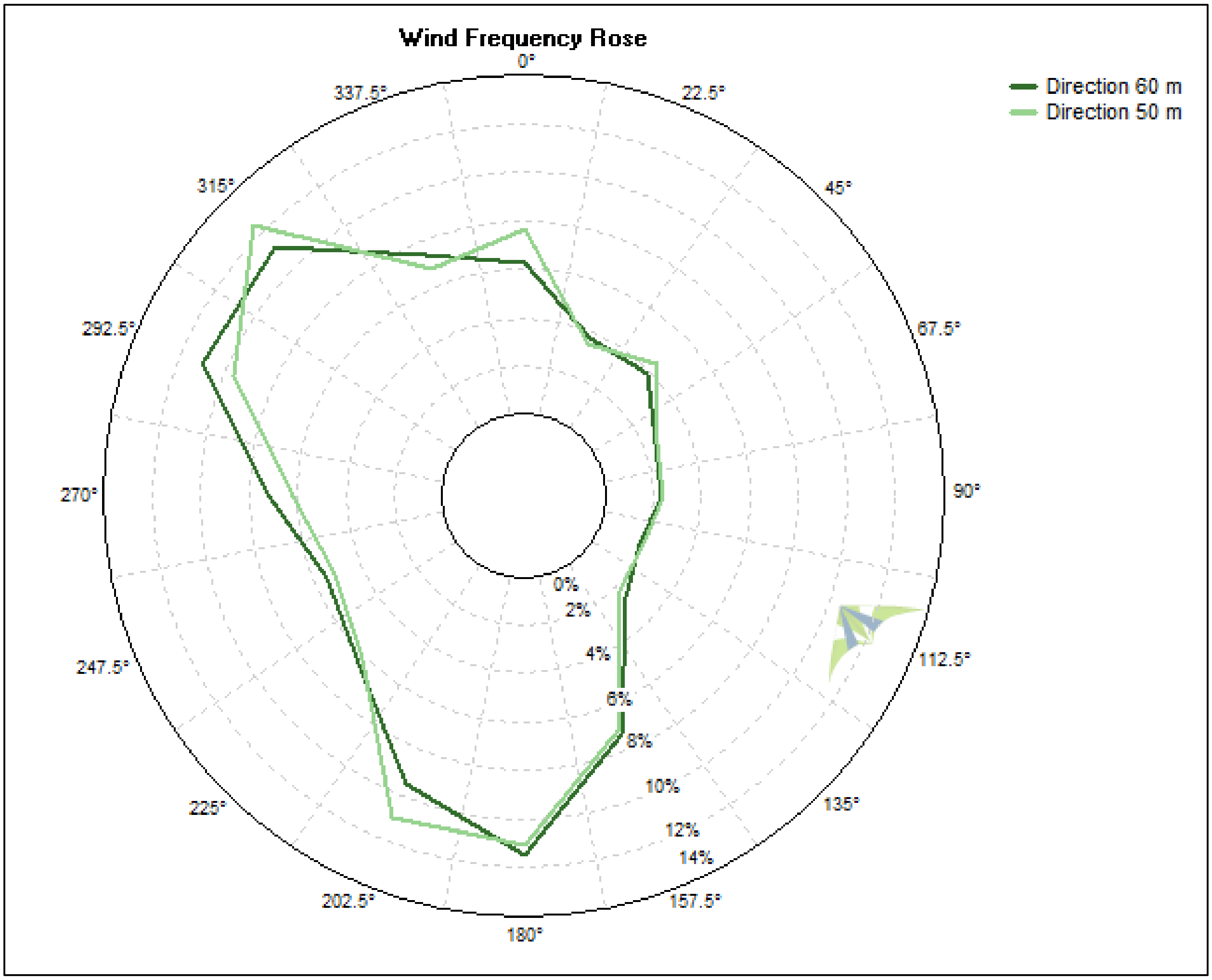

Figure 4.4 – White Flame #10 Wind Frequency Rose (Type A)

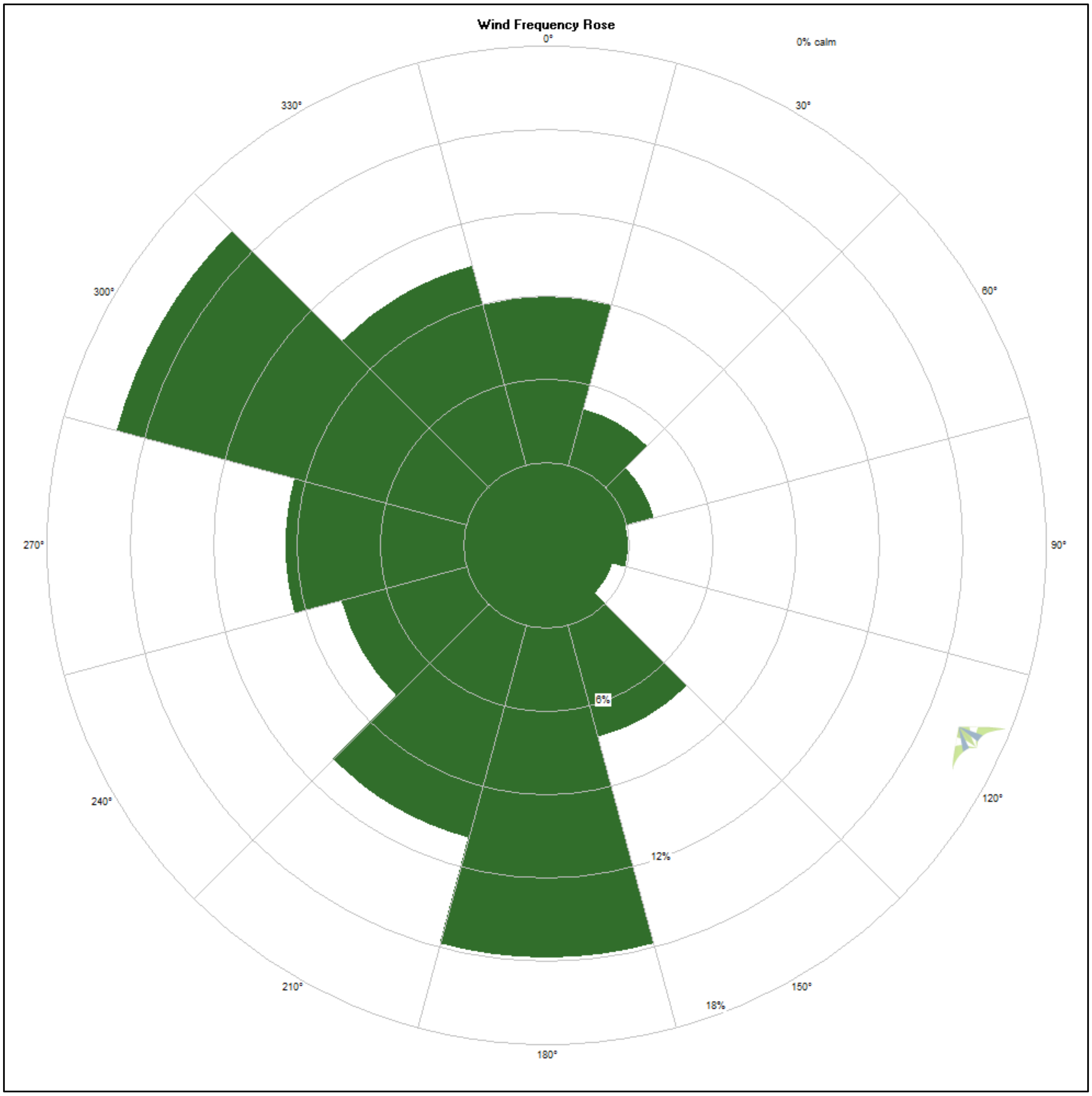

Figure 4.5 – White Flame #10 Wind Frequency Rose (Type B)

Figure 4.6 depicts a probability distribution function plotted on a histogram of the site's mean wind speeds.

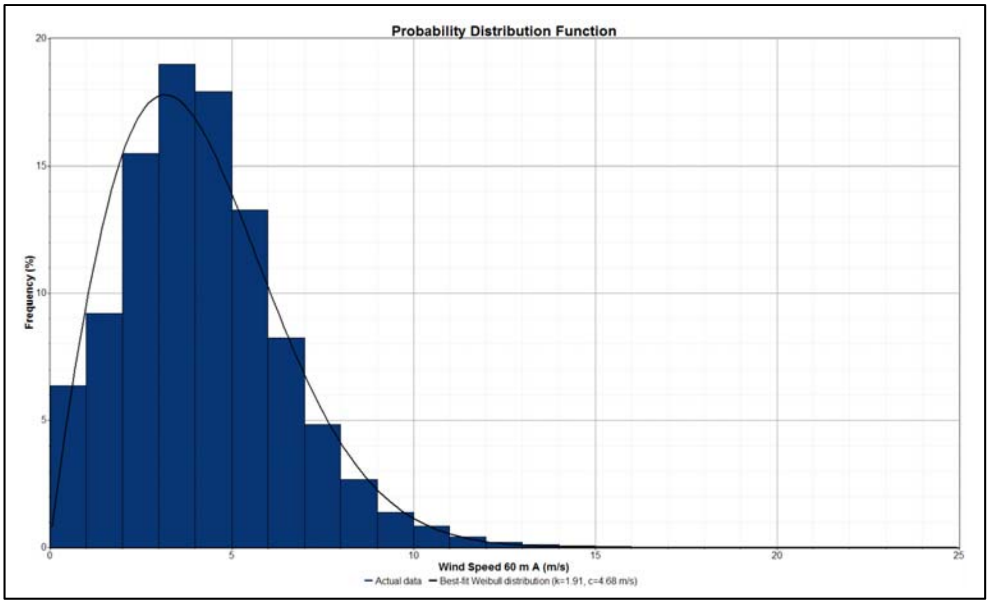

Figure 4.6 – White Flame #10 Wind Speed Histogram

Figure 4.7 depicts turbulence intensity versus wind speed at White Flame #10.

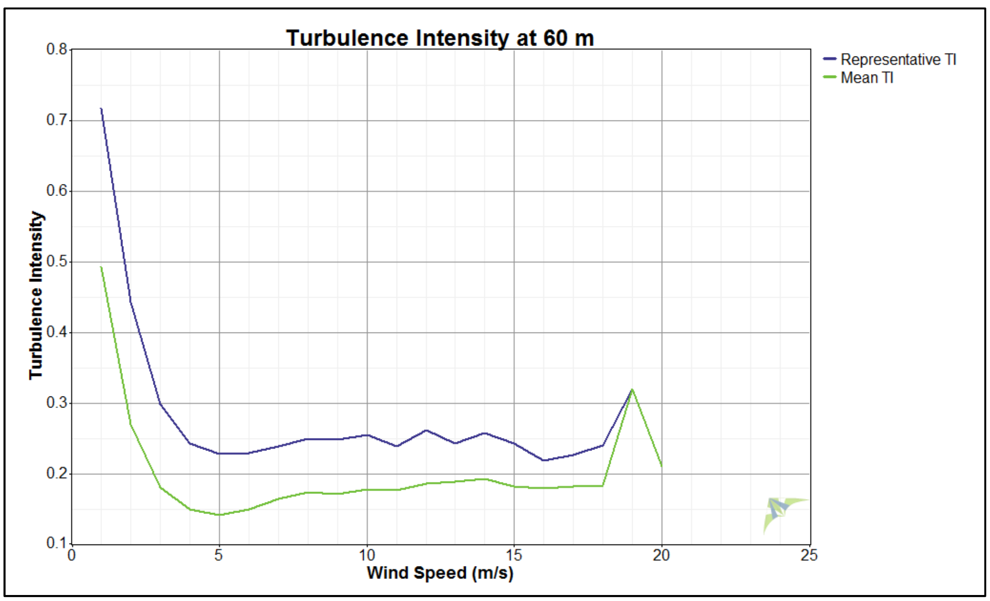

Figure 4.7 – White Flame #10 Turbulence Intensity vs. Wind Speed

The data presented in this section represent the wind conditions of the White Flame #10 mine and will be used in the following chapter to assess the economic wind potential of the site. These results indicate that the White Flame #10 site has a *PD* of 90 W/m^2, which correlates to a DOE Wind Class 1 designation.

4.2. Pax South

This subsection will present the data collected at the Pax South site. Figure 4.8 shows the plot of mean monthly wind speeds.

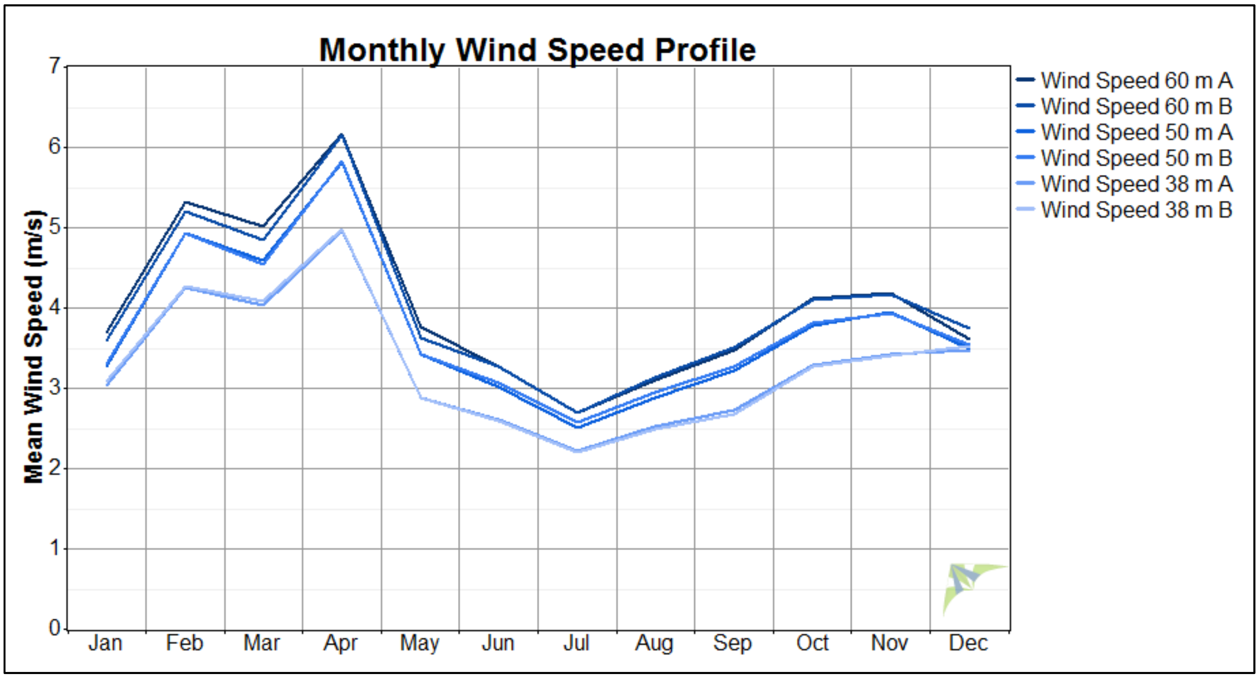

Figure 4.8 – Pax South Monthly Mean Wind Speed

Figure 4.9 shows the plot of hourly mean wind speeds. Cumulatively, these describe the diurnal wind speed fluctuations at the site.

