DEVELOPMENT OF A GIS FRAMEWORK FOR ONSHORE WIND ENERGY FEASIBILITY ASSESSMENT AND SITING EFFORT PRIORITIZATION

by

Nathan David Owens

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Abstract

Already limited by the geophysical requirements inherent to wind energy production, the task of siting wind farms is made all the more daunting for developers by the need to navigate a regulatory environment (undergirded by sociopolitical realities) filled with obstacles to the construction of the tall, rotating structures that comprise a wind farm. Geographic information system analysis is an effective option for managing the vast amounts of data necessary to pinpoint the locations most likely to result in successful development. Past studies have developed methods of combining different limiting factors into a combined score, but efforts within the United States have mostly been theoretical in nature or conducted at a broad scale.

A methodology for high resolution wind energy production site prioritization is developed in this thesis, with the state of Ohio being used for a case study. Data ingested into the model were procured from a broad – though mostly governmental – range of reputable sources. The evolving nature of wind energy siting hindrances necessitates a methodology capable of being adapted as new limitations present themselves. The procedures developed in this thesis rely on converting all pertinent data layers into properly aligned rasters. The overall hindrance presented by each layer is quantified on

a scale from zero to one, with zero being ascribed to any grid cell rendered incapable of supporting wind energy by the consideration represented by the layer in question. Because the final composite scores are calculated via multiplication of the input layers, a zero in any layer results in a similar preclusion in the composite.

The composite scores calculated within this case study confirm that wind farm developers are likely to contend with concerns wherever they attempt to build within Ohio. All of the state's grid cells have at least one hindrance, largely owing to the mobility of potentially impacted animal species. Nevertheless, the methodology developed in this thesis offers a pathway to identify the areas with the lowest overall hindrance, allowing developers to focus on regions where the concerns necessary to address are kept to a minimum.

Primary Reader and Advisor: Daniel Zachary

Secondary Reader: Donna Heimiller

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Executive Summary

The decarbonization benefits of wind energy are well known, but empassioned opposition to wind farm construction is easy to encounter if any substantial time is spent in a rural area where one is proposed. The insertion of wind energy infrastructure amongst a host of existing land and airspace uses was always bound to produce some consternation. Simultaneously, wind farm developers must navigate a host of other physical, environmental, and regulatory limitations while minimizing interference with existing infrastructure. Many of the benefits of wind energy are felt globally, while locals are left to contend with the direct impacts.

Coordinating the conflicting imperatives of the renewable energy transition and the maintenance of modern societal systems requires careful spatial planning. Before a developer even begins the initial consultations and scoping for a certain plot of land, it would be beneficial to begin with a broad understanding of the potential complications inherent to the site and how severe of a hindrance they could collectively present. This case study proposes a methodology for high resolution assessment of site suitability for onshore wind energy. Geographic information system assessment is used to combine inputs representative of the numerous siting considerations into a coherent, composite score of overall site suitability.

With Ohio being assessed for this case study, model results indicate a broad variance of site suitability across the state. Nowhere within the state is without hindrance, but many areas are feasible with implementation of appropriate mitigation efforts. This model offers a procedure for identifying these areas and prioritizing defelopment efforts in areas where successful completion is most probable.

Chapter 1

Introduction

Wind energy developers face numerous hurdles on the path to successfully installing even a single wind turbine. Scaling wind energy output up to the level of market penetration anticipated to be necessary for global decarbonization goals, the hindrances posed by siting constraints become one of several systemic problems (Cole, et al., 2021). Developers must account for geological and meteorological realities while simultaneously coordinating grid interconnection and navigating labyrinthine land use and airspace regulations at the local, state, and Federal levels. Nevertheless, there has been substantial growth in the industry in the last decade (EIA, 2022). Continued development will require careful consideration of these siting limitations, especially as more and more of the easily developable sites are claimed.

The methodology presented below describes a Geographic Information System (GIS) model that quantifies these onshore wind farm siting limitations and combines the corresponding layers into a single, composite score. While certain limitations, such as regulatory setback distances, serve as de facto bans on wind energy development, other limitations warrant consideration and stakeholder consultation but do not forbid wind energy outright. Accordingly, the composite score derived from this GIS model provides a spectrum from zero to one for each grid cell indicating overall difficulty of development.

By identifying acreage that cannot be developed and documenting the surmountable hurdles in feasible areas, this model can elucidate remaining regions that would be most easily developed. Developers could use this methodology for initial scoping during the site selection process to determine ideal project boundaries and to identify which stakeholders and regulatory bodies they should contact early in the development process.

The need to accommodate or avoid impacting stakeholders across a vast swath of industries, activities, and environments presents a multifaceted conundrum. Questions arise about conflicting priorities. The technical, economic, and sociopolitical viability of a proposed wind farm can be impacted by the existing stakeholders within or near a proposed site's boundary, the size of the lots they could potentially lease to the developer, and existing infrastructure and land uses. A developer scouting out initial possible locations for a new wind farm must be prepared to address all of these concerns, along with any unforeseen idiosyncrasies that a specific location presents. It is vital, therefore, that developers rely on a vast knowledge base among its employees and consultants.

While any new wind project will certainly need to be prepared to address these issues, it is still beneficial for a developer to conduct an initial broadscale screening procedure. Weeding out areas that would be infeasible early on in the development process will help to avoid wasted work and boost overall efficiency. This study provides a GIS framework for an analysis of this nature, using the state of Ohio as a case study. A broad range of wind energy siting considerations are depicted, made geographically compatible, and incorporated into a mathematical framework to produce an overall compatibility score for every individual point throughout the state.

Chapter 2

Literature Review

Site selection limitations having long been a known hurdle for wind farm developers, researchers have conducted many localized geospatial analyses in an effort to document these restrictions and facilitate appropriate stakeholder and regulator communication. Many of the early efforts to develop a GIS framework for navigating these limitations were conducted in Europe. Hansen (2005), in a study focused on Denmark, noted that some limitations, dubbed "constraints," are binary in nature – either fully preventing development or not causing any hindrance whatsoever. Other limitations, dubbed "factors," introduce a spectrum of difficulty, which was quantified on a scale from zero to one. Capturing these limitations in a GIS framework and layering them together allowed for holistic geospatial analysis informed by all necessary considerations. Baban and Parry (2001), Watson and Hudson (2015), and Pamučar, et al. (2017), used similar methods, calculating composite scores between zero and one or zero and ten in studies from the United Kingdom (Baban and Parry, Watson and Hudson) and Serbia (Pamučar, et al.). Tsoutsos, et al. (2014), also used a similar methodology for a study in Greece (specifically, Crete), but with five classes.

For the United States, van Haaren and Fthenakis (2011) developed an economic model to calculate wind energy feasibility in New York state, informed by the many variables that affect development costs. Their model incorporated information on "infeasible sites" to negate the model's calculations where regulatory preclusions existed. However, this study was not strictly raster-based; a key "factor," to borrow Hansen's terminology – specifically, “Important Bird Areas” as defined by Audubon – was left as a shapefile overlay rather than being factored into the raster calculations.

More recently, researchers at the National Renewable Energy Laboratory (NREL) have conducted several additional geospatial analyses on this topic for the United States. A study by Tegen, et al. (2016), subdivided the wind farm development process into four separate stages – Prospecting, Early Development, Intermediate Development, and Advanced Development. This study’s model ensemble compared the regulatory burden present at the time of the study with a scenario that prescribed specific wind energy market penetrations by certain dates. Within these two broad categories, scenarios were modeled for three separate siting limitation levels and two separate transmission line availability levels, resulting in twelve total ensemble members. The results of this study quantified the benefits of early conflict identification.

Lopez, et al. (2021) utilized detailed setback datasets (which were unavailable for this study) to model idealized wind turbine height and spacing tradeoffs across the continental United States. Additionally, this study accounted for competing land uses such as transportation infrastructure, dwelling units, protected areas, and radars, along with geological and topographical considerations. Siting feasibility was modeled for three separate regulatory intensity levels and for three separate wind turbine heights.

Finally, Mai, et al. (2021), modeled wind energy demand and buildout under three hypothetical “siting regimes” with varying regulatory burdens – “open access,” “reference access,” and “limited access.” Values were calculated for the entire continental United States, subdivided into 67,000 separate grid cells, using the Renewable Energy Potential, Regional Energy Deployment System, and System Advisor models.

