Multi-Criteria Site Selection for Innovative Wind Turbine Adoption in an Urban Environment

by

John Mason Smith

A Thesis Presented to the
Faculty of the USC Dornsife College of Letters, Arts, and Sciences
University of Southern California
In Partial Fulfillment of the
Requirements for the Degree
Master of Science
(Geographic Information Science and Technology)

May 2021

Acknowledgements

This thesis project, goal, mission from god or whatever it is, could not have been accomplished without the assistance of a great many intelligent, patient and kind people. In chronological order I want to thank my grandparents posthumously, Granville and Edith Caraway whose creativity and inventiveness I must have inherited. I would like to thank NREL's Dr. Carlin Palmer who took an amazing amount of time on the phone to explain to a wind novice, how to discover the load carrying capacity of a windmill using a Prony brake. Great appreciation and kudos to my best buddy and cycling companion Jerry Crim who was sometimes annoyed, perplexed and yet in the end always helpful in lending a hand in the testing and recording of a thing that looked as much like a crude spaceship as it did a wind turbine. I also want to thank Jerry for being a friend and encouraging me in tough times, that is not a fun job to have.

I extend enormous thanks to the great folks at Tarrant County College, Dr Dorothy Jenkins, Dr. William Brown and Jolynn Sproles. Also, at TCC I need to thank the GIS instructors Jennifer Holland, Bob Heselton and Julie Vicars and David Allen for setting up the GIS program. Enormous thanks to Dr. Philip Posey and the great folks at the CAN Network. There was a time, not long ago, that I would not have envisioned myself in graduate school. At that time, attending the University of Southern California's Spatial Sciences Institute would not have been a possibility. However, the transition from a curious data nerd to a MS in Geographic Information Science and Technology was made relatively easily due to distance learning and knowledgeable and helpful instruction. I want to thank all my professors but especially, Dr. Laura Loyola who read my initial clumsy first attempt at writing a prospectus and was helpful and encouraging, Dr. Karen Kemp whose course in spatial analysis was essential in creating the basis for much of this thesis and Dr. Darren Ruddell, who kept me on track despite health issues. I would like to especially thank my thesis advisor Dr. Jennifer Bernstein for being helpful, patient, encouraging, and expressing enthusiasm that was hard for me to muster.

Lastly and most importantly, I would like to “thank” the spider or insect or whatever it was who bit me while working on this thesis in the park. The bite made my arm swell, which led to a trip to urgent care during a global pandemic and fixing the aforementioned vexing health issues, one of which may have done me in. So, thank you little insect, you saved my life.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AOI	Area of Interest
AWEA	American Wind Energy Association
AWS	Automated Weather Station
BNSF	Burlington Northern and the Santa Fe (Railway)
CBD	Central Business District
Cd	Code
CO_2	Carbon Dioxide
DEM	Digital Elevation Model
DFW	Dallas Fort Worth International Airport
EBK	Empirical Bayesian Kriging
EPA	Environmental Protection Agency
FIPS	Federal Information Processing Standard (Code)
FWWR	Fort Worth and Western Railroad
HAWT	Horizontal Axis Wind Turbine
HIFLD	Homeland Infrastructure Foundation-Level Data
KWH	Kilowatt/hour
MCA	Multi-Criteria Analysis
METAR	Meteorological Aerodrome Report
MW	Megawatt
MWH	Megawatt/hour
NAD	North American Datum
NAS JRB	Naval Air Station Joint Reserve Base

NIMBY	Not in my Backyard
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NWS	National Weather Service
ONSWPS	Onshore Wind Power System
OSU	Ohio State University
PPI	Producer’s Price Index
RAWS	Remote Automated Weather Station
ROI	Return on Investment
RLF	Revolving Loan Fund
TAD	Tarrant County Appraisal District
TCEQ	Texas Commission on Environmental Quality
TRC	Texas Railroad Commission
TRE	Trinity Rail Express
UK	United Kingdom
UP	Union Pacific (Railway)
US	United States
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