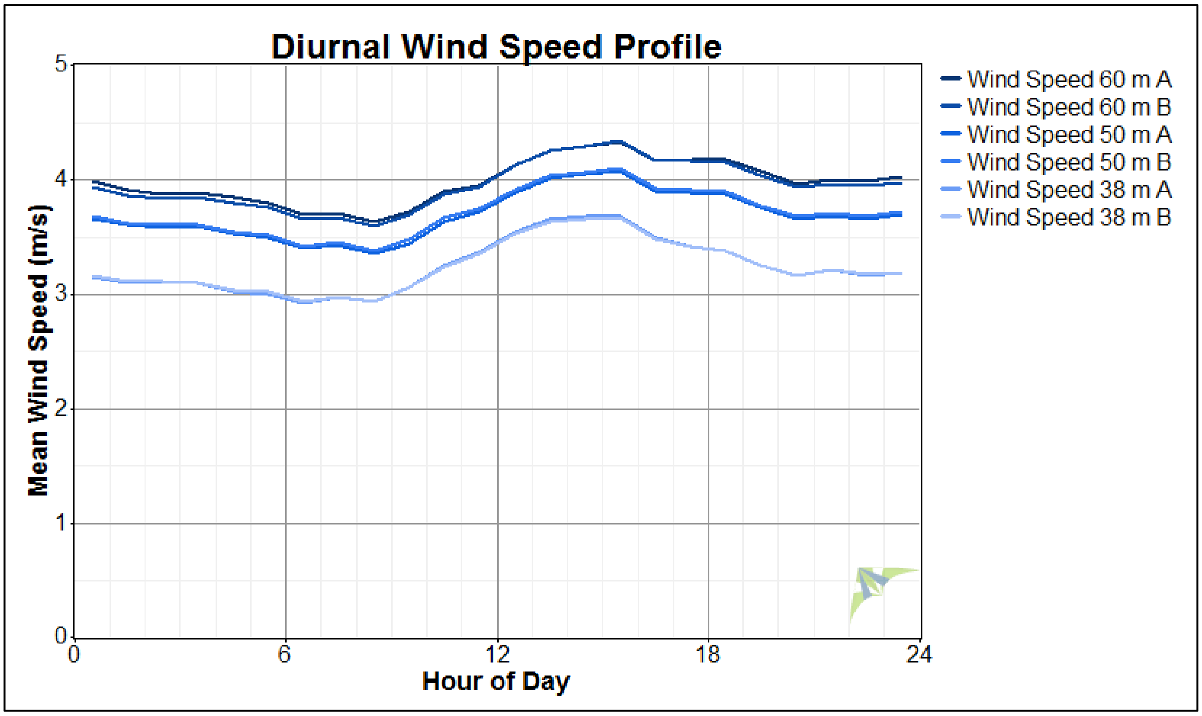

Figure 4.9 – Pax South Diurnal Wind Speed Profile

Figure 4.10 shows the vertical wind shear profile, which is used along with mean wind speed to determine turbine electrical output.

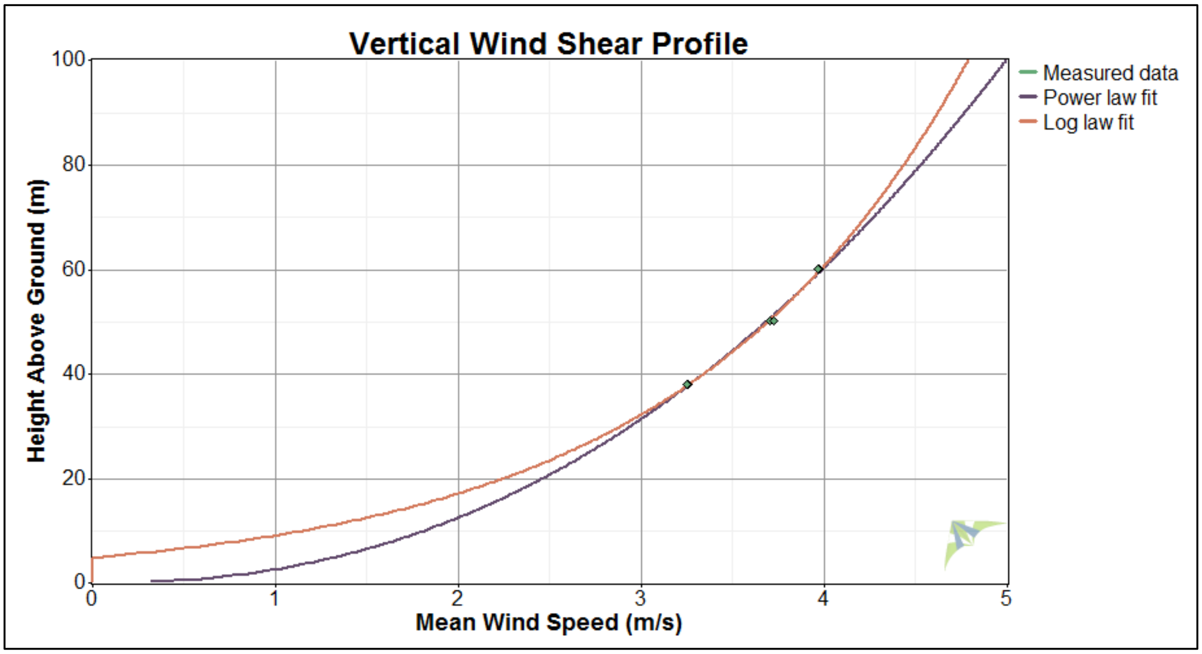

Figure 4.10 – Pax South Vertical Wind Shear Profile

Figure 4.11 and Figure 4.12 show the directional frequency of wind at the site, indicating that winds at Pax South trend between the northwest and south directions.

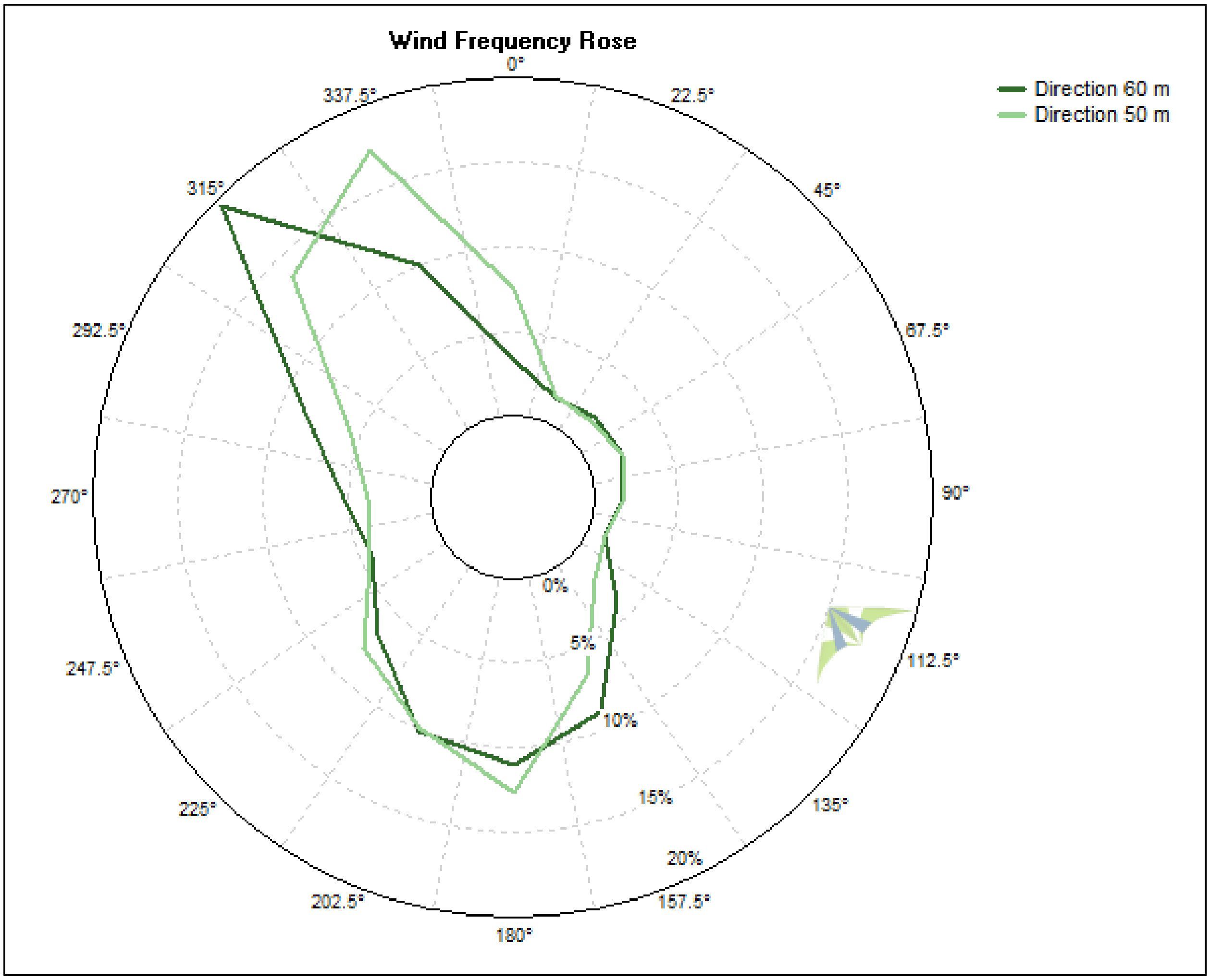

Figure 4.11 – Pax South Wind Frequency Rose (Type A)

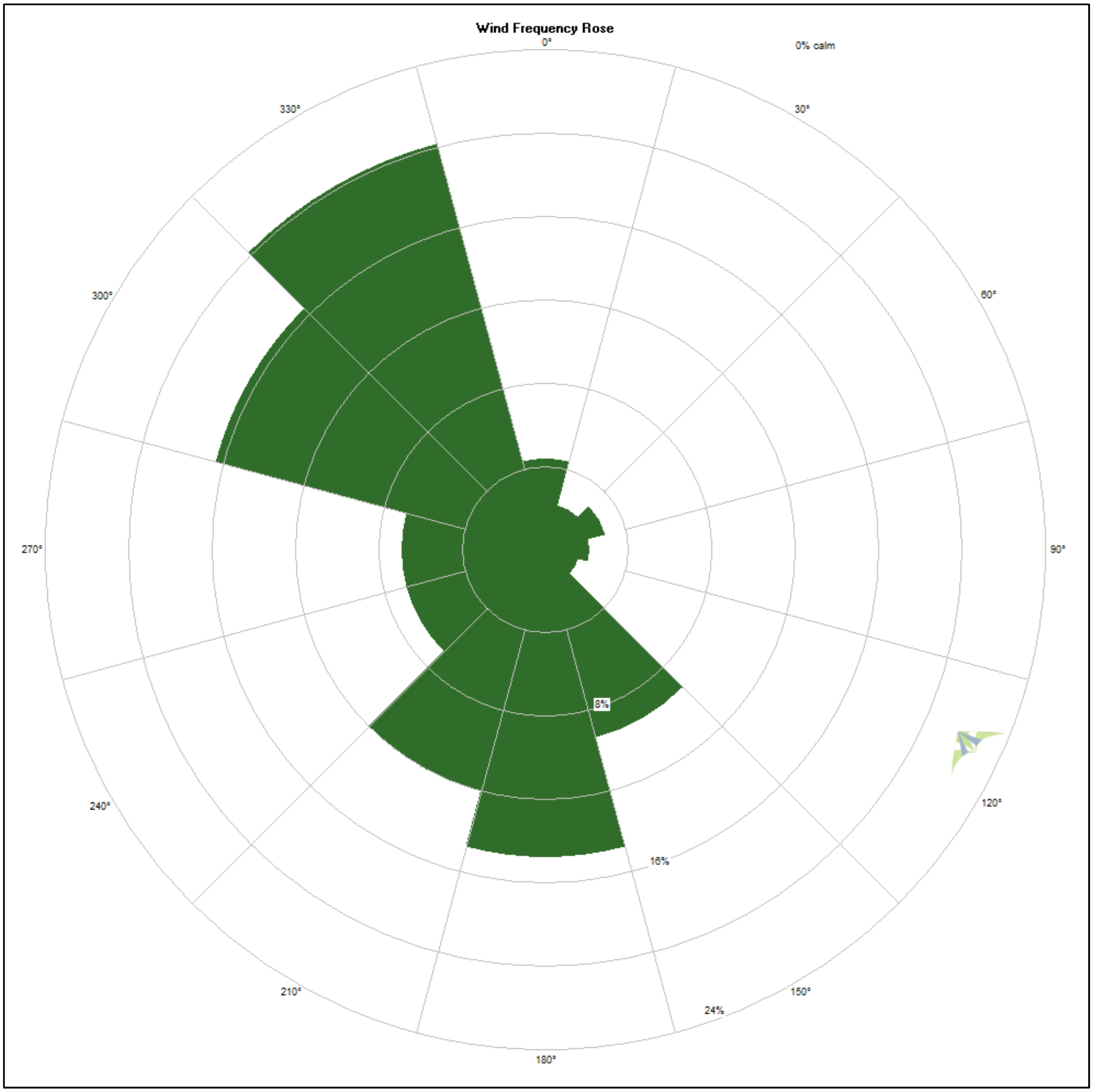

Figure 4.12 – Pax South Wind Frequency Rose (Type B)

Figure 4.13 depicts a probability distribution function plotted on a histogram of the site's mean wind speeds. It should be noted that although the Weibull Distribution plot does not precisely match the histogram data, the distribution function is used exclusively in determining the power density (see Equation 1). All other calculations—including AEP for use in the analysis section—were performed using the bin wind data itself.

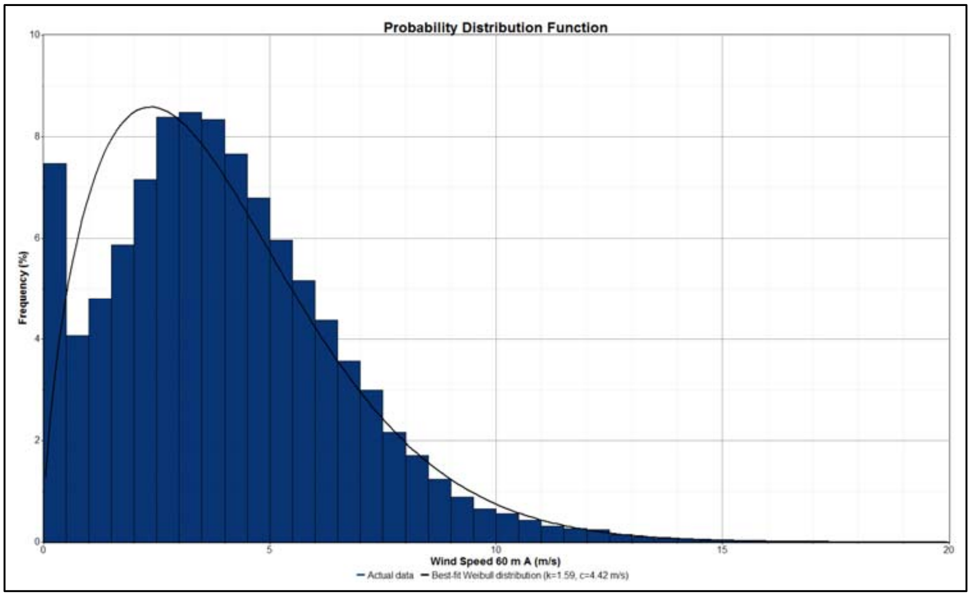

Figure 4.13 – Pax South Wind Speed Histogram

Figure 4.14 depicts turbulence intensity versus wind speed at Pax South.

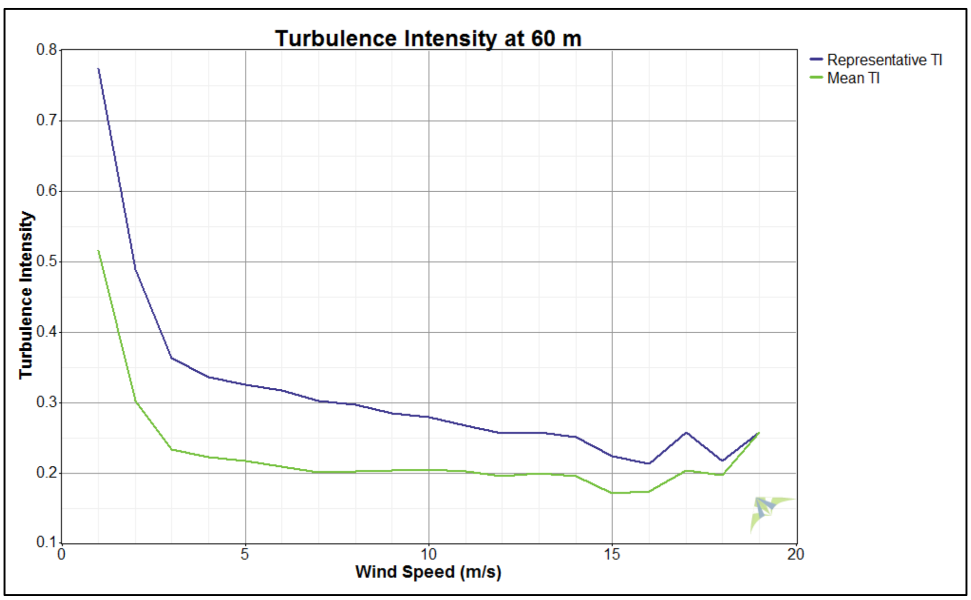

Figure 4.14 – Pax South Turbulence Intensity vs. Wind Speed

The data presented in this section represent the wind conditions of the Pax South mine and will be used in the following chapter to assess the economic wind potential of the site. These results indicate that the Pax South site has a *PD* of 69 W/m^2, which correlates to a DOE Wind Class 1 designation.

