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Pathways Forward for Onshore Wind Energy in the State of Maryland: A GIS Multi-Criteria Analysis

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Pathways Forward for Onshore Wind Energy in the State of Maryland: A GIS Multi-Criteria Analysis

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For

Master of Science In
Geographic Information Science

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Abstract

This study examines pathways forward for onshore wind energy in the State of Maryland. To meet its decarbonization goals, Maryland needs to quickly transition its electric grid away from fossil fuels. The state is currently in the process of developing offshore wind farms that have the potential to represent a significant source of renewable energy. However little progress has been made in expanding Maryland’s onshore wind energy production capacity. Using a multi-criteria GIS analysis, this study found that there is a limited but not inconsiderable area in the state that could be suitable for wind farms of varying scales that are worth investigating for potential future energy projects.

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Introduction

Wind energy is a well-established part of the United States' energy future. In 2020 alone, the United States added 16,836 megawatts (MW) of onshore wind power capacity, with 24.5 billion U.S. dollars invested in the industry nationwide (Wiser et al., 2021). The goal of this study is to provide insights into potential pathways for reducing carbon emissions in the State of Maryland by investigating sites for onshore wind energy projects. According to the U.S. Department of Energy’s (DOE) Office of Energy Efficiency and Renewable Energy, more than 50% of Maryland’s grid energy make up in 2021 came from fossil fuels, specifically coal and natural gas. For the state to meet its goal of net-zero carbon emissions by 2045, it must rapidly decarbonize its electric grid and increase its current grid capacity to meet the electricity needs from of a carbon free economy. There is a clear need to transition more of Maryland’s grid energy capacity away from fossil fuels. The purpose of this analysis is to assist in the transition to renewable energy by investigating the availability of suitable sites for new wind farms in the state using a multi-criteria geographic information system (GIS) analysis.

Background

According to the United States Energy Information Administration (EIA), the U.S. had 4.12 trillion kilowatt hours (KWh) of utility-scale electricity generation capacity in 2021. Fossil fuels like natural gas and coal accounted for 61% of this capacity, nuclear power accounted for 18%, and renewable energy sources, like wind, solar, and hydropower, accounted for just 20%. Wind energy alone accounted for 12% of total national generation capacity in 2021, up from just 1% in 1990, which makes wind a significant source of the United States’ utility-scale capacity and the country's single largest source of renewable energy, ahead of hydropower. Wind is also the country's fastest growing energy source, with 42% of added capacity in 2020 coming from wind power (Wiser et al., 2021). However, even though wind replaced as much as 1.1 billion tons of carbon dioxide emissions globally in 2020 (Lee & Zhao, 2021) and the drastic rise in the percent of national capacity that is accounted for by wind and other renewables, renewable energy still falls behind natural gas and other fossil fuels as a percentage of overall national power generation capacity.

In the United States, wind energy is largely concentrated in the midwestern states. Iowa, Kansas, Texas, and Oklahoma together accounted for 56% of U.S. wind power generation according to the EIA. However, utility-scale wind generation is present in 48 of 50 states, including Maryland, with wind accounting for over a quarter of power generation in five states - Iowa, Oklahoma, Texas, Kansas, and Illinois. In Maryland, wind accounts for a small percentage of grid energy capacity, with just 2% of Maryland's energy in 2021coming from wind energy. According to the DOE's Office of Energy Efficiency and Renewable Energy, 52% Maryland's energy comes from fossil fuels emitting sources, specifically coal and natural gas. Maryland largest source of carbon-free energy is nuclear power, which accounts 37% of grid energy. However, nuclear power is still considered an extractive source of energy because it requires uranium fuel, despite being carbon free. It is also unlikely that more nuclear power plants can be brought online quickly enough to meet the state's needs and its decarbonization goals, which means the state needs to transition to renewable energy sources. Currently, renewable energy accounts for just 9.27% of Maryland's grid energy capacity. Most of this power comes from hydroelectricity, with wind accounting for just 1.3% of the state's total grid energy makeup.

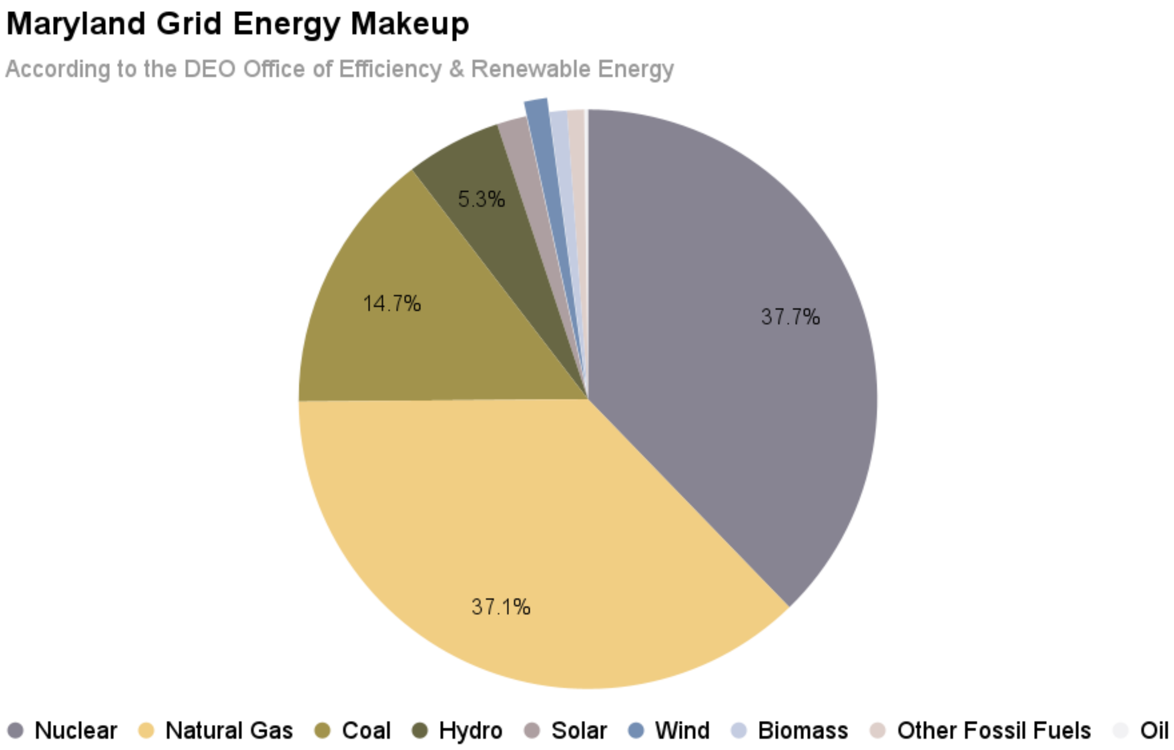

Figure 1: Maryland Electric Grid Mix

The majority of Maryland's in state wind power comes from two wind farms, Criterion Wind and Four Mile Ridge, which are located in Garrett County, in the westernmost reaches of the state. Criterion Wind began operation in 2010 and consists of 28 wind turbines with a combined capacity of 70 MW. Four Mile Ridge came online in 2014 and has a capacity of 40 MW. Maryland is also home to a single smaller-scale wind farm, which consists of three turbines located in Talbot County and operated by the Talbot County Department of Public

Works. Together the three turbines have a combined capacity of 300 kilowatts (KW), or 0.3 MW, and provide power to the Talbot County Bio-Solids Utilization Facility. Finally, there is a single turbine at the Crisfield Wastewater Treatment Plant. Combined, these four projects give the state 110.3 MW of wind-based energy production capacity.

At the time of writing, there were three major proposals for additional wind power production in Maryland. There is a single proposal for an additional onshore wind farm named Great Bay Wind Energy Center. The proposed project site is in Westover, Maryland, on the state's Eastern Shore, and will have a capacity of 100 MW. However, the Great Bay Wind Energy Center has not received final approval at the time of writing, and there are no indicators that the proposal will come to fruition. There are also two offshore wind energy projects under development in the waters off the state's coast: MarWin, under development by U.S. Wind, and Skipjack, under development by Ørsted. MarWin will consist of 22 turbines with a capacity of 300 MW and is planned to come online in 2025. Skipjack will have a capacity of 120 MW and should come online in 2026. Although Skipjack will technically be located off the coast of Delaware, it will provide power to the entire Delmarva Peninsula. Should all three proposals come to fruition, they have the potential to add an additional 420 MW of off-shore generation capacity and 100 MW of on-shore capacity to the state, though it is unclear how this will contribute to Maryland’s grid power makeup.

There are several challenges facing wind energy in Maryland. One of the more critical issues is that the state has a very low estimated production capacity. One study estimated that Maryland may have an onshore production capacity of approximately 3,632 gigawatt hours (GWh) (Lopez et al., 2012). This means the state has low wind energy resources compared to other states with higher average wind speeds and more suitable locations for wind turbines, however, this is still considerably greater than the state's current level of production. Maryland also has a high population density compared with states where wind power is more prevalent, meaning that there is less space available for large wind farms and more opportunities for conflicts with stakeholders over the potential impacts of wind energy projects. With these challenges in mind, this study also considers suitable locations for smaller community-style wind energy projects that would consist of fewer turbines and have lower output capacity but may face different economic and social pressures.

Study Area

With an approximate area of 32,000km^2, Maryland ranks just 42nd of the 50 states in terms of area, however, its limited size doesn’t diminish the state's geographic diversity. This study consists of a statewide analysis and so isn’t limited to a single land cover type or geography. The exact study area for this project was defined by Maryland’s political boundaries. It excludes the District of Columbia and is bound to the state’s Atlantic coastline, which means that the study area does not include any offshore areas where wind farms are currently under development or may be developed in the future. However, the study boundary does include the state’s intercoastal marine areas, the Maryland portion of the Chesapeake Bay, and the Potomac River. The study assesses the state holistically, meaning the study area spans all of Maryland’s internal boundaries such as those between the state's 23 counties and the City of Baltimore. However, the county boundaries were used to subset the study area for a more detailed analysis of the study results. These boundaries are limited by coastlines, including internal coastlines, meaning that they exclude marine areas and major bodies of water. Both boundaries were defined for using spatial data from the Maryland Highway Administration, which was retrieved from the MD GIS catalog (Table I).

