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Concern about energy independence and climate change have driven state and federal governments to promote renewable energy production, mainly in the form of wind generated electricity. There are social costs of wind energy development, however, that can lower its environmental value. Most notably, wind turbines can impact wildlife and wildlife habitat. Wind-wildlife conflicts are particularly intense in Wyoming, which has more high-quality wind resources than all other western states combined. Wyoming also has the largest amount of intact sagebrush ecosystem, which provides habitat for 64% of the known greater sage-grouse (Centrocercus urophasianus) population in the eastern portion of the species range. The greater sage-grouse was recently listed as a candidate on the endangered species list due largely to threats from energy development. Current legislation in Wyoming restricts wind energy development within greater sage-grouse core breeding areas. This suggests that the tradeoff between wind development and greater sage-grouse persistence is steep.

I develop an econometric model to estimate the probability of wind development across 26 million acres of Wyoming. I then use these probabilities to simulate a range of wind energy build-out levels, with and without the current sage-grouse core-area restrictions. The model predicts that locations closer to transmission lines with higher wind classes are most likely to be occupied in the future by a wind farm. Some of the high probability wind locations also coincide with sage-grouse core breeding areas. Thus, there is potential for conflict between sage-grouse conservation and future wind development. There is relatively little conflict at low build-out levels (1,650 MW); however, as more wind development is distributed across the landscape, conflict increases. In the absence of conservation a build-out of 13,770 MW results in potential impacts to 1,346 males on 56 leks (2.4% of Wyoming’s male population based on 2007 maximum lek counts). Restricting development in sage-grouse core areas (as defined by WY state governor in executive order 2011-5) will result in 324 males on 19 leks being potentially influenced, a reduction of 1.82% with an energy development opportunity cost of a 4% reduction in wind energy profits. Thus, while there are certain to be conflicts between sage-grouse and wind energy development, my results suggests that Wyoming can harness its vast wind resources while conserving sage-grouse.
ASSESSING THE CONFLICT BETWEEN WIND ENERGY DEVELOPMENT AND SAGE-GROUSE CONSERVATION IN WYOMING: AN APPLICATION USING A SPATIALLY EXPLICIT WIND DEVELOPMENT MODEL.

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1 Introduction

Societal concern for energy independence and climate change mitigation have driven state and federal policies towards promoting renewable energy production as an alternative to fossil fuels. Wind generated electricity is currently the fastest growing and least-cost utility scale renewable technology being widely implemented. For instance, wind energy is currently the third largest energy source (behind Natural Gas, and Coal) being added to the US electric grid – during the five previous years it was ranked second (Wiser and Bolinger 2011).

The United States is the second largest global emitter of greenhouse gases (GHG’s) (Krupnick et al. 2010), with electrical power generation responsible for more pollution than any other single activity (EIA 2011). Generating electricity with wind is non-polluting, renewable and potentially reduces greenhouse gas emissions by displacing fossil fuel generation. One estimate concluded a 1.5MW wind turbine displaces 2,700 metric tons of CO$_2$ per year (DOE 2008). However, as with all land use activities, there are social costs of wind energy development that can lower its environmental value. Most notably, wind turbines can create visual disamenities and directly or indirectly impact wildlife and their habitats. While not discussed further here, a recent economic study predicted the visual impacts from an offshore wind project in Nantucket, Cape Cod and Martha’s Vineyard to cause a loss of $57,000,000 annually in tourism dollars (Haughton et al. 2003).

The potential impacts from wind energy development to wildlife species and their habitats include both direct and indirect impacts. Direct impacts may include mortality from blade strikes and barotrauma (damage from air pressure differences caused by spinning turbine blades), and habitat loss. Indirect impacts include avoidance or displacement behavior, the introduction of invasive plant species, and increases in predators (USFWS 2011). The most widely documented impacts thus far are bird and bat fatalities caused by direct collision or
barotrauma (in bats) with turbines, support structures, or transmission infrastructure (The Wildlife Society 2007). Wind turbines sit atop structures 80 meters high with average rotor diameters (blade tips) of 84.3 meters (Wiser and Bolinger 2011). Groups of turbines are clustered together into wind farms of 60-1,000 turbines\(^1\) spanning large areas. While the direct disturbance of each wind turbine is small, 1-3 acres per turbine, the extensive fragmentation of the landscape from all the components of a wind farm (e.g., turbines, transmission, substations, facilities, and roads) poses a larger potential threat to wildlife than collision with turbines (Kuvlesky et al 2007).

Wind farm siting has become a large issue for wind energy developers and land managers. To illustrate, while the quality of the wind resource (high consistent wind speeds) may be the most important factor affecting profitability (EWEA 2009), approximately 10-25% of proposed wind energy projects are delayed or canceled because of environmental concerns (DOE 2008). The value of proper siting to maximize winds environmental benefits is illustrated by the United States Fish and Wildlife Service: “siting of a wind energy project is the most important element in avoiding effects to species and their habitats” (USFWS 2011: p. 8).

Many economies in the West rely on developing vast reserves of energy and minerals to sustain themselves. Land use management decisions between conflicting uses, such as managing for profits and managing for wildlife, require tradeoffs. This places a critical need on identifying management objectives that balance energy demands and wildlife habitat protection. This conflict has become particularly notable in Wyoming where the economy is more dependent on energy than any other state in the Intermountain West (Haggerty and Mehl 2009). Wyoming is first in coal production, 2\(^{nd}\) in natural gas production (EIA 2011) and contains more than 50% of

\(^1\) Calculated number of turbines based on: Average wind farm nameplate capacity of 120 MW in 2007, 91 MW in 2009 (Market Report 2007, 2009) and the largest wind farm project (Choke Cherry Sierra Madre) in Wyoming of 2,500MW divided by current average turbine size of 1.5 MW (Wiser and Bolinger 2011) or for the largest, 2.5 MW.
the best class 5-7 winds in the Western US (WREZ 2009). A recent study (National Grid 2008) characterized Wyoming as the “jewel of the region for wind resource” – identifying Wyoming as the lowest cost renewable energy solution for the Desert Southwest. Wyoming’s productive wind resource has not gone unnoticed. Wyoming is currently ranked 10th in the country for installed wind capacity (1,412 MW), and has another 7,869.5 MW in various planning stages (AWEA, 2011a).

At the same time, Wyoming contains the largest amount of intact sagebrush ecosystem remaining, which provides habitat for 64% of the known greater-sage-grouse population (Centrocercus urophasianus) in the eastern portion of its range (Doherty 2008). The greater sage-grouse (hereafter sage-grouse) is a game bird endemic to the western United States (Connelly et al 2004), which is experiencing range wide population declines. The distribution of oil, gas, and wind energy resources closely align with critical sagebrush habitats (Doherty 2008). Researchers have shown that sage-grouse populations decline with oil and gas development (Holloran 2005; Doherty 2008). These declines occur when sage-grouse avoid infrastructure and when development’s cumulative impacts affect reproduction or survival (Naugle 2011, pp 55-70). Many of the impacts from traditional energy development are expected to occur with wind energy development. For example, the impacts of roads and transmission infrastructure are common to all production and generating facilities (NRC 2007).

Together these factors make Wyoming a high conflict area for balancing energy development (in this case wind energy) and wildlife conservation. In 2005, United States Fish Wildlife Service (USFWS) identified energy development as the most significant extinction risk to sage-grouse in the eastern portion of its range (WY and MT) (Johnson and Holloran 2010). The USFWS concluded in 2010 that greater sage-grouse were warranted for protection under the
Endangered Species Act (1973), but because threats to the species are moderate and do not occur across their range at an equal intensity, the listing was precluded by other species under more severe extinction risk (USFWS 2010). A recent study by Doherty (2008) identified that Wyoming has the highest percentage of sage-grouse core breeding areas at risk from both fossil fuel and wind energy development.

The risks of an endangered species listing and the potential losses of energy tax revenues led the Wyoming Governors office to implement an executive order to protect sage-grouse core breeding areas (Executive order 2011-5). The Wyoming Core area executive order is “designed to maintain existing suitable sage-grouse habitat by permitting development activities in core areas in a way that will not cause declines in sage-grouse populations” (Executive order 2011-5). In Core areas, land use activities are limited and regulated based on their known impacts to grouse through buffer requirements, mitigation, and other best management practices. For example, each project developer must complete a Project Implementation Area Analysis (PIAA) (Executive order 2011-5- Attachment B). The PIAA identifies all occupied leks within a 4 mile boundary around the project area and then a 4 mile boundary around each occupied lek within that boundary. All occupied leks within the project area are considered to be “affected” by the proposed project. This information is then used in a Density/Disturbance Calculation Tool to determine the maximum allowable disturbance (up to 5% per 640 acres). In addition to the PIAA the executive order establishes stipulations regarding: No Surface Occupancy, seasonal use, noise, and location of roads and overhead lines that must be followed by a project developer (see Executive order 2011-5- Attachment B for list). However, in the case of wind energy development, where scientific understanding of potential impacts is lacking, no development is
recommended in sage-grouse core areas. This recommendation will be “reevaluated on a continuous basis as new science, information and data emerges” (Executive Order 2011-5).

To date, planning tools that compare the best remaining areas for sage-grouse with the extent of current and anticipated wind development have only considered raw wind resource potential (Naugle et al. 2009; Doherty 2008). An approach that incorporates the economic considerations of developers when selecting locations will more accurately frame the level of risk of wind energy development to species, such as sage-grouse. For example, a developer searching for a wind farm site would certainly prefer higher wind speeds that produce more energy, thus higher profits, than energy produced with lower wind speeds. However, the developer must also consider the tradeoff between remote high quality wind resources that lack transmission access (thus an added expense), and lower quality resources closer to demand loads and existing transmission. Because all habitat protection is not equal and protecting habitat is costly, allocating conservation efforts to lands that have accounted for economic considerations in addition to biological threat will assure a better “bang per buck” for conservation efforts.

I develop an econometric model to estimate parcel level probability of wind energy development for the state of Wyoming. I use GIS to incorporate site specific and landscape characteristics that impact the profitability of wind development. Next I use the model to simulate a range of wind energy build-out levels to account for uncertainty in the actual level of wind power development that may occur in Wyoming. I apply the econometric model and wind energy build-out scenarios to current sage-grouse management policy in Wyoming to quantify the risk of wind development on sage-grouse populations. With information on costs (i.e., foregone profits) the tradeoff between sage-grouse and wind development can be identified by
jointly modeling sage-grouse and wind production from these alternative wind development scenarios.

2 Background/Literature Review

2.1 Brief History of Sage-Grouse Conservation

An extensive body of literature now exists studying the ecology of the greater sage-grouse. Connelly et al. (2004) thoroughly summarizes the population ecology, habitat, impacts and threats, and conservation of the greater sage-grouse and its habitat. Sage-grouse are considered a “sagebrush obligate” species as they rely on large contiguous sagebrush ecosystems throughout their lifecycle for both food and cover. These sagebrush habitats are among the most imperiled ecosystems in North America with few areas remaining undisturbed or unaltered from pre-settlement condition (Knick et al. 2003). Since the 1960’s sage-grouse populations have declined by at least 17-47% (Connelly 2000). Currently sage-grouse occupy habitat in 11 western states and two Canadian provinces-half of their historical pre-settlement range (Connelly et al. 2004).