4.3. Lost Flats

This subsection will present the data collected at the Lost Flats site. Figure 4.15 shows the plot of mean monthly wind speeds.

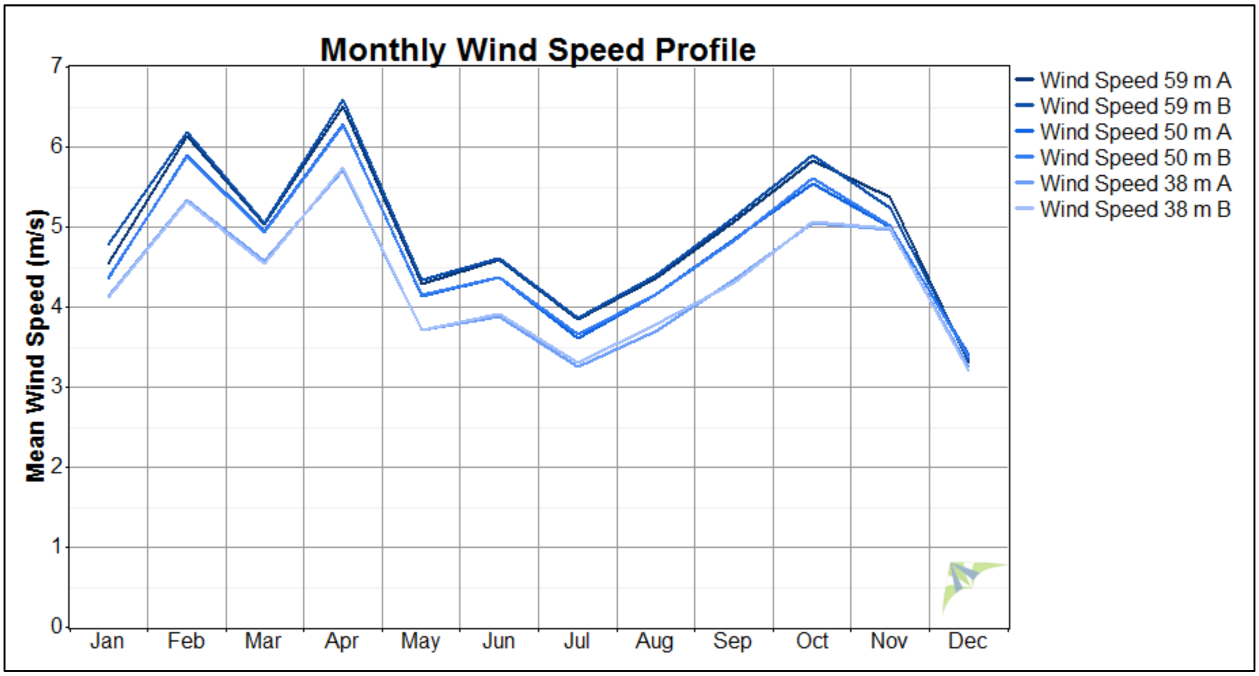

Figure 4.15 – Lost Flats Monthly Mean Wind Speed

Figure 4.16 shows the plot of hourly mean wind speeds. Cumulatively, these describe the diurnal wind speed fluctuations at the site.

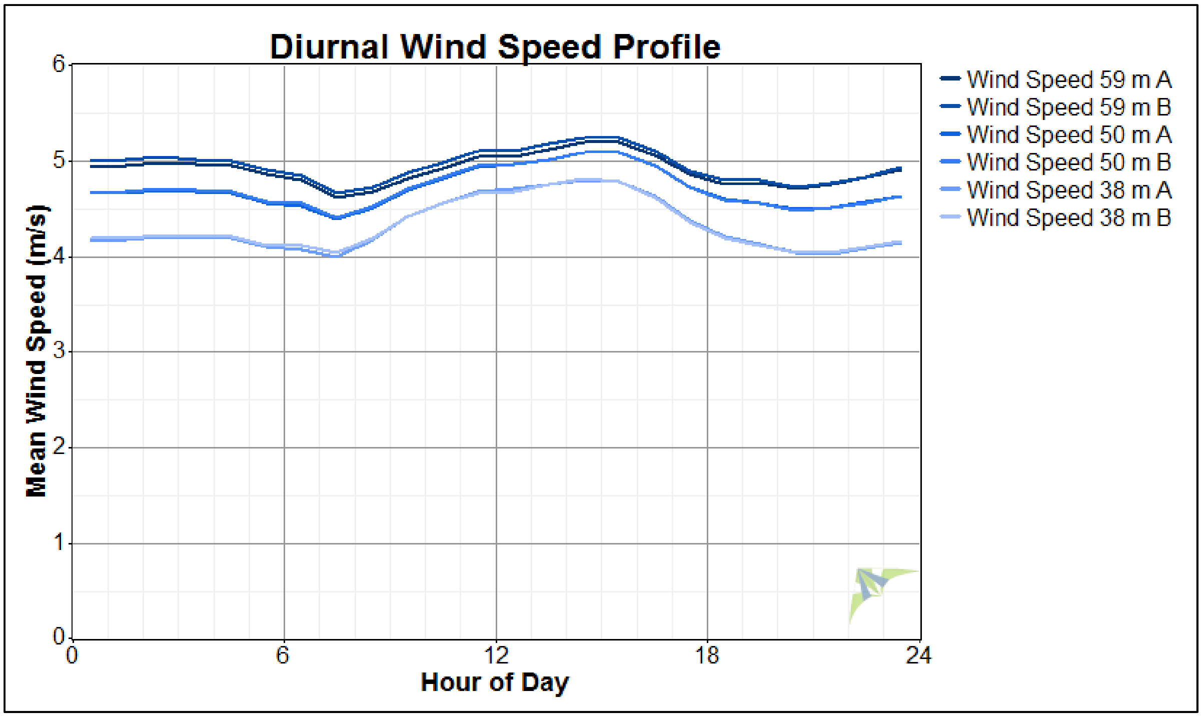

Figure 4.16 – Lost Flats Diurnal Wind Speed Profile

Figure 4.17 shows the vertical wind shear profile, which is used along with mean wind speed to determine turbine electrical output.

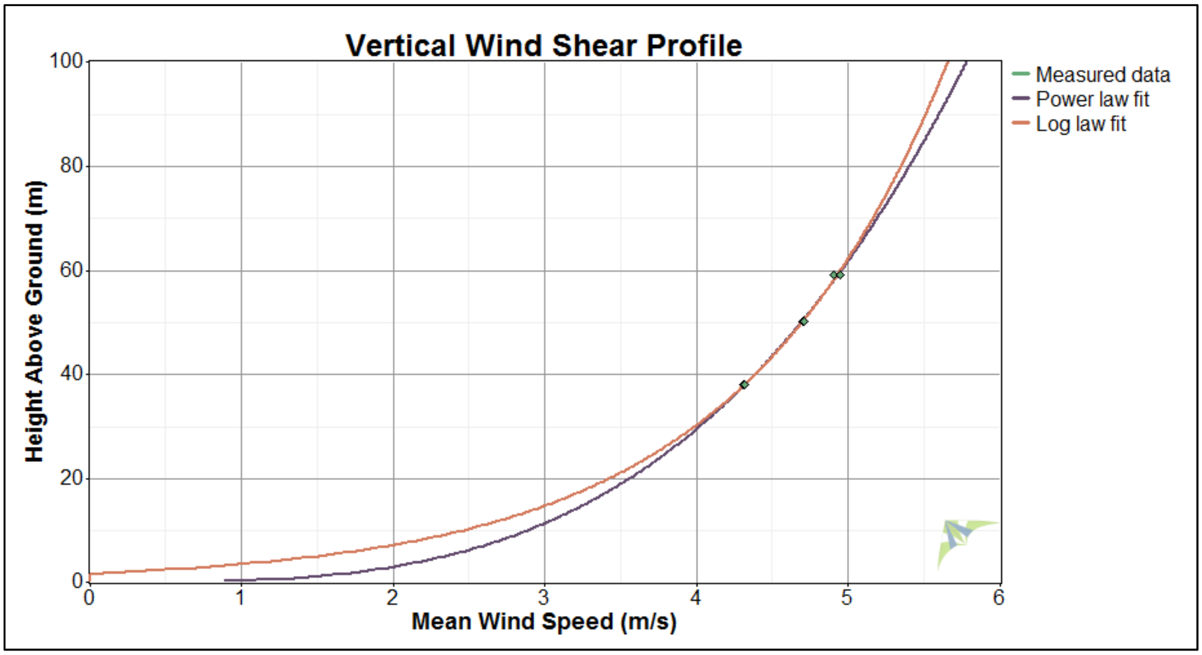

Figure 4.17 – Lost Flats Vertical Wind Shear Profile

Figure 4.18 and Figure 4.19 show the directional frequency of wind at the site, indicating that winds at Lost Flats trend to the northwest and southeast directions.

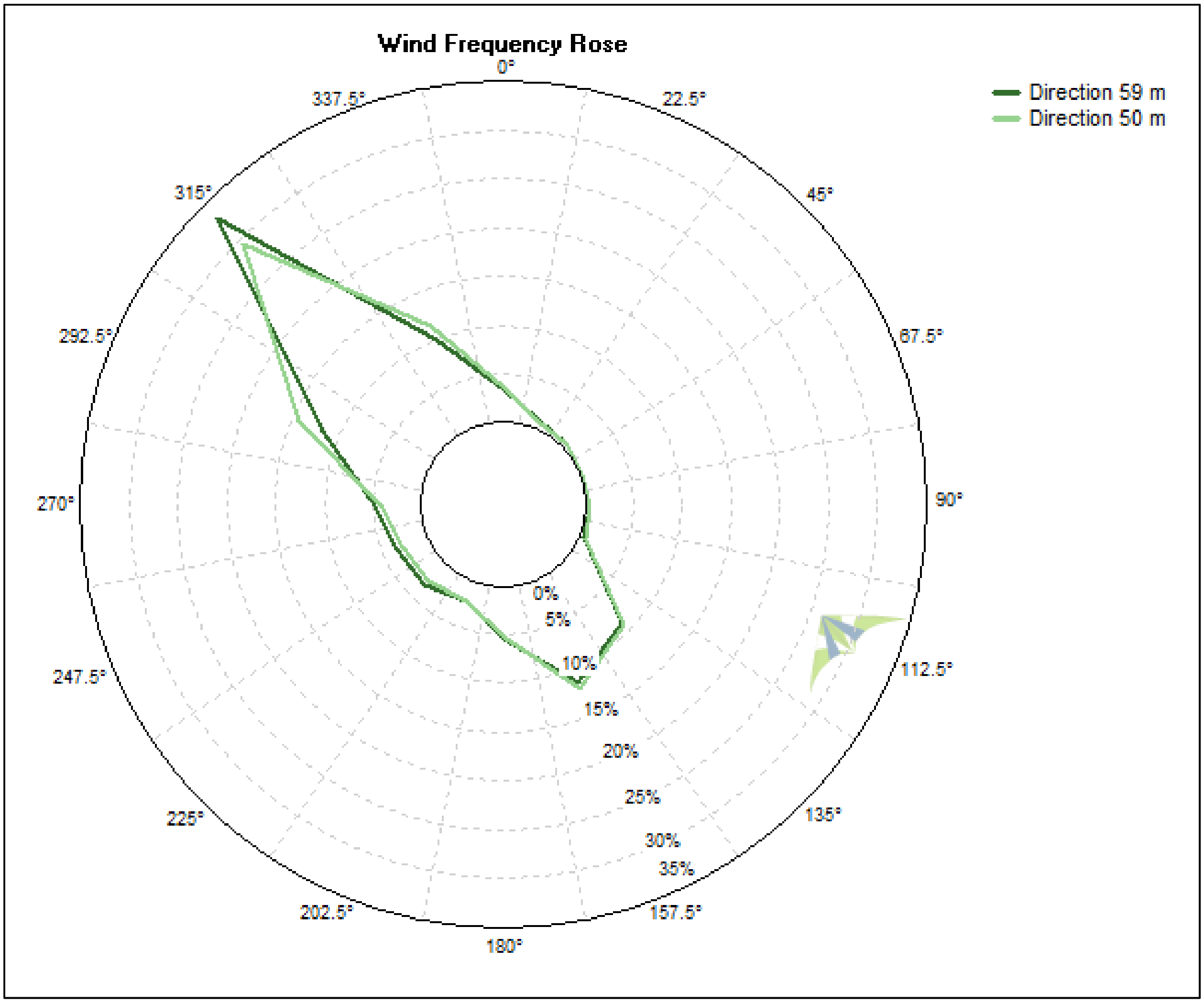

Figure 4.18 – Lost Flats Wind Frequency Rose (Type A)

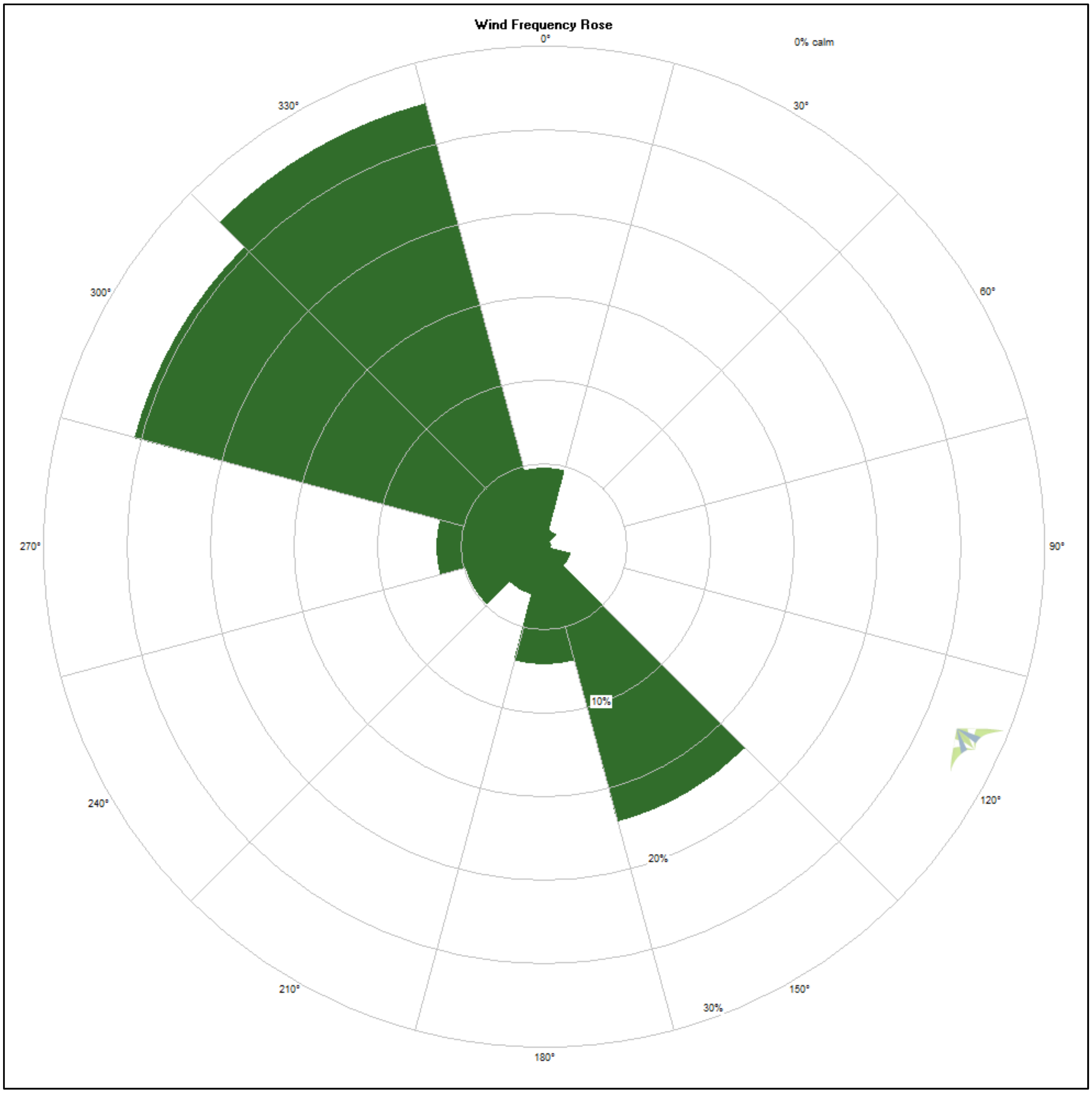

Figure 4.19 – Lost Flats Wind Frequency Rose (Type B)

Figure 4.20 depicts a probability distribution function plotted on a histogram of the site's mean wind speeds. It should be noted that although the Weibull Distribution plot does not precisely match the histogram data, the distribution function is used exclusively in determining the power density (see Equation 1). All other calculations—including AEP for use in the analysis section—were performed using the bin wind data itself.