Abstract

Due to technological advances, wind energy is now a commercially viable input to the electrical grid. However, siting constraints of wind resource availability, regional economics, community concerns, issues with grid integration and ecological concerns are hampering wind technology’s market penetration. This thesis seeks to address these issues by using multi-criteria site selection to demonstrate how a volumetric wind turbine can be used for successful siting of utility scaled wind turbines in urban environments. The urban environment for this study, Fort Worth, Texas, is composed of land use types and zoning restrictions some of which impose exclusion criteria that restrict most of the area of interest from the analysis. Fortunately, there are areas zoned for industrial, agricultural, and other land uses that are compatible for the siting of wind turbines. Furthermore, this research used the spatial inputs of property values, terrain, nearness to electrical infrastructure and wind resource availability to create a weight schema that can identify the best sites in the study area. The results show that a utility-scaled wind turbine could be sited within the city having a wind power ranking of marginal or greater and that has undeveloped open spaces, industrial zones, and areas such as landfills and brownfields that impose limitations to future development.

Chapter 1 Introduction

Due to technological advances that have allowed wind turbine manufactures to increase the size of their product from a turbine with a 17 m diameter in the 1980s to a turbine with a 100 m diameter in 2015, wind energy is now a commercially viable option for inputs to the electrical grid (DuVivier 2015). However, siting constraints of wind resource availability, regional economics, community concerns, issues with grid integration and ecological concerns hampers the adoption of this technology. This analysis seeks to address these issues by using multi-criteria site selection and volumetric wind turbines to allow wind turbines to be sited successfully in urban environments (Figure 1).

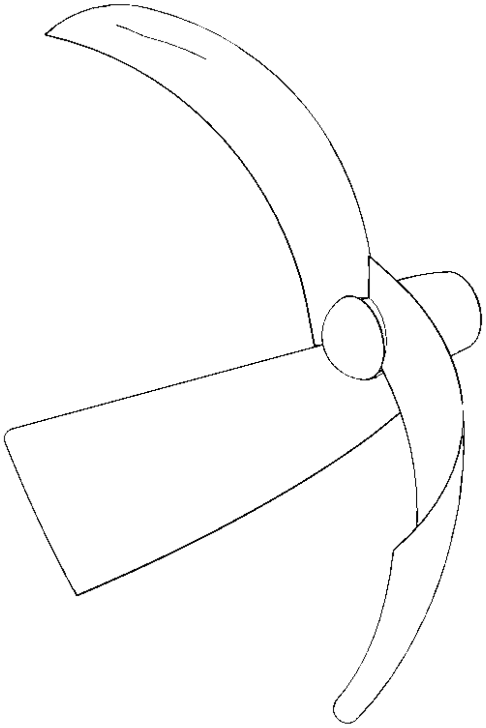


Figure 1: Illustration of a volumetric turbine.

The attributes of a turbine configured with volumetric blades should be spatially advantageous by allowing siting in what would be otherwise considered unusable locations for wind turbines, such as urban landscapes where the wind resource is considered marginal or locations where wildlife might be put in jeopardy. This new innovation, a volumetric airfoil that functions primarily by aerodynamic lift, when configured as a wind turbine, has shown in tests by the author to be significantly more efficient at converting energy from the wind than conventional wind turbines at wind speeds below 7 m s^{-1}. Moreover, due to its volumetric shape it can easily be seen or detected and therefore should have minimal impact on wildlife. Because the blade curves into the incoming flow this blade will create minimal blade tip vortices and therefore should be virtually silent. This study proposes finding sites for wind turbines configured with these blades in Fort Worth, Texas, the area of interest (AOI) (Figure 2).