Conservation and management efforts for greater sage-grouse populations and their habitats occur in all 11 states with habitat for sage-grouse (Connelly et al. 2004). Sage-grouse in WY are managed within Western Association of Fish and Wildlife Agencies Management zones I and II (Fig 1), which, along with management zones IV and V, encompass the core populations of sage-grouse and have the highest reported densities (USFWS 2008).
Numerous threats both anthropogenic and natural have been identified all involving the loss, fragmentation or degradation of sagebrush habitats as well as direct mortalities to the bird. Impacts include: residential development and urbanization, agriculture, energy development, improper grazing, West Nile virus, weather and climate change, invasive species, fences, and fire. Specific threats to sage-grouse populations vary across its range. For example, in Montana a large amount of the sage-grouse habitat is on private lands and these lands are increasingly being converted to agriculture whereas in Nevada and the Great Basin, threats include invasive plant species and fire; in Wyoming and northern Colorado energy development is the major threat. Further, the cumulative impacts from a combination of sources can create a stronger overall impact to populations. Still, the sage-grouse is doing well in some portions of their range. Research suggests that conserving large landscapes with suitable habitat is important for conservation of sage-grouse (Connelly unpublished) and scientists call for protection of the last remaining strongholds as the focus of conservation. The sage-grouse is considered a valuable
species for managing the sagebrush ecosystem because of its strong correlation to intact sagebrush. A study by Rowland 2006 tested the efficacy of using the sage-grouse as an umbrella species of the overall health of the sagebrush ecosystem. They found that protective management of sage-grouse habitats would provide high conservation coverage for other sagebrush obligate species.

Sage-grouse have seasonal habitats over large areas with some populations moving between two-three distinct winter, breeding, and summer seasonal ranges (migratory), while others have highly integrated seasonal ranges (resident) (Connelly et al. 2004). Because of these seasonal use differences the total area of a home range varies based on whether the population is migratory or resident and can be up to 2,700 km² (Connelly 2000) with a single bird requiring an estimated 10,000 acres (Pat Diebert, USFWS, Cheyenne, WY, pers. comm.).

Sagebrush is a major food source for adults throughout the year (Connelly et al. 2004). Sage-grouse select habitat with different aged stands of sagebrush and a healthy understory of forbs and grasses. In winter, sage-grouse rely exclusively on sagebrush for food and cover. In the breeding season sage-grouse select large contiguous stands dominated by sagebrush to provide for mating, nesting and early brood rearing activities (Connelly et al. 2004). The iconic image of the sage-grouse is defined by the elaborate courtship displays performed by males on lek sites to attract females during the breeding season (Connelly et al. 2004). These lek locations are selected in proximity to relatively dense sagebrush stands suitable for nesting. In relatively contiguous habitats females nest within close proximity to the breeding lek with the bulk of sage-grouse nests found under sagebrush (Connelly 2000). During early brood rearing, females raise their brood within short distances of the nest in areas with less sagebrush canopy cover foraging on a diet of forbs and insects; in addition to sagebrush. As broods age and forbs dry out the birds
move to summer habitats (e.g., riparian, upland meadows, sagebrush grasslands), which may be relatively far from nesting/early brood-rearing habitat. Both male and female sage-grouse exhibit high fidelity (i.e., return to the same area year after year) to breeding and nesting sites (Connelly et al. 2004).

2.2 Energy Impacts to Sage-Grouse

There is a growing body of literature documenting the impacts of traditional energy development on sage-grouse populations. The direct and indirect impacts of traditional energy development on sagebrush habitats include the physical removal of sagebrush (clearing an area) fragmentation of habitat (e.g., well pads, roads, transmission), soil disturbance, increases in: noise pollution, vehicle traffic, predation from raptors, and increases in mesopredators and invasive plant species (Connelly et al. 2004). Negative impacts have been identified in numerous sage-grouse populations from coal bed natural gas, deep gas and oil (Naugle et al. 2011, pp.55-70) and wind energy development is expected to cause similar impacts. These studies show sage-grouse avoid energy development. In natural gas fields yearling females avoided infrastructure when selecting sites for nests and yearling males avoided leks inside development (Holloran 2005). Both the density of well pads and distance to infrastructure is associated with declining lek attendance. Holloran (2005) found male lek attendance declined with distance to active drilling rigs, producing gas wells and main haul roads. These lek impacts are most severe near the lek but were discernable at distances greater than 6 km, often resulting in loss of leks within gas fields (Naugle et al. 2011). A review of recent studies found oil and gas development in excess of 1 pad/2.6 km² resulted in impacts to breeding populations and impacts from conventional well densities exceeded the species’ threshold of tolerance (Naugle et al. 2009).
The impacts of wind energy development on sage-grouse populations are relatively unknown – several studies in Wyoming have been initiated but are in their infancy. For instance, funding was recently granted to two projects in Wyoming related to proposed wind developments (NWCC 2011). One will focus on behavior and habitat use by male sage-grouse at the Chokecherry Sierra Madre Wind project and another will be a continuation of research in Carbon County initiated in 2009 studying wind energy development impacts on sage-grouse habitat selection and demographics. Research from traditional energy development has identified a time lag between the onset of development activities and lek loss making long term research necessary to identify impacts to sage-grouse populations. Holloran (2005) identified a 3 to 4 year time lag in natural gas fields resulting from high female nest site fidelity (adults continue to use areas regardless of development) but lower survival of nesting adult sage-grouse combined with avoidance behavior by yearlings that are displaced to the periphery. So adults return to areas regardless of development and as a result experience higher death rates (i.e., not adapting) whereas yearlings that have not yet become imprinted to a breeding or nesting site are displaced (Naugle 2010). A similar time lag was identified with the black grouse and wind energy development in Austria. The first year of operation reported no impacts to the population but by the fifth year the population was declining (Zeiler 2009). Because of the lag, it may be several years before population level impacts of wind energy development on sage-grouse are known.

One of the expected impacts from wind energy development includes direct mortalities through collisions with turbines, towers, distribution and transmission lines and vehicles (Johnson and Holloran 2010). Grouse are grouped into poor fliers (Johnson and Holloran 2010) and the highest collision probability for sage-grouse and wind turbines is expected where
structures are located between foraging and loafing habitats (USFWS 2008). However, while some collisions may occur it is unlikely that these direct mortalities would lead to population declines (USFWS 2008).

The largest impacts from wind development are expected from fragmentation that may displace sage-grouse and/or reduce survival (Johnson and Holloran 2010). Habitat fragmentation is a primary cause of population declines because sage-grouse require contiguous sagebrush (Johnson and Holloran 2010). Fragmentation occurs through actual loss of habitat that leaves remaining habitat in non-contiguous patches or functional loss from alteration that leaves the habitat patches unusable (Johnson and Holloran 2010). Studies of the fragmentation impacts from power lines found population impacts out to five miles (Johnson and Holloran 2010). Power lines can be a collision risk to sage-grouse and may increase predation risk by acting as perches and nesting sites for ravens and raptors (Johnson and Holloran 2010). Current estimates of line length for proposed long distance transmission lines originating in Wyoming range from 180 miles for a line to Colorado, to 1,100 miles to send power to California (WIA 2011). These lines are in addition to the collector lines from individual wind turbines and short distance distribution lines to nearby towns.

The road networks across the landscape are also a source of fragmentation. Impacts from roads include direct habitat loss, direct mortality, spread of invasive plant species, increased access for predators, and noise (USFWS 2008). Currently less than 5% of the sagebrush habitat for sage-grouse is further than 2.5 km from a road (Connelly unpublished). Roads have been found to cause declines in male lek attendance within 1.9 miles of main haul roads with just one vehicle a day in oil and gas development (Johnson and Holloran 2010). A recent study of the land area impacts of current wind development found that roads account for the highest percent
of area impacted (Denholm et al. 2009). This suggests that roads within wind energy development may have similar impacts as those identified in oil and gas development. The largest difference is that gas wells require daily road travel whereas wind turbines are monitored by computer; therefore, they should require less vehicle visits (Johnson and Holloran 2010).

Scientists speculate that turbine towers will decrease habitat suitability (USFWS 2008) and displace sage-grouse from former areas (USFWS 2008). Sage-grouse will avoid areas, including otherwise suitable habitat, because of raptors perching on transmission and other structures, emissions, or other human presence such as vehicle traffic, and noise (Johnson and Holloran 2010).

Given the potential impacts of wind energy development to sage-grouse populations, specific mitigation measures have been suggested, including: slowing the cut in speed of turbines during certain times (the wind speed that turbines begin turning and start generating electricity), buffers around important habitat, and proper siting measures to avoid impacts. Johnson and Holloran (2010) listed potential mitigation measures suggested by various entities including: buffering leks, disallowing construction within four miles of a lek during breeding, restoring temporarily disturbed areas, controlling and managing for invasive species, preventing fire, limiting road development, using un-guyed meteorological towers, and enhancing habitat. However, the efficacy of mitigation measures is unknown. Holloran (2005) and Walker et al. (2007) document the ineffectiveness of implemented mitigation measures in natural gas fields in Wyoming. Avoiding energy developments in sage-grouse habitats is currently the most effective known mitigation measure (Matt Holloran, WWC, Laramie, WY, personal communication).
2.3 Wind Development

Much of the wind energy development completed to date in the United States can be traced to market and regulatory incentives including Renewable Portfolio Standards (RPS) and the Production Tax Credit. As of 2010, global installed wind capacity had reached 196,203 MW with the United States second in installed capacity with 40,180 MW (WWEA 2010). From 1999-2009, 61% of wind power capacity built in the US was located in states with RPS – policies that require a percentage of energy to be generated from renewable resources (Wiser and Bolinger 2010). Currently, 29 States and the District of Columbia have a RPS and another 7 states have renewable portfolio goals (FERC 2011). In the west, only Wyoming and Idaho lack RPS or portfolio goals. Although Wyoming lacks a RPS, the state is expected to play a large role in renewable energy production because of its strong wind resource and lack of in-state demand.

The Production Tax Credit (PTC) is a powerful subsidy that essentially reduces the price of wind-generated electricity (DOE 2008) by providing renewable energy developers a $21 dollar/MWh inflation adjusted tax credit for the first 10 years of generating power. This short term incentive (typically available for two years or less at a time) has created uncertainty in the wind market resulting in boom and bust development. The power of the PTC can be seen in three pronounced lulls in wind development in the years 2000, 2002 and 2004 (Wiser 2008) all due to temporary lapses in the PTC. More recently, the American Recovery and Reinvestment Act of 2009 extended the PTC through 2012 and added an Investment tax credit or 30% cash grant (AWEA 2010) effectively maintaining growth in the wind industry despite the financial crisis.

Clearly, the current drivers of wind development are well known, and there is certainly no question the United States has wind resource potential with estimates projecting more than

\[ \text{Section 1603 Investment Tax Credit} \]
8,000 GW of economically recoverable land based wind resource (DOE 2008). However, there is uncertainty regarding where and at what level wind energy development will occur. In 2010 the wind industry experienced lower capacity additions due to low wholesale electricity prices, low demand for new electricity and low natural gas prices (Wiser and Bollinger 2011). Moreover, the constraints on existing transmission and lack of new transmission have been cited as the greatest barrier to rapid development of utility scale wind energy (WREZ 2009). Finally, as I already alluded to, potential impacts to wildlife and their habitats as well as visual impacts are complicating the role of present and future wind development.