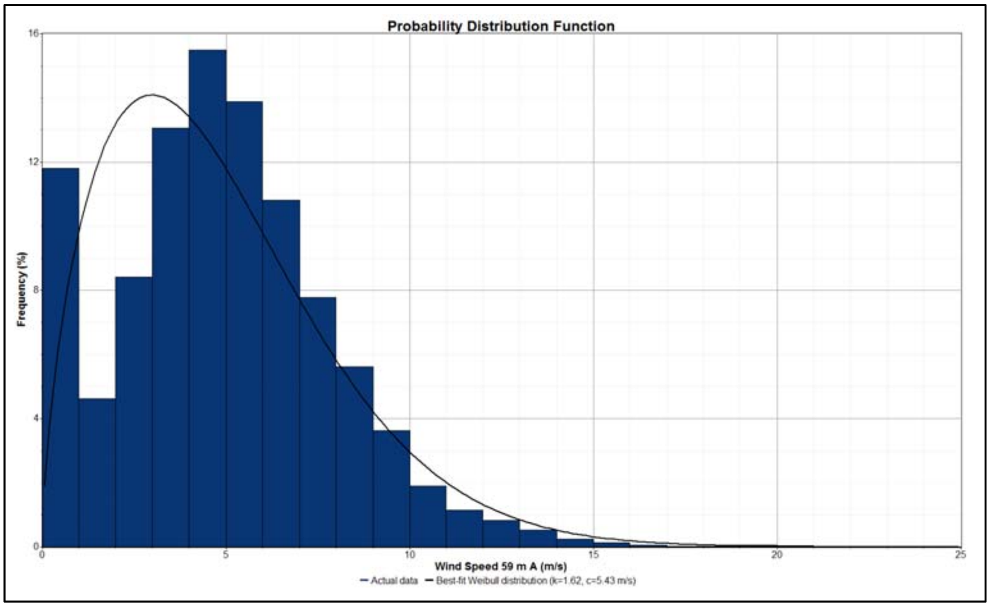

Figure 4.20 – Lost Flats Wind Speed Histogram

Figure 4.21 depicts turbulence intensity versus wind speed at Lost Flats.

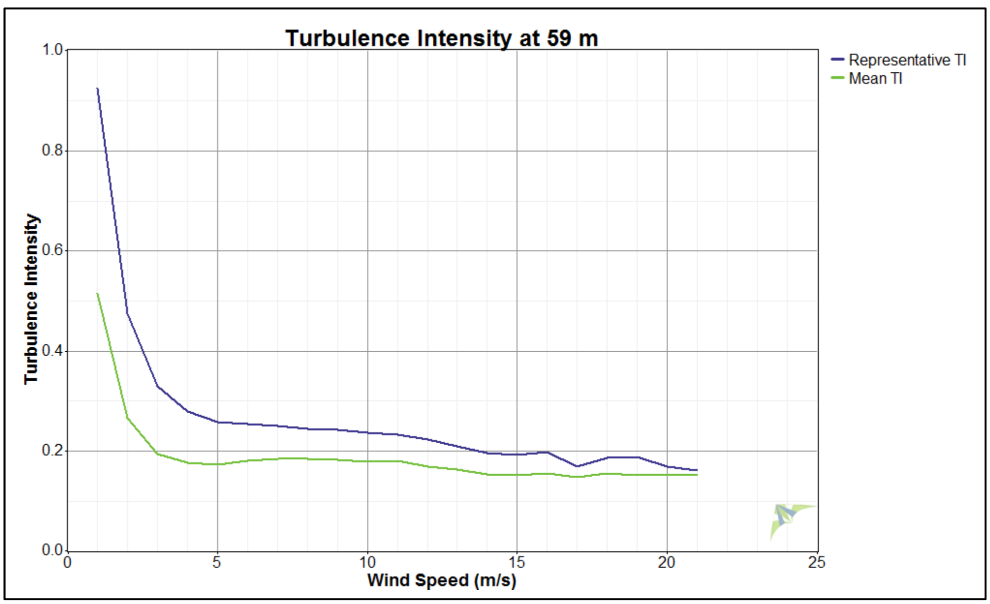

Figure 4.21 – Lost Flats Turbulence Intensity vs. Wind Speed

The data presented in represent the wind conditions of the Lost Flats mine and will be used in the following section to describe the economic wind potential of the site. These results indicate that the Lost Flats site has a *PD* of 130 W/m^2, which correlates to a DOE Wind Class 1 designation.

5. Analysis & Discussion

This section will provide an in-depth discussion of the analysis performed to determine the feasibility of post-mining wind power. After a discussion of the assumptions made in this analysis, three case studies—one for each monitored location—will be presented. Following this, the broader implications drawn from the case studies will be explained. The discussion section will illuminate the common themes in the three case studies and their implications on the broader concept of post-mining wind power.

5.1. Analysis Assumptions

It was necessary to make several assumptions in order to complete the cash flow analysis. The first of these was to use a discount rate of 8.0% and anticipate a project life of 20 years, which is the typical estimate for commercial wind farms. Additionally, the effects of inflation have been ignored. For mine reclamation, it was assumed that overburden replacement is a mine operating cost intrinsic to the strip mining method and, as such, is not a mine closure expense. Additionally, it was assumed that tree planting would not be necessary for pre-wind-development mine reclamation and that additional surface grading would not be needed during turbine construction. In other words, wind developers would give instructions to the mine operator on how to grade the site during mine closure. It was also assumed that existing transmission lines, if present, would be sufficient to convey the electricity generated by the wind farm to the power grid. Interconnection costs, including substation construction, have been included, however. It was assumed that only one row of turbines would be constructed along the ridgelines of each site, using a turbine spacing of three rotor diameters (70.5 m) in either direction [39] [70]. West Virginia's 2009 average sales-price for electricity were used to calculate revenue [91]. It is assumed that prices will not deviate from these averages in future years. For subsidization, the PTC has been utilized for all cases.

Regarding data uncertainty, several assumptions have been made. It has also been assumed that every turbine will have an identical power output, as calculated from the monitoring station's wind data and the GE 1.5s's power curve. It has also been assumed that wind conditions will remain the same during every year of the project's life. Power losses, including those experienced from transmission, turbine availability, turbine performance, grid management, and inclement weather, have been assumed to be 10% from the calculated AEP [39].

Regarding the permitting process, it has been assumed that mine operators will be able to acquire permission to deviate from AOC and limit standard closure activities. Conversely, it has been assumed that wind developers will be able to obtain permits to construct wind energy facilities.

5.1.1. Wind Data Scaling

As the Results section noted, all three monitored locations have DOE Wind Class 1 (poor) conditions. In order to create representative commercial-scale wind development cash flows, the collected wind data was scaled linearly in order to meet the minimum *PD* for Class 4 wind conditions. In this way, the daily and seasonal wind speed fluctuations will still be present in the dataset. This scaling will only affect project revenues and have no bearing on any capital costs, which are the focus of the analysis.

5.2. Case Study: White Flame #10

This section will present the analysis conducted for the White Flame #10 mine site.

5.2.1. Site Characteristics

The White Flame strip mine is located in southwest West Virginia and is still in active production as of September, 2011. The site characteristics used in this analysis are entirely unchanged from those of the actual site. Notable attributes include a total surface area of approximately 760 acres and 15,000 linear feet each of access roads and power lines. The qualities of the reclaimed portion of the site have been used as a template for inferring final site conditions, under which all overburden has been replaced and re-graded to a flat surface. Additionally, permanent drainage has been constructed, topsoil has been deposited, and low-lying vegetation has been seeded. After mine production has been completed, site closure tasks will be performed, including tree planting, bulldozing site access roads, and removing power lines.

5.2.2. *Reference Case*

The reference case for commercial-scale wind development includes all mine closure and wind development costs. There is sufficient ridgeline length to accommodate 23 turbines. Mine closure costs are summarized in Table 5.1.

Table 5.1 – White Flame #10 Mine Closure Cost Summary

Item	Cost			Qty.	Total Cost	
Revegetation	$	500.00	/acre	760	$	380,000.00
Tree Planting	$	1,500.00	/acre	760	$	1,140,000.00
Drainage	$	50,000.00	(lump sum)	1	$	50,000.00
Regrade & Topsoil	$	3,000.00	/acre	760	$	2,280,000.00
Road Removal	$	36.00	/ft	15,000	$	540,000.00
Power Line Removal	$	14.77	/ft	15,000	$	221,590.91
				Mine Closure Total	**$**	**4,600,000.00**

These activities are representative of those typically performed during mine closure. The unit costs were taken from ANR's reported cost ranges, of which the median value was used. All quantities are a function of site geography. Activities highlighted in light green indicate that they would not need to be performed in synergistic mine closure and wind development.

The wind development costs for the White Flame #10 site are summarized in Table 5.2. Note that turbine costs have been exempted from the total development cost figure in order to reflect the price of site preparation.

Table 5.2 – White Flame #10 Wind Development Cost Summary

Item	Cost		Qty.	Total Cost
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Tree Removal	$ 2,500.00	/acre	760	$ 1,900,000.00
Site Grading	$ 5,000.00	/acre	760	$ 3,800,000.00
Road Construction	$ 60.00	/ft	15,000	$ 900,000.00
Transmission	$ 25.00	/ft	15,000	$ 375,000.00
Electrical	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Engn. & QC	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Turbine Foundations	$ 150,000.00	/turbine	23	$ 3,450,000.00
Turbine Construction	$ 100,000.00	/turbine	23	$ 2,300,000.00
Turbines	$ 1,500,000.00	/unit	23	$ 34,500,000.00
			Wind Site Development Total	**$ 18,000,000.00**

These activities are representative of those needed to develop a greenfield site into a functional commercial-scale wind farm. The unit costs were taken from actual West Virginia wind project development reports [70]. Individual values appropriate to the case study were refined through interviews with the author. Activities highlighted in light green indicate that they would not need to be performed in synergistic mine closure and wind development. Activities highlighted in blue indicate that their values will be altered in synergistic mine closure and wind development. Note that the cost of the wind turbines is not included in the site development total. For this site, the turbine cost comprises 66% of the total.

Table 5.3 depicts the White Flame #10 reference case scenario, which includes capital costs, operating expenses, and electricity revenues associated with performing complete mine reclamation and closure followed by wind farm development. Capital costs are based on the value presented in Table 5.1 and Table 5.2.

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Table 5.3 – White Flame #10 Independent Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Tree Removal	$ (1,900,000.00)	$ -	$ -
	Site Grading	$ (3,800,000.00)	$ -	$ -
	Road Construction	$ (900,000.00)	$ -	$ -
	Transmission	$ (375,000.00)	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (2,000,000.00)	$ -	$ -
	Turbine Foundations	$ (3,450,000.00)	$ -	$ -
	Turbine Construction	$ (2,300,000.00)	$ -	$ -
	Turbines	$ (34,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (52,435,000.00)	$ -	$ -
Operating	Operating Costs	$ -	$ (638,888.89)	$ (6,135,632.82)
	Lease Payments	$ -	$ (95,833.33)	$ (920,344.92)
	SUB-TOTAL	$ -	$ (734,722.22)	$ (7,055,977.75)
Revenue	Electricity Sold	$ -	$ 7,521,139.57	$ 72,230,009.92
	SUB-TOTAL	$ -	$ 7,521,139.57	$ 72,230,009.92
Taxation	PTC	$ -	$ 1,870,930.24	$ 17,967,664.16
	Federal Tax	$ -	$ (2,557,187.45)	$ (24,558,203.37)
	WV State Tax	$ -	$ (576,845.47)	$ (5,539,792.73)
	SUB-TOTAL	$ -	$ (1,263,102.69)	$ (12,130,331.95)
Total Mine Closure Expenses		$ (4,611,590.91)	$ -	$ -
Total Wind Farm Expenses		$ (52,435,000.00)	$ -	$ -
Total Revenue		$ -	$ 7,521,139.57	$ 72,230,009.92
Total Taxation		$ -	$ (1,263,102.69)	$ (12,130,331.95)
Net (Profit)		$ (52,435,000.00)	$ 6,258,036.88	$ 60,099,677.97
NPV				**$ 13,900,000.00**
IRR				**12.56%**
Levelized Electricity Cost ($/kWh)				**$ 0.059**
Payback Period (months)				**100.5**

Wind development capital costs are represented in year zero, while all operating expenses and revenues are shown in years 1 through 20. Year 1 is shown separately in order to illustrate the approximate annual expenditures associated with operating a wind farm. Since operating costs and electricity revenues are assumed to remain unchanged from year to year, the sum of all expenses incurred in years 2 through 20 is shown in a single column.

Electricity revenues were calculated by multiplying the annual power output of the turbines by the selling price of electricity. From the scaled wind data and turbine power curve, it was determined that each turbine could produce 4,185,000 kWh/y of electricity under scaled conditions, equating to a capacity factor of 31.8%, which is similar to other wind farms in the region. The facility would produce zero output 17% of the time. Electricity was priced at 7.38¢/kWh, which was taken from the state of West Virginia's average electricity sales price in 2010, as reported by the U.S. Energy Information Administration [91]. An additional 2.0¢/kWh was added in order to reflect the premium which utility companies typically charge for green energy.

Standard state (8.5% of profit in West Virginia) and federal (34% of total revenue) taxation rates were used and site-specific exemptions were ignored. The PTC has been added as a 2.1¢/kWh tax credit. This equates to having wind farms' taxes discounted in proportion to their power output, effectively improving the value of their product (electricity) by around 20%.

The NPV of the separate mine closure & wind development project was found to be $13.9 million, with an IRR of 12.6%, a levelized cost of electricity (LCOE) of 5.9¢/kWh, and a payback period of 101 months.

5.2.3. Synergistic Mine Closure & Wind Development

This scenario will highlight the cost savings associated with synergistic mine closure & wind development. Under these conditions, the mine is reclaimed specifically for a wind power post-mining land use, enabling a corporation to capitalize on the overlap in activities between the two practices. These modified mine closure and wind development costs are summarized in Table 5.4 and Table 5.5, respectively.

Table 5.4 – White Flame #10 Modified Mine Closure Costs

Item	Cost		Qty.	Total Cost
Revegetation	$ 500.00	/acre	760	$ 380,000.00
Drainage	$ 50,000.00	(lump sum)	1	$ 50,000.00
Regrade & Topsoil	$ 3,000.00	/acre	760	$ 2,280,000.00
			Mine Closure Total	**$ 2,700,000.00**

Table 5.5 – White Flame #10 Modified Wind Development Costs

Item	Cost		Qty.	Total Cost
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Engn. & QC	$ 1,000,000.00	(lump sum)	1	$ 1,000,000.00
Turbine Foundations	$ 220,000.00	/turbine	23	$ 5,060,000.00
Turbine Construction	$ 100,000.00	/turbine	23	$ 2,300,000.00
Turbines	$ 1,500,000.00	/unit	23	$ 34,500,000.00
		Wind Site Development Total		**$ 9,600,000.00**

The cash flow for synergistic post-mining wind power development is presented in Table 5.6, with its capital costs based on the values given in Table 5.5.