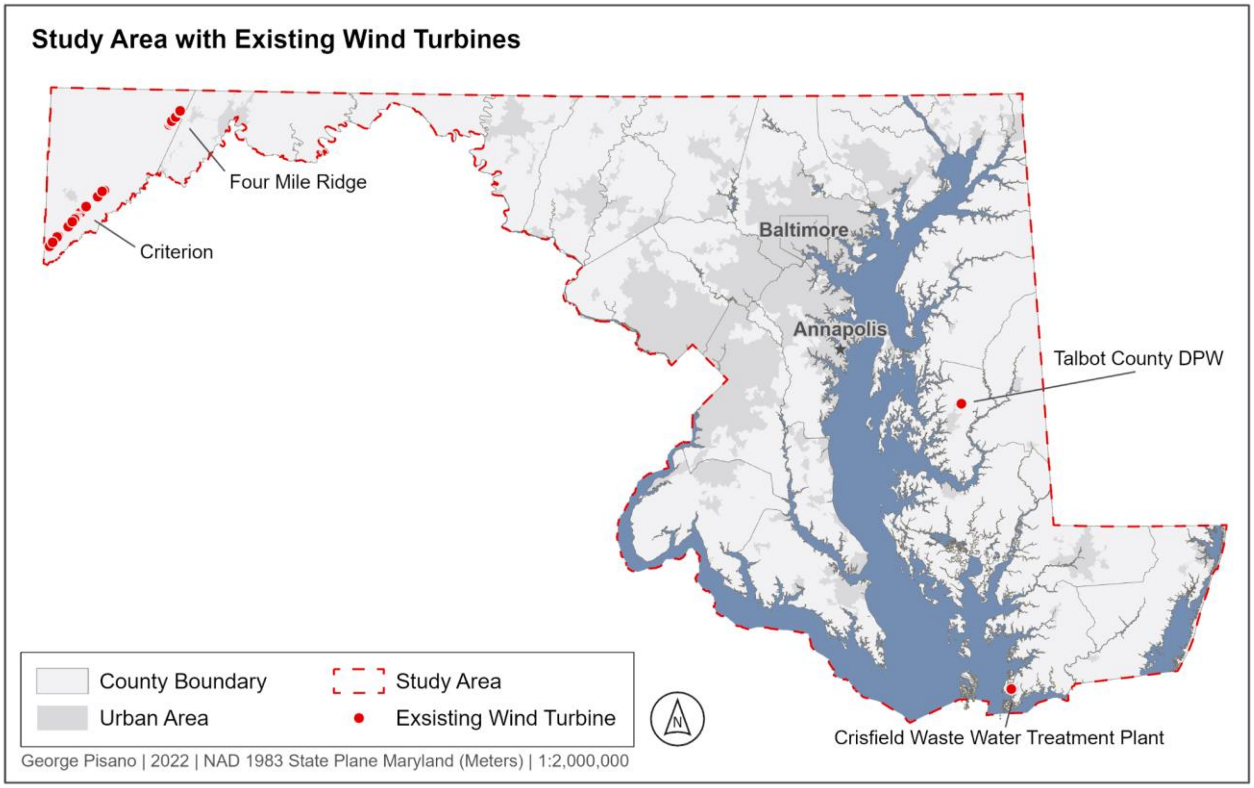

Figure 2: Study area with existing wind turbines and urban areas.

Table I: Data Used to Define Study Area

Data	Source
Existing Wind Turbines	Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database v5.2: U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.
Study Area	Maryland State Highway Administration. Maryland Political Boundaries - State Boundary. Baltimore, Maryland: 08/07/2017.
County Boundaries	Maryland State Highway Administration. Maryland Physical Boundaries - County Boundaries (Detailed). Baltimore, Maryland: 12/21/2017.

Literature Review

Part I: Criteria and Elimination Areas

This study began with a review of literature focused on wind turbine site suitability, which included six recent GIS-based multi-criteria studies. These studies include a set of discrete criteria that contribute to wind turbine suitability and form the basis of the analysis. Most studies begin by identifying elimination areas, or areas that are easily identifiable as impractical for development as wind turbine sites. This is typically accomplished by identifying constraints based on the criteria that prevent an area from being practical for wind turbine development. These constraints are often not limited to the areas occupied by a particular elimination factor but may also include a buffer area that is constrained due to its proximity to the elimination factor. For example, all the studies reviewed for this analysis eliminate urban and/or residential areas with an additional buffer zone around those areas. This can be for safety reasons, a matter of regulation, and/or because wind turbine proposals for those areas are likely to face high social opposition. These criteria then form the basis for a preference analysis that assesses the suitability of the remaining area for wind turbines. Together the six principal studies reviewed for this analysis include a total of 22 criteria that were used to assess both elimination areas and form the basis the suitability assessment process.

Table II: Criteria Identified by The Reviewed Studies

Wind Resources	Elevation	Transmission Lines
Urban Areas	Max Slope	Roads and Railroads
Residential Areas	Water	Fault Lines
Industrial Areas	Quarries	Mining Sites
Protected Land	American Indian Reservations	Farmland
Wetlands	Karst Geology	Military Bases
TV and Radio Towers	Archaeological or Cultural Sites	Tourist Area
	Airports and Airstrips	

Generally, criteria fall into four categories: physical, safety, economic, and environmental criteria. However, many do not neatly conform to a single category. Safety criteria typically deal with possible dangers posed by wind turbines that are often managed using safety buffers. For example, safety distances are used to mitigate danger from debris thrown off by the turbines, such as ice throws in the winter, or electromagnetic interference. Safety criteria are sometimes dictated by regulations, which can pose a significant challenge or limitation for studies that deal with a large, border-spanning, study area. For example, one study (Arnette & Zobel, 2011), with a focus area that spanned the borders of four U.S. states, noted disparities in the regulations not only between states but also between the different counties and municipalities within those states. Military bases and airports are another regulator concern for wind turbines. One study noted that the tall structures of wind turbines pose a physical obstruction to air traffic near airport and electromagnetic interference from the turbines can disrupt the communication and navigation equipment used by aircraft (Aydin et al., 2010). As a result, wind turbines are typically prohibited in proximity to those locations, which then need to be accounted for as elimination areas.

Economic criteria tend to deal with factors that increase the costs associated with building the turbines as well as factors that influence their production potential once constructed. This includes accessibility factors that affect construction costs like access to roads, steepness of the terrain, or the presence of existing energy infrastructure. For example, one study considered a slope of 10% or greater as infeasible for the construction of wind turbines (van Haaren & Fthenakis, 2011). Another study considered slopes up to 20% to be acceptable despite increases in construction cost as the slope increases (Arnette & Zobel, 2011). Other factors affect the economic success of the turbines once they are built. For example, average annual wind speed (AAWS) or wind power density (WPD), which are measures of wind resources. Surprisingly, just two of the studies reviewed here (Peri & Tal, 2020) & (Miller & Li, 2013), included elimination criteria for minimum wind resources. However, in most cases, wind resources were factored into the suitability process later in the analysis.

Physical criteria consist of land cover, terrain, or geological factors that affect site suitability. All the studies reviewed for this analysis include exclusions for urban and residential areas. Other common land cover-based exclusion zones include forests, farmland, and bodies of water like lakes and rivers, which may prevent or increase the cost of turbine construction. Typically, the land cover types that are considered unsuitable is dictated by the circumstances of the study area. For example, just one study avoided placing turbines in productive farmland, because farmland is scarce in their study area, in Greece (Konstantinos et al., 2019). The terrain of the landscape can also have a significant impact on the force and production potential of the wind. For example, one study accounted for two effects in their study: the hill effect and the wind tunnel effect (Abdelaziz et al, 2012). The hill effect occurs when the wind is accelerated as it passes over hilltops and the tunnel effect occurs when the wind is accelerated as it passes through a narrow valley. Both phenomena can increase energy production, however, those benefits come with detriments because irregular terrain can cause turbulence that decreases energy production and turbine life. Power production can also be affected by elevation because the thinner air at higher elevations can reduce turbine efficiency (Atici et al., 2015). Finally, Geology can also be a factor in wind turbine site selection. For example, one study considered the impact of Karst geology (van Haaren & Fthenakis, 2011). This is because the porous ground, which has an occurrence of caves, is often unsuitable for turbine foundations, which transfer high loads into the ground.

Finally, environmental criteria assess the effect on the ecology of the landscape that will host the turbines. For example, sensitive habitats such as wetlands or important bird areas are often eliminated because of their high potential to be damaged or disturbed by the presence of turbines. Some areas may already be protected by statutes, such as national parks or designated wilderness areas, but many are not. Nevertheless, they are important to the local ecology and should be considered when designing a study. One of the most common environmental concerns associated with wind turbines is their effects on bats and birds. Some studies (Peri & Tal, 2020) & (van Haaren & Fthenakis, 2011) consider birds when selecting their criteria. One study (van Haaren & Fthenakis, 2011) even used data from the Important Bird Area (IBA) database from the Audubon Society to create buffer zones around significant bird habitats to help reduce bird mortality from potential future wind turbines. This strategy was employed by another study (Peri & Tal, 2020) which noted that the placement of wind turbines plays a significant role in reducing bird and bat mortality rates. While some studies do not place a heavy emphasis on protecting birds when selecting and weighting criteria, there appears to be general agreement that wind turbines do threaten avian species. The exact nature of that threat is a matter for further study, but it is still important to site wind turbines in a responsible manner that accounts for species vulnerability.

Ultimately the exact makeup of criteria depends upon the study priorities and the specific needs of a given study area. For example, one study, when examining site suitability in the state of New York, excluded areas within 3000m of American Indian Reservations, which was unique among the studies reviewed here (van Haaren & Fthenakis, 2011). Another was the only study to exclude productive farmland because it is somewhat scarce in their study area (Konstantinos et al, 2019). Of the 22 elimination criteria, only eight were accounted for in more than two of the studies and the actual application of these eight criteria was not consistent between studies. For example, one study excluded areas more than 15000m from the road network because constructing wind turbines in those areas may be prohibitively expensive due to the inaccessibility of the site (Konstantinos et al, 2019). In contrast, another study also considered the distance to roads as an elimination constraint. However, it eliminated areas within 100m of an existing road for safety reasons while not identifying a maximum distance from the road network (Miller & Li, 2013).

Table III: Elimination Criteria and Constraints Used Most by the Similar Studies Reviewed for This Analysis

	Peri & Tal, 2020	van Haaren & Fthenakis, 2011	Atici et at., 2015	Miller & Li, 2013	Harper et al., 2019	Konstantinos et al., 2019
Urban Areas	-	<2000m	<2000m	<1600m	<2000m	<1500m
Residential Areas	<500m	<1000m	-	No intersect >150 ppl/mi^2	-	<1000m
Protected Lands	No Intersect	No Intersect	<2000m	-	<2000m	No Intersect
Airports	<5000m	No Intersect	<5000m	-	<2000m	-
Slope	>20%	>10%	>10%	40 Degrees	40 Degrees	-
Waterbodies	No Intersect	<3000m (lakes)	<3000m (lakes)	No Intersect	-	-
Transmission Lines	-	-	>250M	-	<150M	>15000m & <85m
Roads and Railroads	-	<500m	<500m	<100m	<150m	>15000m & <85m

Part II: Preference and Selection

With their assessment criteria defined and their elimination areas identified, most studies then moved to the suitability assessment phase of their analysis. While most studies appear to follow a basic structure where they eliminate unsuitable areas then conduct their suitability assessment, it is important to note that not all studies follow this pattern. For example, one study did not separate the elimination areas phase of the analysis from the site preference phase. Instead, they used the elimination areas as constraints within their selection process (Miller & Li, 2013). However, most of the studies reviewed for this analysis identify elimination areas and then use those constraints to help focus the assessment portion of their study. The assessment process also tends to be narrower in scope than the elimination phase, with most studies using a smaller subset of the factors used for the elimination assessment or a smaller unique set of criteria to assess site suitable. In either case, the assessment phase tends to be narrower in scope than the elimination phase.

Often studies choose to assess suitably based on a particular vector. In all cases, this includes an assessment of the economic suitability of a particular site for wind turbines. However, most studies include additional suitability factors for their analysis. Some studies also include a separate assessment based on other factors that is then combined with their economic assessment. For example, one study (van Haaren & Fthenakis, 2011) conducted two preference analyses, one for the economic potential of the site, and the other for the ecological impact of the site, and then combined these two analyses into a final product. In other studies, all the suitability factors were assessed together. This strategy was also used in another study (Peri & Tal, 2020) that also balanced ecological responsibility and economic potential. Still another study (Harper et al., 2019), combined their economic assessment with an assessment of the social acceptance of their study area for wind turbines. This study largely assesses economic factors in its suitability analysis, while using the elimination phase of the constraint factors like environmental impacts of social acceptance. Some studies also further filter sites after they have been scored. For example, when identifying suitable areas, a final physical consideration for one study (Arnette & Zobel, 2011) was the minimum size of a suitable area. That study deemed that turbines require a minimum area of 40 acres, with viable sites requiring adequate space for at least three turbines.