Tegen, et al., noted that "[i]t is unrealistic to expect that all U.S. wind resource areas will be evaluated and designated as available or unavailable for wind deployment in one comprehensive assessment." The methodology proposed for this project is designed to develop a framework (using Ohio as a case study) for conducting such analyses at a smaller state or regional scale, building upon these studies' examples by consolidating the many spatial limitations placed on wind farm development into a unified feasibility score.

The production of ensembles for differing scenarios in several of the aforementioned studies is a useful exercise for forecasting the broad range of possible renewable energy market penetration rates, which could subsequently inform public energy policy decisions. These models are not designed, however, for informing specific site selection processes. The methodology described in the following section seeks to provide just such a tool for maximizing wind energy developers' workflow efficiency.

Chapter 3

Methodology

3.A. Methodology Overview

Developing this feasibility score requires incorporating a diverse group of limiting factors for wind farm siting. Detailed in the following subsection, these categories span geophysical, technical, environmental, regulatory, and social considerations. While these limitations are derived from the disparate (and sometimes conflicting) needs of countless different stakeholders, all share one commonality: they are spatial in nature and can therefore be collocated with each other and used to create a composite score, assuming compatible data resolutions and being careful to avoid redundancies between layers.

The Ohio data used as inputs for this model were collected from a broad range of sources, most of them governmental. (Both governmental agencies and private entities collaboratively produced some, and structure footprints were gathered from an entirely nongovernmental Microsoft dataset.) See Table 1 for a complete list of data sources. Data from adjacent states were included for parameters that were a function of proximity. These original datasets came in differing formats, necessitating conversion for many into a single, compatible data format. All inputs were reprojected into a projected coordinate system deemed appropriate for the state of Ohio: NAD_1983_2011_ StatePlane_Ohio_North_FIPS_3401_Ft_US. The ArcGIS geographic information system software suite, developed by Esri, was utilized for this analysis, and terminology from this software's toolsets are used henceforth.

Category	Data Layer	Source
Geophysical	Wind Resource	National Renewable Energy Laboratory
	Elevation*	United States Geological Survey
	Karst Geology	United States Geological Survey
	Land Cover	United States Geological Survey
	Tree Canopy Height	Interagency (DOI, USDA, USGS) and The Nature Conservancy [501(c)(3)]
Designations	State Borders	United States Geological Survey
	County Borders	United States Census Bureau
	Ohio Township Borders	Ohio Department of Transportation
	Protected Areas	United States Geological Survey
	Federal Lands	United States Geological Survey
	Military Airspace	Department of Defense
Infrastructure	Existing Wind Turbines	Interagency (United States Geological Survey, Lawrence Berkeley National Laboratory) and American Clean Power Association [501(c)(6)]
	Roadways	United States Census Bureau
	Structures	Microsoft Bing Maps for Enterprise
	Substations	Energy Information Administration
	Weather Radars	Interagency (BOEM, NOAA)
	Airports	Federal Aviation Administration
	Capacity Factor	National Renewable Energy Laboratory
Environmental	Population Density	United States Department of Agriculture
	Threatened and Endangered Species	United States Fish and Wildlife Service
	Other Impacted Species	United States Fish and Wildlife Service
Regulatory	2021 SB 52	Ohio State University, Ohio Capital Journal, Cleveland Plain Dealer, County Records
	Ohio Revised Code, Title 49, Section 4906	Ohio Legislative Service Commission

*Used to derive slope dataset

Table 1 – List of data layers and sources

The raster format was most appropriate for the purposes of this analysis, as it would facilitate the multiplication of collocated grid cells to create the composite score. Point datasets were either buffered or interpolated using the inverse distance weighting method as appropriate. Shapefiles, including those directly downloaded and those derived from other data (e.g. buffers), needed to be converted into raster format to facilitate the composite calculation. The land cover dataset, with a grid cell resolution of 98.425 meters after conversion to the state plane projection, was used as the original reference snap raster for initial conversions to keep all rasters' grid cells properly aligned.

Once each layer was rasterized and aligned with the reference snap raster, it was subsequently reclassified to a value between zero and one. One was used to indicate a lack of any hindrance to wind farm development from the siting consideration represented by the layer in question. Zero, meanwhile, was used for grid cells where wind energy was made infeasible by the associated consideration. As will be discussed in more detail below, certain parameters were given a weight between zero and one in one-tenth increments, indicating that the consideration presented a hindrance – but not an outright preclusion – to wind farm development. For instance, a value of 0.9 would have been used for a very minor concern that would only slightly impede development; a value of 0.1 would have been used for a major concern requiring expensive, detailed, controversial, and/or time-consuming mitigation efforts to properly address. When practical, values were assigned relative to the parameter's actual values, with more favorable values being reclassified to values near one and less favorable values being set closer to zero. In some cases, when the associated parameter was categorical rather than following a progression from high- to low-feasibility, appropriate values were chosen to represent the parameter consistently throughout the composite raster.

The final stage of the assessment involved multiplying all of these aligned layers together using the Raster Calculator tool to create a single, composite feasibility score. To disperse computational load, layers were categorized into several separate groups. Composites produced from these groups were then fed into the Raster Calculator to produce the final composite. Because a value of zero was used to indicate a preclusion, this value was carried through to the final composite score through the multiplication. Therefore, if any of the constituent layers acted as an exclusion for wind farm development, the composite score would include an identical preclusion for that grid cell. Areas likely to be most suitable for wind energy development would be those where none of the inputs act as preclusions and a large number of input layers have values at or near one.

3.B. Data Overview

Providing a holistic encapsulation of the multitude of considerations that factor into onshore wind energy siting requires a broad range of physical, technical, environmental, social, and regulatory datasets. All of these data must be made compatible to facilitate the final calculation of the composite score. Rasters need to be resampled to have the same grid cell size and snapped to the same reference layer. Shapefile datasets must be converted to raster and similarly aligned with the reference layer. Datasets were categorized into two primary types. Layers that were primarily binary in nature – wind energy being either functionally precluded or not hindered at all by the parameter – were deemed “mask layers.” These are akin to the “constraints” used by Hansen (2005). With grid cells for these layers receiving values of either zero or one, mask layers had an outsized influence on the final composite layer. A grid cell with a zero in any of its constituent layers would remain a zero after the final calculation because the zero would be multiplied through to the composite. This way, all fully infeasible areas remain infeasible in the final model output. Aside from these mask layers, other layers represented siting considerations that hinder wind farm development but that could be addressed through appropriate stakeholder engagement. These layers, deemed “spectrum layers” (akin to the “factors” from Hansen [2005]), were given values ranging from zero to one in increments of 0.1. Some layers containing categorical data were treated as hybrids, with certain categories acting as masks and others being given spectrum values. The final composite layer, the product of multiplying all spectrum and mask layers together, reflects the overall hindrance wind farm developers will likely face in each grid cell throughout the state. Note, however, that certain datasets that warrant consideration in the wind farm development process must be assessed in consultation with governmental entities that have access to the data, as they have been deemed unfit for release to the general public. Detailed NEXRAD weather radar lines of sight, for instance, were unavailable for incorporation into this study, necessitating a buffer as a rudimentary proxy. Coordination with the National Weather Service's Radar Operations Center (ROC) could produce a more detailed radar viewshed assessment. The following is an overview of all layers included in this model and how each layer was weighted.

3.B.1.a Regulatory Mask Layers

Setbacks: Wind energy siting regulations in Ohio have been in flux in recent years. Ohio Revised Code / Title 49 Public Utilities / Chapter 4906 Power Siting (September 15, 2014) specifies that the Ohio Power Siting Board has authority over wind energy siting and defines setback requirements from neighboring property lines equivalent to a coefficient of 1.1 times the blade tip height at the top of rotation, with a minimum required distance of 1,125 feet from the blade's position when perpendicular to the tower. However, the way the law is written, this setback requirement can be dismissed when "all owners of property adjacent to the wind farm property waive application of the setback to that property pursuant to a procedure the board shall establish by rule."

An October, 2019, amendment to Section 4906.13 (Ohio Revised Code/Title 49 Public Utilities/Chapter 4906 Power Siting, 2014) placed the siting authority for wind farms between five and 50 megawatts with the state government, stating that "[n]o public agency or political subdivision of this state may require any approval, consent, permit, certificate, or other condition for the construction or operation of a major utility facility or economically significant wind farm authorized by a certificate issued pursuant to Chapter 4906 of the Revised Code."