Since wind energy development is driven largely by its potential to limit GHG emissions, rather than as a substitute for diminishing fossil fuel resources (peak oil and coal is expected in 2030, peak natural gas in 2050) (Kerr, 2010) its benefits to society should outweigh its costs. To illustrate, the United States Fish and Wildlife Service (USFWS) states that climate change may be one of the greatest challenges it has ever faced in conserving fish wildlife and their habitats and “a projects contribution to one aspect of ecosystem health (air quality) should not come at the expense of other aspects of the ecosystem” (USFWS 2011, p. 3).

Although wind energy is considered for its lower environmental impacts due to lower GHG emissions it shares some similarities with traditional fossil fuel development. For one, the area impacted by wind development is similar to the area impacted by the production of a natural gas, geothermal and oil, where 3-5% of area is impacted by structures and clearing of area and the other 95-97% of the areas impact comes from fragmenting habitat, species avoidance and direct mortality (McDonald et al., 2009). Meeting just 20% (305 GW) of U.S. electricity demand with wind energy would require approximately 50,000 square kilometers of land area (DOE 2008). This would require the equivalent of 152,500 turbines at 2 MW each placed across
the landscape. But the benefits may outweigh the costs if wind energy developments are properly sited. One major difference between wind energy development and traditional energy development (i.e., oil, gas and coal) is that external effects (land use) are largely local versus the widespread effects of fossil fuel generation (Cropper 2010). Wind energy is both generated and produced in a local area creating impacts that are, for the most part, felt by local populations both human and wildlife. One caveat is the transmission lines shared by both wind and traditional energy development, which impact all communities along its route. In contrast, the production and generation of fossil fuels creates a global externality with the emissions sent into the atmosphere in addition to local impacts.

2.3.1 Wind Siting

There are many aspects to developing a wind farm that can affect overall costs of construction and performance (Mark Griswold, pers. comm.). A developer searching for a site faces constraints related to: land, environmental, cultural, political, wind resource, available markets, and engineering/constructability. To extract the most out of the wind and avoid influence from surrounding terrain or structures, turbines must be spaced a certain distance from one another, as well as setback distances from road and other structures. Currently there have been several large-scale efforts to provide guidance (i.e., National Wind Coordinating Council, USFWS) in the siting of wind energy development to minimize impacts to wildlife and sensitive landscapes. The USFWS created Voluntary Guidelines for land based wind to assist in avoiding and minimizing impacts to wildlife and their habitats (USFWS 2011). The guidelines provide an iterative decision making process based on science and expected impacts to help developers make siting, construction and operational decisions.
The Department of Interior Bureau of Land Management (BLM) which manages 245 million acres of surface land throughout the west released a Programmatic Environmental Impact Statement (PEIS) as a provision of the National Environmental Policy Act that evaluated wind energy’s potential impacts on public lands. The result of the PEIS and a Biological Assessment (BA) was to implement a Wind Energy Development Program that establishes best management practices to guide wind development. In addition, as part of the PEIS and as directed by Section 368 of the Energy Policy Act, the BLM along with other government entities designated energy corridors on public lands in 11 western states with the preferred routes for pipelines and transmission with minimal potential harmful impacts to the environment, wildlife and their habitat. They also identify certain projects as “fast track projects” to facilitate “environmentally responsible development on public lands.” Projects labeled “fast track” receive expedited processing and are permitted easier in part because of low environmental impacts. Additionally, a map of Wind Energy Potential on BLM lands with minimal constraints was created for Wyoming that removed from development sage-grouse core areas, historic trails, wilderness study areas, no surface occupancy areas and visual resource management areas.

At the state level, Wyoming has developed a Wind Energy Development-Environmental Conflicts map (see appendix Figure 8) indicating areas with wind classes 4 and greater that have minimal environmental conflicts (WGFD 2010). This map takes into consideration Wyoming’s protected lands as well as crucial habitat and range for many of Wyoming’s wildlife species, including the greater sage-grouse. These efforts provide guidance as to where wildlife/environmental conflicts exist but do not consider the suite of economic variables (only wind class was considered) crucial to wind energy developers.
There are currently two publically available datasets that have identified economically feasible renewable resource areas within the western interconnect: the Western Renewable Energy Zones (WREZ 2009), and the Western Wind Integration Study (WWIS 2010). The Western Interconnection is one of three separate transmission systems in the United States. The western states, including Wyoming fall into the Western Interconnection. The Western Governors Association, along with numerous stakeholder groups, is developing Western Renewable Energy Zones (WREZ) to facilitate development of renewable energy development and transmission expansion (WREZ 2009). WREZ identify the lowest delivered cost and lowest environmental impact areas for renewable resource development. Currently, the Western Governors Association has identified Qualified Resource Areas (QRA), which include the best resources in each state. Each QRA has a minimum of 1, 500 MW of power within 100 miles of the center, enough to support the construction of a 500 kV high voltage transmission line. While this study helps to pinpoint large areas of economically feasible resource potential (see inset fig 3) it does not indicate where wind development is most likely to be located given the full suite of economic incentives facing private wind developers. Additionally, many wildlife and environmental exclusions, including the governor’s sage-grouse core area, were implemented after QRAs were developed; therefore the map cannot be used to analyze sage-grouse conflict.

The Western Wind Integration Study (WWIS 2010) was created to examine the operation impact of up to 35% energy penetration from wind and aims to understand the costs and operating impacts due to winds variability and uncertainty. The study included the entire western interconnect at 4-km$^2$ intervals, with each grid cell supporting 30MW of wind power. Selection criteria was based on geographic scenarios to examine tradeoffs between local
resources with low capacity factors\textsuperscript{3} and distant wind resources with high capacity factor but requiring long distance transmission. In their local scenario AZ, NV, and CO produce most of the wind; in their “Mega Scenario,” Wyoming produces the most. While the dataset is informative to my research, their dataset only includes areas within 50 miles of existing or planned transmission or in WREZ. Their data therefore precludes many areas that are technically feasible for wind development. Excluding these areas \textit{a-priori} could bias wind siting predictions and therefore systematically misrepresent potential sage-grouse conflict.

3 Methods

3.1 Empirical Model of Wind Farm Location Decisions

Before I can assess the potential conflict between wind energy development and sage-grouse it is first necessary to identify the most likely locations for wind energy development. A wind developer’s location decision is complicated by many technical, economic, social and environmental constraints. Although some of the factors driving location decisions are unobservable in a modeling environment (e.g., site-specific environmental concerns), I assume developers are utility maximizers, and that developer utility is primarily determined by profits. Then, using the standard random utility model framework, a representative wind developer chooses among \(i\) alternative locations \((i = 1, \ldots, N)\), to maximize utility \(U_i\):

\[
\text{Max } U_i = V_i + e_i
\]

Utility is not observed directly in this approach, I only observe the attributes of alternative sites that influence representative utility \((V_i)\). Unobserved factors influencing utility of site choice are captured in the error term \((e_i)\). Given that I do not observe the random error

\textsuperscript{3} Capacity factor is used to measure the productivity of a generating facility and is calculated as: amount of energy actually produced during a given time period/ amount of energy produced if operating at nameplate capacity (Doe 2008).
term for each location, I can only model the site decision probabilistically. Following the random utility literature (see e.g., Train 2003), the probability that a wind developer chooses parcel $i$ is:

\begin{equation}
P_i = \text{Prob} \left( U_i > U_j, \forall j \neq i \right) \\
= \text{Prob} \left( V_i + e_i > V_j + e_j, \forall j \neq i \right) \\
= \text{Prob} \left( V_i - V_j > e_j - e_i, \forall j \neq i \right).
\end{equation}

Given (2), a wind developer’s site decision can be empirically modeled as a binary outcome using discrete choice modeling techniques. Discrete choice models are widely used to model this type of location decision (Train 2003). By selecting observable site attributes that economic theory suggests will influence the siting decision (i.e., influence representative utility), and by assuming $e_i$ is distributed iid extreme value, the probability in (2) can be estimated using a standard binary logit model of the following general form:

\begin{equation}
P(Y_i = 1 | \beta) = \frac{1}{1 + e^{X_i \beta}},
\end{equation}

where $Y_i$ is a dichotomous outcome variable equal to 1 if a wind turbine is observed on parcel $i$ and zero otherwise, $X$ is an $N \times k$ matrix of explanatory variables believed to influence the profit of developing a wind farm on parcel $i$, and $\beta$ is a $k \times 1$ vector of parameters to be estimated. Rather than choosing parameters that minimize the sum of squared errors as in linear regression, logistic regression chooses parameters that maximize the likelihood of observing the sample values. Thus the resulting estimators are those that agree most closely with the observed data (Hosmer and Lemeshow 2000).

3.1.1 Data

The variables I use to specify the logistic model (3) are derived from spatial data using a GIS. I first use ArcMap 10 fishnet tool (ESRI 2010) to partition the state of Wyoming into a
uniform grid at a spatial scale of 3.2 km\(^2\) (800 acres) for a total of 81,500 grid cells. The grid creates the spatial unit of analysis for my regression model. This scale represents an improvement from highly aggregated models, such as the WREZ model (WREZ 2009), and allows me to observe tradeoffs between potential locations for a representative wind farm. In addition, the scale is similar to the scale used in the recently completed Western Wind Integration Study (WWIS 2010). Within a grid cell, hereafter referred to as parcel, I assume characteristics are homogeneous with heterogeneity expected across parcels. Consistent with the empirical motivation above, I include variables expected to influence wind farm profitability: wind resource, land ownership, distance to transmission and roads, elevation, and slope.

Accurate wind resource measurements are very important to the profitability of a wind project because the amount of energy available in the wind increases with the cube of the wind speed (EWEA 2000). Thus, a 10% reduction in expected wind speeds causes a 30% fall in expected energy yield (WWEA 2011). I measure wind resource using wind power class\(^4\) data extrapolated to 50m hub height originally created by National Renewable Energy Lab (NREL) and obtained from Wyoming Geolibrary (WyGISC 2011). Wind power classes (WPC) range from 1-7 (1 = poor, 7 = excellent) with WPC > 2 considered feasible for utility scale wind development – class 3 is equivalent to wind speeds of at least 6.4 m/s (14.3 mph). Since the NREL wind resource dataset was first created, wind turbine technology has reached 80m hub heights. Wind speeds generally increase with turbine height; as a result there is potential for wind speeds at 80m to be higher than those measured at 50m (DOE 2008). Experts at NREL, however, indicate that for Wyoming there are minimal differences between wind output at 50m

\(^4\) Simulated and validated meteorological wind data of average annual wind speed at 10m extrapolated to 50m height.
and 80m (Donna Heimiller, NREL, Golden, CO, pers. comm.); thus, the 50m wind data should accurately capture the relative tradeoff in wind potential across parcels.

Access to transmission is as important as good wind resource for wind project development (Windustry 2011). Developers face a tradeoff between remote high quality wind resources that lack transmission access, and lower quality resources closer to demand loads and existing transmission. Acquiring accurate transmission data, however, is difficult and expensive as detailed data is not publically available. In lieu of an actual vector layer of digitized transmission lines, I use a derivative product created by Wyoming Geographical Information Sciences Center (Lanning, 2010). This layer is essentially a distance, in meters, from the centroid of each parcel to the nearest transmission line above 115 kV. In addition, since most transmission in Wyoming is at or near capacity, much of the anticipated wind development will require new transmission. There are six proposed interstate transmission projects currently under development in Wyoming with over 15,000 MW of capacity (WIA 2011). Therefore, I also collect data on distance to all proposed transmission lines. Since the proposed transmission was not in place when the currently observed wind farms were located, proposed transmission cannot help explain the site decisions used in the logit model. I, instead, use the distance to proposed transmission to inform the build-out scenario simulations (see Section 4).