Part III: Anthropocentric Concerns

Social and political opposition represents a significant impediment to any wind energy project; however, it is a challenging concern to quantify and factor into his type of analysis. There are countless anecdotes describing well-planned clean energy projects that failed because of opposition from both local stakeholders and outside pressures. Ironically, wind projects can often be the subject of green versus green conflicts where both detractors and supporters of the wind energy proposal claim that they are attempting to protect the environment, however environmental concerns are far from the only motivation for opposition to wind turbines. One study that examined social opposition to wind turbines identified 13 common causes for social opposition (Table IV) that were characterized as environmental impacts, visual impacts, and socioeconomic impacts (Enevoldsen, 2016). In the United States the first offshore wind farm proposal, Cape Wind, gained local, state, and federal approval in 2009 and 2010, but eventually failed due to opposition from a patchwork of both local and national groups with a diverse set of motivations. A recent poll by the Pew Research Center suggests that public opinion in the United States on wind turbines is overwhelmingly positive with 77% of Americans in favor of expanding reliance on wind energy nationwide (Kennedy & Spencer, 2021). However, the fact remains that when it comes time to construct turbines, in many cases, the dominant attitude appears to be “not in my backyard,” with wind turbines being popular in concept but with few people willing to host the turbines in their community and shoulder the external effects that are associated with them. This is not a uniquely American issue; for example one study found that community opposition, at all stages of development, is one of the most common reasons wind energy projects in Sweden fail (Enevoldsen & Permien, 2018).

Table IV: Causes of Social Opposition to Wind Turbines Identified By (Enevoldsen, 2016).

Environmental Impacts:	Impact on flora and fauna health, Reduction of wildlife, Felling of trees.
Visual Impacts:	Size and shape of wind turbine, Number of turbines, Flicker effect, Disruption of landscape.
Socioeconomic Impacts:	Tourism, Property and land values, Benefits to the local community, General lack of information, Market acceptance, The number of wind projects.

While it is easy to ascribe selfish or misguided motives to those are unwilling to host wind turbines in their community or do not wish to live near wind turbines, it is important to remember that wind turbines do come with external impacts that will be felt by the communities who host and these impacts are not yet fully understood (Peri et al., 2020). However, they include impacts such as visual and auditory impacts, like noise pollution or flicker effects, which is a strobing effect caused by the rotation of the turbine blades in front of a light source. Ultimately, the true impact of wind turbines is, to an extent, a matter of the person, circumstances, and even opinion. For example, notes that to some wind turbines disrupt the landscape, but to others they represent a more environmentally friendly future and are a sign of progress (Enevoldsen & Permien 2018). Interestingly, there is some evidence that a negative outlook on wind turbines may predispose an individual to experiencing negative wind turbine effects, which suggests that these effects are at least partially somatic (Karasmanaki, 2020). However, an extensive review of studies indicates that wind turbines can cause diminished quality of sleep in those exposed to the low vibration of turbine noise (Karasmanaki, 2022).

Of the studies reviewed for this analysis, many do not mention social or political opposition as a factor in their decision process. However, they do incorporate criteria that are associated with that opposition. For example, two studies (Harper et al, 2019) & (Konstantinos et al, 2019) incorporated factors such as important cultural, historic, and archeological sites, or important tourist areas into their elimination and preference criteria. Others (Peri & Tal, 2020) explicitly incorporate social opposition into their decision process. However, all the studies reviewed here place the turbines away from urban and residential areas to limit their potential impact on the local population. In some places, these setback distances are determined by regulations, for example in Garrett County Maryland the minimum setback distance for a wind turbine is related to the height of the turbine structure. However, regardless of the regulatory environment, implementing setback distances to mitigate noise and flicker effects from impacting host communities appears to be simply a matter of best practice.

The site selection process is only one aspect of mitigating external impacts from wind turbines. Improvements to turbine design and construction can help to mitigate turbine noise and increase acceptance. For example, one study which conducted a choice experiment on wind turbine site preferences in Israel, found that the majority of respondents would prefer wind turbines to be closer and quieter rather than louder and farther away, which suggest social acceptance of closer turbines can be improved by investing in quieter turbines and noise dampening technology (Peri et al., 2020). Ultimately, the potential for social opposition to new energy projects depends upon the community at hand, their needs, and their attitude toward renewable energy projects, with most studies agreeing that educating the local population on the impacts of wind turbines and the steps taken to reduce their impacts is fundamentally important to encourage social acceptance of wind energy projects (Karasmanaki, 2022).

Methodology

This analysis uses a two-phase process that is largely inspired by two studies, (Miller & Li, 2014) & (van Haaren & Fthenakis, 2011). In the first phase, infeasible sites were identified and eliminated from consideration, in the second phase a suitability surface was created that assesses the study area based on factors that affect the economic viability of wind energy as well as ecological and cultural responsibility. This suitability surface was created using a weighted overlay, which is the same analysis method used by Miller & Li, 2014. These two surfaces were then combined into a single layer that shows wind turbine suitability and the constrained areas. This two-phase process is similar to the three-phase process used by van Haaren & Fthenakis, 2011, which uses a three-phase process that identified elimination areas, assessed economic suitability, and then assessed impacts on birds. This process has the benefit of being relatively simple and modular, which allows for changes to the model to improve the accuracy of the output and tailor the analysis to evolving priorities. The data for this analysis were retrieved from various sources in both raster and vector formats. Some processing was completed in the original format; however, all datasets were converted to raster format with a cell size of 30 meters for the actual analysis. This cell size was reached because it matches with land cover and elevation data used for this study, which was natively in raster format, and because it provides an adequate resolution for this study that allows for both reasonable resolution at a statewide scale while remaining detailed enough to examine specific counties. All the data processing and analysis for this study was completed in Esri's ArcGIS Pro Version 3.0.2.

Data Sources

This analysis was built almost entirely upon publicly available datasets from state and federal databases. Most of the data for this analysis was obtained via the State of Maryland's GIS database which brings together GIS data from several Maryland state agencies, as well as federal data pertaining to Maryland. Further data has also been obtained from the United States Census Bureau, and the United States Fish and Wildlife Service, as well as the United States Geographic Survey's National Map. In addition to data from governmental sources, the study also uses average annual windspeed data from the Global Wind Atlas. The Global Wind Atlas is "*a free, web-based application developed, owned, and operated by the Technical University of Denmark (DTU).*" Exclusively using publicly available data means that this study is low-cost and could easily be replicated or further built upon at a later time.

Phase I: Elimination Areas

Table V: Elimination Areas and Constrains Used for This Analysis

Category	Criteria	Constraint	Source Data
Terrain	Slope	>20%	U.S. Geological Survey. USGS 1 Arc Second. U.S. Geological Survey, 2022.
	Water	No Intersection	Jon Dewitz. National Land Cover Database (NLCD) 2019 Land Cover Conterminous United States. Sioux Falls, SD: U.S. Geological Survey, 06/04/2021.
	Wetlands	No Intersection	Jon Dewitz. National Land Cover Database (NLCD) 2019 Land Cover Conterminous United States. Sioux Falls, SD: U.S. Geological Survey, 06/04/2021.
Anthropocentric	Urban Areas	<2000m	Maryland Department of Planning. Maryland Census Designated Areas - Urban Areas 2010. Baltimore, Maryland: Maryland Department of Planning, 01/01/2010.
	Residential Areas	<500m	Maryland Department of Planning. Maryland Land Use Land Cover - Land Use Land Cover 2010. Baltimore, Maryland: Department of Planning, 01/01/201
	Other Developed Areas	No Intersection	Jon Dewitz. National Land Cover Database (NLCD) 2019 Land Cover Conterminous United States. Sioux Falls, SD: U.S. Geological Survey, 06/04/2021.
Protected Land	Federal Protected Land	No Intersection	Maryland Department of Natural Resources. Maryland Protected Lands - Protected Federal Lands. Baltimore, Maryland: Maryland Department of Planning,05/31/2018.
	State Protected Land	No Intersection	Maryland Department of Natural Resources. Maryland Protected Lands - DNR Owned Properties and Conservation Easements. Baltimore, Maryland: Maryland Department of Planning, 09/29/2017.
	Private Protected Land	No Intersection	Maryland Department of Natural Resources. Maryland Protected Lands - Private Conservation Lands. Baltimore, Maryland: Maryland Department of Planning,05/31/2018.
	Military Bases	No Intersection	Maryland Department of Natural Resources. Maryland Federal Lands - Federal Lands. Baltimore, Maryland: Maryland Department of Planning, 05/31/2018.

The first phase of this analysis identified elimination areas. In this analysis, these generally fall into three categories. First, are terrain-based elimination areas, or places where it is prohibitively complex or expensive to construct wind turbines due to terrain factors. These are places with high slopes, bodies of water, or wetlands. High-slope areas increase construction costs or may prohibit construction entirely. This is due to the large size of wind turbine components, which are difficult to transport over uneven or sloping terrain and may render some areas inaccessible for turbine construction or prohibitively expensive (van Haaren & Fthenakis, 2011). One study (Baban & Parry, 2001), surveyed turbine installers and found that areas with a slope greater than 10% may increase construction cost and complexity. However, areas with gradients of up to 20% may still be suitable for turbine construction (Peri & Tal, 2020). For this analysis areas with an average slope of 20% or greater were eliminated. This analysis also eliminates areas covered by water including bodies of water like rivers, and lakes. This includes eliminating major bodies of water that may be large enough to support wind turbines, namely the Chesapeake Bay because this analysis is focused exclusively on looking at the availability of sites for onshore wind turbines. This analysis also eliminates wetlands on the basis that they are important habitat areas, help to control flooding, and may be more difficult for construction. Both wetlands and waterbodies were identified by extracting the appropriate cells from the Multi-Resolution Land Cover Consortium data.

Next are anthropocentric elimination areas, which for this analysis are those places where it is not possible to construct turbines because the land is already developed or in use for human activities. This study identified and eliminated significant urban areas using the US Census's designated urban areas dataset. These urban areas could consist of any urban land uses, including commercial or residential areas. This dataset identifies the most densely populated or developed areas in the state but does not encompass all residential parcels or structures. To account for as many residential areas as possible, further residential areas were extracted from the state's land use dataset, which includes residential areas beyond the already identified urban areas. In addition to eliminating these areas, this analysis also eliminates buffer zones around urban and residential areas to mitigate external turbine impacts upon humans and reduce opportunities for political opposition. These buffers are 2000m for urban areas (Harper et al., 2019) and 500m for residential areas (Peri & Tal, 2020). Additional developed areas, beyond urban and residential areas, were extracted from the land cover data and eliminated on the basis that they are already in use and so are not available for development as wind turbine sites. Finally, this study also eliminates areas that have protected status that prohibits development. This includes state or national parks, conservation easements, historic places, or private conservation lands. This process was completed using three datasets from the Maryland Department of Natural Resources to determine the extent of state, private and federal protected lands. Also, this analysis eliminated military bases consideration using the from the Maryland Department of Planning. Once these three surfaces were created, they were combined into a single surface showing all elimination areas across the study area.