More recently, however, 2021's Senate Bill 52 (134th General Assembly, 2021) granted additional siting authority to county governments, stating that "[t]he board of county commissioners may adopt a resolution designating all or part of the unincorporated area of a county as a restricted area, prohibiting the construction of" large or economically significant wind farms. Section 4906.13 defines economically significant wind farm as being within a range of 5-50 MW, whereas Section 4906.1 more broadly defines a "large wind farm" as being a "major utility facility" with a "single interconnection." According to a recent article by the Ohio Capital Journal (Zuckerman, 2022), nine counties (Allen, Auglaize, Butler, Hancock, Knox, Logan, Medina, Seneca, and Union) had already passed strict countywide or township-specific wind energy siting limitations as of the date of the model run.

Because of the possibility of waiving the setback requirements from property lines, this setback requirement was omitted from the model. It is assumed that the population density raster (discussed below) serves as a proxy for land parcel sizes and, therefore, the difficulty of negotiating setback waivers with adjacent property owners or, more generally, avoiding resistance from other stakeholders with sightlines to a proposed wind farm (although low population density certainly does not guarantee minimal resistance). County- and township-specific bans or moratoria, however, were treated as mask layers in the model, being given values of zero.

Regulatory setbacks and other similar limitations are inherently derived from the political dynamics affecting whichever governing body has the jurisdiction over a study area's energy siting decisions and are therefore subject to both regional and temporal variance. Underscoring this point, and as discussed in more detail in Section 3.B.3 below, even during the development of this case study a county-level public referendum was held that would influence the model's input layers if re-run. The political realities of siting regulations will warrant detailed legal assessments, potentially at multiple levels of governance, for each new study area. Periodic reassessments will also be necessary. Development of methodologies for geographic depiction of these regulations and subsequent analyses will require careful assessment, particularly near jurisdictional boundaries.

3.B.1.b Avoidance Mask Layers

Existing Wind Turbines: With the goal of this assessment being to inform future real-world wind farm siting decisions – as opposed to identifying hypothetically ideal sites if development were starting from scratch – it is assumed that the locations of existing wind energy facilities are not available for future development, the possibility of repowering existing facilities to increase nameplate capacity notwithstanding. Accordingly, the United States Wind Turbine Database, co-developed by Lawrence Berkeley National Laboratory, the United States Geological Survey, and the American Clean Power Association, is used as an input layer. Since this database is updated regularly, any assessment can only offer a snapshot of which areas are off the table for future development due to past development. Existing wind turbines are buffered using rotor diameters specified in the database, meaning that a small portion of existing wind turbines, likely mostly older ones, have been omitted from this assessment for lack of data. It is common to space wind turbines at least five rotor diameters (5RD) apart to minimize the impacts from upwind turbines on downwind ones, and often farther in the direction of the site's prevailing winds (Sustainable Energy Development Authority of NSW, 2001). A 5RD buffer is therefore used as a mask layer, precluding future development. For more restrictive spacing requirements, and to account for small slivers that may be present within existing wind farms' overall footprints based on 5RD spacing, a buffer of 10 rotor diameters (10RD) is also included as a spectrum layer, with a value of 0.3. The 5RD buffer is erased from the 10RD buffer, leaving behind a toroidal shapefile. While this model relies on radial buffers to guide avoidance of existing wind farms, future analyses could be informed by prevailing wind directions to account for varying required setback distances in off-peak directions.

Existing Structures: While property boundary lines rather than structures define Ohio's codified setback distances, it is nevertheless pertinent to factor in a setback from existing buildings. Wind turbines clearly cannot be built on existing building footprints, the largest of which can exceed the model's grid cell resolution. Construction of a utility scale wind turbine in very close proximity to an inhabitable structure would present a host of logistical issues for the building's inhabitants (e.g. noise), for those constructing the turbine (e.g. turbine component transportation logistics), and for operations of the turbine itself (e.g. unpredictable wind eddies influenced by the structure). It was therefore deemed appropriate to provide a buffer of 660 feet from all buildings, although this would not preclude alternative emerging wind energy technologies tailored for rooftop or otherwise urban energy production. This buffer distance is slightly more than the maximum blade tip height recorded in the U.S. Wind Turbine Database for the tallest existing wind turbine in Ohio or adjacent states. Structure information was downloaded from Microsoft Bing Maps for Enterprise, making this the only strictly non-governmental shapefile incorporated into the model. These buffers were given values of zero to remove them from consideration.

Roadways: Similar to structures, roadways and, to a lesser extent, the easements surrounding them present another clear blockade to wind turbine construction. An appropriate setback from roadways minimizes concerns stemming from shadow flicker, noise, ice throw, and other concerns that could worsen driver safety (Seifert, et al., 2003) while simultaneously avoiding operational impacts from passing traffic exacerbating the effects of turbulence from airflow eddies already incumbent on wind turbines (Mahmoodilari, 2012) or potentially the risk of car accidents impacting the tower base. The same buffer that was applied to structures – 660 feet – was similarly used for roadways and given values of zero.

Weather Radars: NEXRAD WSR-88D weather radars (NEXRADs) and airport Terminal Doppler Weather Radars (TDWRs) both provide critical meteorological information vital to maintaining public safety. Wind turbines' potential to impact radar operations are well documented. According to a report by the ROC (Vogt, et al., n.d.), the presence of a wind turbine within roughly one and a half kilometers of a NEXRAD can produce return signals intense enough to cause physical harm to the radar's components. Out to three kilometers, severe signal interference can occur that renders data along that radial largely unintelligible. With the exception of some mountaintop NEXRADs where the terrain drops off steeply in near proximity to the radar location, the ROC therefore considers locations within three kilometers of a NEXRAD to be a "No-Build Zone" where they "would want to discourage developers from building" because "[w]ork-arounds are few and impacts are likely to be great." Beyond this range, the ROC also identifies "Mitigation" and "Notification" zones. Spectrum layers for these zones, along with TDWR coverage zones, are discussed in greater detail below.

Critical Habitats: While impacts to fauna from wind farm development are a common concern, species range datasets are very broadly characterized, often covering entire states or large regional swaths. Thus, impacted species' ranges were categorized as spectrum layers, as detailed in section 3.B.2.d. Ranges for species listed as threatened or endangered are more geographically limited and were therefore handled as mask layers. Range shapefiles were acquired from the U.S. Fish and Wildlife Service's Environmental Conservation Online System. The only species within Ohio's borders in either category was a threatened mussel, *Quadrula cylindrica cylindrica*, colloquially known as the rabbitsfoot (U.S. Fish & Wildlife Service, n.d.). Because this mussel species inhabits riverine ecosystems, the shapefiles denoting its territories were linear. To reflect this linearity yet to assure full coverage in a raster format, a buffer of 330 feet – half of the setback distance used for roads and structures – was conducted on these shapefiles, and the resulting polygon was used to facilitate conversion to raster.

Federal Lands: Federal lands data, acquired from the U.S. Geological Survey's National Map data portal, were used to categorize regions that were potentially feasible for leasing out to wind farm developers. Several land designations were deemed unsuitable for wind energy development and were given zero values. National Parks, National Recreation Areas, National Wildlife Refuges, National Wilderness Areas, Wild and Scenic Rivers, Lakes, National Lakeshores, Research Natural Areas, and Wildlife Management Areas all represent natural resource areas with inherent protection from large-scale development. To avoid interference with defense operations, military installations for the Army, Army National Guard, Air Force, Air Force National Guard, and the Navy were all placed off limits in the model, as were National Military Parks and National Battlefields. Other cultural resources, including National Historic Sites, National Historic Parks, National Cemeteries, and National Memorials were weighted to zero in the same manner.

Other federal lands, including National Forests, and Native American Reservations were given values of one. Development on federal or tribal lands are governed by differing regulatory schema, potentially with differing development timelines. The National Environmental Policy Act (NEPA) is a major regulatory framework for federal lands, while the Helping Expedite and Advance Responsible Tribal Home Ownership Act of 2012 (HEARTH Act) governs much of the land use planning on tribal lands. These regulatory frameworks prescribe detailed procedures for permitting wind farms and other infrastructure. Although the resulting timelines for these steps may be drawn out, these areas also represent large swaths of land under single, unified jurisdictions. The ability to make land use decisions independent of many of the land use constraints inherent to smaller, private plots could compensate for any regulatory delays. Many of the considerations that are incorporated into the reviews governed by such laws are included elsewhere in this model's calculations. Moreover, the severity of the hindrance or delay caused by these reviews may vary with the shifting political landscape. Given these facts, no additional layer was incorporated in this model to penalize areas for legislatively governed review processes.