Wind farms can be placed on state, private, or federally managed lands. Data on existing wind farms suggest that developers prefer state and private lands due to less strict regulations. On non-federal lands, the main legal constraints on wind development are in accordance with the Bald and Golden Eagle Protection Act, Migratory Bird Treaty Act, and the Endangered Species Act (NRC 2007). Federal lands, however, are also governed by the National Environmental Policy Act (NEPA), which requires environmental review of all actions and an Environmental
Impact Statement when there are potentially significant environmental effects (NRC 2007). These additional federal requirements add time and money to wind development projects.

Locally, the Wyoming sage-grouse core area policies as interpreted for wind energy development are upheld on both federal and state lands, but are only applied to private lands when a wind farm project is required to seek a permit from the DEQ Industrial Siting Council. This occurs when a project's cost is greater than $178.3 million or contains more than 30 wind turbines (W.S. 18-5-503). When projects are not subject to the Industrial siting they are still required to submit a detailed summary of any “significant adverse environmental, social or economic effects ... together with any preliminary plan developed to alleviate any of the adverse effects” (W.S. 18-5-503). I derive land ownership categories (federal, state, and private) from the Wyoming surface ownership data layer (Wyoming GeoLibrary, 2011) to capture potential tradeoffs of siting wind farms on different land ownership types. Lands that were not attributed to the three above categories were removed from the dataset (e.g., water and Department of Defense land).

Along with wind resource and access to transmission, an economically viable wind farm must be technically and physically accessible. Both distance to roads and complexity of terrain influence the capital cost of a project (WWEA 2011). I include distance to the nearest federal or state highway to proxy for accessibility and transportation issues. Road data was obtained from the Wyoming Geolibrary. I also use 90m digital elevation data (DEM) to determine the slope and elevation of each parcel. Slope and elevation proxy for terrain characteristics that can increase wind farm development costs (DOE 2008).

The data on the explanatory variables vary in spatial scale. Before applying the discrete choice model described in (3), I first summarize explanatory variables so that each parcel has one
value for each variable. I perform sensitivity analysis to identify the statistic that most accurately
captures the variation within a parcel. Based on sensitivity results, I use the mean (i.e., area
weighted average within each parcel) to represent wind class, slope, and elevation, and majority
(i.e., category with the largest share of each parcel) to summarize landownership. For each
parcel, I assign the dependent variable a value of one if at least one wind turbine is observed in a
parcel and zero otherwise. The wind turbine dataset is a combination of two sources, with 776
turbines identified by O’Donnell (2010) and three additional farms from Federal Aviation
Administration data (FAA 2010). In total, the dataset contains 24 wind farms with 956 turbines.

Finally, before estimating the logit model I remove all parcels that have zero probability
of being developed (i.e., are technically or legally infeasible). Early in the development stages
developers will make an assessment of known environmental and land use constraints that
impede where they can place wind turbines and associated infrastructure. Excluding infeasible
areas is consistent since, in logistic regression, a probability for an alternative is never exactly
zero; thus if an alternative has no chance of being selected it should be removed from the choice
set or it will bias parameter estimates (Train 2003).

Where appropriate I followed the decision criteria of the DOE 20% by 2030 study (DOE
2008) to determine excluded areas; however, I omitted some DOE criteria because they were too
coarse for the scale of my study. Specifically, I excluded areas with the following
characteristics: incompatible land uses (e.g., municipalities and airports), incompatible land
cover (e.g., water), regulations/rules forbidding development (e.g., state/federal parks and
wildlife management areas), and technical infeasibility (e.g., excessive slope) (see appendix for
full list of exclusion criteria). I also exclude all parcels with average wind classes 1 and 2, which
are considered by NREL to be uneconomical for utility scale wind turbines. I did, however,
retain two wind farms that overlapped with exclusion areas (BLM wilderness habitat management) – the Foot Creek Rim and the Casper Wind Farm – to maintain sufficient dependent variable observations. The excluded area encompassed 51,621 parcels, approximately 167,122 km\(^2\). The resulting final dataset includes 33,379 parcels (Fig. 2) with 140 parcels containing at least one wind turbine. As expected the feasible area contains substantial variation in the value of explanatory variables – both across parcels (Table 1), and between parcels with and without wind turbines (Table 2).

Figure 2. Map of feasible area (after exclusions) for the wind farm site decision model.
Table 1. Descriptive Statistics\(^a\) of Continuous Explanatory Variables.

<table>
<thead>
<tr>
<th>Variable(^b)</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmean</td>
<td>3.79</td>
<td>1.06</td>
<td>2.03</td>
<td>7</td>
</tr>
<tr>
<td>Slopemean</td>
<td>3.53</td>
<td>3.73</td>
<td>0</td>
<td>26.75</td>
</tr>
<tr>
<td>Demmean</td>
<td>1,845.06</td>
<td>393.15</td>
<td>974.34</td>
<td>3409.2</td>
</tr>
<tr>
<td>Distroads</td>
<td>8.63</td>
<td>6.68</td>
<td>0.92</td>
<td>40.14</td>
</tr>
<tr>
<td>Distrans</td>
<td>12.73</td>
<td>10.88</td>
<td>0</td>
<td>49.66</td>
</tr>
</tbody>
</table>

\(^a\) Descriptive statistics are calculated across parcels.  
\(^b\) WINDMEAN is average wind class, SLOPEMEAN is average slope measured in degrees, DEMMEAN is average elevation measured in meters. DISTROADS and DISTRANS are the distance to roads and distance to transmission measured in miles.

Table 2. Average Values of Explanatory Variables between Parcels With and Without Wind Turbines.

<table>
<thead>
<tr>
<th>Binary Response</th>
<th>Windmean</th>
<th>Disttrans</th>
<th>Distroads</th>
<th>Slope</th>
<th>Demmean (m)</th>
<th>Priv (%)</th>
<th>State (%)</th>
<th>Fed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.79</td>
<td>17.07</td>
<td>8.34</td>
<td>6.63</td>
<td>1,883.77</td>
<td>64.53%</td>
<td>4.92%</td>
<td>30.54%</td>
</tr>
<tr>
<td>1</td>
<td>4.47</td>
<td>7.42</td>
<td>6.03</td>
<td>3.18</td>
<td>1,988.55</td>
<td>89.29%</td>
<td>5.71%</td>
<td>5%</td>
</tr>
</tbody>
</table>

3.1.2 Estimation Issues

I incorporate two separate estimation issues into my modeling framework. First, there is likely to be spatial dependence between the parcel-level error terms given the spatially explicit nature of the data. Intuitively, error in estimation (i.e., error variance) for one location, due to, for example, measurement error or omitted variables, will likely be correlated with the errors for
neighboring locations. As a result the error terms in the logit model will violate the identical and independently distributed (IID) assumption causing bias in parameter estimates and predictions.

Second, the final dataset includes 33,379 parcels potentially available for wind energy development, of which only 140 contain wind turbines. Hence the dataset contains a significantly higher proportion of parcels without wind turbines then parcels with an observed wind turbine (i.e., the proportion of parcels with at least one wind turbine is 0.0042). Logit models estimated with data exhibiting rare-events (significantly higher proportion of “no events”) result in biased probability predictions – predictions systematically underestimate the probability of the rare event occurring (King and Zeng, 2001). Given that my primary interest is to predict the probability of observing a wind farm at a given location in space (i.e., site choice), I must correct for the rare events bias to apply a logit model.

I use the procedure developed by King and Zeng (2001) to correct for rare events and apply a bootstrap estimation procedure to reduce the likelihood of spatial error dependence5. Bias created by data exhibiting rare events can be corrected using a sampling procedure that increases the observed proportion of the rare outcome (i.e., the realization of \( Y=1 \)) (see King and Zeng, 2001 for details). To illustrate, King and Zeng 2001 show that when a logit model has explanatory power, the “ones” (the rare event) are statistically more informative than zeros, having both higher predicted probabilities and smaller variances. Thus, additional observations of “ones” will cause the variance of an estimate to drop more than additional observations of “zeroes”. Unfortunately, sampling techniques such as sampling on \( Y \) generally results in sample selection bias. Thus, the solution to one problem generates another. King and Zeng (2001),

\footnote{Alternatively, a nested-logit or mixed logit model could be used to correct for error dependence; however, I lack the information necessary to systematically define appropriate nests that result in IID errors across nests but correlation within.}
however, developed a rare-events procedure to correct for rare events in logit models without adding additional sample selection bias.

I apply the following rare-events bootstrap procedure to correct the logit model for rare events bias and reduce any potential bias caused by spatial error dependence:

1) Apply a case-cohort sampling procedure to select a sub-sample of the original data that contains a higher proportion of “yes events”. Specifically, I select a sample that contains all observations of existing wind farms (i.e., $Y_i = 1$) and a random sample of observations without wind farms (i.e., $Y_i = 0$). Several sample sizes were considered but yielded no differences in relative probabilities, so I used a sample size of 840 (i.e., 140 yes-events and 700 randomly sampled no-events).

2) Estimate the logit model (3) on the case-cohort sample, retaining the parameter estimates $\left(\hat{b}_k\right)$.

3) Correct the parameter estimate of the intercept term following King and Zeng (2001).

King and Zeng (2001) show that all parameter estimates except the intercept term are consistently estimated in the logit model, even with the case-cohort sampling procedure for sample selection using the method of prior correction (King and Zeng, 2001: 700):

$$\tilde{b}_0 = \hat{b}_0 - \ln \left[ \left( \frac{1 - \tau}{\tau} \right) \left( \frac{\bar{y}}{1 - \bar{y}} \right) \right],$$

where,

- $\tilde{b}_0$ is the corrected intercept estimate,
- $\hat{b}_0$ is intercept estimate from the logit model applied to the case-cohort sample,
- $\tau$ is the proportion of observations with $Y_i = 1$ in the original data, and
- $\bar{y}$ is the proportion of observations with $Y_i = 1$ in the case-cohort sample.
4) Repeat steps 1-3 by drawing new case-cohort samples \((j = 1, \ldots, J\) samples). I assume that drawing random samples greatly reduces the likelihood of observing many parcels that are spatially or temporally correlated, and therefore reduces any potential bias caused by error dependence.

3.1.3 Logit Model Results

Model Tests
I check for multicollinearity by examining variance inflation factors (VIF). VIF in the model ranges from 1 to 1.4, well below the rule of thumb of values >10 that are cause of concern. Each bootstrapped model is also significantly different from zero according to standard Wald Tests. Hosmer-Lemeshow test for over-dispersion indicate no oversdispersion for all bootstrap samples with Pearsons and Deviance statistics at or around 1. I did a correlation test on the overall bootstrap sample and found no significant correlation between explanatory variables. Lastly, I perform a t-test of the slope parameters and all were statistically different from 0 at the 1% level.