Table 5.6 – White Flame #10 Synergistic Mine Closure & Wind Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (1,000,000.00)	$ -	$ -
	Turbine Foundations	$ (5,060,000.00)	$ -	$ -
	Turbine Construction	$ (2,300,000.00)	$ -	$ -
	Turbines	$ (34,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (46,070,000.00)	$ (638,888.89)	$ (6,135,632.82)
Operating	Operating Costs	$ -	$ (638,888.89)	$ (6,135,632.82)
	Lease Payments	$ -	$ (4,166.67)	$ (40,015.00)
	SUB-TOTAL	$ -	$ (643,055.56)	$ (6,175,647.82)
Revenue	Electricity Sold	$ -	$ 7,521,139.57	$ 72,230,009.92
	SUB-TOTAL	$ -	$ 7,521,139.57	$ 72,230,009.92
Taxation	PTC	$ -	$ 1,870,930.24	$ 17,967,664.16
	Federal Tax	$ -	$ (2,557,187.45)	$ (24,558,203.37)
	WV State Tax	$ -	$ (584,637.14)	$ (5,614,620.78)
	SUB-TOTAL	$ -	$ (1,270,894.35)	$ (12,205,159.99)
Total Mine Closure Expenses		$ (2,710,000.00)	$ -	$ -
Total Wind Farm Expenses		$ (46,070,000.00)	$ -	$ -
Total Revenue		$ -	$ 7,521,139.57	$ 72,230,009.92
Total Taxation		$ -	$ (1,270,894.35)	$ (12,205,159.99)
Net (Profit)		$ (46,070,000.00)	$ 6,250,245.21	$ 60,024,849.93
NPV				**$ 20,200,000.00**
IRR				**14.78%**
Levelized Electricity Cost ($/kWh)				**$ 0.047**
Payback Period (months)				**88.5**

As was previously mentioned, this scenario eliminates numerous mine closure and wind development tasks which would, under independent completion, conflict with each other. The only added cost lies in foundation construction, which is expected to be more expensive due to having to build competent foundations in blasted material, as opposed to fully consolidated soils with underlying bedrock. The Engineering Quality & Control cost has been lowered due to much of the relevant work being done by mining engineers during closure. All other costs, revenues, and taxes are identical to the reference case. The NPV of the synergistic mine closure & wind development project was found to be $20.2 million, with an IRR of 14.78%, an LCOE of 4.7¢/kWh, and a payback period of 89 months.

The data collection regime has indicated that wind conditions at White Flame #10 are only Class 1 (poor), rendering it unsuitable for commercial-scale wind development. However, valuable insight may still be gained from the site by scaling the wind speeds to more favorable levels and analyzing the mine closure and wind development costs. In this way, a more realistic scenario of post-mining wind power has been presented and assessed. Table 5.7 highlights the key savings found from performing the case study. These values were calculated from the cash flows summarized in Table 5.3 and Table 5.6.

Table 5.7 – White Flame #10 Performance Summary

Scenario	Category	Value
Reference	Mine Closure Cost	$ 4,600,000.00
	Wind Development Cost	$ 17,900,000.00
	NPV	$ 13,900,000.00
	IRR	12.6%
	LCOE	$ 0.059 /kWh
	Payback Period	100.5 months
Synergistic Development	Mine Closure Cost	$ 2,700,000.00
	Wind Development Cost	$ 9,600,000.00
	NPV	$ 20,200,000.00
	IRR	14.8%
	LCOE	$ 0.047 /kWh
	Payback Period	88.5 months
Performance Improvement	Mine Closure Cost	41.3%
	Wind Development Cost	46.4%
	NPV	45.3%
	IRR	17.6%
	LCOE	19.9%
	Payback Period	12.0%

Note that the wind development savings calculation excludes the cost of wind turbines and their construction in order to portray the site preparation savings, since turbine costs cannot be altered from the manufacturer's sales price. Regardless, a total capital savings of $8.3 million is realized and all financial metrics are improved through synergistic mine closure and wind development.

5.3. Case Study: Pax South

This section will present the analysis conducted for the Pax South mine site.

5.3.1. Site Characteristics

The Pax South strip mine is located in central West Virginia and is still in active production as of September 2011. The site characteristics used in this analysis are entirely unchanged from those of the actual site. Total surface area is approximately 600 acres. Both roads and power access pass directly through the site. These infrastructure items are publically owned and will not be removed during mine closure.

5.3.2. Reference Case

The reference case for commercial-scale wind development includes all mine closure and wind development costs. There is sufficient ridgeline length to accommodate 17 turbines. Mine closure costs are summarized in Table 5.8.

Table 5.8 – Pax South Mine Closure Cost Summary

Item	Cost	Qty.	Total Cost
Revegetation	$ 500.00 /acre	600	$ 300,000.00
Tree Planting	$ 1,500.00 /acre	600	$ 900,000.00
Drainage	$ 50,000.00 (lump sum)	1	$ 50,000.00
Regrade & Topsoil	$ 3,000.00 /acre	600	$ 1,800,000.00
Road Removal	$ 36.00 /ft	-	$ -
Power Line Removal	$ 14.77 /ft	-	$ -
		Mine Closure Total	**$ 3,100,000.00**

These activities are representative of those typically performed during mine closure. The unit costs were taken from ANR's reported cost ranges, of which the median value was used. All quantities are a function of site geography. Activities highlighted in light green indicate that they would not need to be performed in synergistic mine closure and wind development.

The wind development costs for the Pax South site are summarized in Table 5.9.

Table 5.9 – Pax South Wind Development Cost Summary

Item	Cost		Qty.	Total Cost
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Tree Removal	$ 2,500.00	/acre	600	$ 1,500,000.00
Site Grading	$ 5,000.00	/acre	600	$ 3,000,000.00
Road Construction	$ 60.00	/ft	-	$ -
Transmission	$ 25.00	/ft	-	$ -
Electrical	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Engn. & QC	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Turbine Foundations	$ 150,000.00	/turbine	17	$ 2,550,000.00
Turbine Construction	$ 100,000.00	/turbine	17	$ 1,700,000.00
Turbines	$ 1,500,000.00	/unit	17	$ 25,500,000.00
			Wind Site Development Total	**$ 14,000,000.00**

These activities are representative of those needed to develop a greenfield site into a functional commercial-scale wind farm. Activities highlighted in light green indicate that they would not need to be performed in synergistic mine closure and wind development. Activities highlighted in blue indicate that their values will be altered in synergistic mine closure and wind development. Note that the cost of the wind turbines is not included in the site development total. For this site, the turbine cost comprises 65% of the total.

Table 5.10 depicts the Pax South reference case scenario, which includes capital costs, operating expenses, and electricity revenues associated with performing complete mine reclamation and closure followed by wind farm development.

Table 5.10 – Pax South Independent Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Tree Removal	$ (1,500,000.00)	$ -	$ -
	Site Grading	$ (3,000,000.00)	$ -	$ -
	Road Construction	$ -	$ -	$ -
	Transmission	$ -	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (2,000,000.00)	$ -	$ -
	Turbine Foundations	$ (2,550,000.00)	$ -	$ -
	Turbine Construction	$ (1,700,000.00)	$ -	$ -
	Turbines	$ (25,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (39,460,000.00)	$ -	$ -
Operating	Operating Costs	$ -	$ (472,222.22)	$ (4,535,032.96)
	Lease Payments	$ -	$ (70,833.33)	$ (680,254.94)
	SUB-TOTAL	$ -	$ (543,055.56)	$ (5,215,287.90)
Revenue	Electricity Sold	$ -	$ 6,673,209.65	$ 64,086,830.84
	SUB-TOTAL	$ -	$ 6,673,209.65	$ 64,086,830.84
Taxation	PTC	$ -	$ 1,660,002.40	$ 15,941,997.72
	Federal Tax	$ -	$ (2,268,891.28)	$ (21,789,522.48)
	WV State Tax	$ -	$ (521,063.10)	$ (5,004,081.15)
	SUB-TOTAL	$ -	$ (1,129,951.98)	$ (10,851,605.91)
Total Mine Closure Expenses		$ (3,050,000.00)	$ -	$ -
Total Wind Farm Expenses		$ (39,460,000.00)	$ -	$ -
Total Revenue		$ -	$ 6,673,209.65	$ 64,086,830.84
Total Taxation		$ -	$ (1,129,951.98)	$ (10,851,605.91)
Net (Profit)		$ (39,460,000.00)	$ 5,543,257.67	$ 53,235,224.92
			NPV	**$ 19,300,000.00**
			IRR	**15.39%**
			Levelized Electricity Cost ($/kWh)	**$ 0.044**
			Payback Period (months)	**85.4**

This cash flow was developed with the same methodology discussed in the White Flame #10 case study.

From the recorded wind data and turbine power curve, was determined that each turbine could produce 5,000,000 kWh/y of electricity. This represents a capacity factor of 38.2%, which is excellent compared to other commercial-scale wind farms in the region. Conversely, the turbines would produce zero output 21% of the time.

The NPV of the separate mine closure & wind development project was found to be $19.3 million, with an IRR of 15.4%, an LCOE of 4.4¢/kWh, and a payback period of 85 months.

5.3.3. Synergistic Mine Closure & Wind Development

This scenario will highlight the cost savings associated with synergistic mine closure & wind development. Under these conditions, the mine is reclaimed specifically for a wind power post-mining land use, enabling a corporation to capitalize on the overlap in activities between the two practices. These modified mine closure and wind development costs are summarized in Table 5.11 and Table 5.12, respectively.

Table 5.11 – Pax South Modified Mine Closure Costs

Item	**Cost**		**Qty.**	**Total Cost**
Revegetation	$ 500.00	/acre	600	$ 300,000.00
Drainage	$ 50,000.00	(lump sum)	1	$ 50,000.00
Regrade & Topsoil	$ 3,000.00	/acre	600	$ 1,800,000.00
			Mine Closure Total	**$ 2,200,000.00**

Table 5.12 – Pax South Modified Wind Development Costs

Item	**Cost**		**Qty.**	**Total Cost**
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Engn. & QC	$ 1,000,000.00	(lump sum)	1	$ 1,000,000.00
Turbine Foundations	$ 220,000.00	/turbine	17	$ 3,740,000.00
Turbine Construction	$ 100,000.00	/turbine	17	$ 1,700,000.00
Turbines	$ 1,500,000.00	/unit	17	$ 25,500,000.00
			Wind Site Development Total	**$ 7,700,000.00**

The cash flow for synergistic post-mining wind power development is presented in Table 5.13.

Table 5.13 – Pax South Synergistic Mine Closure & Wind Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (1,000,000.00)	$ -	$ -
	Turbine Foundations	$ (3,740,000.00)	$ -	$ -
	Turbine Construction	$ (1,700,000.00)	$ -	$ -
	Turbines	$ (25,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (35,150,000.00)	$ (472,222.22)	$ (4,535,032.96)
Operating	Operating Costs	$ -	$ (472,222.22)	$ (4,535,032.96)
	Lease Payments	$ -	$ (4,166.67)	$ (40,015.00)
	SUB-TOTAL	$ -	$ (476,388.89)	$ (4,575,047.95)
Revenue	Electricity Sold	$ -	$ 6,673,209.65	$ 64,086,830.84
	SUB-TOTAL	$ -	$ 6,673,209.65	$ 64,086,830.84
Taxation	PTC	$ -	$ 1,660,002.40	$ 15,941,997.72
	Federal Tax	$ -	$ (2,268,891.28)	$ (21,789,522.48)
	WV State Tax	$ -	$ (526,729.76)	$ (5,058,501.55)
	SUB-TOTAL	$ -	$ (1,135,618.64)	$ (10,906,026.31)
Total Mine Closure Expenses		$ (2,150,000.00)	$ -	$ -
Total Wind Farm Expenses		$ (35,150,000.00)	$ -	$ -
Total Revenue		$ -	$ 6,673,209.65	$ 64,086,830.84
Total Taxation		$ -	$ (1,135,618.64)	$ (10,906,026.31)
Net (Profit)		$ (35,150,000.00)	$ 5,537,591.00	$ 53,180,804.53
			NPV	**$ 23,600,000.00**
			IRR	**17.61%**
			Levelized Electricity Cost ($/kWh)	**$ 0.036**
			Payback Period (months)	**76.2**

As was previously mentioned, this scenario eliminates numerous mine closure and wind development tasks which would, under independent completion, conflict with each other. The

NPV of the synergistic mine closure & wind development project was found to be $23.6 million, with an IRR of 17.6%, an LCOE of 3.6¢/kWh, and a payback period of 76 months. Table 5.14 highlights the key savings found from performing the case study. A total capital savings of $5.2 million is realized through synergistic mine closure and wind development.

Table 5.14 – Pax South Performance Summary

Scenario	Category	Value
Reference	Mine Closure Cost	$ 3,100,000.00
	Wind Development Cost	$ 14,000,000.00
	NPV	$ 23,400,000.00
	IRR	15.3%
	LCOE	$ 0.045 /kWh
	Payback Period	79.8 months
Synergistic Development	Mine Closure Cost	$ 2,200,000.00
	Wind Development Cost	$ 9,700,000.00
	NPV	$ 27,700,000.00
	IRR	17.5%
	LCOE	$ 0.036 /kWh
	Payback Period	71.1 months
Performance Improvement	Mine Closure Cost	29.5%
	Wind Development Cost	30.9%
	NPV	18.4%
	IRR	14.4%
	LCOE	19.8%
	Payback Period	10.9%

5.4. *Case Study: Lost Flats*

This section will present the analysis conducted for the Lost Flats mine site.

5.4.1. *Site Characteristics*

The Lost Flats reclaimed mine site is located in eastern West Virginia in Greenbrier County. Mining was completed over ten years ago and the site has been reclaimed. Unlike Pax South and White Flame #10 (which both have entirely cleared land), the vegetation at Lost Flats has regrown substantially to include tall grass, shrubs, and trees in excess of thirty feet high. The site has an area of 525 acres and lies approximately 2000ft from public road access. At 22,000ft away, Lost Flats is the furthest from power lines of the three monitored locations.

5.4.2. Reference Case

The reference case for commercial-scale wind development includes all mine closure and wind development costs. There is sufficient ridgeline length to accommodate 21 turbines. Mine closure costs are summarized in Table 5.15. Activities highlighted in light green indicate that they would not need to be performed in synergistic mine closure and wind development.

Table 5.15 – Lost Flats Mine Closure Cost Summary

Item	Cost			Qty.	Total Cost	
Revegetation	$	500.00	/acre	525	$	262,500.00
Tree Planting	$	1,500.00	/acre	525	$	787,500.00
Drainage	$	50,000.00	(lump sum)	1	$	50,000.00
Regrade & Topsoil	$	3,000.00	/acre	525	$	1,575,000.00
Road Removal	$	36.00	/ft	2,000	$	72,000.00
Power Line Removal	$	14.77	/ft	22,000	$	325,000.00
				Mine Closure Total	**$**	**3,100,000.00**

The wind development costs for the Lost Flats site are summarized in Table 5.16. Activities highlighted in blue indicate that their values will be altered in synergistic mine closure and wind development. Note that the cost of the wind turbines is not included in the site development total. For this site, the turbine cost comprises 68% of the total.

Table 5.16 – Lost Flats Wind Development Cost Summary

Item	Cost		Qty.	Total Cost
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Tree Removal	$ 2,500.00	/acre	525	$ 1,312,500.00
Site Grading	$ 5,000.00	/acre	525	$ 2,625,000.00
Road Construction	$ 60.00	/ft	2,000	$ 120,000.00
Transmission	$ 25.00	/ft	22,000	$ 550,000.00
Electrical	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Engn. & QC	$ 2,000,000.00	(lump sum)	1	$ 2,000,000.00
Turbine Foundations	$ 150,000.00	/turbine	21	$ 3,150,000.00
Turbine Construction	$ 100,000.00	/turbine	21	$ 2,100,000.00
Turbines	$ 1,500,000.00	/unit	21	$ 31,500,000.00
			Wind Site Development Total	**$ 15,100,000.00**

Table 5.17 depicts the Lost Flats reference case scenario, which includes capital costs, operating expenses, and electricity revenues associated with performing complete mine reclamation and closure followed by wind farm development.