All Mask Layers: Compiling all of the aforementioned mask layers together, Figure 1 shows a composite image of all areas where wind energy development is functionally or legislatively precluded. Notably, counties with wind energy moratoria and major urban conglomerations, where roadway and building setbacks largely bleed into each other, clearly stand out. Elsewhere, particularly in more rural areas, the gridded pattern of roadway buffers are far more apparent, as little else serves to fully preclude construction of wind turbines.

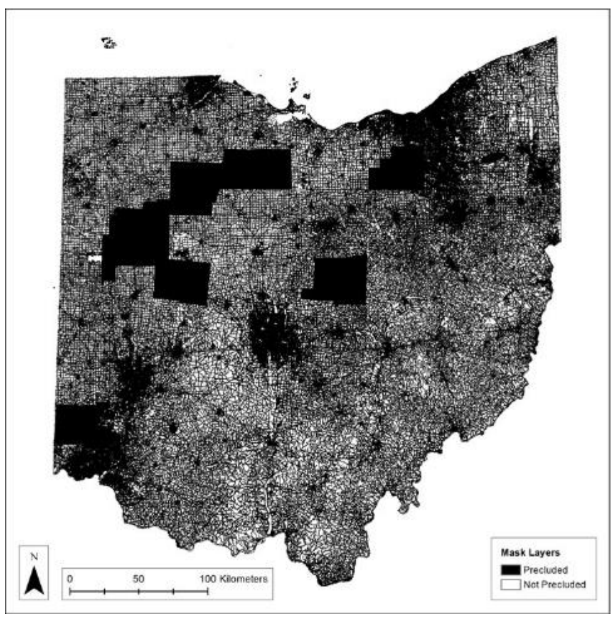

Figure 1 - Mask Layers Composite

3.B.2.a Buffer Spectrum Layers

Additional Buffers Around Mask Layers: Several of the aforementioned mask layers are of a nature such that the severity of impacts from wind turbine operations are inversely related to distance. It was deemed appropriate, then, to include additional buffers beyond those used to create the mask layers in certain cases. The 660-foot mask buffers for roads and structures, for instance, had additional 330-foot buffers (totaling 990 feet in all) applied that were given values of 0.3.

As discussed above, beyond the three kilometer "No-Build" threshold for NEXRAD radars, the Doppler shift caused by wind turbines' rotating elements can still confuse the radars' data processing algorithms, which rely on the lack of a Doppler shift to filter out large, stationary structures like skyscrapers. The ROC's Mitigation Zone describes regions where wind turbine construction would have "significant impacts to the radar" that "limit forecaster workarounds," warranting consultation on potential mitigation options. Notification Zones, meanwhile, as their name suggests, are designed solely for facilitating communication of an intent to build; no mitigations are necessary. This zone has therefore been omitted from consideration in the model. Though detailed line of sight analyses are informed by digital elevation models and the radar beam's elevation angle, these datasets, as mentioned above, have not been made available for public use. However, the ROC describes the parameters used to define these zones. By default, the Mitigation Zone extends out to 36 kilometers from the radar location, but it is stretched to 60 kilometers if a second elevation angle is penetrated. Accordingly, this model applies a weight of 0.8 to a buffer of 60 kilometers and 0.5 to a buffer of 36 kilometers around NEXRAD radars. Airport TDWRs, according to the ROC, are similarly "focused on the airport terminal areas and within a 60 [kilometer radius]." These were therefore buffered to the same distance and weighted in the same manner as NEXRADs' 60-kilometer buffers. Note that the three kilometer No-Build zones' mask layers, when multiplied through, cause the Consultation Zones to be toroidal in shape. While a detailed line-of-sight analysis would provide a more informed impact assessment, such analysis is outside the scope of this model. The NEXRAD line of sight layers used in this model are, therefore, a conservative estimate erring on the side of greater impact avoidance. Consultation with the ROC could help developers to identify regions on the periphery of these layers with lower impacts.

3.B.2.b Geophysical Spectrum Layers

Wind Resource: Clearly, the primary factor dictating where wind farm development is feasible is the wind itself. Wind resource data developed with the Wind Integration National Dataset (WIND) Toolkit (Draxl, et al., 2015) were collected from the National Renewable Energy Laboratory in raster format with two-kilometer resolution. A hub height of 100 m was selected as a reasonable reference height. As wind energy technology evolves and areas with lower wind resource values are targeted for development, average hub heights may increase. Future expansions of this study could therefore be conducted for alternative hub heights reflecting probable future wind turbine configurations. While different wind turbine designs will have their own unique power curves and associated cut-in and cut-out wind speeds, it was assumed that developers will opt for turbines tailored to their site's wind regime. No zeros were assigned for this layer because mandates such as renewable portfolio standards or incentives such as high energy market strike prices on high demand days could potentially improve a wind farm's financial viability despite a poor wind regime. Rather, wind speeds within the rectangular extent of Ohio and its adjacent states were binned into five groups, with scores ranging from 0.2 to 1.0 in increments of 0.2. This larger area, which was selected to provide more regionally relevant results, had its lowest values outside of Ohio's borders. The lowest value within Ohio itself was 0.6, which represented wind speeds of approximately 4.9 to 6.0 meters per second. The 0.8 bin corresponded to values between roughly 6.0 and 7.2 meters per second, and values above this range, nearing 8.0 meters per second, were left unpenalized with a score of 1.0. The wind speeds corresponding to these chosen weights under this methodology could vary with the extent of the study area. Inclusion of windier areas would necessitate lower values within Ohio.

Figure 2 depicts the results of this binning. Developers implementing a model similar to this one may choose to weight these layers differently based on their own site-specific considerations and financial decision-making processes.

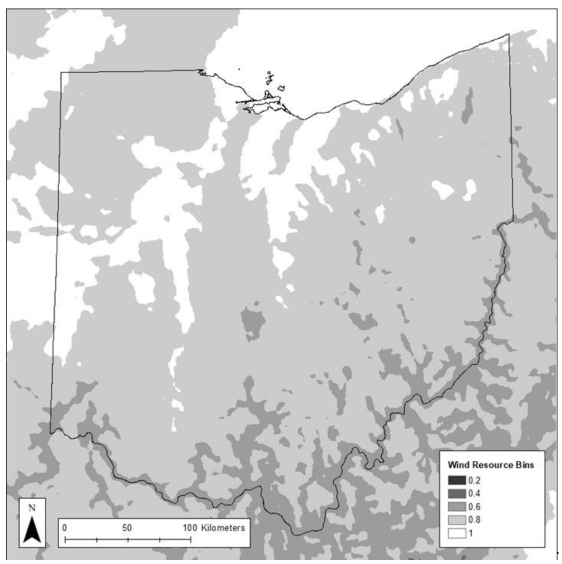

Figure 2 - Wind Resource Scores

Capacity Factor: Wind farms' real-world performance (and, thus, financial payback periods) are highly contingent on the actual amount of energy they are able to produce and feed into the grid (Lawrence Berkeley National Laboratory, 2022). Therefore, overall capacity factor is a key consideration for determining economic viability. There is some redundancy with wind resource in this layer, but capacity factor calculations incorporate additional considerations beyond high or low wind speeds that could reduce wind farm energy output, such as temperature impacts and icing. The higher resolution of the available wind resource data (two kilometers versus eleven kilometers) warranted its inclusion as a separate layer despite its being an input for this parameter. A site with relatively steady winds, all else being equal, will generally have better financials than one with a similar average windspeed but greater variability, regularly dipping below the cut-in wind speed or being curtailed due to exceeding the cut-out wind speed (Burke and O'Malley, 2011). Capacity factor data were collected from the National Renewable Energy Laboratory's wind supply curves. Mid-tier assumptions were made, with the moderate Annual Technology Baseline Scenario and Reference Access Siting Regime being incorporated into this model. Grid cells with capacity factors below fifteen percent were deemed unreliable enough to justify treatment as a preclusion zone and were given zero values. Above this, hindrance scores were incremented upward by 0.2 for every five capacity factor percentage points, with values above 35% receiving scores of 1.0. These values were considered generalizable for all wind regimes and for future studies in other regions. In practice, however, none of Ohio's grid cells had capacity factors below 26.8%. This means that the lowest capacity factor hindrance score fed into the final composite for Ohio was 0.6.