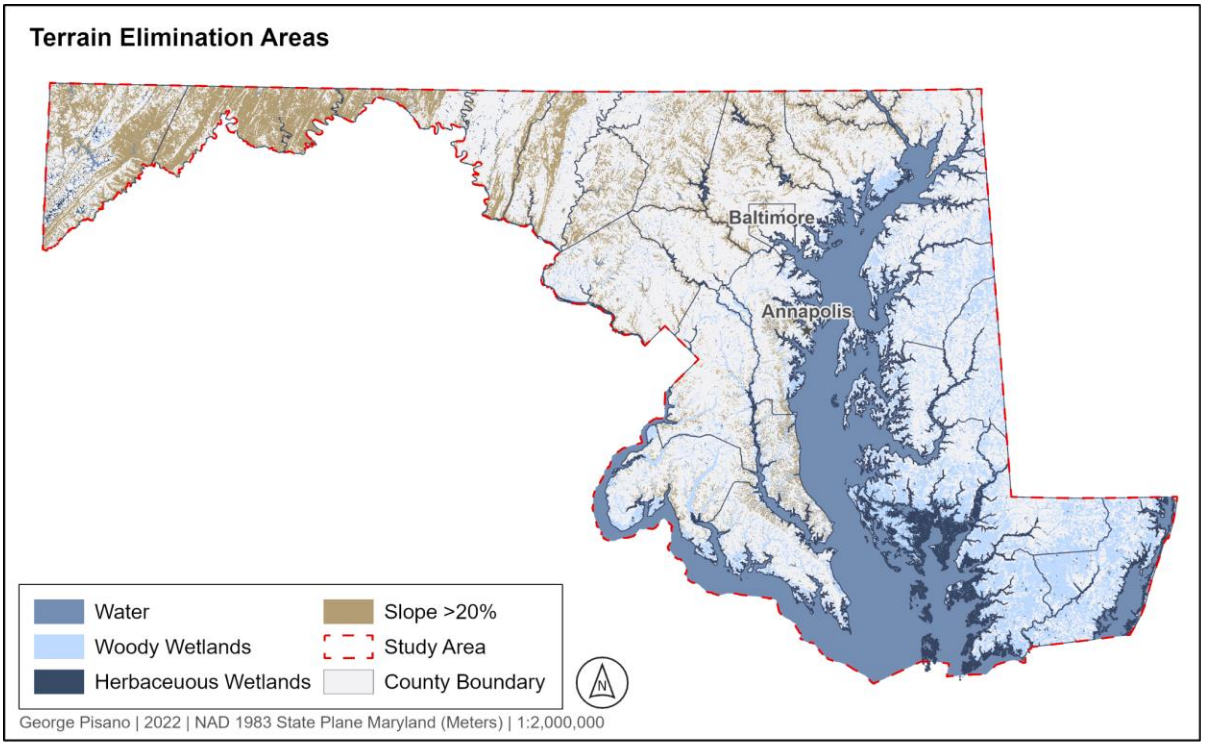

Figure 3: Terrain based eliminations areas.

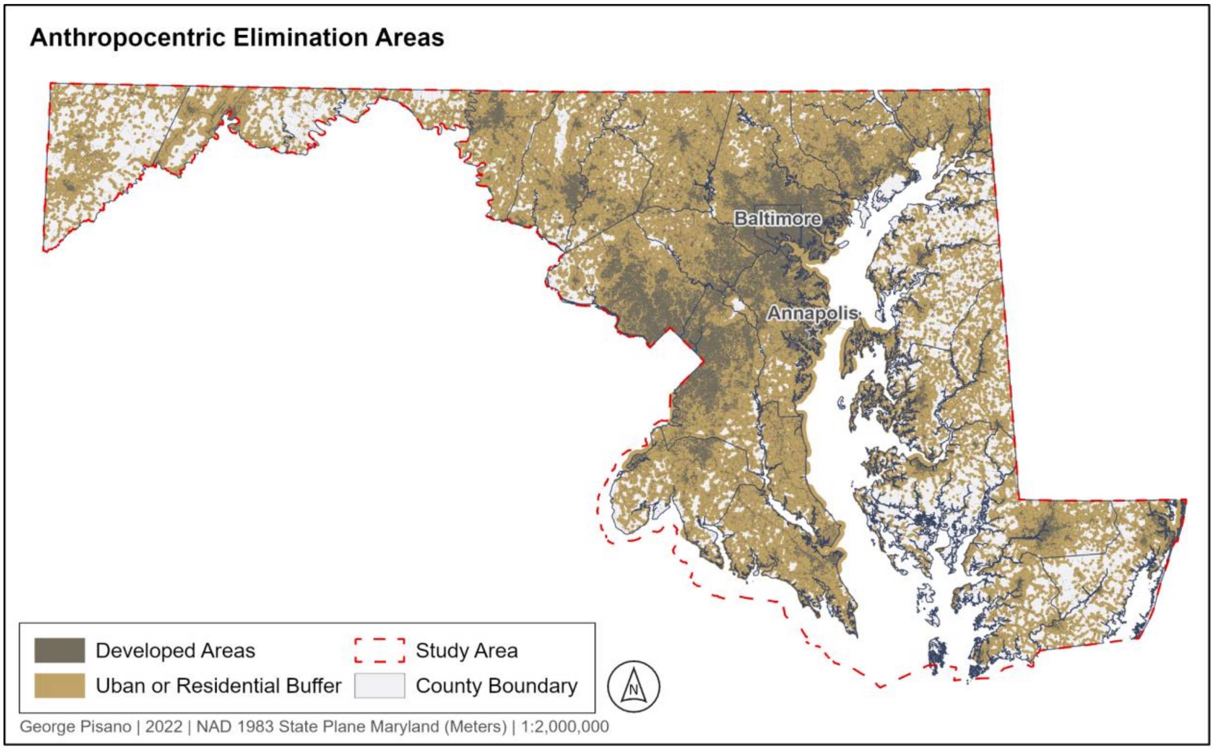

Figure 4: Anthropocentric elimination areas.

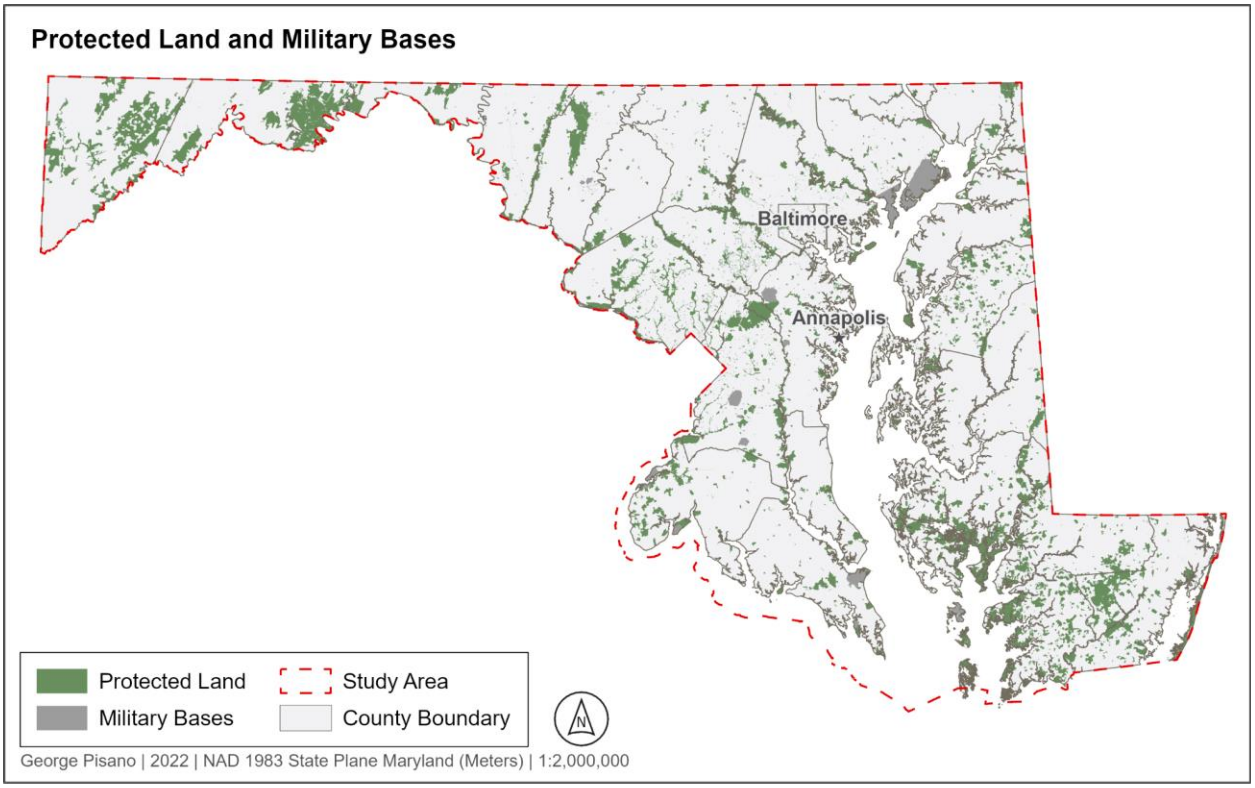

Figure 5: Protected land and military bases - elimination areas

Phase II: Suitability

Table VI: Site Assessment Criteria and Scoring

		SCORE					
Criteria	**Weight**	**4**	**3**	**2**	**1**	**0**	**Source Data**
Average Annual Wind Speed (m/s)	40%	≤ 10.5	≤ 9.5	≤ 8.5	≤ 7.5	≤ 6.5	Global Wind Atlas 3.0. Lyngby, Denmark: Technical University of Denmark, 2019.
Proximity to Transmission Lines (m)	20%	≤ 2500	≤ 5000	≤ 10,000	≤ 20,000	> 20,000	U.S. D.H.S. Homeland Infrastructure Foundation-Level Data (HIFLD). Electric Power Transmission Lines. Washington, DC: US Department of Homeland Security, 09/19/2018.
Land Cover	20%	Barren Land, Shrub / Scrub,	Pasture	Crops	Forest	Water, Wetlands, Developed Places	Jon Dewitz. National Land Cover Database (NLCD) 2019 Land Cover Conterminous United States. Sioux Falls, SD: U.S. Geological Survey, 06/04/2021.
Targeted Ecological Areas	10%	No Intersect	-	-	Intersect	-	Maryland Department of Natural Resources. Maryland Focal Areas - Targeted Ecological Areas. Annapolis, Maryland, 12/01/2011.
Rural Legacy Areas	10%	No Intersect	-	-	Intersect	-	Maryland Department of Natural Resources. Maryland Focal Areas - Rural Legacy Areas. Annapolis, Maryland, 09/19/2018.

The second phase of this analysis examines the suitability of the study area for wind farms. This analysis is largely based on the economic viability of a site for wind energy, but it does include some additional non-elimination factors. This phase of the study consists of a weighted overlay analysis, in which a series of continuous data layers scoring different suitability vectors were created and then combined into a single surface. This process allows the user to weight the inputs so that the output values incorporate the relative influence of the inputs. In other words, inputs affect the final value of a given location based on their importance as assigned by the user. During this phase of the analysis, sites were grouped into five categories that scored them on a scale of zero to four, with zero representing areas that are unsuitable based on a given suitability factor and four representing the most suitable areas. This means that some areas were constrained in this phase of the analysis, like in the previous phase. While this is somewhat redundant, it helped to organize and simplify the analysis. In the first phase, all the factors were binary. Meaning that they were either a zero for places that were elimination areas, or a one for places that were not. The second phase of the analysis allows for a more complex consideration of factors. While these elimination areas could be considered together with the preference section of the analysis, splitting the analysis into two sections allows for a certain degree of modularity.