Table 5.17 – Lost Flats Independent Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Tree Removal	$ (1,312,500.00)	$ -	$ -
	Site Grading	$ (2,625,000.00)	$ -	$ -
	Road Construction	$ (120,000.00)	$ -	$ -
	Transmission	$ (550,000.00)	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (2,000,000.00)	$ -	$ -
	Turbine Foundations	$ (3,150,000.00)	$ -	$ -
	Turbine Construction	$ (2,100,000.00)	$ -	$ -
	Turbines	$ (31,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (46,567,500.00)	$ -	$ -
Operating	Operating Costs	$ -	$ (583,333.33)	$ (5,602,099.53)
	Lease Payments	$ -	$ (87,500.00)	$ (840,314.93)
	SUB-TOTAL	$ -	$ (670,833.33)	$ (6,442,414.46)
Revenue	Electricity Sold	$ -	$ 7,968,583.78	$ 76,527,084.80
	SUB-TOTAL	$ -	$ 7,968,583.78	$ 76,527,084.80
Taxation	PTC	$ -	$ 1,982,234.77	$ 19,036,588.26
	Federal Tax	$ -	$ (2,709,318.48)	$ (26,019,208.83)
	WV State Tax	$ -	$ (620,308.79)	$ (5,957,196.98)
	SUB-TOTAL	$ -	$ (1,347,392.50)	$ (12,939,817.55)
Total Mine Closure Expenses		$ (3,072,000.00)	$ -	$ -
Total Wind Farm Expenses		$ (46,567,500.00)	$ -	$ -
Total Revenue		$ -	$ 7,968,583.78	$ 76,527,084.80
Total Taxation		$ -	$ (1,347,392.50)	$ (12,939,817.55)
Net (Profit)		$ (46,567,500.00)	$ 6,621,191.28	$ 63,587,267.25
NPV				**$ 23,600,000.00**
IRR				**15.61%**
Levelized Electricity Cost ($/kWh)				**$ 0.043**
Payback Period (months)				**84.4**

This cash flow was developed with the same methodology discussed in the White Flame #10 case study.

From the recorded wind data and turbine power curve, it was determined that each turbine could produce 4,850,000 kWh/y of electricity, which equates to a capacity factor of 37.0%, which is excellent relative to other wind farms in the region. The site would produce zero output 17% of the time.

The NPV of the separate mine closure & wind development project was found to be $23.6 million, with an IRR of 15.6%, an LCOE of 4.3¢/kWh, and a payback period of 84 months.

5.4.3. *Synergistic Mine Closure & Wind Development*

This scenario will highlight the cost savings associated with synergistic mine closure & wind development. Under these conditions, the mine is reclaimed specifically for a wind power post-mining land use, enabling a corporation to capitalize on the overlap in activities between the two practices. These modified mine closure and wind development costs are summarized in Table 5.18 and Table 5.19, respectively.

Table 5.18 – Lost Flats Modified Mine Closure Costs

Item	Cost		Qty.	Total Cost
Revegetation	$ 500.00	/acre	525	$ 262,500.00
Drainage	$ 50,000.00	(lump sum)	1	$ 50,000.00
Regrade & Topsoil	$ 3,000.00	/acre	525	$ 1,575,000.00
			Mine Closure Total	**$ 1,900,000.00**

Table 5.19 – Lost Flats Modified Wind Development Costs

Item	Cost		Qty.	Total Cost
Wind Analysis	$ 310,000.00	(lump sum)	1	$ 310,000.00
Interconnection Studies	$ 300,000.00	(lump sum)	1	$ 300,000.00
Environmental Studies	$ 100,000.00	(lump sum)	1	$ 100,000.00
Permitting	$ 500,000.00	(lump sum)	1	$ 500,000.00
Engn. & QC	$ 1,000,000.00	(lump sum)	1	$ 1,000,000.00
Turbine Foundations	$ 220,000.00	/turbine	21	$ 4,620,000.00
Turbine Construction	$ 100,000.00	/turbine	21	$ 2,100,000.00
Turbines	$ 1,500,000.00	/unit	21	$ 31,500,000.00
			Wind Site Development Total	**$ 8,900,000.00**

The cash flow for synergistic post-mining wind power development is presented in Table 5.6, with its capital costs based on the values given in Table 5.20.

Table 5.20 – Lost Flats Synergistic Mine Closure & Wind Development Cash Flow

Expenditures		Year		
Category	**Type**	**0**	**1**	**Σ (2-20)**
Wind Development	Wind Analysis	$ (310,000.00)	$ -	$ -
	Interconnection Studies	$ (300,000.00)	$ -	$ -
	Environmental Studies	$ (100,000.00)	$ -	$ -
	Permitting	$ (500,000.00)	$ -	$ -
	Electrical	$ (2,000,000.00)	$ -	$ -
	Engn. & QC	$ (1,000,000.00)	$ -	$ -
	Turbine Foundations	$ (4,620,000.00)	$ -	$ -
	Turbine Construction	$ (2,100,000.00)	$ -	$ -
	Turbines	$ (31,500,000.00)	$ -	$ -
	SUB-TOTAL	$ (42,430,000.00)	$ (583,333.33)	$ (5,602,099.53)
Operating	Operating Costs	$ -	$ (583,333.33)	$ (5,602,099.53)
	Lease Payments	$ -	$ (4,166.67)	$ (40,015.00)
	SUB-TOTAL	$ -	$ (587,500.00)	$ (5,642,114.53)
Revenue	Electricity Sold	$ -	$ 7,968,583.78	$ 76,527,084.80
	SUB-TOTAL	$ -	$ 7,968,583.78	$ 76,527,084.80
Taxation	PTC	$ -	$ 1,982,234.77	$ 19,036,588.26
	Federal Tax	$ -	$ (2,709,318.48)	$ (26,019,208.83)
	WV State Tax	$ -	$ (627,392.12)	$ (6,025,222.47)
	SUB-TOTAL	$ -	$ (1,354,475.84)	$ (13,007,843.05)
Total Mine Closure Expenses		$ (1,887,500.00)	$ -	$ -
Total Wind Farm Expenses		$ (42,430,000.00)	$ -	$ -
Total Revenue		$ -	$ 7,968,583.78	$ 76,527,084.80
Total Taxation		$ -	$ (1,354,475.84)	$ (13,007,843.05)
Net (Profit)		$ (42,430,000.00)	$ 6,614,107.94	$ 63,519,241.76
NPV				**$ 27,700,000.00**
IRR				**17.40%**
Levelized Electricity Cost ($/kWh)				**$ 0.036**
Payback Period (months)				**77.0**

As was previously mentioned, this scenario eliminates numerous mine closure and wind development tasks which would, under independent completion, conflict with each other. The NPV of the synergistic mine closure & wind development project was found to be $27.7 million, with an IRR of 17.4%, an LCOE of 3.6¢/kWh, and a payback period of 77 months.

Table 5.7 highlights the key savings found from performing the case study. A total capital savings of $5.3 million is realized through synergistic mine closure and wind development.

Table 5.21 – Lost Flats Performance Summary

Scenario	Category	Value
Reference	Mine Closure Cost	$ 3,100,000.00
	Wind Development Cost	$ 15,100,000.00
	NPV	$ 23,600,000.00
	IRR	15.6%
	LCOE	$ 0.043 /kWh
	Payback Period	84.4 months
Synergistic Development	Mine Closure Cost	$ 1,900,000.00
	Wind Development Cost	$ 8,900,000.00
	NPV	$ 27,700,000.00
	IRR	17.4%
	LCOE	$ 0.036 /kWh
	Payback Period	77.0 months
Performance Improvement	Mine Closure Cost	38.7%
	Wind Development Cost	41.1%
	NPV	17.4%
	IRR	11.4%
	LCOE	16.5%
	Payback Period	8.8%

5.5. *Commercial-Scale Wind Development Discussion*

5.5.1. *Project Economics*

Though the wind conditions at the monitored locations were all found to be Class 1 (poor), the savings demonstrated in the case study cash flows (which utilized scaled wind data) clearly demonstrate the savings potential of post-mining wind power. Table 5.22 summarizes the savings found from the case studies.

Table 5.22 – Synergistic Mine Closure & Wind Development Savings Summary

Scenario	Category	Improvement	STD (% of avg.)
Performance Improvement	Mine Closure Cost	36.3%	14.5%
	Wind Development Cost	44.1%	5.1%
	NPV	28.3%	43.0%
	IRR	14.5%	17.4%
	LCOE	18.8%	8.7%
	Payback Period	10.5%	12.7%

These savings represent an ample financial opportunity for mine operators and wind developers alike should a site appropriate for both coal mining and wind power be identified. The primary savings are realized through the elimination of tasks which are either common to both mine closure and wind development or which are conflicting to each other. Prime examples include tree planting, road removal, and power line removal, which would normally be performed during mine closure. Under normal conditions, a mining company would be required to fulfill these tasks in order to release their reclamation bond, after which a prospective wind developer would need to re-clear the site (removing the recently-planted trees) and rebuild access roads and electrical infrastructure.

In order to realize savings comparable to those presented in Table 5.22, two very important criteria must be met. First, wind conditions must be suitable for wind farm development. As was noted in the Wind Data Scaling section, all three sites were found to be Class 1 (poor) and the wind data needed to be scaled up in order to provide a realistic representation of a wind project revenue stream.

The second criterion is that wind farming be a post-mining land use approved by all relevant regulatory agencies and the local population. If the post-mining land use is not included in the mining permit, conventional reclamation and closure practices must be followed prior to wind development and the cost savings exemplified in the case study will not be realized.

As the Literature Review noted, wind project financing is a significant barrier to new development, especially in the shadow of policy and market uncertainty. Though synergistic mine closure and wind development reduce the capital costs of wind farm construction, they are not likely to be reduced sufficiently to alter the availability of financiers. The primary reason that capital costs cannot be reduced further is that wind turbines occupy such a large portion of first costs (65-68% in the provided case studies). Despite this limitation, cost reductions without sacrificing performance are always positive from an economic perspective; post-mining wind development will always reduce first costs.

Finally, the development of post-mining wind power will be a marketable activity for both mining companies and wind producers. The benefits of a "sustainable image" are not easily quantified, but are universally accepted as being both real and significant. For both mining companies and wind developers, enhanced cooperation may lead to future ease of permitting and improved community relations. Improvement in either of these areas would lead to enriched corporate functionality.

5.5.2. Community Impacts

The wind development proposed in the case studies would also have positive impacts on the local communities. Lantz notes that total employment impacts from completed community wind projects are estimated to be on the order of four to six 1-year jobs per-MW during construction and 0.3 to 0.6 long-term jobs per-MW during operations [74]. The potential job creation afforded by the case studies' plans is shown in Table 5.23.

Table 5.23 – Wind Development Job Creation

Site	MW Installed	Construction Jobs	Operation Jobs
White Flame #10	35	138 - 207	10.4 - 20.7
Pax South	26	102 - 153	7.7 - 15.3
Lost Flats	32	126 - 189	9.5 - 18.9

In addition to facilitating local employment, wind development would also contribute to state tax revenues. Estimated tax contributions from each case study are shown in Table 5.24.

Table 5.24 – Wind Development 20-year State Tax Contributions

Site	Tax Revenue (20y)
White Flame #10	$ 7,400,000.00
Pax South	$ 6,600,000.00
Lost Flats	$ 7,900,000.00

As was previously mentioned, the development of post-mining wind power projects will communicate two important messages to the local community: mining and utility companies are both interested in local job creation and in minimizing local environmental impacts. Ultimately, these efforts will foster goodwill and enhanced company-community relations; these effects will benefit all involved parties.

5.5.3. West Virginia Renewable Portfolio Standard

West Virginia has passed a Renewable Portfolio Standard which requires all power providers to generate 25% of their electricity from alternative and renewable sources by 2025. Providers receive one credit per MWh generated from alternative sources, two credits for renewable sources, and three credits from renewable sources on reclaimed surface mine lands (see Literature Review for additional details). A standard wind farm would qualify for two credits per MWh, while a post-mining wind facility would qualify for three.

As a representative economic example, the neighboring state of Pennsylvania has also passed a similar portfolio standards program [92]. In their legislation, a utility provider may pay a $45/MWh fee in the event of failing to provide sufficient power from alternative and renewable sources. However, these credits traded at an average value of $4.77/MWh in 2010 [93]. This credit value was used to determine the approximate effects of RPS credit sales on site revenue. The results of these calculations are shown in Table 5.25.

Table 5.25 – RPS Credit Effects on Case Study Revenues

Site	Annual Income	RPS Income	% Increase
White Flame #10	$ 8,400,000.00	$ 1,400,000.00	16.7%
Pax South	$ 7,400,000.00	$ 1,200,000.00	16.2%
Lost Flats	$ 8,900,000.00	$ 1,500,000.00	16.9%

While the value of the RPS credits sold in West Virginia will likely vary from those sold in Pennsylvania, it is clear that the RPS standards will significantly improve post-mining wind project economics.

5.5.4. Carbon Credits

Though neither a carbon tax nor cap-and-trade system is currently in place in the United States, the adoption of either would benefit post-mining wind power. The EIA reported that 2.095 lb-CO_2 were emitted per kWh of electricity produced from coal in 2010 [94]. Wind power emits zero lb-CO_2 during electricity production, so a financial value may be inferred from estimated carbon prices. Table 5.26 was generated using a price of \$20/ton-CO_2-eq, which is the approximate trading price of a carbon credit in the European Union. At the aforementioned value, a carbon credit would add a value of 2.095¢/kWh, which is almost identical to the value currently offered through the PTC system.

Table 5.26 – Carbon Tax Effects on Case Study Revenues

Site	Annual Income	Carbon Tax Income	% Increase
White Flame #10	$ 8,356,821.74	$ 2,015,793.70	24.1%
Pax South	$ 7,414,677.39	$ 1,788,534.01	24.1%
Lost Flats	$ 8,853,981.98	$ 2,135,716.38	24.1%

As the table shows, revenue increases of 24% would be realized if a utility were able to use the emissions credits from post-mining wind power. A carbon tax or cap-and-trade system may never be adopted in the United States, but it is clear that post-mining wind power would stand to benefit if the situation were to change.

5.5.5. *Sensitivity Analysis*

This section will discuss the impacts of AEP uncertainty on project economics, followed by the effects of synergistic mine closure and wind development on the AEP values required to meet benchmark IRRs of 15, 8, and 0%.

5.5.5.1. *AEP Uncertainty*

Sensor, vertical wind speed extrapolation, turbine placement, long-term prediction, and plant loss estimation errors all contribute to overall AEP uncertainty, as explained in section 3.3.3. Figure 5.1, Figure 5.2, and Figure 5.3 show the plotted effects of ±10% AEP on the financial metrics used in the case studies.