Parameter Estimates
The rare events bootstrap procedure above generates \(J\) (\(J=100\)) consistent estimates of each parameter \((\hat{b}_k, k = 1,2,\ldots,K\)) in the logit model (3). The width of the CI around the average mean parameter estimates converge at \(J=100\) bootstraps, thus drawing additional samples is unlikely to change the parameter estimates or predicted probabilities in a meaningful way. I report the parameter estimates and standard errors for the simple average across the 100 bootstraps (Table 3), which are calculated as:

\[
(5) \quad \hat{b}_k = \frac{1}{J} \sum_{j=1}^{J} \hat{b}_{kj},
\]

where \(\hat{b}_{kj}\) is the parameter estimate on the \(k^{th}\) variable in the \(j^{th}\) sample.
Table 3. Average Parameter Estimates across bootstraps.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmean</td>
<td>0.3398</td>
<td>0.00</td>
</tr>
<tr>
<td>SlopeMean</td>
<td>-0.045</td>
<td>0.046</td>
</tr>
<tr>
<td>Private</td>
<td>2.38</td>
<td>0.00</td>
</tr>
<tr>
<td>State</td>
<td>2.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Demmean</td>
<td>0.0019</td>
<td>0.00</td>
</tr>
<tr>
<td>Distrans</td>
<td>-0.000019</td>
<td>0.000002</td>
</tr>
<tr>
<td>Distroads</td>
<td>-0.000034</td>
<td>0.000001</td>
</tr>
</tbody>
</table>

*p-values

As expected wind mean (average wind class), private land and state land are positive. Likewise slope, federal lands (the intercept), distance to roads and distance to transmission are negative. Intuitively, the likelihood of observing a wind farm is greater on parcels with higher wind classes and those dominated by private or state lands. Similarly, parcels on steeper slopes and farther away from transmission and roads are less preferred for wind development.

Elevation is positive in the model, this makes sense because higher elevations exhibit higher wind classes. However, not many high elevation wind sites are being considered in Wyoming due to lack of access and transmission, among other things. Keeping elevation in the model always resulted in a smaller AIC.

Marginal Effects
Since the magnitude of parameter estimates is difficult to interpret directly in logit models (i.e., because of the non-linear logit function), I also calculate the marginal effects (ME) of relevant parameters. I calculate marginal effects as the average across all 3,379,000 bootstrapped observations to measure the effects of a change in the parameter estimates on the probability of a wind farm (Table 4). Specifically, the average marginal effect of variable \( x \) on the probability of observing at least one wind farm is given by:

\[
ME_x = \frac{1}{J} \sum_{j=1}^{J} \sum_{i=1}^{I} \left( \frac{\partial \hat{P}_{ij}}{\partial x} \right) = \frac{1}{J} \sum_{j=1}^{J} \sum_{i=1}^{I} \left[ b_{ij} \hat{P}_{ij} (1 - \hat{P}_{ij}) \right]
\]

Had I just computed the marginal effects at the mean of all explanatory variables, it is possible that none of the parcels actually exhibit those mean values.

Table 4. Average Marginal Effects Across Parcels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmean</td>
<td>0.0015</td>
</tr>
<tr>
<td>Slope mean</td>
<td>-0.00019 (0.05)*</td>
</tr>
<tr>
<td>Demmean</td>
<td>0.000008</td>
</tr>
<tr>
<td>Private</td>
<td>0.01</td>
</tr>
<tr>
<td>State</td>
<td>0.009</td>
</tr>
<tr>
<td>Distrans</td>
<td>-0.00013</td>
</tr>
<tr>
<td>Distroads</td>
<td>-0.0002</td>
</tr>
</tbody>
</table>

* Calculated P-value, all other variables are <0.001

The ME for continuous variables (windmean, slope mean, demmean, distrans, and distroads) can be interpreted as the change in the probability of observing a wind turbine in a given parcel for a one unit change in each explanatory variable, *ceteris paribus*. Thus, a one unit increase in the average windclass (recall I use WINDMEAN) increases the probability of observing a wind turbine by 0.1%. Similarly, a one degree increase in the slope of a parcel decreases the probability of observing a wind turbine 0.02%. The interpretation of ME of landownership, a categorical variable, is a bit different since it can only take on discrete values: state, private, federal. The ME shows the difference in the predicted probabilities for parcels in
one category relative to the reference category (i.e., federal land). Thus, parcels dominated by private or state land are, on average, approximately 1% more likely to have a wind turbine than federal parcels. Although these marginal effects appear small, they are significant relative to the average probabilities (see below). The average probability across all parcels of observing a wind turbine is 1.13%; thus, a 0.1% change in the probability represents a significant increase.

*Predicted Probabilities of Observing a Wind Farm*

The rare-events bootstrap procedure generates a set of 100 parameter estimates for each explanatory variable, one for each bootstrapped sample. Thus, the model results can be used to generate 3,379,000 predicted probabilities (i.e., 100 predictions for each parcel). At a minimum, there are 33,379 probabilities when averaged across bootstrapped samples:

\[
\bar{P}_i = \frac{1}{J} \sum_{j=1}^{J} P_{ij}.
\]

For simplicity, I report various average predicted probabilities across parcels to highlight the models ability to predict within sample. Overall, the predicted probabilities are small – the average probability of observing at least one wind turbine is 1.13%. These relatively small probabilities are consistent, however, with the rare-events nature of the data. They are also intuitively consistent. Wyoming contains large areas with suitable characteristics for wind development that have yet to be developed; thus, the probability of one specific parcel being developed should be relatively low. Despite the small probabilities, the model deciphers well within sample between yes- and no-events (Table 5). Parcels with observed wind turbines have, on average, predicted probabilities more than twice as large as parcels without turbines.

Table 5. Average Predicted Probability of Observing a Wind Farm Grouped by Parcels With \((Y=1)\) and Without \((Y=0)\) Existing Wind Farms.

<table>
<thead>
<tr>
<th>Turbine Present</th>
<th>Avg mean prob</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The model also predicts consistently with expectations. One way to confirm how the model performs is to compare the predicted probabilities to those areas identified as Qualified Resource Areas (QRA) as part of the WREZ initiative (WREZ 2009) (Figure 3). As mentioned previously, Qualified Resource Areas in Wyoming are based on the best wind resource areas sufficient to justify at least a 500 kV AC transmission line ~1,500 MW and within 100 miles of the geographic center of a QRA. The QRA’s shown in figure 3 are those designated prior to consideration for wildlife, so they are before core area exclusions. The new QRA maps no longer have QRA in the central portion of the state. Specifically areas in Carbon, Fremont and much of Natrona County were removed (see inset Fig 3).

<table>
<thead>
<tr>
<th></th>
<th>1.13%</th>
<th>0.03%</th>
<th>8.89%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.43%</td>
<td>0.0009%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Figure 3. Map of predicted wind development locations in comparison to Qualified Resource Areas.
As shown in figure 3, the majority of the higher probabilities are contained within QRAs. Thus, my model appears generally consistent with results from other predictions. Additionally, my predicted probabilities are highly positively correlated with existing turbines and met towers (Figure 4). Since met towers are significant investments for wind developers, their locations likely identify the areas where developers are currently concentrating development efforts.

Figure 4. Map of predicted wind development locations in comparison to existing wind turbines and met tower locations.

4 Simulating Wind Farm Build-Out Scenarios and Assessing Sage-grouse Habitat Conflicts

4.1 Wind Build-Out Scenarios

The level of wind development that will actually occur in Wyoming and across the United States is uncertain. In order to represent a range of possible future landscapes I selected five wind energy build-out scenarios that were modeled for Wyoming in the WWIS 2010. The levels range from a low of 1,650 MW to a high of 13,770 MW, including: 1,650 MW, 3,390
MW, 4,020 MW, 8,790 MW, and 13,770 MW. In addition, I also model a build-out of 12,000 MW as utilized in the Wyoming Wind Collector System and Integration Study (ICF International 2011). As of January 2011 Wyoming’s installed capacity had reached 1,412 MW (AWEA 2011); thus, the 1,650 MW scenario is essentially a doubling of existing wind energy capacity. This level of development will be met with the Choke Cherry and Sierra Madre wind project alone, a 2,500 MW wind development planned for Carbon County (Power Company of Wyoming 2011). The middle build-out scenario (8,790 MW), is realistic in the short term as there are currently 7,869.5 MW of wind energy projects in the transmission queue in Wyoming (AWEA 2011). The high end build-out scenarios (12,000-13,770 MW) represent longer term possibilities based on current capacity levels of proposed transmission in Wyoming (WIA 2011), build-out predictions by the DOE (2008), and levels of wind energy development already observed in states such as Texas (10,135 MW) (AWEA 2011b).

Following the methods developed in the (WWIS 2010), I assume each parcel can fit 10, 3 MW Vestas V90 turbines with a rotor diameter of 90m. Each parcel available for wind development is therefore a “representative” wind farm that supports 30MW of nameplate capacity. A wind developer’s minimum desired wind farm size is at least 30 MW (Power Naturally 2005).

There are, for practical purposes, an infinite number of different ways a new wind farm could appear on the landscape and still be consistent with the probabilities predicted in my logit model. In order to simulate the most likely spatial distribution of new wind farms, I define a

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6 The WWIS uses a spacing of 10 Rotor Diameters between strings (that is 900m) and 4 rotor diameters between turbines (that is 360m). They also buffer the edges because the next grid cell could also contain turbines. We used \( \frac{1}{2} \) the spacing required between strings for the edges. So the whole grid is buffered by 180 meters on all sides leaving a usable space of 1620 \( \times \) 1620. On the diagonal we calculate 12 turbines and 8 turbines on the horizontally.

7 In the small build-out scenario (1,650 MW) there are \( 4.6561 \times 10^{155} \) possible unique ways the wind farms could be distributed across the 33,379 parcels.
build out scenario (e.g., amount of new MWs) and translate it into a number of new wind farms (i.e., parcels with 30 MWs). Wind farms are assigned to parcels according to each parcel’s average predicted probabilities – the parcels with the highest probabilities are assumed to be developed first. The highest probability parcels are selected in descending order until the build-out level is reached. This approach results in the expected wind farm distribution given the predicted probabilities, but ignores the potential variability in alternative locations (particularly given the relatively small difference in predicted probabilities). Unfortunately, computational constraints limit my ability to run enough simulations to arrive at the frequency distributions of all possible landscape combinations, thus I cannot calculate confidence intervals for the predicted wind farm locations.

4.2 Measures to Capture Tradeoff between Wind Energy Development and Sage-grouse

4.2.1 Profit

In addition to the predicted probabilities, which are in theory correlated with profitability, I calculate a coarse measure of profit that captures additional unique characteristics of each parcel. Profit is calculated as the difference between total revenue and total annualized cost. I calculate total revenue by multiplying the total MWh’s generated in a year by a price of $50/MWh (DOE 2010 wind technologies report weighted average price of wind energy $45/MWh).

Total energy generated in a year is calculated by adjusting nameplate capacity with the capacity factor\(^8\) (CF) specific to the wind class observed in the parcel (Table 6). The CF estimates were developed by the DOE (2008) and used in Kieskecker et al. (2010). Thus, total energy generated per parcel per year is given by:

\[
\text{Energy (MWh/parcel/yr)} = 3 \text{ MW/turbine} \times 8,760 \text{ hours/year} \times 10 \text{ turbines/parcel} \times \text{CF}
\]

\^ Capacity factor is used to measure the productivity of a generating facility and is calculated as: amount of energy actually produced during a given time period/ amount of energy produced if operating at nameplate capacity (Doe 2008). For example, each 30MW parcel operating at 100% CF would produce 262,800 MWh/year.
Table 6. Capacity Factors by Wind Class used to Estimate Total Wind Farm Revenue.