Average annual wind speed is perhaps the most important assessment factor for this phase of the analysis. At the end of the day, the turbines at a given site identified here must be able to produce power on an economically viable level, which cannot happen without adequate wind. This analysis uses an average annual wind speed surface from the Global Wind Atlas that measures wind at 100m above the earth’s surface. A review of wind turbines in production by Vestas, the largest wind turbine producer in the world, showed that most of their models designed for onshore production had a cut-in speed - the speeds at which they started producing power - as low as 3m/s with more viable power production beginning at 6m/s. For example, the V172-7.2MW IECS, which is meant for low to moderate wind areas, can produce 18.0 GWh annually with average annual wind speeds of 6m/s, according to manufacturer documentation. Currently, the United States Department of Energy estimates that in order to be considered viable for wind energy production a site should have an average annual wind speed of 6.5m/s at 80m above the ground (U.S. DOE, Energy Efficiency and Renewable Energy (EERE), 2020). Therefore, areas with less than 6.5m/s winds were deemed unsuitable for this analysis, with suitability increasing by a value of one per every 1m/s increase in average wind annual wind speed. As technology improves it is possible to generate power with lower average wind speeds, meaning that areas with lower and lower average wind speeds are viable for wind production (Wichser & Klink, 2008). This is being achieved by optimizing wind turbines through larger rotors, improved blade designs, and increased tower height (Yang et al., 2018). With these improvements in mind and the possibility of entirely new wind turbine designs on the horizon, it is possible that even lower resource areas will be viable for large-scale wind energy production.

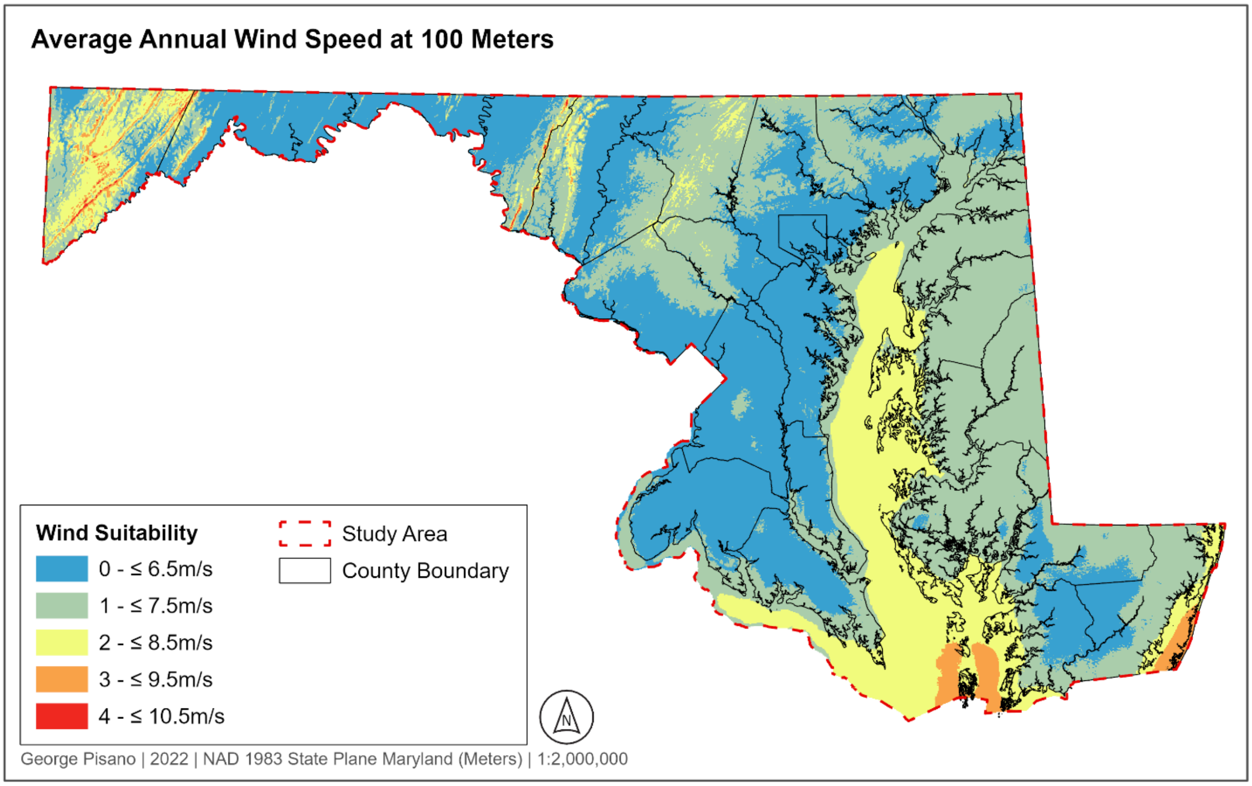

Figure 6: Wind resource suitability based on average annual wind speed at 100m.

This analysis also considers land cover in its site selection model. Land cover data for this analysis was obtained from the Multi-Resolution Land Cover Consortium, which, for the Maryland area, classifies land into 15 categories, 14 of which were present in the study area. Like the wind data, these 14 categories were reclassified into five categories based on their suitability for development as wind turbine sites. Because this data was used in the elimination areas portion of the analysis, some of these areas that were constrained were already identified and eliminated in the previous phase of the analysis, however, they were maintained for this portion of the analysis to avoid no-data gaps in the output surface. These include all developed areas, water, and wetlands. With these areas scored at zero, the remaining eight original categories included forests, hay and pastures, cultivated crops, and herbaceous or shrubby areas. Of these areas, shrubby or herbaceous areas were given first preference on the basis that they are not in use and would be easiest to clear. Next, areas covered by pastures or hay were scored at three and cultivated crops were scored at two. Both areas are easy to clear for wind turbines and in both cases, the land can be returned to its original use once the turbines have been constructed despite the loss of productivity due to the loss of available area. The pastures were deemed to be preferable because wind turbines appear to have minimal impacts on domesticated mammals like cows and horses (Helldin et al., 2012), and the turbines will reduce the productive capacity of the farmland, which reduces crop yields. Finally, forests were given a score of one on the basis that wind turbines can function in forests however, they incur additional costs related to construction, may face increased opposition due to land clearance (Enevoldsen, 2016), and are subject to turbulence related to the interaction between the forest and wind (Cheng et al., 2021).

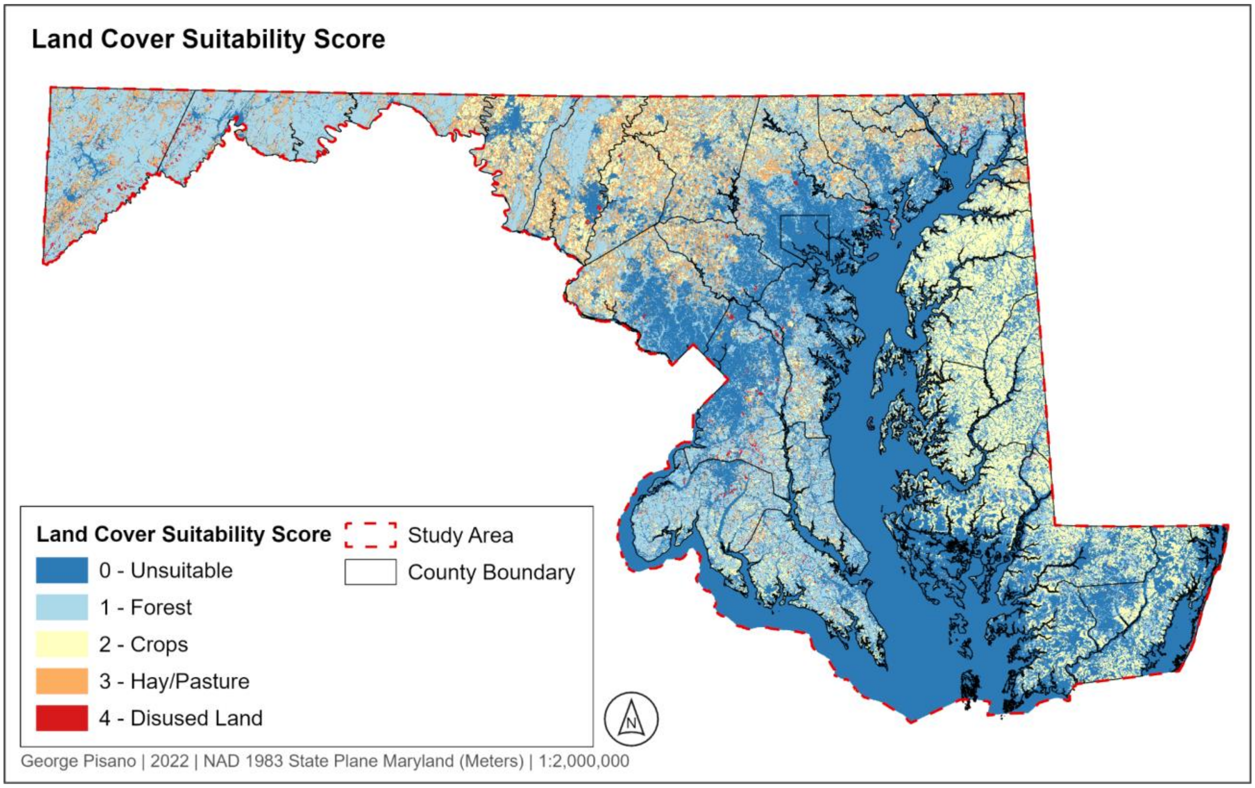

Figure 7: Land cover suitability.

Next, this analysis also considered the distance to transmission lines. This is an important factor when selecting a site for wind turbines because the wind farm needs to be integrated into the existing electric infrastructure. The farther the turbines are from existing transmission lines, the more challenging and expensive it will be to integrate them into the electrical grid (Atici et al., 2015). A 2010 survey of wind farm developers in the UK found that turbines should be no more than 10,000m from the existing energy grid (Baban & Parry, 2001). However, more recent analysis (Miller & Li, 2014) suggests that areas out to 20,000m from transmission lines are acceptable for development as wind farms. Areas greater than 20,000m were marked as unsuitable with the suitability score increasing by a value of one each time the distance to transmission lines halved with areas up to 2500m from transmission lines receiving the highest suitability score.

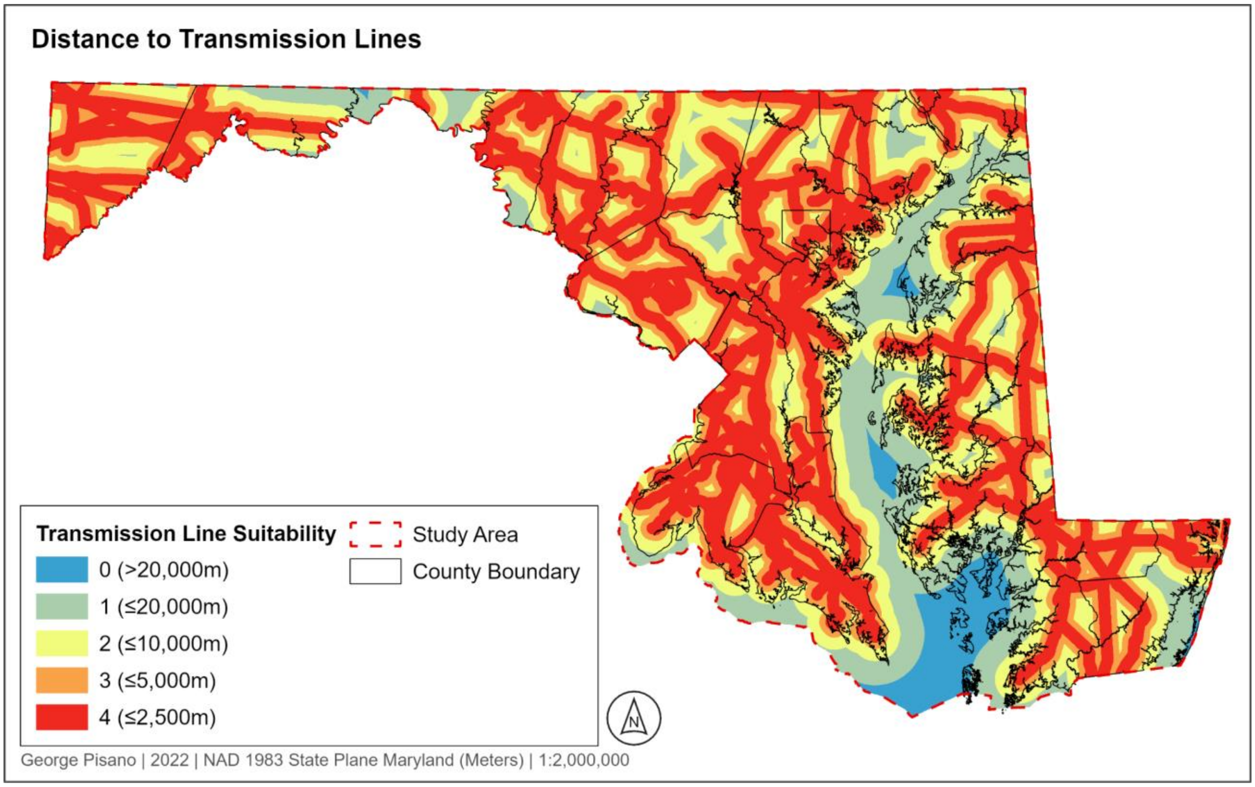

Figure 8: Distance to transmission line suitability.