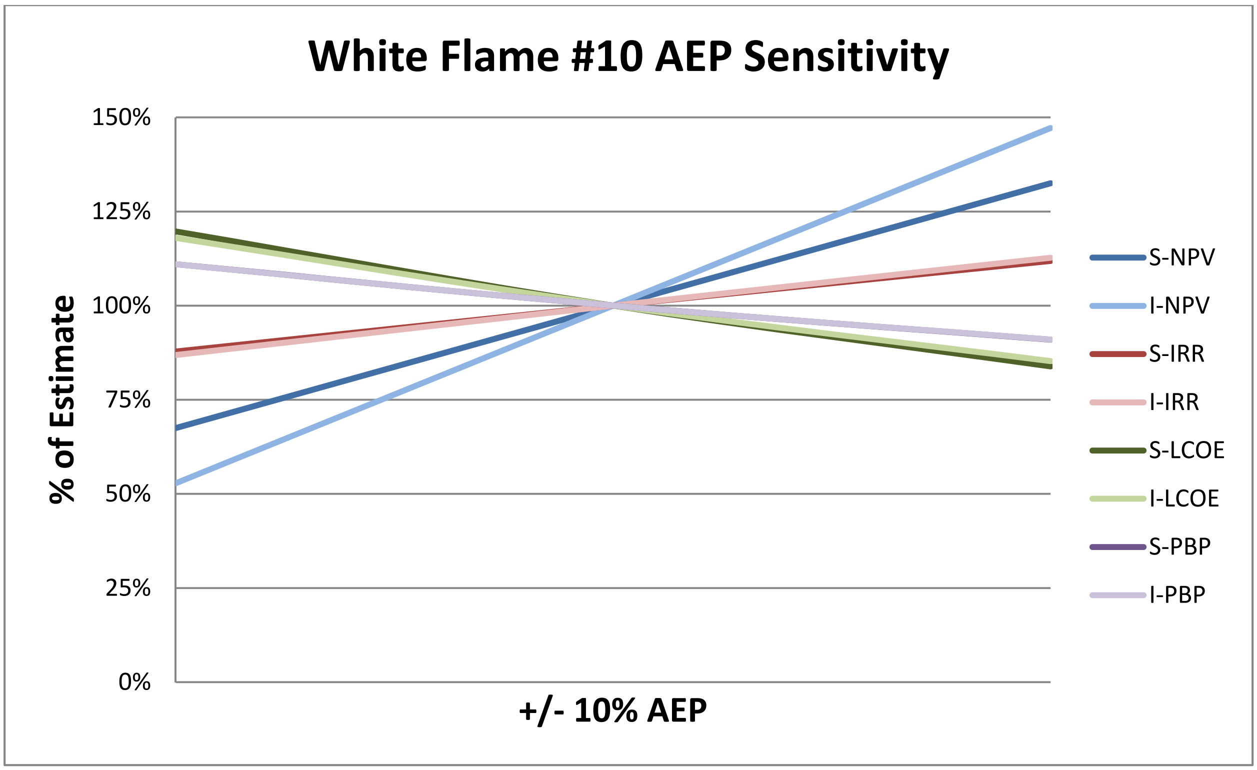

Figure 5.1 – White Flame #10 AEP Sensitivity

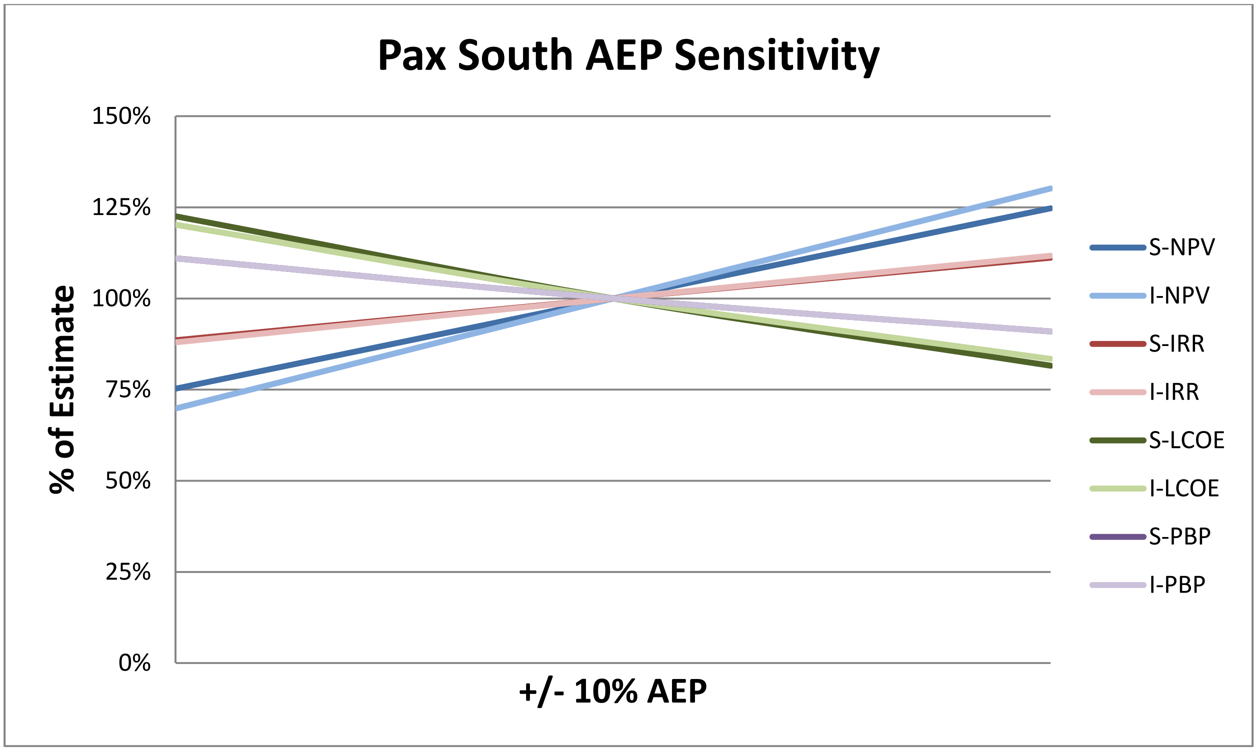

Figure 5.2 – Pax South AEP Sensitivity

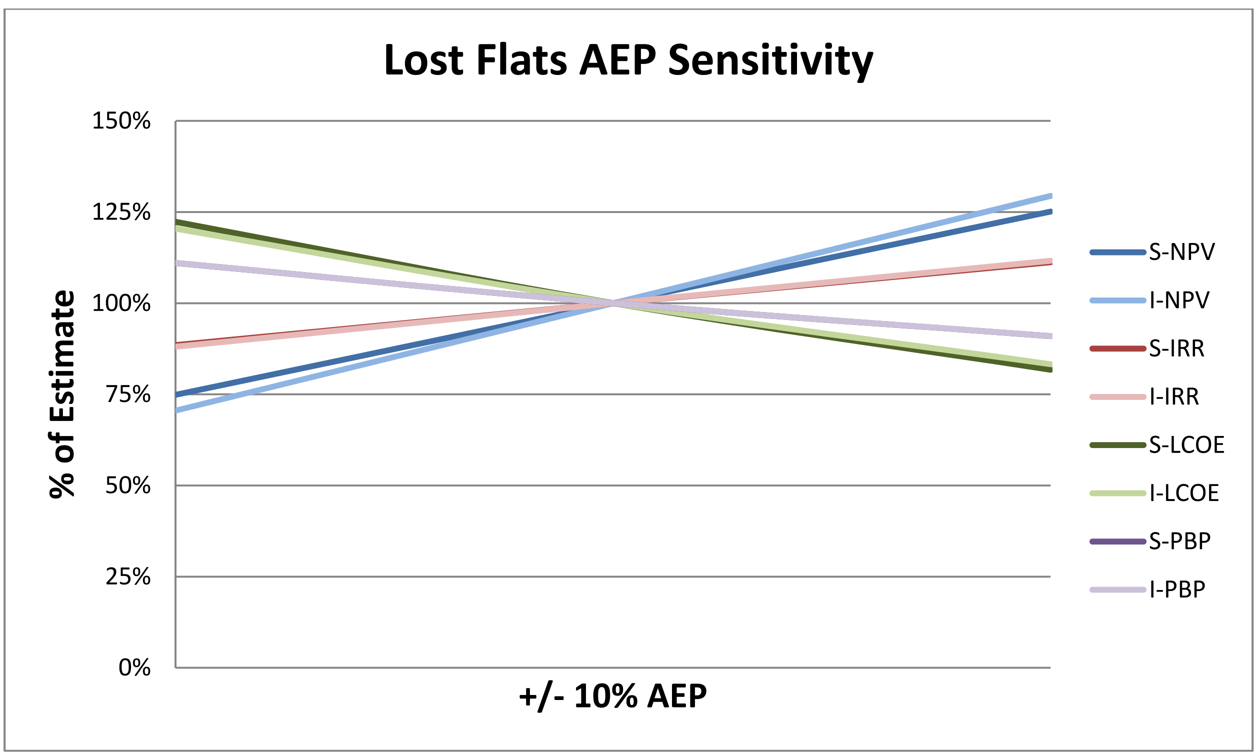

Figure 5.3 – Lost Flats AEP Sensitivity

The previous plots indicate that AEP variations profoundly influence NPV and LCOE, with less significant effects on IRR and PBP. The NPV was the only metric which was changed at a noticeably different rate between independent and synergistic development scenarios, which is due to the fact that identical shifts in revenue will have proportionally greater influence on NPVs including different capital costs.

The projects' sensitivity to AEP demonstrates the importance of performing a thorough site analysis prior to investment. Synergistic mine closure and wind development affords a minor reduction to NPV sensitivity, but has no significant effect on the other financial metrics.

5.5.5.2. Wind Condition Threshold

The effects of synergistic mine closure and wind development have been quantified in terms of AEP required to meet IRRs of 15, 8, and 0%. These values were calculated by solving for the AEP in order to achieve the specified IRR; all other values in the cash flow were held constant. Each site's annual mean wind velocity, v_{avg}, was back-calculated by re-scaling the recorded wind data in order to match the newly determined AEPs. These operations were performed for four cases: the Reference Case, RPS Credits, Carbon Credits, and Both Credits. The Reference Case utilizes identical inputs as the cash flows summarized in Table 5.7, Table 5.14, and Table 5.21. The RPS Credits case adds an additional revenue stream from the sale of RPS credits, as explained in section 5.5.3. The Carbon Credits case adds an additional revenue stream from the sale of carbon credits, as explained in section 5.5.4. The Carbon & RPS Credits case combines the latter two cases. The results of the calculations performed to determine AEP and v_{avg} values to achieve a 15, 8, and 0% return are presented in Table 5.27, Table 5.28, and Table 5.29, respectively.

Table 5.27 – 15% Return AEP and v_{avg} Sensitivity

IRR=15%							
Site	**Scenario**	**Reference Case AEP**	**Synergistic AEP**	**Improvement**	**Reference Case v_{avg} (m/s)**	**Synergistic Case v_{avg} (m/s)**	**Improvement**
White Flame #10	Reference	4,854,333	4,264,325	13.8%	7.56	7.03	7.5%
	RPS Credits	4,305,365	3,580,562	20.2%	7.10	6.49	9.4%
	Carbon Credits	3,793,041	3,332,609	13.8%	6.65	6.32	5.2%
	Carbon & RPS Credits	3,449,805	2,899,834	19.0%	6.38	5.90	8.1%
Pax South	Reference	4,942,411	4,401,886	12.3%	6.89	6.43	7.2%
	RPS Credits	4,383,496	3,696,065	18.6%	6.43	5.85	9.9%
	Carbon Credits	3,861,874	3,440,114	12.3%	6.00	5.65	6.2%
	Carbon & RPS Credits	3,512,410	2,993,378	17.3%	5.72	5.29	8.1%
Lost Flats	Reference	4,721,500	4,301,445	9.8%	6.90	6.56	5.2%
	RPS Credits	4,187,533	3,611,729	15.9%	6.44	5.98	7.7%
	Carbon Credits	3,689,230	3,361,618	9.7%	6.07	5.79	4.8%
	Carbon & RPS Credits	3,355,389	2,925,076	14.7%	5.79	5.47	5.9%

Table 5.28 – 8% Return AEP and v_{avg} Sensitivity

IRR= 8%							
Site	**Scenario**	**Reference Case AEP**	**Synergistic AEP**	**Improvement**	**Reference Case v_{avg} (m/s)**	**Synergistic Case v_{avg} (m/s)**	**Improvement**
White Flame #10	Reference	3,064,446	2,688,300	14.0%	6.07	5.76	5.4%
	RPS Credits	2,715,955	2,257,244	20.3%	5.77	5.37	7.4%
	Carbon Credits	2,392,765	2,100,931	13.9%	5.50	5.24	5.0%
	Both Credits	2,176,242	1,828,103	19.0%	5.31	4.99	6.4%
Pax South	Reference	3,120,631	2,776,031	12.4%	5.40	5.13	5.3%
	RPS Credits	2,765,794	2,330,908	18.7%	5.13	4.77	7.5%
	Carbon Credits	2,436,674	2,169,494	12.3%	4.86	4.64	4.7%
	Carbon & RPS Credits	2,216,177	1,887,762	17.4%	4.68	4.40	6.4%
Lost Flats	Reference	2,979,770	2,711,974	9.9%	5.49	5.28	4.0%
	RPS Credits	2,640,841	2,277,122	16.0%	5.24	4.93	6.3%
	Carbon Credits	2,326,590	2,119,432	9.8%	4.98	4.82	3.3%
	Both Credits	2,116,055	1,844,201	14.7%	4.82	4.59	5.0%

Table 5.29 – 0% Return AEP and v_{avg} Sensitivity

Cutoff (IRR=0%)							
Site	Scenario	Reference Case AEP	Synergistic AEP	Improvement	Reference Case V_{avg} (m/s)	Synergistic Case V_{avg} (m/s)	Improvement
White Flame #10	Reference	1,515,009	1,330,356	13.9%	4.70	4.50	4.4%
	RPS Credits	1,343,914	1,117,040	20.3%	4.51	4.25	6.1%
	Carbon Credits	1,183,993	1,039,685	13.9%	4.34	4.17	4.1%
	Carbon & RPS Credits	1,076,852	904,671	19.0%	4.21	4.00	5.3%
Pax South	Reference	1,542,454	1,373,288	13.9%	4.09	3.94	3.8%
	RPS Credits	1,368,261	1,153,088	20.3%	3.94	3.72	5.9%
	Carbon Credits	1,205,442	1,073,237	13.9%	3.77	3.63	3.9%
	Carbon & RPS Credits	1,096,361	933,866	19.0%	3.66	3.48	5.2%
Lost Flats	Reference	1,473,404	1,341,941	13.9%	4.26	4.12	3.4%
	RPS Credits	1,307,008	1,126,767	20.3%	4.08	3.90	4.6%
	Carbon Credits	1,151,479	1,048,739	13.9%	3.92	3.83	2.3%
	Carbon & RPS Credits	1,047,280	912,549	19.0%	3.83	3.66	4.6%

The performance improvements achieved from synergistic mine closure and wind development are summarized in Table 5.30, Table 5.31, and Table 5.32 for all scenarios. In all cases, synergistic mine closure and wind development yield performance improvements.

Table 5.30 – 15% Return Performance Improvement Summary

Profitable Return (IRR=15%)		
Scenario	AEP Improvement	V_{avg} Improvement
Reference	12.0%	6.6%
RPS Credits	18.3%	9.0%
Carbon Credits	11.9%	5.4%
Carbon & RPS Credits	17.0%	7.4%

Table 5.31 – 8% Performance Improvement Summary

IRR=8%		
Scenario	AEP Improvement	v_{avg} Improvement
Reference	12.1%	4.9%
RPS Credits	18.3%	7.1%
Carbon Credits	12.0%	4.3%
Carbon & RPS Credits	17.1%	5.9%

Table 5.32 – 0% Performance Improvement Summary

Cutoff (IRR=0%)		
Scenario	**AEP Improvement**	**V_{avg} Improvement**
Reference	13.9%	3.9%
RPS Credits	20.3%	5.5%
Carbon Credits	13.9%	3.4%
Carbon & RPS Credits	19.0%	5.0%

Though previous tables clearly indicate that synergistic mine closure and wind development yields improvements in threshold AEP values for achieving both breakeven and profitable returns, it should be noted that the relative improvement in v_{avg} values is not sufficient to alter the site selection process during preliminary wind assessment. The reductions in v_{avg} are very similar to the anticipated uncertainties in sensor error alone (~5%), as summarized by Jain. Similarly, AEP uncertainty is approximately 10% [39]. As the tables show, v_{avg} and AEP improvements range from 3.4-9.0% and improvements 11.9-20.3%, respectively. The similarity between these values and the anticipated uncertainty indicates that the improvements afforded by post-mining wind power, while positive, are not sufficient to alter the threshold wind conditions sought during the site selection process.

6. Conclusions & Recommendations

This thesis has presented the work performed to evaluate the feasibility of wind power as an alternative post-mining land use. The project began with a literature review, followed by the creation of a wind analysis program for multiple mine locations in West Virginia and an investigation into the primary costs associated with surface mine closure and Appalachian wind development. These costs were analyzed and combined in case studies of the monitored locations.

Though none of the monitored locations were found to be viable for commercial-scale wind development, it is clear from analyzing them that ample financial savings may be realized through combining mine closure and wind development activities. These savings are evidenced in the 35% and 30% reductions in mine closure and wind site preparation costs, respectively, of the case studies presented. These cost reductions led to universal improvements in the financial evaluation metrics used to evaluate each project. These savings stem from the elimination of activities common to or redundant between mine closure and wind power site preparation. Under West Virginia's RPS, additional bonuses would be realized through the construction of renewable energy systems on surface mine land. Companies would also be able to market themselves as sustainable developers and renewable energy contributors, both of which would lead to enhanced corporate value. In addition to the financial benefits, local communities will be provided with a long-term economic post-mining land use that, in combination with the employment of responsible mine operation and environmental controls, will enhance the sustainability of surface coal mining practices.