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Capacity Factor (%)</th>
<th>MWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>38</td>
<td>99,864</td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>113,004</td>
</tr>
<tr>
<td>5</td>
<td>46</td>
<td>120,888</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
<td>128,772</td>
</tr>
<tr>
<td>7</td>
<td>53</td>
<td>139,284</td>
</tr>
</tbody>
</table>

The main elements impacting the cost of wind power can be broken down into capital costs and variable costs (Blanco, 2008). Capital costs can be as much as 80% of the total cost of a project over its entire life. Electricity produced, and hence variable costs, is a function of the local wind resource, the technical specifications of the wind turbine, site characteristics and reductions based on capacity factor and line losses (Blanco, 2008). I calculate total cost using the following assumptions: a capital cost of $2,000,000/MW (WWIS 2009), transmission costs for 230 kV feeder lines of $600,000 per mile (Matt Grant, pers. Comm.)\(^9\), and a terrain slope penalty that increases \(\frac{1}{4}\) of the capital cost by 2.5% per degree of terrain slope (DOE 2008). I use a fixed cost for O&M of $50,000/MW (E3 2010). Finally I annualize costs by assuming a wind farm useful life of 25 years (EWEA 2009) and a discount rate of 4%.

4.2.2 Sage-Grouse Impacts

Counts of male sage-grouse on leks are the primary method used by scientists to estimate abundance, and are used as indicators of population level habitat selection because of the close proximity in which hens nest to the breeding lek (Doherty 2008). In addition, long term lek

---

\(^9\) Cost per mile of transmission depends on capacity required. The literature supports estimates based on $/KW or $/MW/mile. Wiser (2009) examined recent projects average transmission cost and found $500/KW, whereas the Wyoming Collector study assumes $1 million mile for a 230kV line (not including substations/transformers). My cost estimate is consistent with the size lines built by existing wind farms according to Industrial siting applications I select the cost for a 230kV line.
count data is available across the species range (Connelly et al 2000). Most land management strategies for protecting sage-grouse include various stipulations about the distance from a lek that anthropogenic activities can take place, as well as timing restrictions and mitigation measures near leks. For example, the BLM stipulates no surface occupancy during the breeding season within a 0.4 km (0.25 mile) radius around leks and noise and other development activities are often limited seasonally within 0.8-3.2 km’s (0.5-2 miles) of leks (USFWS 2008).

As reviewed earlier, researchers have identified negative impacts to sage-grouse at various distances from traditional energy development. Walker (2007) reported negative impacts on lek attendance out to 3.2 km (2 miles) of coal bed methane development. In natural gas fields Holloran (2005) observed declines in male lek attendance extending to 6.2 km (3.9 miles) from natural gas wells, with the most severe impacts within 5 km of drilling activities and 3km of producing wells. To protect sage-grouse populations, Connelly et al. (2000) suggested different buffers from leks based on whether the sage-grouse population is migratory or non-migratory and whether the surrounding sagebrush is uniformly or non-uniformly distributed. They suggest a 3.2 km buffer for non-migratory birds in uniform habitat and 4.19 km (2.6 mile) for non-migratory birds when habitat is non-uniform. Connelly et al. (2000) also suggests the lek can be treated as the focal point of year round management for non-migratory populations; however, they recommend a buffer of 18 km (11.2 miles) for migratory populations. Alternatively, the USFWS recommends an 8.05 km (5 mile) buffer from leks to wind farms in prairie grouse habitat (USFWS 2008). Other research has shown that the 0.25 km and 3.2 km buffer around active sage-grouse leks during breeding season is inadequate to prevent adverse impacts to sage-grouse at a local level (USFWS 2008). The existing research demonstrates that there is significant uncertainty regarding the appropriate buffer size to eliminate energy development
impacts on sage-grouse. Nonetheless, the buffer approach remains a significant component of ongoing policy development (a buffer of 6.4-8.4 km is used in core breeding area identification) and is therefore relevant concept for my analysis.

Given the literature on disturbance, I identify parcels within a 3.2 km buffer and 6.4 km buffer from each lek location. The 6.4 km (4 mile) buffer is used because female nest selection occurs in relation to the breeding lek, with 79% of nests located within a 6.4 km radius of leks (Doherty 2008) - within that distance is defined as breeding habitat (USFWS 2008). The 6.4 km buffer is therefore likely to identify potential population impacts. For each build-out scenario I calculate the number of leks and number of males (i.e., to capture differences in lek quality) expected to be impacted. A lek is assumed to be impacted if a wind farm is placed within the buffer distance. These impacts may include but are not limited to: displacement to lower quality habitat, lower nest success, direct bird mortality etc. Wyoming State-wide lek data through 2010 was acquired through the Wyoming Game and Fish Department (WGFD) FTP site. I use the WGFD definition of an occupied lek (a lek that has been active at least one strutting season in the last 10 years) and, determine peak male count as the largest count of males observed between the years 2007-2010. Wyoming currently has 1,899 leks with total peak male count of 56,006 (Table 7). I use the total peak male count of 56,006 to determine proportion of the population impacted. Since I retain all occupied leks as defined by the WYGFD; 461 of the 1,899 occupied leks have 0 males from 2007-2010. Therefore it is possible that some lek conflicts that are identified in my analysis may currently have no strutting males within the last three years-this would however be captured in the total number of peak males.
Table 7. Characteristics of Wyoming Game and Fish Sage-grouse Lek Data in Wyoming through 2010.

<table>
<thead>
<tr>
<th>Wyoming Lek Data Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Leks</td>
<td>1,899</td>
</tr>
<tr>
<td>Largest Lek</td>
<td>292 males</td>
</tr>
<tr>
<td>Avg. Lek size</td>
<td>29.5 males (s.d. 37.33)</td>
</tr>
<tr>
<td>Total Peak Males</td>
<td>56,006</td>
</tr>
</tbody>
</table>

4.2.3 Method to Assess Tradeoffs between Wind Development and Sage-grouse.

I assess the level of conflict between wind development and sage-grouse populations using two scenarios. First, I use the lek buffers discussed above to evaluate the expected impacts to sage-grouse populations by the different wind build-out levels assuming no sage-grouse conservation policies. Thus, for each build-out level, I first identify the parcels most likely to be developed given the probabilities predicted in the logit model. Then, for each parcel selected, I determine expected MWh produced and profits, and the number of sage-grouse leks potentially impacted. These predictions provide a baseline of expected wind energy production in the absence of any sage-grouse conservation policies (i.e., unrestricted development).

Second, using the same selection criteria described for wind build out in the unrestricted development model, I implement Wyoming’s sage-grouse core area conservation strategy. The core area strategy was developed by the Wyoming Governors Sage-grouse Implementation team following methods developed in Doherty (2008) to identify priority landscapes based on high-abundance population areas or “core areas.” Using this approach Doherty found 75% of the breeding population in the eastern portion of its range is protected within 30% of the area. The
final designation of core areas in Wyoming (Core Breeding areas Version 3; Figure 5) were negotiated and reflect some removal of actual core breeding areas as first developed to reflect current/planned land uses in certain areas. The core area represents habitats where restrictions apply to several activities to the extent the state has regulatory authority. Currently Wyoming’s core area policy (Executive order 2011-5) restricts wind energy development within core areas.

To simulate the core area policy, I remove all core area parcels such that they cannot be chosen in any build-out scenario. All but three Wyoming Counties (Goshen, Platte and Laramie) include some core area (Figure 5). The counties with the highest potential conflict between wind resources class three and greater and sage-grouse core areas include: Fremont, Natrona, Albany, Carbon, and to a lesser extent, Sweetwater and Converse counties. After removing all parcels that are within the core (10,416), the final dataset contains 22,823 parcels available for wind development. Then, for each build-out scenario, I select parcels for wind development and determine MWh, profits and leks impacted using the same procedure described above. I can then compare the build-out results between the unrestricted and core-area scenarios to determine the effect of the core area policy on wind development and sage-grouse.
Figure 5. Version 3 map of Wyoming executive order protecting sage-grouse core breeding areas.

I use an extension of Doherty (2008) for assessing tradeoffs where he overlaps high biological value core areas with wind classes 4 and greater to frame the development risk to sage-grouse populations (i.e., identifying areas of high energy high sage-grouse conflict). I use our econometric results to identify the most likely locations for wind development within the state, versus relying on wind class maps alone to determine conflict areas.

4.3 Results and Policy Implications

I ran unrestricted build-out scenarios on current and current plus proposed transmission separately. The difference between the two datasets is that current only includes the currently available transmission and current plus proposed includes the current lines and all proposed
transmission lines. Most development, regardless of transmission scenario, was concentrated in the south central portion of the State including: Albany, Carbon, Laramie, Natrona and either Fremont or Sweetwater (negligible development) counties depending on the scenario (Figure 6).
Figure 6. Various build-out levels for the current plus proposed transmission: a. 1,650 MW, b. 4,020 MW, c. 8,790 MW, and d. 13,770 MW.

For the large build-out (13,770 MW), the average characteristics of parcel chosen were: wind class six, transmission length of three miles, elevation of 2,348 meters, slope of 3.6 degrees and private land ownership. Although many parcels were the same between the two transmission models (407 of the 459 parcels in the large build-out), the models do show some variation in parcels selected for development under alternative transmission assumptions. In addition, more annual profits and energy are generated in every build-out scenario with the current plus proposed relative to the current transmission (Table 8). Hereafter, I focus on the results for current plus proposed transmission, since some new transmission will be required to accommodate all but the smallest build-out scenarios, and refer only to the current transmission as a relative comparison.
Table 8. Wind Energy (MWh) and Profits for Alternative Build-out Scenarios given Current and All Transmission*a

<table>
<thead>
<tr>
<th>Build-Out Level (MW)</th>
<th>Current Transmission</th>
<th>All Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWh</td>
<td>Profit</td>
</tr>
<tr>
<td>1,650</td>
<td>7,229,628</td>
<td>$60,702,631</td>
</tr>
<tr>
<td>3,390</td>
<td>14,919,156</td>
<td>$124,970,514</td>
</tr>
<tr>
<td>4,020</td>
<td>17,678,556</td>
<td>$146,288,015</td>
</tr>
<tr>
<td>8,790</td>
<td>38,552,760</td>
<td>$307,462,035</td>
</tr>
<tr>
<td>12,000</td>
<td>52,378,668</td>
<td>$401,146,682</td>
</tr>
<tr>
<td>13,770</td>
<td>60,073,452</td>
<td>$457,577,080</td>
</tr>
</tbody>
</table>

*a Current transmission refers to the model results assuming that only the current electrical transmission lines are available; All transmission includes all current transmission plus assumes that all proposed transmission lines are installed.

As expected, sage-grouse lek impacts vary by build-out scenario (Table 9). A parcel for development is assumed to impact a sage-grouse lek if it is within the 3.2 km buffer or the 6.4 km buffer. Clearly the measured number of lek impacts will be greater at the 6.4 km buffer distance than at 3.2 km because more leks will fall into the buffer zone. As alluded to previously distance impacts at a 3.2km buffer have been well documented in Holloran 2005. My discussion, however, will largely focus on the lek impacts observed with the 6.4km distance (buffer) because I did not want to make the mistake of having the impact be at a larger scale than my discussion. The results of the 3.2 km buffer are reported in the appendix (Table 14).