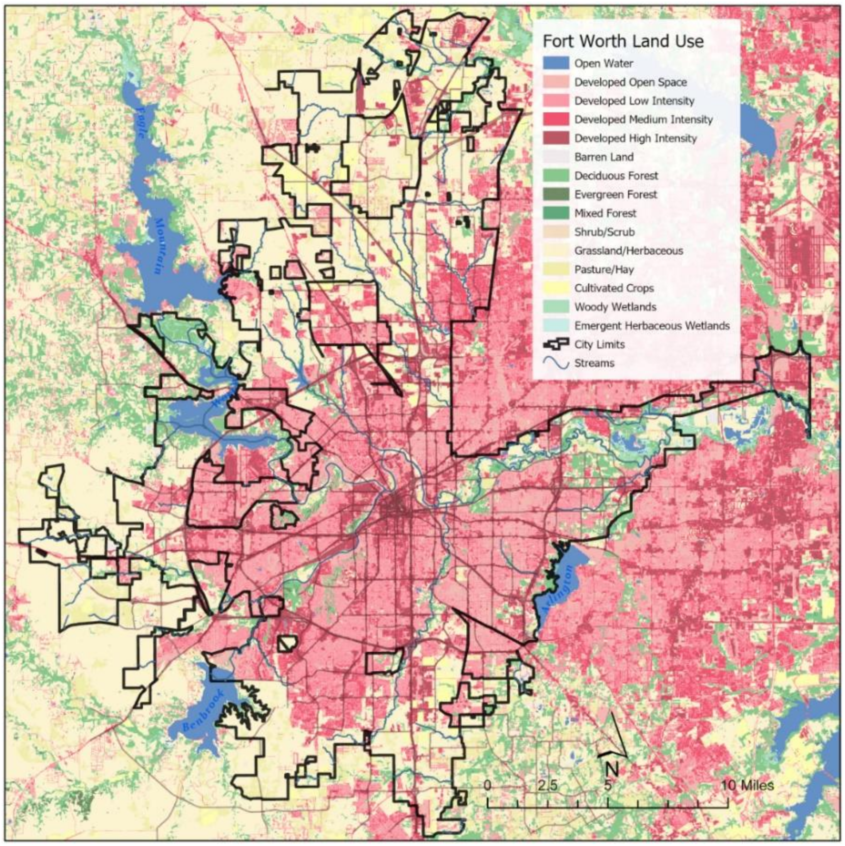


Figure 2: Land use map of the Fort Worth, TX study area

Fort Worth is located in North Central Texas and was established in 1849 as a US Army fort on a bluff overlooking the mouth of the Clear Fork of the Trinity River. Fort Worth’s elevation varies from 150 to 320 m above mean sea level. Fort Worth currently encompasses about 356 square miles most of which is contained within Tarrant County, but the city extends into adjoining, Denton, Parker, and Wise counties. One of the data sources, property valuation for Parker County was unavailable for this study and therefore the area of the city that extends into Parker County was excluded. In 2019, the US Census estimated the population at 909,585 or about 2,600 residents per sq. mi. Fort Worth’s climate is considered humid subtropical according to the Köppen climate classification.

The Trinity River basin, the river that runs through the city of Fort Worth, TX, possesses riparian, woodland, and grassland habitats. Ducks, geese, other birds, and Monarch butterflies pass through Fort Worth on their seasonal migrations on the central flyway. North Texas is also home to bat species who make their home in wooded areas. This AOI is also habitat for woodpeckers, chickadees, hawks and owls in the riparian woodland, emergent wetland, and upland woodland habitats along the river’s path.

The city’s constructed environment consists of a central business district “Downtown”, and areas of town designated Northside, Southside, Westside, and Eastside. Each of these areas has subdivisions containing neighborhoods, warehouses, shopping malls and heavy industry. There is significant railroad infrastructure within the city. There are large railyards for the Burlington Northern Santa Fe (BNSF), and Union Pacific (UP). The Trinity Rail Express (TRE) runs a commuter link between Fort Worth and Dallas and the Fort Worth and Western Railroad (FWWR) runs freight to railroad sidings throughout the area. There are four major airports in or near Fort Worth, Dallas Fort Worth International Airport (DFW), Meacham Airport, Alliance

Airport, and the Naval Air Station Joint Reserve Base (NAS JRB). Major manufacturers in the area are Lockheed Martin and Bell Helicopter. Along the rivers and streams within the city the Army Corps of Engineers maintains a levee system and greenspaces for flood mitigation. The city manages about 100 miles of hike and bike trails along these levees and greenspaces. As can be distinguished in Figure 2, low to medium intensity development dominates within the city and some relatively undeveloped land can be found on the city's periphery.