Finally, this analysis also accounted for some non-economic factors in its selection phase. These were important ecological areas and ecological heritage areas. Target ecological areas are places that are not explicitly protected but have been identified by the Maryland Department of Natural Resources (DNR) as being priorities for conservation. They consist of wildlife corridors, important habitat areas for sensitive species, aquatic life hotspots, and even inundation zones that are important for resilience in flooding events. Similarly, Rural Legacy Areas are places that have been identified by Maryland's Rural Legacy Program as priorities for preservation or conservation. These are areas that have been identified because they are significant landscapes that provide ecological services, or because they are working farms that constitute an important natural resource for the state. While neither of these programs provides absolute protection from development, they are meant to encourage responsible development, so this analysis will give preference to those sites that fall outside these areas. They also may affect site acceptance because culture and ecological damage contribute to opposition to wind farms (Enevoldsen, 2016). These areas were given a binary score with areas inside the identified zone receiving a score of one and areas outside receiving a score of four, they were then given the lowest weight in the weighted overlay analysis.

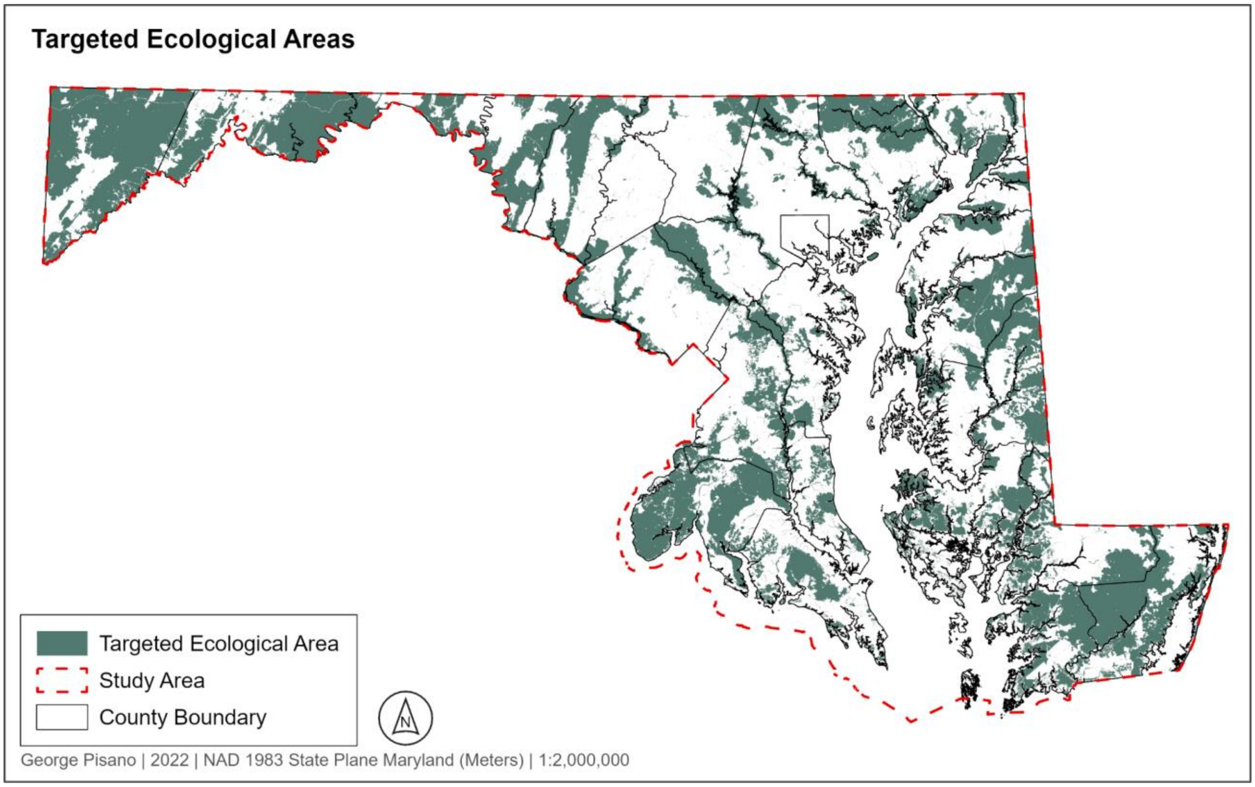

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Figure 9: Maryland targeted ecological areas.

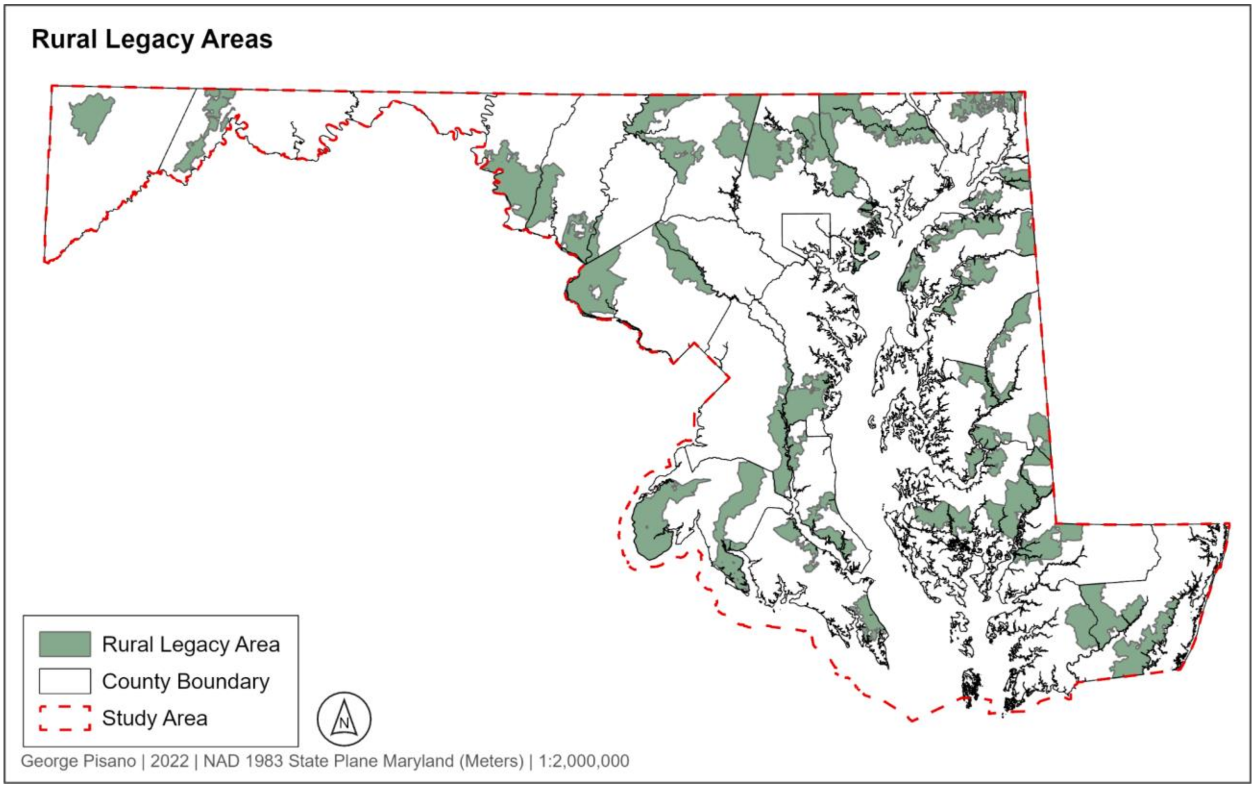

Figure 10: Maryland rural legacy areas.

Results

Phase I Results: Elimination Areas

Table VII: Phase One Results

Phase One Results: Elimination Areas		**Phase Two Results: Wind Turbine Suitability**	
Elimination Constraint	Area Km^2	Suitability Score	Area Km^2
*Protected Land	2,985.43	0	19,574.24
*Anthropocentric	20,119.48	1	1,558.32
*Unsuitable Terrain	11,371.51	2	30,059.63
Combined	28,468.33	3	1,463.8
*May overlap		4	2.85

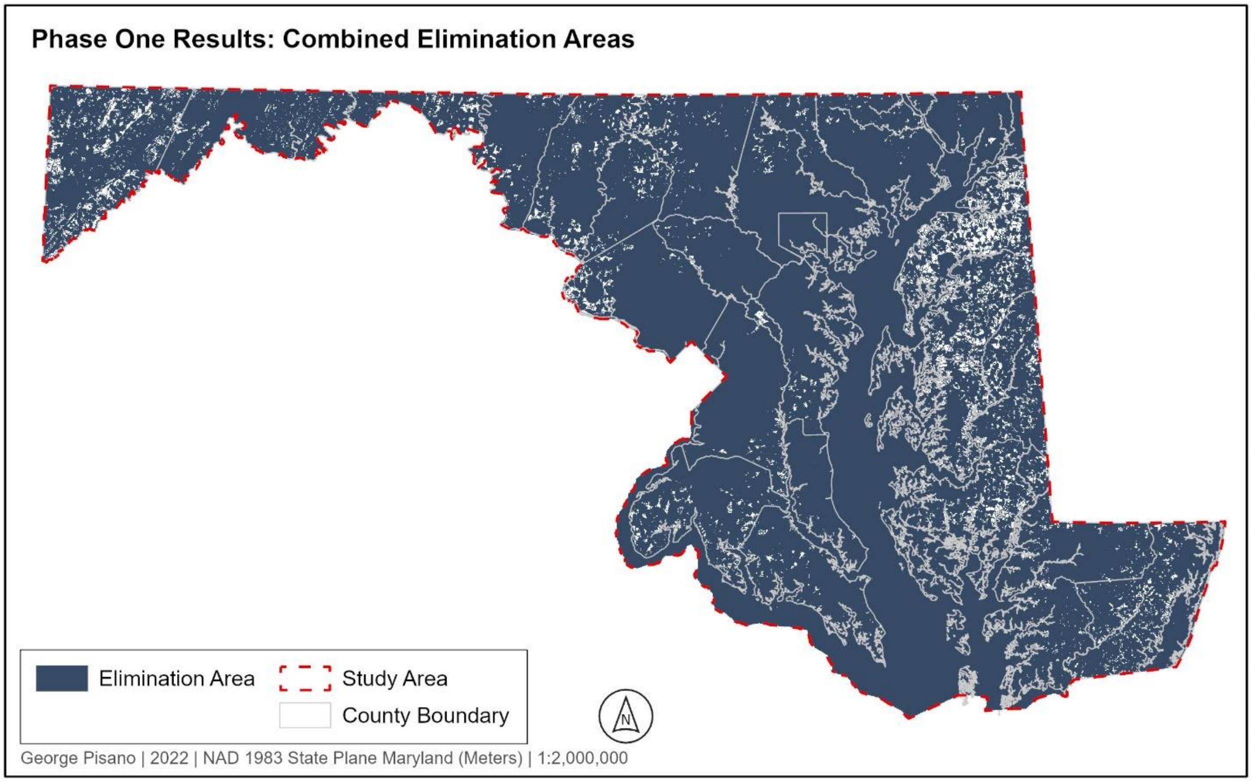

Figure 11: Phase I results - elimination areas.