With the smallest build-out scenario (1,650 MW) and unrestricted development (i.e., no core-area restrictions), my results suggest that there is little conflict between wind development and sage-grouse leks. This implies that 100% of the best parcels for development (i.e., the 55 highest probability parcels selected in this scenario) are not located near leks. This small build-out scenario, however, is likely to be met immediately with the upcoming Choke Cherry and Sierra Madre wind project and much larger development levels are expected for Wyoming in the future.
Table 9. Impact of Wind Development on Sage-Grouse for Alternative Build-Out Levels Assuming No Sage-grouse Conservation Policies at 6.4km Buffer

<table>
<thead>
<tr>
<th>Build-Out Level (MW)</th>
<th>Impacts with Current Transmission&lt;sup&gt;a,b&lt;/sup&gt;</th>
<th>Impacts with All Transmission&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leks Males</td>
<td>Leks Males</td>
</tr>
<tr>
<td>1,650</td>
<td>0     0</td>
<td>3   29</td>
</tr>
<tr>
<td>3,390</td>
<td>1     1</td>
<td>5   67</td>
</tr>
<tr>
<td>4,020</td>
<td>1     1</td>
<td>8   169</td>
</tr>
<tr>
<td>8,790</td>
<td>25    757</td>
<td>41  1086</td>
</tr>
<tr>
<td>12,000</td>
<td>36    958</td>
<td>50  1277</td>
</tr>
<tr>
<td>13,770</td>
<td>50    1281</td>
<td>56  1346</td>
</tr>
</tbody>
</table>

<sup>a</sup> Current transmission refers to the model results assuming that only the current electrical transmission lines are available; All transmission includes all current transmission plus assumes that all proposed transmission lines are installed.

<sup>b</sup> This is the number of leks impacted at 6.4km buffer. Leks can be impacted by multiple parcels potentially resulting in a larger impact.

As the build-out level increases, so do the conflicts with sage-grouse. This is expected as the number of parcels increases to meet the number of new MW’s required. The more parcels required increases the chance that the best wind parcels are also close to leks. Impacts to sage-grouse leks increase quickly at first in the model. For example, notice the jump from eight lek impacts with a build-out of 4,020 MW (134 parcels) to 41 lek impacts with the addition of 4,770 MW for a total of 8,790 MW (293 parcels). The bulk of the 159 additional parcels selected to meet this new demand were concentrated just east of the center of Carbon county-an area containing numerous leks. However, it appears that the lek impacts become less steep at the largest build-out, suggesting diminishing returns. The parcels with the highest lek impacts were located in Carbon County with a few impacts occurring in Albany County.

The results above assumed no sage-grouse core area restrictions. Many parcels selected in the unrestricted build-out scenarios, however, were core parcels (Table 10). With the core
area policy imposed, impacts on sage-grouse are substantially reduced. For simplicity I focus on two of the larger build-out scenarios, 8,790 MW and 13,770 MW. A build-out of 8,790 MW requires 293 parcels (234,582 acres). In the unrestricted model with access to current and proposed transmission the parcels selected potentially impact 1,086 males (based on 2007-2010 maximum male lek counts) on 41 leks. Additionally, of the parcels selected in the unrestricted model, 37 are within core areas. Thus, imposing the core requires some wind farms to be relocated.

Table 10. Number of Sage-Grouse Core-Area Parcels Impacted by Unrestricted Build-Out

<table>
<thead>
<tr>
<th>Build-Out Level (MW)</th>
<th>Current Transmission(^a)</th>
<th>All Transmission(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core Parcels</td>
<td>% of build-out</td>
</tr>
<tr>
<td>1,650</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3,390</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4,020</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8,790</td>
<td>16</td>
<td>5.5%</td>
</tr>
<tr>
<td>12,000</td>
<td>40</td>
<td>10%</td>
</tr>
<tr>
<td>13,770</td>
<td>54</td>
<td>12%</td>
</tr>
</tbody>
</table>

\(^a\) Current transmission refers to the model results assuming that only the current electrical transmission lines are available; All transmission includes all current transmission plus assumes that all proposed transmission lines are installed.

With the core area restrictions in place, the same 8,790 MW modeled in the unrestricted build-out can be developed without impacting any core breeding areas (as defined by the state of Wyoming Executive order 2011-5) by relocating the wind farms to lower probability parcels. Applying the 6.4 km buffer framework, 11 leks with 220 males would still potentially be impacted (see appendix Table 15). This level of impact is, however, relatively small; 0.39% of the Wyoming population of peak males.

The affect on wind farm profits of relocating development outside core areas is also relatively small (Table 11). With a build-out of 8,790 MW, applying the core area restrictions
results in a profit loss of 0.03% ($10,031,066) for the current plus proposed transmission scenario. This profit loss appears to be related to an increase in the average distance to roads and distance to transmission, as well as a decrease in the average wind class for parcels displaced in the restricted scenario.

The average wind class decreased by 0.05 which resulted in twelve parcels that were located in class 7 wind resources in the unrestricted scenario to be sited in areas with class 6 winds with the core area restrictions (i.e., displaced to lower capacity factor sites). In addition, the distance to transmission increased by 0.28 miles and distance to roads increased by 0.16 miles. As a comparison, build-out restrictions with current transmission has a profit loss of 0.001% ($392,118). The larger loss in profits from the current plus proposed dataset is likely because of the larger number of core parcels that were impacted during the unrestricted build-out (13% vs. 5.5%; see Table 10); thus, the core restrictions displace more wind development to lower probability parcels when proposed transmission is included. For example, there are 21 more core parcels that are impacted by the unrestricted current plus proposed than with current transmission only. Restricting development in core areas given current plus proposed transmission results in a loss of 134,028 MWh, versus 21,024 MWh with current transmission only. While the effect on profits of the core policy is small relative to total profits, it still represents a substantial opportunity cost to protect sage-grouse. The current plus proposed results, for example, imply an opportunity cost of approximately $334,368.87 per lek protected or $11,583.22 per male protected.

Table 11. Effect of Core Area Restrictions on Wind Farm Profits and Sage-Grouse with a Build-Out of 8,790 MW

<table>
<thead>
<tr>
<th>Transmission¹</th>
<th>Unrestricted⁸</th>
<th>Core</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Profit</td>
<td>MWh</td>
<td>Profit</td>
</tr>
</tbody>
</table>

47
At the largest build-out level (13,770MW), the unrestricted build-out potentially impacts 1,346 males on 56 leks (Table 12). A build-out of 13,770 MW requires 459 parcels and, of these, 18% (83 parcels) in the unrestricted model are located in sage-grouse core areas (Figure 7). In this scenario the implementation of the governor’s core area management strategy results in more wind farms being displaced just outside of and along the core area boundary (Figure 7). Assuming a 6.4-km impact distance, development along the boundary will influence habitat in the core. This displacement results in a total profit loss of $18,574,676 and a loss of 239,148 MWh of energy. Applying the same 6.4 km buffer as in the unrestricted build-out there are still expected impacts to 324 males on 19 leks (0.58% of the Wyoming peak males). These results imply an opportunity cost of approximately $502,018.27 per lek protected or $18,174.83 per male protected.

Table 12. Effect of Core Area Restrictions on Wind Farm Profits and Sage-Grouse with a Build-Out of 13,770 MW

<table>
<thead>
<tr>
<th>Transmission</th>
<th>Unrestricted</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Profit</td>
<td>MWh</td>
</tr>
<tr>
<td>Current</td>
<td>$457,577,080</td>
<td>60,073,452</td>
</tr>
<tr>
<td>Current plus proposed</td>
<td>$483,865,132</td>
<td>60,220,620</td>
</tr>
</tbody>
</table>

a Current transmission refers to the model results assuming that only the current electrical transmission lines are available; All transmission includes all current transmission plus assumes that all proposed transmission lines are installed.

b Unrestricted does not include any core area wind development restrictions.
In all four 13,770 MW build-out scenarios (Unrestricted, Core, Current, and Current plus Proposed) 360 of the 459 parcels are the same no matter the transmission model. Most of this development is concentrated in the south-Central portion of the state. There is potentially an important bridge (i.e., habitat that is conducive and limited that maintains and facilitates movements between populations) from North Park, CO, north into the sage-grouse populations in central and southwest Wyoming (USFWS 2008). This bridge is not expected to be impacted based on results in figure 7; however, development predicted across a stretch of core area extending into the Medicine Bow/Hanna country (bottom center figure 7a) may present a potential barrier. Development in this region may have a larger impact than just the areas within 6.4 km buffer because of larger scale fragmentation (Matt Holloran, WWC, Laramie, WY, personal communication).

5 Conclusion

This study examines the tradeoff between wind energy development and sage-grouse conservation in Wyoming. An econometric model of wind farm location was estimated and the
results were used to predict wind farm locations for alternative wind farm build-out scenarios (1,650 MW to 13,770 MW). For each scenario, I estimate the expected wind farm profits and sage-grouse impacts (i.e., number of leks or peak males in proximity to a wind farm). Lastly, current Wyoming sage-grouse management policy restricting wind farm development in sage-grouse core areas was applied to the econometric model to assess effectiveness of the core area and to capture differences in costs and conservation threat from an unrestricted build-out scenario.

Results suggest that Wyoming can harness its vast wind resources while conserving sage-grouse. At low build-out levels there is relatively little overlap between the most likely wind development parcels (i.e., parcels with the highest predicted probability of containing a wind farm) and sage-grouse leks. Conflict increases, however, at higher build-out levels. The number of leks potentially impacted increases from 8 leks at 4,020 MW to 41 leks at 8,790 MW. They then become less steep at the largest build-out considered (13,770 MW) with 56 sage-grouse leks (2.4% of the Wyoming peak male population) potentially impacted by wind farms. These results provide indications of the spatial location and development level where threats to sage-grouse are most severe.

Impacts were largely mitigated by restricting development in sage-grouse core areas (0.58% of Wyoming’s peak male population remains potentially impacted). However, even with core area protection there may still be habitat in the core that is impacted. Wind farms on the edge of core will influence some core habitat even though they do not impact the lek itself. Nonetheless, my analysis shows that the core area restrictions largely protect Wyoming’s sage-grouse population. However, imposing the core-area development restrictions is not costless. By relocating wind farms outside of core areas (i.e., to parcels with lower probabilities of being
developed), wind farm profits are reduced by 0.03% to 4% across build-out scenarios. While these profit losses are relatively small, they imply opportunity costs of $334,369 to $502,018 per lek protected.

Though my results suggest a low opportunity cost of sage-grouse conservation, the analysis is not the result of a social optimization model. Therefore, my results do not necessarily represent the optimal amount of sage-grouse conservation and wind energy development. The current limited scientific understanding of wind farm impacts to sage-grouse restricts our ability to infer actual impacts or to quantify a value for sage-grouse. I also assume that all leks within a 3.2 km or 6.4 km buffer around wind farms would experience an impact. These buffers are consistent with existing literature on disturbance; however, few studies have been completed that examine the specific impacts to sage-grouse of wind farms. Thus, the degree of impact from placing a wind farm near a lek remains an open question. If, for example, future research indicates that wind farms have severe negative population-level impacts (e.g., from both direct impacts and interference with migration), then the opportunity cost of sage-grouse protection from wind development could be higher than my estimates.

Results of this analysis indicate that the development of Wyoming’s wind resources may not represent as large of a direct threat to sage-grouse as thought, especially in comparison with other extractive industries. Expansion of traditional energy sources is likely to play a much larger role on the future landscape than wind farms. Future oil and gas development, for example, is predicted to cause an additional 7-19% decline from 2007 lek counts by impacting 4.7 million hectares of shrub and grassland (Copeland et al. 2009). Furthermore, wind energy will require additional fossil fuels, such as natural gas, to balance wind energy’s variability. For example, for each 9,000 MW of transmission built there will be demand for up to 90,000
MMBTU/day for natural gas to “firm wind energy” [i.e., balance wind’s lower capacity factor] (Ellenbecker 2010).