Elevation and Slope: While the tops of ridgelines can be a particularly productive option for wind farm siting (EIA, 2022), steep hillsides leading up to higher elevations can prove challenging for wind farm development. Miller and Li (2014) defined slopes of less than seven percent as the being ideal for wind energy development. To account for this issue, a slope raster was used to define three separate topographic regimes. This slope raster was derived using a digital elevation model acquired from the U.S. Geological Survey. Terracing may be an option in highly sloped locales, so it was deemed inappropriate to treat any slope as an outright zero mask, but regions with a slope of 60-90° were heavily penalized, receiving values of 0.2. Between 30° and 60°, a less-severe penalty value of 0.7 was applied. Areas with a slope between zero and 30° were deemed flat enough to receive no penalty – a value of one.

The vast majority of the state received no penalty under these criteria. While individual grid cell slope calculations, rounding to the nearest degree, reached as high as 85 degrees, 99.6 percent of Ohio's grid cells were between zero and thirty degrees. Almost all of the rest were between thirty and sixty degrees; with slopes exceeding sixty degrees representing less than two, ten thousandths of a percent of grid cells. Elevation itself was not included in this assessment outside of being used to derive the slope raster, but similar future analyses may need to factor in a separate elevation layer if, unlike Ohio, the study area has elevations that rise high enough for air density reductions to be non-negligible.

Karst Landscapes: Subsurface geology can be another key consideration influencing wind farm siting decisions. Because of the potential for sinkhole development, karst landscapes pose challenges. Accordingly, karst landscape datasets from the U.S. Geological Survey are incorporated into the model as a spectrum layer to account for this issue. Areas with deep karst formations, fifty or more feet beneath the surface, were given values of 0.8. Karst formations nearer to the surface were penalized at a greater amount, receiving values of 0.6.

3.B.2.c Land Use Spectrum Layers

Land Cover: Arguably, the primary problem underlying all wind energy siting difficulties outside of the wind itself stems from the fact that wind energy is experiencing mass industry growth in the twenty-first century, not the nineteenth or twentieth. The massive industrial and population growth of those centuries in the United States means that there has been a similar growth in the number of stakeholders with unique and sometimes conflicting interests and assets. Even – perhaps especially – in rural areas, economic, aesthetic, and environmental concerns are seemingly omnipresent. Existing land cover information, therefore, is a vital consideration, serving as a first-order approximation of how severe these complications can become in different regions. Land cover information was collected from the United States Geological Survey. Of the land cover categories included in this dataset, three broad categories were factored into the model as exclusion masks with values of zero: wetlands (both woody and emergent herbaceous), developed land (of any intensity), and water bodies or areas perennially covered in snow or ice. Land covers left unpenalized included barren land, cultivated crops, hay or pasturelands, herbaceous areas, shrub, scrub, and any area left unclassified. Finally, forests, be they deciduous, evergreen, or a mixture, were deemed to be feasible for wind development, but only with sufficient tree clearing or particularly tall wind turbines. Accordingly, forests were partially penalized with values of 0.5.

Canopy Heights: Because vegetation can have a frictional influence on surface-level windspeeds that can be extrapolated upwards, being reflected at common wind turbine hub heights, vegetative canopy heights were factored into this analysis. There was some overlap between this input and land cover. The value of 0.5 applied to forests in the prior section, therefore, was functionally combined with this layer to form the actual penalty for forests, informed by canopy height. Incorporating canopy height as a separate parameter allowed for lower penalties to be applied for vegetation in non-forested areas where vegetation was nevertheless still tall enough to influence wind speeds. Areas where canopy heights were five meters or less (or unknown) were assigned values of one, being deemed short enough as to have negligible impact on hub height winds. Above this canopy height, penalties of 0.2 were added incrementally for every ten meters: 0.8 for canopies between five and 15 meters, 0.6 between 15 and 25 meters, 0.4 between 25 and 35 meters, and 0.2 for all areas with canopies above 35 meters.

Airports: Flight navigation in the vicinity of wind farms presents a twofold complication. First, in close proximity to airports, wind farms can present a physical obstruction to airplanes. Safety procedure changes induced by wind farm construction can force a change to the minimum vectoring altitudes that air traffic controllers use to dictate inbound and outbound planes' approach paths (Capitol Airspace Group, 2021). Second, air traffic control radars can receive return signals from wind turbines' rotating blades – particularly from the lightning protection systems built into them (Karlson, 2019) – that reflect radar pulses and move at speeds that mimic the signals and Doppler returns of actual planes (McDonald, et al., 2012). This can lead flight tracking programs to lose track of actual planes, as not enough consecutive radar pulses pick up a clear return from the aircraft being tracked (Office of the Director of Defense Research and Engineering, 2006). Radar operators must define a preset Constant False Alarm Rate (CFAR) to manage the cluttered radar returns from wind farms, finding the right balance to assure detection of aircraft flying near wind farms without triggering multiple false alarm detections (He, et al., 2020). Accordingly, developers must coordinate with the Federal Aviation Administration (FAA) on siting wind farms through the FAA's Obstruction Evaluation/Airport Airspace Analysis program (Federal Aviation Administration, n.d.) in order to identify potential impacts and explore deconfliction options. In order to capture both radar and flight obstruction complications, all major airports – those with dedicated, on-site air traffic control radars – were buffered by 36 kilometers. The resulting circular shapefiles were converted to raster and reclassified with values of 0.8.

Low-Level Military Airspace: While aircraft flying close enough to the ground to be obstructed by wind turbines is primarily a concern in the vicinity of airports, there are certain contexts, particularly for military training, that call for prolonged flight mere hundreds of feet above ground level. Military training routes (MTRs) and other special use airspace (SUA) are detailed in the National Geospatial-Intelligence Agency's Area Planning 1B (AP/1B) publication. MTR and SUA shapefiles were acquired from the DoD Military Aviation and Installation Assurance Siting Clearinghouse. (Note: At the time of writing, this paper's author is employed as a contractor embedded in this DoD office.) SUAs were given a value of 0.7. MTR segments with both crossing and en route floors too high to be penetrated by a wind turbine's maximum blade tip height were omitted via a definition query prior to raster conversion. Some MTR segments' floors are recorded in feet above mean sea level; since actual height above ground level would vary with terrain for these, the same threshold was assumed to be appropriate for these MTRs. These MTRs were then subdivided into two nautical mile-wide lanes using a multiple ring buffer tool around their centerlines and clipped to the defined MTR boundaries. In an unobstructed scenario, it was assumed that the lanes around the centerline were most important to protect. If an obstruction was listed in the AP/1B, the two nautical mile-wide lane in which the obstruction was located was deemed to be a flight avoidance area, and its value was reset to one, as aircraft flying through this leg of the route would already be avoiding the existing obstacle. However, this increases the importance of protecting the other lanes in the affected MTR segment, so these values were all set to 0.5 within the affected segment.

3.B.2.d Cultural and Environmental Spectrum Layers

Additional Impacted Species: Tegen, et al., identified several species that warranted special consideration in relation to habitat impacts caused by wind farm development. These species included bats (Indiana, Northern Long-Eared, Little Brown, and Tri-Colored) and birds (Whooping Crane, Bald Eagle) that are found in Ohio, according to the Fish and Wildlife Service.   In fact, all of these species, save for the whooping crane, are found throughout Ohio. This warrants particular note, as it means that the entirety of the state has at least one topic of concern and source for potential pushback for wind farm developers. The primary purpose of this paper is to quantify overall development difficulty, rather than relative difficulty. The presence of multiple species of concern presents a greater challenge than the presence of a single species. Each of these species was therefore given a value of 0.9. When multiplied together, this calculation lowers the composite score for essentially the entire state.

Protected Areas: Species-specific assessments for endangered, threatened, or commonly impacted animals offer a safeguard against some of the most plausible unforeseen environmental permitting snafus, but overall biodiversity statistics provide additional protections against any less-predictable species impacts. The U.S. Geological

Survey's Protected Areas Database was used to provide this backstop. Collected data were initially grouped by the manner of their original definition (e.g. ownership versus designation), but the included GAP Status Code attribute (GAP_STS) was used to differentiate those areas with biodiversity concerns from other considerations incorporated into the dataset. Areas with a GAP status of one ("Managed for biodiversity – disturbance events proceed or are mimicked") were treated as mask layers and given values of zero. Any area with a GAP status of two ("Managed for biodiversity – disturbance events suppressed") was penalized heavily with a value of 0.2, but not treated as an outright exclusion area. GAP statuses three and four were assigned values of one, as these categories offer more land use flexibility.