Due to the capital intensiveness of wind turbine costs, which were shown to occupy between 65-68% of total capital costs in the presented case studies, constructing wind power facilities on reclaimed mine land is not likely to impact first costs significantly enough to green-light projects which would otherwise be only marginally feasible. This statement is further justified by noting that the reductions in threshold AEP and mean annual wind speed for profitable and breakeven returns, while positive, are comparable to the data and revenue uncertainty present in the analysis. These factors yield a clear conclusion: post-mining wind power does not lower the wind conditions threshold needed for a successful wind power project. That being said, it has been demonstrated that significant cost-saving opportunities are available *if* acceptable wind conditions are found to be on reclaimed (either presently or in the future) surface mine land.

The benefits of synergistic mine closure and wind development cannot be realized without additional cooperation between mine operators and wind developers in the Appalachian region. It is the recommendation of this thesis that wind power be investigated as a post-mining land use during the pre-feasibility stages of site assessment so that maximum cost savings may be experienced. This would justify the time and expense to conduct a more thorough analysis than the case studies presented here and, along with the dissemination of future projects' findings, would dramatically assist in improving the knowledge base of co-developing coal mining and wind farming sites. These practices will enable corporations to lower first costs of wind farms, capitalize on financial incentives offered to renewable energy developers, and contribute to the enhanced sustainability of the Appalachian region.

6.1. Future work

Several additional tasks may assist in the promulgation of synergistic mine closure & wind development. The first of these activities is to perform additional case studies of mine sites in the Appalachian region. Analyses of other properties, especially greenfield sites, will enhance cost-savings estimates.

The second activity is to quantify state-specific financial incentives for renewable energy development, principally the value of West Virginia's RPS credits under its new system. These credits have the potential to further encourage post-mining wind power. They may also contribute to the investigation of non-commercial-scale wind technologies, which would have much lower capital costs while still being able to take advantage of the RPS credit system.

The third and most important activity is to develop a functioning post-mining wind power facility. This project would provide real information for assisting with future development and would clarify many of the assumptions made in this thesis regarding post-mining wind power. Ideally, it would prove that post-mining wind power is an opportunity worth pursuing in order to advance renewable energy development and enhance the reputation of mining sustainability in Appalachia.

References

1. Appalachian Regional Commission, *The Appalachian Region*, 2011.

2. E.R. Slatick, B.D.H., *Coal geology, reserves and production in northern and central Appalachia.* Mining Engineering, 1995.

3. Riddel, F.S., *Appalachia : its people, heritage, and problems*1974, Dubuque, Iowa: Kendall/Hunt Pub. Co.

4. West Virginia Office of Miners' Health, Safety and Training. *West Virginia Coal Mining Facts*. 2011; Available from: http://www.wvminesafety.org/wvcoalfacts.htm.

5. Roenker, J., *The Economic Impact of Coal in Appalachian Kentucky*, in *Kentucky Annual Economic Report*2002, University Kentucky Center for Business and Economic Research.

6. Rose, A. and D. Wei, *The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015*, 2006, The Pennsylvania State University: The Center for Energy and Economic Development, Inc.

7. Davis, G.V., *Where once there were mountains: the grassroots struggle against mountaintop removal coal mining in central Appalachia.* Environmental politics, 2009. **18**(1): p. 135-140.

8. Fox, J., *Mountaintop removal in West Virginia.* Organization & environment, 1999. **12**(2): p. 163.

9. Burns, S.S., *Bringing down the mountains : the impact of mountaintop removal surface coal mining on southern West Virginia communities, 1970-2004*2007, Morgantown, W. Va.: West Virginia University Press.

10. Craynon, J. and M. Karmis. *Optimizing coal mine design for sustainable development*. in *Sustainable Development in the Minerals Industry*. 2011. Aachen, Germany.

11. United Nations Department of Economic and Social Affairs (DESA), *Report of the World Commission on Environment and Development*, U. Nations, Editor 1987.

12. Kirsch, S., *Sustainable Mining.* Dialectical anthropology, 2010. **34**(1): p. 87-93.

13. Horowitz, L., *Section 2: mining and sustainable development.* Journal of cleaner production, 2005. **14**(3-4): p. 307-308.

14. International Institute for Environment and Development, *Breaking New Ground: Mining, Minerals and Sustainable Development*, L. Danielson, Editor 2002, International Institute for Environment and Development.

15. Grieg-Gran, M., *Financial Incentives for Improved Sustainability Performance: The Business Case and the Sustainability Dividend*, 2002, World Business Council for Sustainable Development.

16. Eysel, P. and M. Götze. *Financing of mining projects - Can banks drive sustainability?* in *Sustainable Development in the Minerals Industry*. 2011. Aachen, Germany.

17. Williamson, R., *Politics of Mining - What They Don't Teach You in School*, ed. D. Malhotra2001: Society for Mining, Metallurgy, and Exploration, Inc.

18. Duerksen, A. and E. Westman. *Wind power as an alternative post-mining land use in surface coal mines in West Virginia, U.S.* in *Sustainable Development in the Minerals Industry*. 2011. Aachen, Germany.

19. Malcolm, S., M. Mary Louise, and M.V. Marcello, *Mining with communities.* Natural resources forum, 2001. **25**(3): p. 191.

20. Whiteman, G. and K. Mamen, *Community consultation in Mining.* Cultural survival quarterly, 2001. **25**(1): p. 30.

21. Glass, P., *Participatory Development in Appalachia: Cultural Identity, Community, and Sustainability.* Journal of cultural diversity, 2011. **17**(4): p. 154.

22. Harris, L. and R. Harris, *The Importance of Community Assistance in the Mining Industry*. Politics of Mining - What They Don't Teach You in School, ed. D. Malhotra2001: Society of Mining, Metallurgy, and Exploration, Inc.

23. Kleinmann, R., *Mine Reclamation and Remediation*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier. p. 475-485.

24. Lyle, E.S., *Surface mine reclamation manual*1987, New York, N.Y.: Elsevier Science.

25. Hartman, H. and J. Mutmansky, *Introductory Mining Engineering*2002: John Wiley & Sons, Inc.

26. Office of Surface Mining, *Surface Mining Control and Reclamation Act*, in *U.S. Code: Title 30, Chapter 25*1977.

27. Kaas, L.M., *Major federal environmental laws and regulation*. SME Mining Engineering Handbook, ed. H. Hartman1992, Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

28. McCarter, M.K., et al., *Open Cast (Strip) Mining*. SME Mining Engineering Handbook, ed. H. Mutmansky1998, Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.

29. United States Office of Surface Mining Reclamation Enforcement, *An evaluation of approximate original contour and post-mining land use in Kentucky. final report*, 2000,

U.S. Dept. of the Interior, Office of Surface Mining, Lexington Field Office: [Lexington, Ky.].

30. Torbert, J.L., et al., *Commercial forestry as a post-mining land use*1994, Blacksburg: Virginia Cooperative Extension.

31. Fields-Johnson, C.W., *Appalachian surface mine reforestation techniques effects of grading, cultural treatments and species selection*, in *Crop & Soil Environmental Science*2011, Virginia Polytechnic Institute & State University: Blacksburg, Va.

32. Baker, K.L., *Costs of reclamation on southern Appalachian coal mines a cost-effectiveness analysis for reforestation versus hayland/pasture reclamation*, in *Forestry*2008, Virginia Polytechnic Institute & State University: Blacksburg, Va.

33. Bens, O., R. Bungart, and R.F. Huttl, *Production of bioenergy in post-mining landscapes in Lusatia - Perspectives and challenges for alternative landuse systems.* Ecological engineering, 2000. **16**: p. S5-S16.

34. Zhang, J., et al., *Land use-based landscape planning and restoration in mine closure areas.* Environmental management (New York), 2011. **47**(5): p. 739-750.

35. Gross, M., *Communicating ignorance and the development of post-mining landscapes.* Science communication, 2007. **29**(2): p. 264-270.

36. Eyll-Vetter, M., M. Kosma, and M. Henneman. *Recultivation and regional cooperation for a sustainable development of the post-mine landscape*. in *Sustainable Development in the Minerals Industry*. 2011. Aachen, Germany.

37. Idaho National Laboratory. *Wind energy for mining applications*. 2005; Available from: http://purl.access.gpo.gov/GPO/LPS103873.

38. Hansen, E., et al., *The long-term economic benefits of wind versus mountaintop removal coal on Coal River Mountain, West Virginia*, 2008, Downstream Strategies.

39. Jain, P., *Wind energy engineering*2011, New York: McGraw-Hill.

40. Burton, T., *Wind energy handbook*2011, Chichester, West Sussex: Wiley.

41. Vanek, F.M. and L.D. Albright, *Energy Systems Engineering*2008: The McGraw Hill Companies, Inc. .

42. Pasqualetti, M., R. Righter, and P. Gipe, *History of Wind Energy*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

43. U.S. Department of Energy, *20% Wind Energy by 2030*, 2008.

44. Wind Powering America, *U.S. Installed Wind Capacity and Wind Project Locations*, 2011.

45. U.S. Energy Information Administration, *Wind Resource Potential*, 2003.

46. U.S. Department of Energy, *Wind Powering America: U.S. Installed Wind Capacity and Wind Project Locations Current Installed Wind Capacity Map*, 2011.

47. National Renewable Energy Laboratory, *West Virginia 50m Wind Resource Map*, 2010.

48. Morrison, M. and K. Sinclair, *Environmental Impacts of Wind Energy Technology*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

49. Welch, J.B. and A. Venkateswaran, *The dual sustainability of wind energy.* Renewable & sustainable energy reviews, 2008. **13**(5): p. 1121-1126.

50. Michael, S., *The Economics of Wind Energy.* Petroleum accounting and financial management journal, 2010. **29**(3): p. 55.

51. Dragoon, K., *Valuing Wind Generation on Integrated Power Systems*2010: Elsevier.

52. Denholm, P., et al., *The Role of Energy Storage with Renewable Electricity Generation*, 2010, National Renewable Energy Laboratory.

53. Eyer, J. and G. Corey, *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*, 2010, Sandia National Laboratories.

54. National Renewable Energy Laboratory. *Creating baseload wind power systems using advanced compressed air energy storage concepts*. 2006; Available from: http://purl.access.gpo.gov/GPO/LPS93460.

55. Kirby, B., M.R. Milligan, and L. National Renewable Energy. *Facilitating wind development the importance of electric industry structure*. 2008; Available from: http://purl.access.gpo.gov/GPO/LPS116755.

56. Slattery, M. and J. Swofford, *Public attitudes of wind energy in Texas: Local communities in close proximity to wind farms and their effect on decision-making.* Energy policy, 2010. **38**(5): p. 2508-2519.

57. Laborgne, P., S. Mimler, and A. Jobert, *Local acceptance of wind energy: Factors of success identified in French and German case studies.* Energy policy, 2007. **35**(5): p. 2751-2760.

58. Coburn, T. and B. Farhar, *Public Reactions to Renewable Energy Sources and Systems*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

59. Bailey, B., *Overcoming Barriers to Wind Development in Appalachian Coal Country*, in *West Virginia Wind Working Group*2011: Davis, WV.

60. Haegele, G. *An Alternative to Mountaintop Removal Coal Mining in West Virginia*. 2008.

61. Slavin, P. *How Wind Farms May Really Replace Coal Mining*. 2008.

62. Zeller, T., *A Battle in Mining Country Pits Coal Against Wind*, in *The New York Times*2010.

63. Risch, C., *Overcoming the Challenges to Acceptance of Wind Energy in PJM*, in *West Virginia Wind Working Group - Annual Conference*2009: Davis, WV.

64. AWS Scientific, *National Renewable Energy Laboratory Wind Assessment Handbook*1997.

65. Carico, G., *A season of wind assessment on surface mined land*, in *West Virginia Wind Working - Annual Conference*2010: Davis, WV.

66. Miyashita, K., *Full Scale Measurements for Wind Environment Assessment.* Wind Engineers, JAWE, 2009. **34**(3): p. 357-360.

67. McCarthy, E., et al., *Wind potential assessment of Quebec Province.* Renewable energy, 2003. **28**(12): p. 1881-1897.

68. Crespo, A., et al., *Wind energy resource assessment in Madrid region.* Renewable energy, 2007. **32**(9): p. 1467-1483.

69. Marshall University Center for Environmental, Geotechnical and Applied Sciences (CEGAS), *Sonic Detection and Ranging (SODAR) Data Collection and Evaluation Report*, 2011.

70. Duncan, E., *The Cost of Developing and Constructing Wind Farms*, in *West Virginia Wind Working Group*2009: Davis, WV.

71. Joselin Herbert, G.M., et al., *A review of wind energy technologies.* Renewable & sustainable energy reviews, 2007. **11**(6): p. 1117-1145.

72. United States Government Accountability Office and United States Committee on Agriculture, Nutrition and Forestry. *Renewable energy wind power's contribution to electric power generation and impact on farms and rural communities : report to the Ranking Democratic Member, Committee on Agriculture, Nutrition, and Forestry, U.S. Senate*. 2004; Available from: http://purl.access.gpo.gov/GPO/LPS55258.

73. Lantz, E. *Economic development benefits from wind power in Nebraska a report for the Nebraska Energy Office*. 2009; Available from: http://purl.fdlp.gov/GPO/gpo2852.

74. Lantz, E. and S. Tegen. *Economic development impacts of community wind projects a review and empirical evaluation*. 2009; Available from: http://purl.access.gpo.gov/GPO/LPS116566.

75. Aitken, M., *Wind power and community benefits: Challenges and opportunities.* Energy policy, 2010. **38**(10): p. 6066-6075.

76. Bacon, R., *Taxation of Energy*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

77. Szarka, J., *Wind power, policy learning and paradigm change.* Energy policy, 2006. **34**(17): p. 3041-3048.

78. Schreurs, M., *National Energy Policy: United States*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

79. Koplow, D., *Subsidies to Energy Industries*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

80. Andriano, J.R., *The Power of Wind: Current Legal Issues in Siting for Wind Power.* Planning & environmental law, 2009. **61**(5): p. 3-13.

81. Brown, M., et al., *Policies and market factors driving wind power development in the United States.* Energy policy, 2005. **33**(11): p. 1397-1407.

82. Brit, T.B. and A.E. Benjamin, *Wind Power: Generating Electricity and Lawsuits.* Energy law journal, 2007. **28**(2): p. 489.

83. Jaccard, M., *Renewable Portfolio Standard*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

84. Steven, J.H., *Wind energy: Power and policy.* The Appraisal journal, 1999. **67**(1): p. 24.

85. Marshall University Center for Business and Economic Research, *Energy Efficiency and Renewable Energy in Appalachia: Policy and Potential*, 2006.

86. West VIrginia Public Service Commission, *West Virginia Alternative and Renewable Energy Portfolio Standard*, 2011.

87. Chupka, M., *Carbon Taxes and Climate Change*, in *Encyclopedia of Energy*, C.J. Cleveland, Editor 2004, Elsevier.

88. Carpenter, S.M. and C.R. Hairfield, *Fundamentals of Carbon Regulations and their Impacts on the Mining Industry*, in *SME 2010 Annual Meeting*2010: Phoenix, AZ.

89. Stanfield, J.R. and M.C. Carroll, *Sustainable Regional Economic Development.* Journal of economic issues, 2001. **35**(2): p. 469-476.

90. Stermole, F.J. and J.M. Stermole, *Economic Evaluation and Investment Decision Methods*. 11th Edition ed2006.

91. Energy Information Administration, *Average Retail Price of Electricity by State, 2009*, 2010.

92. Pennsylvania Public Utility Commission, *Alternative Energy Portfolio Standard*, 2004.

93. Pennsylvania Public Utility Commission. *Alternative Energy Portfolio Standards (AEPS) Program - Pricing for AEC Sales*. 2011 9/22/2011]; Available from: http://www.puc.state.pa.us/electric/electric_alt_energy.aspx.

94. U.S. Energy Information Administration, *Emissions of Greenhouse Gases Report*, 2009, U.S. Department of Energy.