Phase II Results: Turbine Suitability

Table VIII: Phase two results - Suitability Results by County in Km^2

County	0 Constrained	1	2	3	4
Allegany	1,584.9	19.7	194.3	49.1	0.2
Anne Arundel	1,689.6	2.9	84.6	0.9	0.0
Baltimore	1,757.7	43.9	758.9	47.1	0.0
Baltimore City	352.3	0.0	0.1	0.0	0.0
Calvert	706.7	4.1	193.3	4.7	0.0
Caroline	380.2	87.3	897.6	2.3	0.0
Carroll	773.5	50.7	1,006.3	130.8	0.0
Cecil	641.7	132.3	709.3	32.8	0.0
Charles	1,866.0	11.0	71.9	1.1	0.0
Dorchester	1,405.4	84.6	799.5	7.1	0.0
Frederick	1,762.1	19.2	944.1	158.0	0.0
Garrett	667.0	12.3	1,648.2	520.4	2.7
Harford	1,182.2	83.9	612.3	31.8	0.0
Howard	583.9	20.8	470.7	13.7	0.0
Kent	318.7	58.5	832.4	1.8	0.0
Montgomery	1,526.9	4.7	557.5	52.2	0.0
Prince George's	2,044.5	0.0	21.5	5.1	0.0
Queen Anne's	494.8	27.7	1,061.2	16.5	0.0
Somerset	1,172.7	6.6	154.3	6.0	0.0
St. Mary's	1,186.2	0.6	316.9	11.9	0.0
Talbot	363.5	7.6	735.1	44.5	0.0
Washington	1,516.3	107.9	333.2	39.3	0.0
Wicomico	1,016.9	15.1	543.0	9.1	0.0
Worcester	1,317.4	80.5	560.5	12.1	0.0
Total:	**26,311.2**	**882.0**	**13,506.5**	**1,198.2**	**2.8**

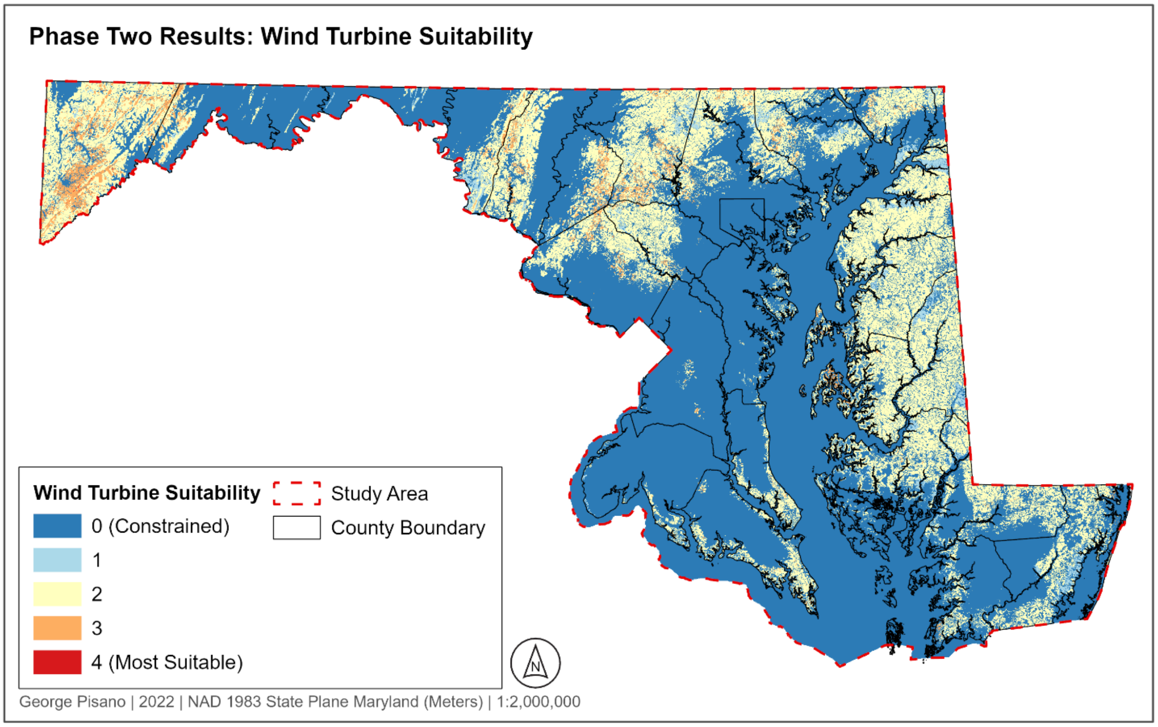

Figure 12: Phase II results - wind turbines suitability.

Combined Result

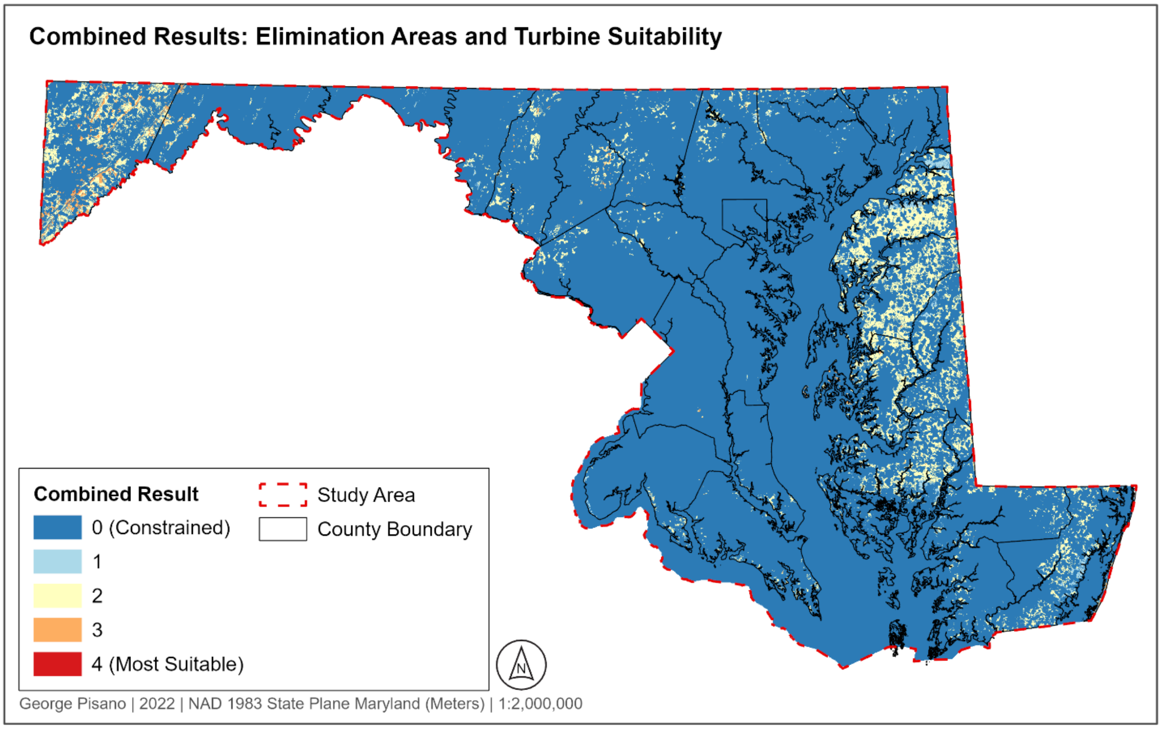

Figure 13: Combined results.

Table IX: Combined Suitability and Elimination Areas Results by County in Km^2

County	0-Constrained	1	2	3	4
Allegany	1,788.33	1,788.33	39.49	16.82	0.1
Anne Arundel	1,776.48	1,776.48	1.11	0.01	0
Baltimore	2,525.84	2,525.84	71.87	2.29	0
Baltimore City	352.37	352.37	0	0	0
Calvert	893.93	893.93	14.55	0.06	0
Caroline	1,066.56	1,066.56	272.7	0.21	0
Carroll	1,898.94	1,898.94	58.97	2.05	0
Cecil	1,304.92	1,304.92	161.4	0.22	0
Charles	1,921.18	1,921.18	21.99	0.23	0
Dorchester	1,933.37	1,933.37	322	1.94	0
Frederick	2721.76	2,721.76	143.3	16.43	0
Garrett	2,070.41	2,070.41	603.4	170.9	1.4
Harford	1,867.87	1,867.87	33.93	0.07	0
Howard	1,066.43	1,066.43	20.24	0.35	0
Kent	696.85	696.85	473	0.41	0
Montgomery	2,083.24	2,083.24	57.25	0.29	0
Prince George's	2,069.05	2,069.05	0.81	1.14	0
Queen Anne's	1,109.5	1,109.5	475.5	1.48	0
Somerset	1,306.14	1,306.14	32.25	0.22	0
St. Mary's	1,479.8	1,479.8	34.59	0.92	0
Talbot	888.42	888.42	250.1	8.21	0
Washington	1,949.69	1,949.69	29.94	2.09	0
Wicomico	1,500.78	1,500.78	78.99	0.61	0
Worcester	1,721.52	1,721.52	193.2	12.95	0
Total	**37,993.37**	**37,993.4**	**3,391**	**239.9**	**1.6**

Discussion

This analysis shows two possible pathways forward for onshore wind in Maryland. Looking at the initial result, there are two counties with areas that received the highest possible score from this analysis. These are Garrett and Allegany Counties with 1.42 km^2 and 0.13 km^2 of level four area respectively. These counties also have the most area with the second highest suitability level, 239 km^2 (Garrett) and 170 km^2 (Allegany). This result is unsurprising considering that both counties are in the far western portion of Maryland, which reaches into the Appalachian Mountains, and so they experience the highest onshore AAWS thanks to the mountains. They also have the benefit of prominent ridges, which increase apparent wind speeds (Abdelaziz et al., 2012). Garrett County is also home to Maryland's only large onshore wind farms, Criterion Wind and Four Mile Ridge. Examining a closer view of these two counties, we can see that the state's existing wind turbines occupy the majority of the most suitable area identified by this study. However, considerable space is still available, which could be investigated for further wind energy projects that could help to transition more of the state’s grid energy makeup away from carbon-emitting energy sources. These new project would likely be able to generate a similar amount of power despite being located in less preferable locations thank to improvements in technology in the time since Criterion Wind and Four Mile Ridge were brought online.