Population Density: Dense conglomerations of people, of course, come with dense concentrations of housing, office and commercial buildings, and public infrastructure, collectively leading to high energy demand. The need to meet this demand, in turn, encourages construction of energy generation infrastructure as near as is feasible to minimize transmission line losses. However, densely populated areas simultaneously present several problems for wind farm developers, who must compete with conflicting infrastructure and land uses. The more people in line of sight of a wind farm, the greater the likelihood of neighbors raising aesthetic or nuisance complaints, for instance. Above a certain population density threshold, it would be reasonable to consider traditional, grid scale wind energy entirely incompatible (nontraditional urban wind energy options notwithstanding). There is a high likelihood that densely populated areas will have densely packed road networks and numerous structures, resulting in significant overlapping of setbacks. As discussed above, applicability of property line setbacks is contingent on adjacent landowners' insisting that a setback be enforced. It would, thus, be inappropriate to treat proximity to a parcel boundary as a mask layer. Instead, population density is used in this model as a proxy for the likelihood of a neighboring property owner seeking to enforce the setback requirements or issuing a complaint.

These competing needs – staying as close as possible to the load while minimizing land use conflicts – illustrates a conundrum at the heart of many difficult wind energy siting decisions. For the purposes of this analysis, two separate rasters are used to capture this dynamic. First, population density, acquired from the United States Department of Agriculture, is used as a spectrum value, with values ranging from 0.5 in the most highly urbanized regions to one in rural areas to reflect lower (though certainly still notable) overall resistance and cheaper land acquisition or royalty costs.

3.B.2.e Technical Spectrum Layers

Transmission Infrastructure: Second, proximity to existing substations is used as a proxy for interconnection feasibility. Substation location data from the Energy Information Administration were subjected to an inverse distance weighting interpolation procedure to produce a substation proximity raster. It is assumed that existing substations are already concentrated around population centers in an economically viable manner. Existing substations can be uprated or supplemented with additional equipment to accommodate additional energy flowing from new infrastructure such as a wind farm, or entirely new substations and associated transmission infrastructure can be built if the financial analysis favors such a course (Csanyi, 2021) This model assumes interconnection to existing – and uprated or expanded if needed – substations, but future iterations will need to incorporate newly-built substations and transmission lines as they are completed.

3.B.3. Future Analyses

While efforts were made to incorporate as many pertinent layers as possible into this analysis, the sheer complexity of the wind energy siting process presents developers with a constantly evolving challenge. New legislation and ballot measures, for instance, can lead to modifications of regulatory siting restrictions. During the drafting of this study, for instance, Crawford County, Ohio, held a referendum on wind energy siting regulations. According to local newspaper the Bucyrus Telegraph Forum, the referendum resulted in a new ten-year moratorium preventing wind farm construction in all unincorporated county land (Goble, 2022). This referendum, having taken place after completion of the model run, is not reflected in the results of this study. This is an example of the fluid nature of wind energy siting regulations and why models like this require constant upkeep to remain current.

If this methodology were to be expanded to additional states, there could, of course, be entirely unique regulatory requirements alongside differing environmental and cultural considerations. The morphing and localized nature of such regulations illustrates that the assessment described herein merely represents a snapshot in time of the geographic distribution of wind farm development feasibility.

Some limitations on wind farm development, meanwhile, are derived from the qualities of the surrounding area, rather than the nature of the site itself. For instance, the difficulty of transporting wind turbine blades and tower segments to a new wind farm site can be a limiting factor (Cotrell, et al., 2014). Overpasses can act as an obstacle in the vertical sense, while buildings along a roadway with a tight turning radius can limit infrastructure transportation horizontally. These considerations, being contingent on a broadscale assessment of infrastructure capacity and potentially remediable through additional infrastructure investments or innovative transportation techniques, were not factored into this assessment.

Finally, as mentioned above, certain data layers that were first considered for inclusion in this model were not made available for academic use by the governmental agencies that originally produced them. These included NEXRAD weather radar lines of sight and airspace radars. In lieu of these layers, proxies – circular buffers of weather radars and the generic locations of airports with air traffic control towers, respectively – were used. Data access issues like these underscore the need for continued consultation with affected stakeholders, be they Federal, state, local, tribal, private, or any other categorization.

Chapter 4

Results

4.A. Results Overview

After multiplying all of the aforementioned layers, the map shown in Figure 3A was created, depicting the overall composite wind energy feasibility scores across the entire state of Ohio. Figure 3B shows the same information but symbolized into color bins in increments of 0.1 from zero to one. As mentioned above, some animal species that the existence of a wind farm may impact are present in the entirety of Ohio, thereby lowering the score for the vast majority of the state. While this reflects an overall feasibility score, Figure 3C offers a relative score, with the most-feasible green color set to any score at or above 0.5. Finally, Figure 3D displays the composite dataset with a binary color scheme, with grid cells having values of 0.5 or greater being split out from all others to indicate the most feasible regions.

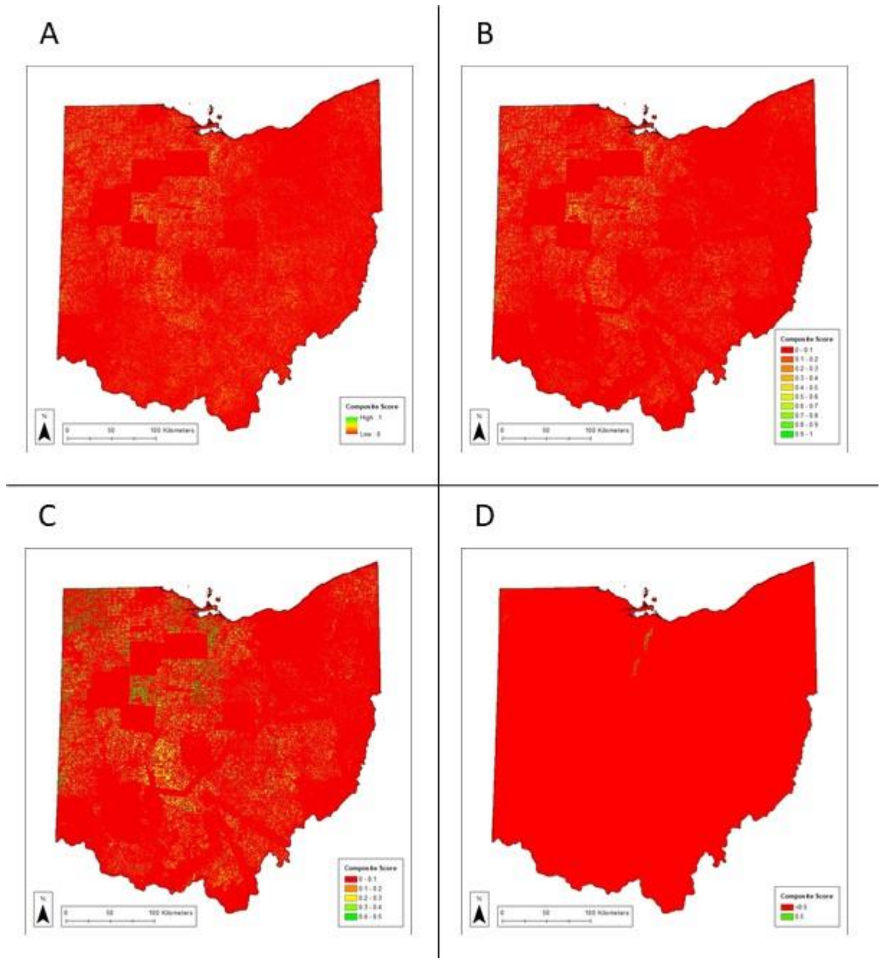

Figure 3 - (A) Composite score symbolized with a spectrum, (B) Composite score symbolized in absolute color bins, (C) Composite score symbolized in relative color bins, (D) Composite score symbolized with binary categorization split at 0.5

These symbology alternatives offer utility for different contexts. The binary color scheme in Figure 1D provides the most rudimentary, macroscopic assessment, useful for the most initial stages of site scoping. Binning the dataset in one tenth increments with the colors extending to one (Figure 1B) offers a holistic representation of wind energy opportunities for developers seeking to determine if wind energy is feasible at all, whereas capping the color spectrum at the highest actual value (Figure 1C) offers a relative score for developers already intent on construction simply seeking to identify the most ideal options. Unbinning the dataset and providing a full spectrum (1A), meanwhile, provides the most detailed scoring.