The Wyoming Governor’s office has stated that the core area policy justifies being more lenient to development activities outside the core. The loss of MWh from sage-grouse core restrictions may mean that developers need more land area to produce the same amount of MWh, potentially impacting more land and species. Forcing wind energy development outside of core breeding areas could potentially influence more of the peripheral leks, which could negatively influence populations. In fragmented landscapes peripheral populations are important to maintaining genetic diversity and are important to species persistence. Many of the impacts measured in my model at the 6.4km buffer after the core area was implemented were to peripheral leks (Figure 7).

Perhaps the most interesting results in this analysis hint to the placement of proposed transmission as a potential opportunity to reduce impacts to sage-grouse while having less economic impact on wind developers (e.g., cost per mile of transmission). Transmission is a high cost component because of the low capacity factor of wind turbines and the remoteness of good wind resources. In my model, most development is located close to planned and existing transmission lines – much of which is outside of sage-grouse core area. If new transmission lines proposed turbines are located near high quality winds and outside of sage-grouse core areas it should represent an economic incentive for wind developers while protecting sage-grouse (note: this appears to be one of the Wyoming Infrastructure Authority’s objectives, see ICF 2011, WIA 2011).

6 Future research

Results of this thesis raise many questions for future research as well lessons learned to improve the existing model’s results. There are several potential improvements to the
econometric model that would further refine estimates of the tradeoffs between wind farm development and sage-grouse. Improvements in data would improve model precision. For example, wind associations (i.e., landowner cooperatives that promote wind energy on their property) have become common in WY; however, I lack data to include associations in my model. Additionally, because of the limited number of wind farms, I could not include any temporal variables (e.g., energy prices or federal policies) in my model. Once a longer time-series is available, researchers will be better able to statistically model the spatial and temporal drivers of wind farm development. The econometric model may also be improved by considering more sophisticated techniques to address spatial autocorrelation, such as a stratified sampling design (e.g., eliminating nearest neighbors) and a mixed logit estimation procedure.

Another model run could have been conducted with just proposed transmission. Neither the current nor the current plus proposed transmission model predicted much development in the south-eastern portion of the state, an area that is expected to receive substantial wind build-out (ICF 2011). I suspect a model run with just proposed transmission would shift the development to the SE portion of the state, where the bulk of the proposed transmission lines as well as Western Renewable Energy Zones are planned (WREZ 2009, WIA 2011). Development in the eastern portion of the state would represent a shift from the shrub steppe ecosystem to Wyoming’s short grass prairie ecosystems.

In addition to the econometric model, my simulation of build-out scenarios could also be refined. I allocated new wind farms to individual parcels assuming that each parcel could contain a 30 MW wind farm. This implies that a single isolated parcel could be assigned a wind farm based on the probability estimates. This scale, however, is at the low end of current nameplate capacity of a wind farm. In 2009, the average U.S. wind farm size was 91MW (Wiser
and Bolinger et al. 2009). A more sophisticated simulation procedure could account for agglomeration of parcels, thereby capturing larger developments. Such a procedure may reallocate wind farms across the landscape thereby implying different tradeoffs between wind development and sage-grouse.

Lastly, my analysis concentrates solely on the distance impacts to leks from a wind farm; however, studies have shown that sage-grouse are also negatively influenced by density effects (Holloran 2005, Walker et al. 2007). Future research accounting for the density of turbines in both an individual wind farm and the agglomeration of wind farms would produce more precise estimates of sage-grouse impacts. Second, the greatest impacts from wind development are anticipated to come from habitat fragmentation effects, which – with wind energy development – are likely to come from transmission and road infrastructure. I believe my model does incorporate the area of some of this infrastructure (e.g., I assume 30 MW per 3.24 km²) but incorporating these linear features into the modeling environment would improve results. Finally, future research should account for indirect effects of development on sage grouse, such as avoidance impacts (i.e., displacement) on habitat selection and demographics, and cumulative impacts from multiple land-use activities.
7 Literature Cited


Wiser Ryan and Bolinger Mark 2011. 2010 Wind Technologies Market Report. DOE (Department of Energy)

Wyoming Department of Environmental Quality. Wyoming Industrial Development Information and Siting Act W.S. 35-12-109

WREZ (Western Renewable Energy Zones)-Phase 1 Report. 2009. Mapping concentrated, high quality resources to meet demand in the Western Interconnection’s distant markets. June 2009


Wyoming Game and Fish 2010. Wind Energy Development-Environmental Conflicts map.


8 Appendix

8.1 Data Descriptions

Table 13. Exclusion list for Econometric Model.

<table>
<thead>
<tr>
<th>Exclusion</th>
<th>Data source</th>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind class 1, 2 Wind</td>
<td>NREL; WYGolibrary</td>
<td>100% zonal stats if &gt;50% of parcel; exclude</td>
</tr>
<tr>
<td>Water</td>
<td>NLCD</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>NLCD</td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>NLCD</td>
<td></td>
</tr>
<tr>
<td>wetland</td>
<td>NLCD</td>
<td></td>
</tr>
<tr>
<td>Airports</td>
<td>ESRI file North American Airports</td>
<td>100%</td>
</tr>
<tr>
<td>Municipal</td>
<td>WYGisc municipal boundaries</td>
<td>100%</td>
</tr>
<tr>
<td>&gt; 20% slope</td>
<td>90m dem</td>
<td>if &gt;50% parcel then exclude</td>
</tr>
<tr>
<td>Wild Scenic Rivers</td>
<td>from Rivers.gov</td>
<td>3km buffer, 100%</td>
</tr>
<tr>
<td>Wy state parks</td>
<td>managed layer*</td>
<td>100%</td>
</tr>
<tr>
<td>NPS</td>
<td>managed layer*</td>
<td>100%</td>
</tr>
<tr>
<td>Wildlife habitat mgt areas</td>
<td>managed layer*</td>
<td>100%</td>
</tr>
<tr>
<td>VRM I</td>
<td>VRM 1 and 2 from Larry BLM</td>
<td>100%</td>
</tr>
<tr>
<td>FWS WY</td>
<td>fws approved file (clipped from USFWS US file)</td>
<td>100%</td>
</tr>
<tr>
<td>NRA</td>
<td>managed layer*</td>
<td>100%</td>
</tr>
<tr>
<td>Wilderness study areas</td>
<td>blm file wywsa</td>
<td>100%</td>
</tr>
<tr>
<td>Wilderness Boundaries</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>WYACEC (areas of critical env concern)</td>
<td>excel file of ACEC from Ken</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most protected layers were obtained from the Wyoming Geolibrary Managed Layer.

However this layer did include several land use types that I removed including USFS, Federal Tribal Trust Land and all unknown land types. I received BLM Visual Resource Management Layers I and II from (Mary Wilson, pers comm.). Consistent with current BLM regulations, only VRM I areas were excluded from development. I clipped the two wild and scenic rivers located in Wyoming from and created a 3 km buffer around them. I clipped the ESRI North American
Airports to Wyoming. I use two different criteria for excluding parcels. I extracted open water, perennial ice/snow, deciduous forest, evergreen forest, mixed forest, woody wetlands, emergent herbaceous wetlands, and created a polygon layer from National Land Cover Database 2001NLCD and excluded water, forest, wetlands if >50% of the parcel contained any of these features. I exclude all parcels that had any portion of a protected area, municipal, or airport within its boundary. All GIS data layers were re-projected to Wyoming Lambert and converted to 90m raster.

DATA


B. Distance to transmission The transmission dataset was a 1-off product from WYGISC derived from Rextag Strategies Zone 3 Electricity Transmission data. Proposed transmission was a 1-off product from Amy Pocewicz at The Nature Conservancy

C. QRA: Obtained original QRA from private source, obtained public QRA at Mercator (WREZ 2011)

D. Lek DATA: Wyoming Game and Fish FTP site

GIS Data steps:

Wind Turbines

I merge two datasets into one to include all existing wind turbines in Wyoming as of 2010. I use a point dataset from USGS of wind turbines existing before 2010 (O’Donnell and Fancher 2010). In addition, I added GIS point locations from the Federal Aviation Administration for two wind farms\(^\text{10}\) that went online in 2010. I removed three wind farms

\(^{10}\) Dunlap and Top of the World
(Warren Air force Base, Liberty Turbine Test and Cheyenne TM Vertical Axis) from the dataset because they do not match the theoretical economic decision maker I am modeling (i.e., the site decision for these wind farms is unlikely to be consistent with profit maximization). The dataset contains a total of 24 wind farms with 956 (+20 points that come from the FAA Dunlap farm that were not actually built) wind turbines ranging from 0.6 MW to 2.3 MW. The data span six counties including: Albany, Carbon, Converse, Laramie, Natrona, and Uinta. Pacificorp is the largest purchaser of power in the dataset.

As an alternate wind resource dataset I received three-year average (2008-2010) 12km NAM WPD for Wyoming from the program GEMPAK as well as a two-year winter average (2008-2009) 12 km NAM from Tom Parish in Atmospheric Sciences. The file was uploaded to ARCGIS and re-projected to WYLAM. This data is point class and to be usable I needed a smooth continuous surface. Following Tchou, I used natural neighbors which interpolate data between points using thiessen polygons.

Wind resource and landownership were converted from polygon to 90m raster to match the scale of the 90m elevation dataset. This was necessary to use Zonal statistics based on the fishnet (grid). Landownership was also reclassified to four classes, private, state, federal and other-other was then dropped. Slope was derived from the 90m DEM in % (0-181, which corresponds to a degree slope of 0-61). Distance to roads, and transmission was done to the proximity to the centroid of the grid.

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11 This total counts stages of wind farms as separate farms (e.g., Foote Creek 1, 2 and 3).
Figure 8. Wyoming environmental conflicts map
Figure 9. 50m wind resource map for Wyoming available from Wind Powering America.

8.2 Appendix Results


<table>
<thead>
<tr>
<th>Build-Out Level (MW)</th>
<th>Impacts with Current Transmission$^{ab}$</th>
<th>Impacts with All Transmission$^{ab}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impact Leks</td>
<td>Impact Males</td>
</tr>
<tr>
<td>1,650</td>
<td>0</td>
<td>0</td>
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<tr>
<td>3,390</td>
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<td>0</td>
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<tr>
<td>4,020</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8,790</td>
<td>12</td>
<td>185</td>
</tr>
<tr>
<td>12,000</td>
<td>17</td>
<td>282</td>
</tr>
<tr>
<td>13,770</td>
<td>22</td>
<td>360</td>
</tr>
</tbody>
</table>
Current transmission refers to the model results assuming that only the current electrical transmission lines are available; All transmission includes all current transmission plus assumes that all proposed transmission lines are installed.

This is the number of leks impacted at 3.2km buffer. Leks can be impacted by multiple parcels potentially resulting in a larger impact.

Table 15. Core Area Restrictions Expected Lek Impacts within 6.4km Buffer.

<table>
<thead>
<tr>
<th>Build-Out Level (MW)</th>
<th>Impacts with Current Transmission&lt;sup&gt;a,b&lt;/sup&gt;</th>
<th>Impacts with All Transmission&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leks</td>
<td>Males</td>
</tr>
<tr>
<td>8,790</td>
<td>8</td>
<td>153</td>
</tr>
<tr>
<td>13,770</td>
<td>14</td>
<td>281</td>
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