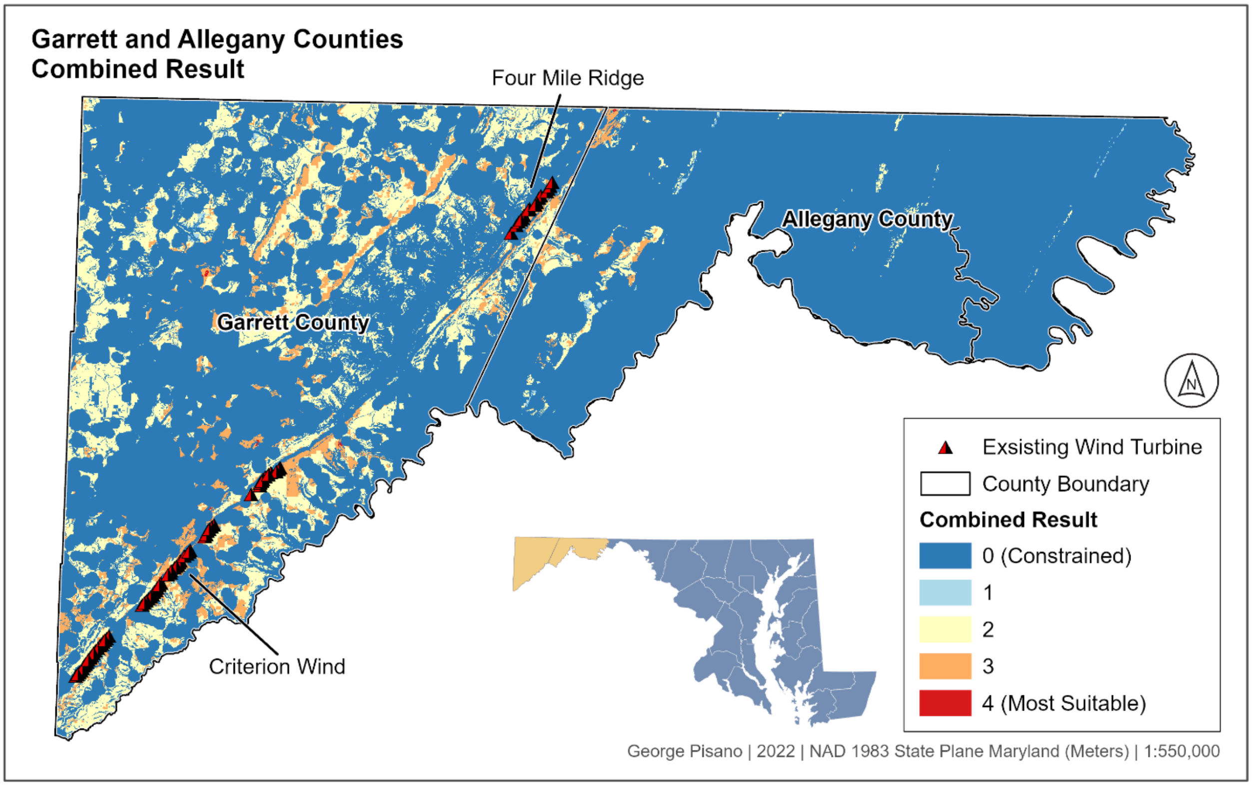

Figure 14: Combined suitability in Garrett and Allegany counties.

When constructing this study, one of the challenges is balancing the need to prioritize wind, which is the basic requirement for energy production, and other suitability factors like distance to transmission lines and potential land clearing costs, which affect the initial cost of the energy project. This study gave AAWS, our measure of wind resources, 40 out of 100 total influences in the weighted overlay (table VI), which made it the highest weighted factor in the suitability analysis. This resulted in the windiest areas having very high scores in the output despite scoring lower with other suitability factors, which may increase construction cost and complexity. In an area with more wind resources overall, it may make sense to give comparatively more weight to factors other than AAWS to achieve a lower-cost, more socially and environmentally responsible, site. In a study area like Maryland, which has very low wind resources, the turbines need to be placed in the absolute windiest part of the state to maximize energy production and meet the needs of a for-profit energy producer. However, it is possible that areas with lower wind resources could be suitable for smaller-scale wind farms that will produce less power over their lifetimes but have lower construction costs.

During phase one of the analysis over 28,000 Km^2 of the study area was constrained (Table VII), which means that there is little space available for wind turbines to begin with. This area was further constrained during the second phase of the analysis because some locations failed to meet the 6.5m/s threshold to be considered economically viable for wind energy production. Examining the counties that make up the Eastern Shore of the Chesapeake Bay - Caroline, Cecil, Dorchester, Kent, Queens Anne’s, and Talbot Counties - we can see that there is considerable area that wasn't constrained but which received a low score in the weighted overlay analysis. This result is largely because these areas have low wind resources compared to western Maryland, despite scoring well with other suitability factors like land cover and distance to transmission lines. Looking at the AAWS surface for these six counties, we see these areas have average annual wind speeds between 6.5m/s and 7.5m/s. Returning to the Vestas V172-7.2MW IECS, which was used as an example in a previous section, at 7.5m/s AAWS a single turbine could produce around 25GWh annually. Another turbine, the Northern Power Systems 100C-28, can produce as much as 25.7GWh annually with wind speeds of just 6.5 m/s, according to manufacturer documentation. If you accept that these areas have adequate wind resources for sustainable energy production, there may be areas that are suitable for smaller-scale community energy projects.

To test this, I created another weighted overlay surface that has the same parameters and relative weights as the original analysis but does not include wind as a factor. The result of this test shows that there is considerable area in these countries that receive the highest possible score, suggesting that these areas would make excellent sites for wind turbines, but lack the level of energy production needed for commercial energy production. The definition of community energy can vary somewhat, but for the purposes of this analysis, community energy projects are those energy projects where local stakeholders have direct input into the construction and management of energy projects and where the community directly participates in the benefits from those projects. One study (Brummer, 2018) conducted a literature review of studies that focus on the benefits and barriers to community energy in the United States, United Kingdom, and Germany, and found that there is agreement on a wide range of benefits to communities from community energy projects. The most tangible of these appears to be economic benefits. Wind energy projects can provide communities with low-cost reliable sources of energy, additional income streams that can be reinvested in the community, as well as additional jobs relating to the maintenance of the energy infrastructure. However, just as meaningfully, Brummer notes that community energy projects help to empower communities by allowing them to take responsibility for their energy future and contribute to increased awareness of issues like climate change, renewable energy, and energy resilience (Brummer, 2018). The feasibility of any potential sites for community energy projects is a matter for further study, but this study shows that there are many locations throughout

Maryland that meet the basic requirements for wind energy and so are worthy of further consideration.

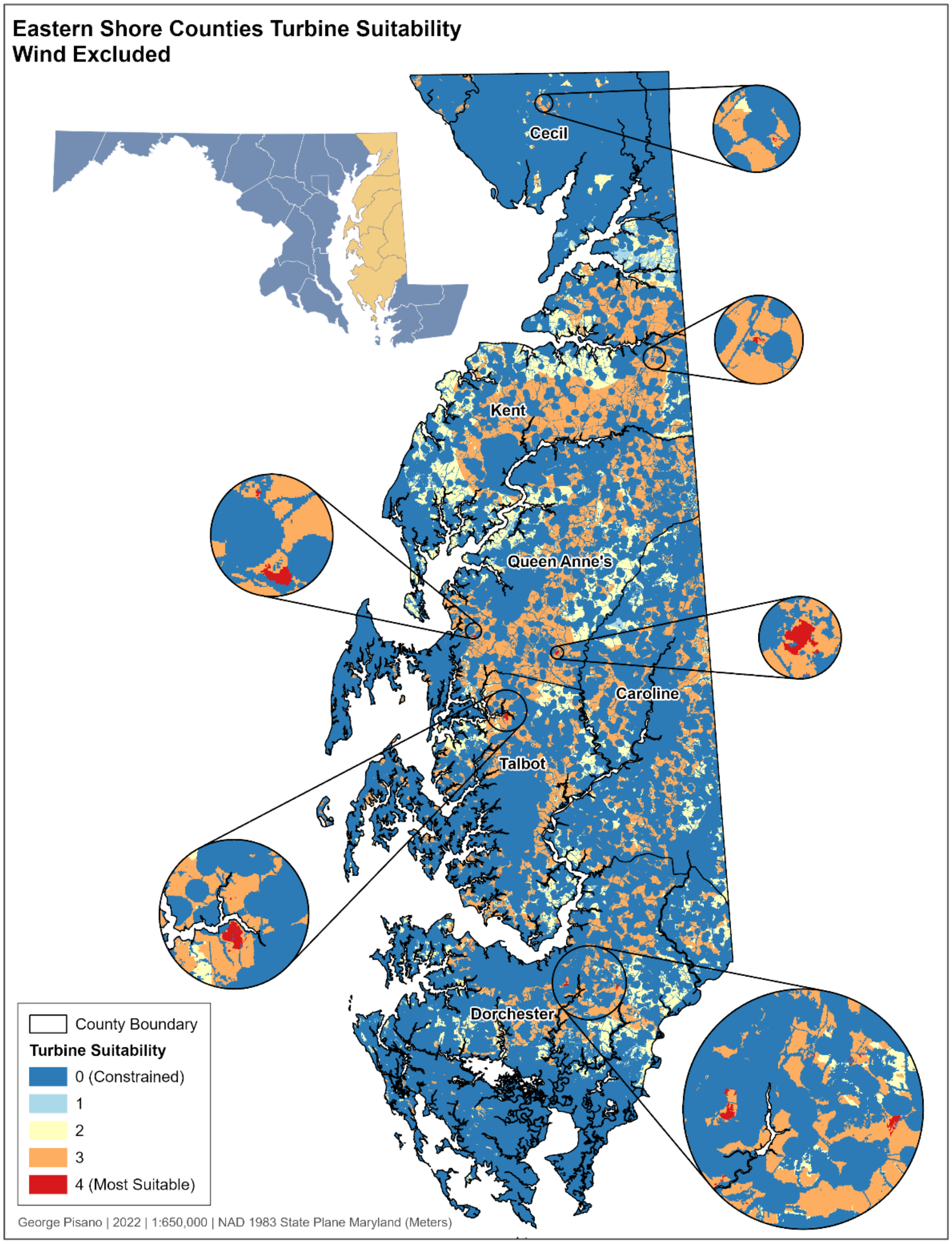

Figure 15: Wind turbine suitability (excluding wind) in the Eastern Shore counties.

Table IX: Suitability in Eastern Shore Counties in Km^2 (Wind Excluded)

County	0 (Constrained)	1	2	3	4
Caroline	1,076.6	6.9	93.2	192.4	0.2
Cecil	1,300.4	31.4	80.1	108.9	0.3
Dorchester	1,939.1	10.3	151.7	194.9	1.5
Kent	720.3	14.5	201.2	275.8	0.4
Queen Anne's	1,124.4	5.0	135.6	334.7	1.3
Talbot	897.0	2.1	82.2	168.5	1.1
Total	**7,057.8**	**70.2**	**743.9**	**1,275.2**	**4.9**

Areas for Further Research

This analysis indicates that there is considerable amount area in Maryland that meets the basic requirement to be suitable for wind turbines, but it has some inherent limitations that mean that further research is required to advance onshore wind energy in the state. This is a statewide analysis and so it doesn’t specifically consider any site in detail. When selecting criteria for this study, the goal was to create a set of criteria that would be applicable in most cases, however each case is different. For example, this study considered sites that are within 500m of residential parcel to be unacceptable for wind turbines. However, in Garrett County, the county with the most potential for future onshore wind energy projects, the minimum set back distance for wind turbines is tied to the height of the turbines, which mean that the 500m set back distance for residential areas is greater than what may be required in some cases. In fact, there are currently wind turbines that are within 500m of residential parcels in Garrett County. The 500m distance was derived from a literature review of similar suitability studies, but this distance could be reduced or expanded depending on a particular focus location. Similarly, this analysis showed that there are sites that may be suitable for lower output wind energy project, however any projects that proceed in these areas would require dedicated feasibility studies to determine the economic viability and their potential impacts. The purpose of this study isn’t to definitively demonstrate that a particular location is suitable for wind turbines, but rather to indicate that that there is a high likelihood that those location would be suitable based on common metrics. With these limitations in mind, this study can act as a finding guide to help locate potential site for new sources of renewable wind energy in Maryland.

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Appendix I: Analysis Model Flow Chart