4.B. Map Analysis

Zooming into the county level, some of the driving patterns that will limit wind farm siting become apparent. Figure 4A and Figure 4B show a comparison of an urbanized region, Franklin County (home to Columbus), and a more rural area, Williams County, in the northwest corner of the state, respectively. Unsurprisingly, the vast majority of Franklin County has minimal grid scale wind energy development potential, given its high population (and therefore structure) density, well-developed road network, and other hindrances. Williams County, however, shows far more development potential. While the buffers of the county's primarily gridded road network clearly stand out against the background alongside some of the county's population centers, there are clearly pockets between these minimally developable areas where there is potential, albeit tempered by the aforementioned species ranges that are omnipresent throughout the state and suppress any achievement of a composite score near one.

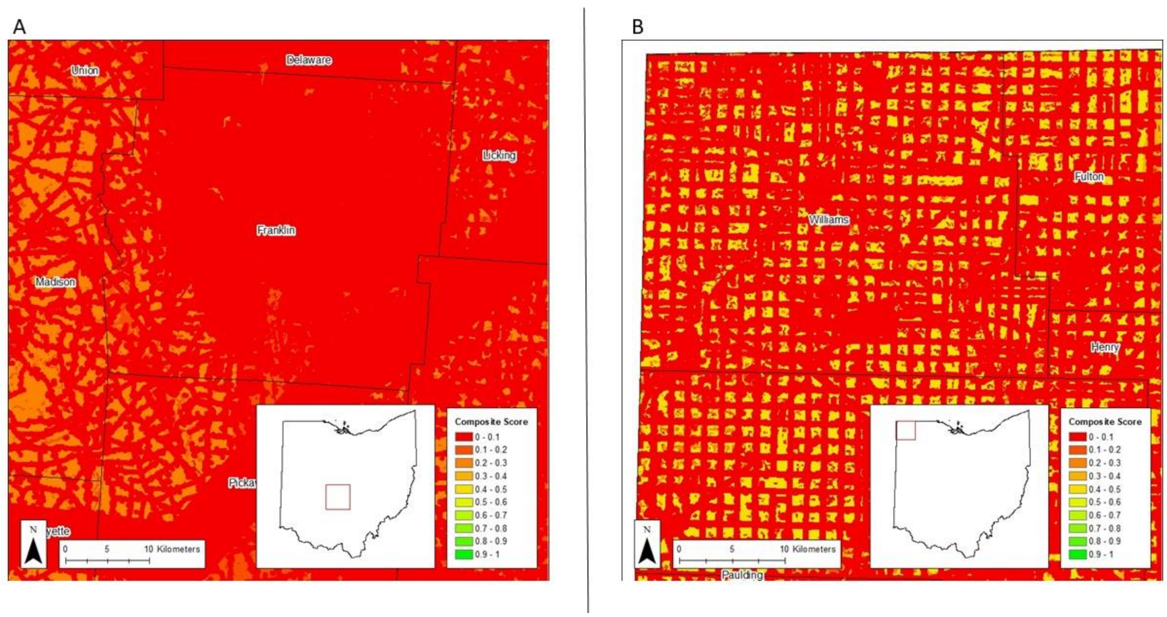

Figure 4 - (A) Detailed view of the absolute composite score for an urbanized county: Franklin County [Columbus], (B) Detailed view of the absolute composite score for a rural county – Williams County

Focusing on Williams County, Figure 5A shows the relative composite score, while Figure 5B shows the same dataset with the 990-foot roadway buffers removed. Clearly, roadway setbacks are one of the key limitations in this county and those with similar land use characteristics, although it should be noted that this mask layer would generally overlap with other masks, notably building setbacks. While this model offers a pathway toward identifying and targeting areas that are most developable, the idiosyncrasies of all potential sites must be understood in granular detail, particularly if development is being considered in areas with relatively moderate composite scores.

Figure 5 - (A) Detailed view of the relative composite score for a rural county – Williams County, (B) Detailed view of the relative composite score for Williams County with 990 foot roadway buffers removed

The datasets used to compile this model offer pertinent information. The area highlighted by the purple rectangle in Figure 6A is shown in more detail in Figure 6B to offer an example. Much of the low-potential area outside of the roadway buffers in this region corresponds to a listing from the protected areas input. The original, associated shapefile identifies this as the Lake La Su An Wildlife Area, administered by the State Department of Natural Resources. This model identifies the broadscale difficulty of developing in an area such as this, but, should wind farm development nevertheless be pursued in an area such as this, further due diligence and stakeholder engagement would certainly be warranted.

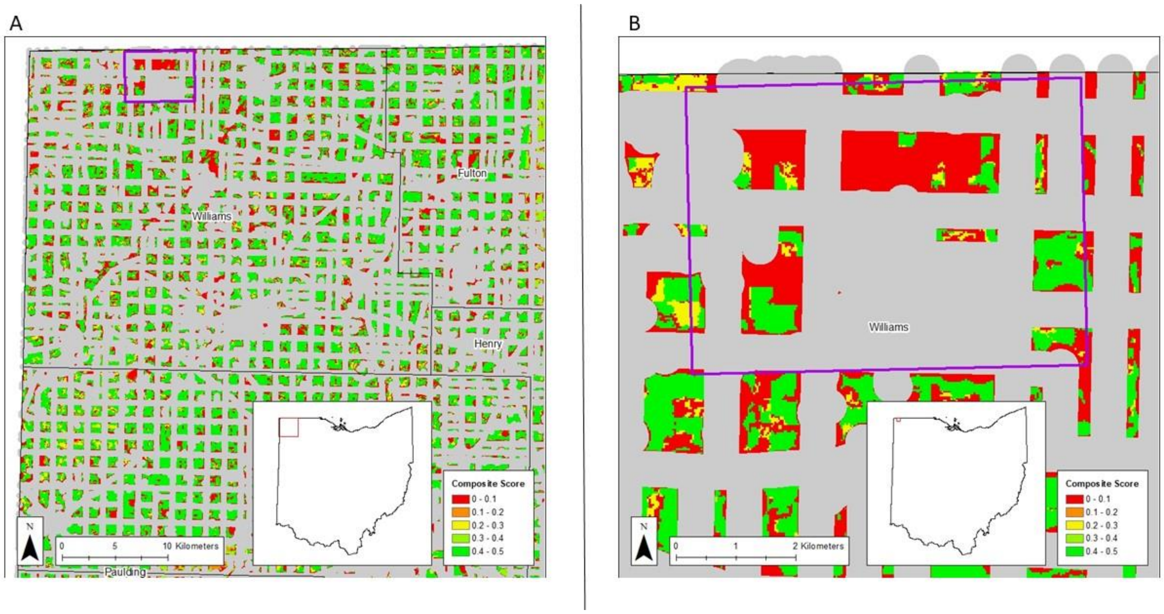

Figure 6 - (A) Extent indicator showing area of focus in Figure 6B, (B) Area of focus with examples of road buffers, low-feasibility areas, and high-feasibility areas

Focusing now instead on an area the model indicates is more fit for wind energy development, the green area outlined in blue in Figure 7 (note the "Focus Area" callout bubble) covers approximately 104 acres, or roughly 420,800 square meters. The average rotor diameter in the U.S. Wind Turbine Database among wind turbines for which a value is recorded – the 5RD and 10RD buffers for which were used as mask and spectrum layers above, respectively – is approximately 96.98 m. Therefore, if a rotor diameter of 100 meters is assumed and the same five rotor diameter separation (2.5 rotor diameters around each wind turbine) that was used as a mask layer above is used to minimize wake effect impacts, then each wind turbine requires roughly 196,349.5 square meters of space. Accordingly, the area outlined in blue could potentially accommodate two wind turbines with these dimensions. This may become increasingly overestimated as average wind turbine dimensions evolve; Lawrence Berkeley National Laboratory's 2022 Land-Based Wind Market Report, for instance, notes that the 2021 mean rotor diameter was 127.5 meters. Larger turbines could potentially be accommodated in the same area by optimizing turbine placement near the periphery. Further due diligence accounting for topographic considerations, meteorological assessments, and wake effect modeling could influence wind turbine spacing decisions, potentially reducing the plausible number of turbines within this parcel. Determining a precise plausible turbine count is beyond this study's scope, but this methodology can be used to develop a potential range for possible energy production capacity. Coordinating this area in tandem with adjacent areas with relatively high feasibility scores would allow for expansion of a hypothetical wind farm's turbine count and cumulative rated capacity to meet a developer's overall production targets.