Fort Worth acquires its energy for electrical generation from natural gas sourced from the Handley Power Plant, nuclear from the Comanche Peak Power Plant located 30 miles to the south in Glen Rose TX and from various wind farms located in South and West Texas.

Fort Worth has an average surface level wind speed of around 3.13 m s^{-1}, placing Fort Worth in the marginal wind resource classification according to the National Renewable Energy Laboratories (NREL). This marginal classification is ideal for this study insofar as it expands the range of what is considered possible for wind energy collection. The current state-of-the-art horizontal axis wind turbine (HAWT) typically starts operation at 3.13 m s^{-1} which leaves about half of the total hours of wind in Fort Worth unusable with this device. This limitation typically forces HAWTs to be sited in rural areas where an increase in size and height allow, the turbines to take advantage of higher wind speeds. Figure 3 provides a graph of surface level wind speed distribution at Meacham Airport in Fort Worth, TX. This graph shows that wind is present throughout the period albeit skewed to the left and under 20 mph. Figure 4 shows a power curve (watts/wind speed) comparison of the performance of a volumetric wind turbine and a conventional HAWT of equal diameter. The power curve for the volumetric wind turbine shown in Figure 4 was constructed from data of a field test of a six-foot diameter rotor using a prony dynamometer. A prony dynamometer is a way of measuring torque and rotational speed simultaneously and therefore the mechanical power of a rotating object. To make this curve 1,413 measurements were taken in a field test conducted to construct a mechanical power curve.

Figure 5 illustrates that a volumetric turbine is better designed to take advantage of the available surface level winds and can net a 47% increase in overall wind energy conversion over the course of a year at this site. Because of the volumetric shape and ample surface area, a rotor configured with these blades can capture significantly more energy from the wind, especially at wind speeds below 3.13 m s^{-1} and can start at just over 0.9 m s^{-1}. This low wind speed capability will allow successful siting in areas that heretofore were unworkable for wind turbines such as urban environments and areas where wind energy potential is marginal.

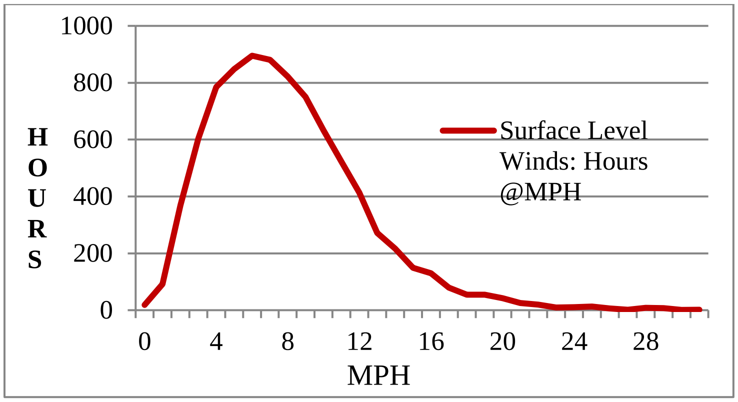


Figure 3: Surface level wind speed distribution recorded at Meacham Airport, Fort Worth, TX in 2017

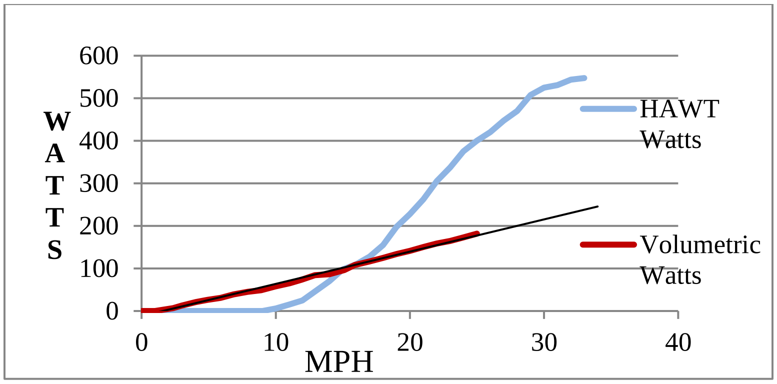


Figure 4: Power curve comparison of the performance of a volumetric turbine and a conventional HAWT of equal diameter.