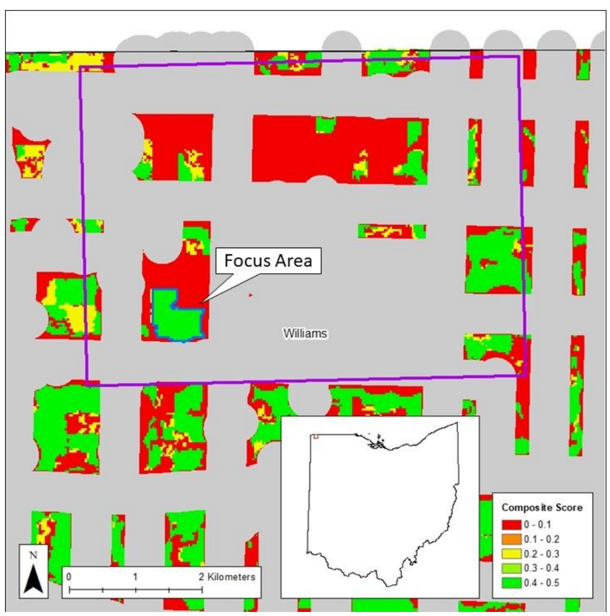

Figure 7 - High feasibility focus area (blue outline)

This methodology provides a high-level overview of wind energy feasibility. It is primarily intended to be used to funnel initial site identification efforts – the Prospecting stage, as defined by Tegen, et al. – towards sites more likely to be successfully developed. The process is flexible enough, however, to be of use for case-specific analyses. In practice, for instance, there is a key omission from the layers incorporated into this model: the receptiveness of the landowners to whom the land on which any wind farm would be built belongs. This layer cannot be included for a general scoping process like this one, as such a consideration would need to be factored in at a later stage of the development process after stakeholder communication has been initiated. However, developers following this methodology could define their own zero-scored mask layer representative of parcels owned by unreceptive stakeholders. Conversely, parcels owned by receptive landowners could be assigned coefficient scores in excess of one, offsetting some of the calculated hindrance from the spectrum layers. Similarly, any site-specific idiosyncrasies not incorporated into this broadscale model could also be incorporated as separate layers on an ad hoc basis.

4.C. Statistical Analysis

Figure 8 provides a bar chart of all grid cell values in the binned raster capped to the calculated values. Clearly, the vast majority of the state of Ohio is minimally feasible for wind energy development; 88.04% of the grid cells within the state were calculated to be in the lowest bin, 5.42% received ones, 3.04% received twos, 2.17% received threes, 1.25% received fours, and only 0.07% were grouped into the highest bin. Especially given that any values closer to one are omitted, this chart elucidates the difficulty of the wind siting task in the state of Ohio.

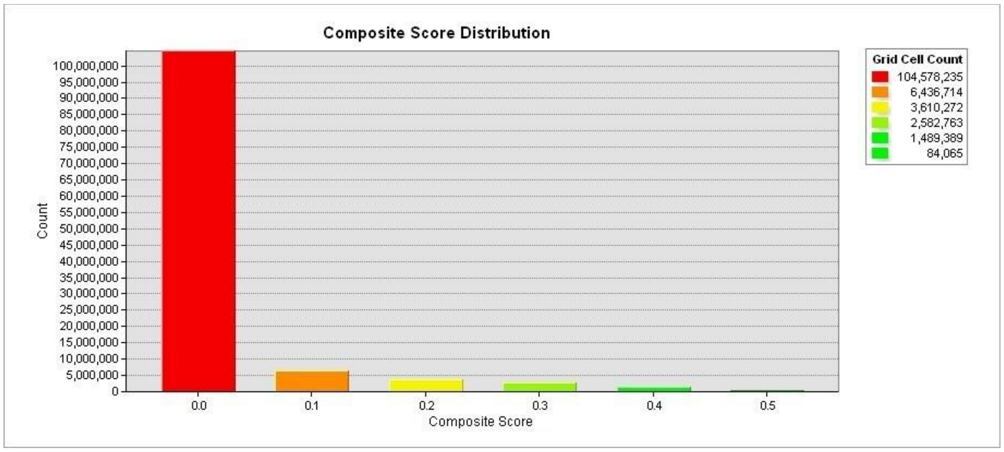

Figure 8 - Overall prevalence of each relative composite score bin

Nevertheless, difficult is far from impossible. The output from this model indicates that there are sites feasible for development of onshore wind in the state, and the methodology developed above can be used to pinpoint their locations. With grid cell sides measuring in at 98.425 meters, derived from the land cover snap raster, each of these grid cells represents 9,687.5 square meters of space. The 84,605 grid cells in the highest bin, therefore, represent over 819.6 million square meters. Under the one-hundred-meter rotor diameter and 5RD offset assumptions used above, with 196,349.5 square meters being required for each wind turbine, this small percentage of Ohio's area still leaves room for 4,174 wind turbines. Certainly, there are still limitations, most notably identification of landowners interested in leasing land for a wind farm, that developers must address. Moreover, each grid cell will require assessment of the potential impacts to the species that lower all of Ohio's composite scores. Optimization would be required, meanwhile, to quantify the tradeoffs between larger wind turbines' extra output and larger footprints. Clearly, however, even in the relatively miniscule portion of the state with the highest feasibility scores, there is immense wind energy production potential.

Chapter 5

Conclusion

The siting considerations incumbent on wind farm developers are numerous and, in many ways, onerous, but they are not insurmountable. The results of this case study showing that no area within the entire state of Ohio is without at least one wind energy siting limitation – largely owing to the expansive habitats of disproportionately impacted animals – is indicative of the importance of this type of analysis. Species range datasets and geospatial boundaries for other protected areas provide a topline overview of where avoidance of such impacts will be most cumbersome. The twin goals of short-term environmental impact avoidance and long-term decarbonization, itself an effort targeted at preserving more livable ecosystems for both people and animals alike, must be coordinated in tandem, neither one fully superseding the other.

For the residents of the regions most suitable for wind energy, strict livability is, of course, not the baseline consideration; developers must also account for the quality-of-life impacts from wind farm construction and operations. Population density data provide a first order approximation of the potential for pushback, but not necessarily its vehemence. Even the most sparsely populated regions can have unique cultural and socioeconomic characteristics that produce different levels of openness to development. Regulatory siting limitations imposed by local, state, tribal, or federal entities with land use jurisdiction are key to addressing these residents' concerns. Even when such regulations are not directly enshrined in law by a statehouse, county commission, municipality, or other regulatory body, simple practicality imposes some natural setbacks. Developers must therefore be aware of the geospatial ramifications of such avoidances.

Wind energy must also coexist with other public services, technologies, and existing realities of the modern economy. Most notably, wind farms' energy naturally must be delivered onto the grid. This makes developers reliant on the presence of interconnection options, which evolve with the buildout or upgrading of transmission infrastructure. Wind turbines' interactions with other technologies and the regulations supporting their safe use must be accounted for to maintain continuity of the services achieved through the technologies' use. Safety of low-level aircraft operations in the vicinity of a wind farm, whether they be for passengers, cargo, military, or any other use case, must be maintained. Particularly in close proximity to airports, wind farm developers are likely to encounter notable regulatory burden. The radars that track these aircraft or the weather through which they fly present a separate set of technological interactions warranting careful impact assessment. Developers' cognizance of these existing cooperation requirements necessitates intricate spatial planning efforts to minimize or mitigate deleterious impacts while maintaining technical and economic feasibility.

Finally, and perhaps most basically, developers must account for the physical realities of each site they consider. This must be done in a full, three-dimensional manner. Limitations exist below the surface, warranting appropriate geological assessments; at the surface, requiring detailed topographic and land cover analyses; and above the surface, where the wind itself actually spins the turbines' blades. Wind resource and obstruction assessments, capacity factor calculations, geological compatibility reviews, and topographic limitations all must be incorporated into any mapping effort seeking to identify an ideal wind farm site.

By factoring all of these considerations into a single geospatial model, this analysis seeks to answer a basic question: which locations within the study area will require the least effort to develop a wind farm. Grid cells with low but nonzero composite scores may well present opportunities if interested landowners are identified and other stakeholders' concerns are addressed. Developers seeking to prioritize due diligence reviews of potential locations in the most efficient manner possible would be served well, however, by knowing ahead of time the overall level of company resources and employee hours likely to be required by any potential site. This model provides a first order approximation of this criterion. By regularly updating this model as the characteristics of the input layers themselves morph over time, this methodology can serve to guide wind farm developers toward the decisions most likely to result in success, simultaneously minimizing wasted resources and accelerating overall decarbonization efforts.

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