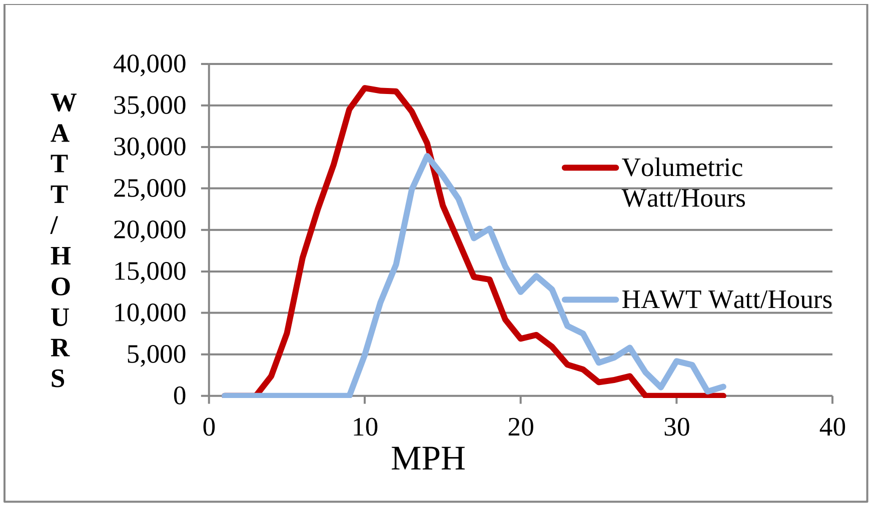


Figure 5: Watt/Hour Comparison of 6 ft volumetric and a HAWT

1.1 Motivation

There are two central motivations for conducting this research. First, it contributes to the spatial sciences by exploring socio-economic and meteorological factors to identify the places in which a new technology (i.e. innovative wind turbines) can be sited and by better defining the potential of using remote monitoring stations to monitor wind in an urban land use scenario. Second, it may benefit society by documenting the potential of a new energy source, urban wind energy, to provide renewable energy.

1.1.1 Contribution to Spatial Science

The inspiration for developing this invention is essentially spatial. If wind energy is free and inexhaustible, why are there no utility scaled wind turbines in Fort Worth, TX where the researcher lives? The answers to this question are spatial as well. One reason is that an urban landscape slows the wind and causes turbulence (Mathew 2006). This loss of wind speed and turbulence can nullify wind potential for all but the windiest locations and/or the largest of turbines. The second is that few residents want a utility-scaled wind turbine on or near their property (Wolsink 2000, 2007). This thesis seeks to address these issues. Another contribution to the spatial sciences is to demonstrate the capacity of using automated weather stations to gather wind data.

There are thousands of meteorological stations across the continental United States, collecting wind speed and direction measurements hourly. In order to make a proper assessment of the wind resource within an urban environment, wind speed and direction measurements for an extended period need to be interpolated and aggregated for as many sites as possible within the area of interest. Although these networks exhibit variability from station to station and between networks, they nonetheless can provide a basis for historical wind analysis (Brown et al. 2011). This research employs a meteorological network to aggregate and interpolate the wind resource for the designated area of interest. This interpolated wind surface can then be used in conjunction with other land use and terrain information to identify suitable sites for wind energy capture.

1.1.2 Contribution to Society

Global warming caused by CO_2 emissions is threatening society due to sea-level rise, drought, flood, desertification, and stronger storms (U.S. Environmental Protection Agency 2017). It will take global efforts in conservation and green technology implementation innovation to curb these emissions. Wind energy is a mature and economically viable technology compared to carbon-based solutions (Blanco 2009). However, wind energy penetration has yet to make much of a dent in total carbon output (Hall and Klitgaard 2018). Spatial analysis can quantify renewable resources such as wind, solar, hydro, biomass, or geothermal and show how these resources can best be deployed to help meet carbon reduction goals.

1.2 Thesis Organization

The remainder of this thesis consists of four chapters. Chapter 2 provides a synopsis of research previously conducted on the criteria that are the basis for this thesis, including wind resources, economic and community impacts, grid integration, and environmental impact. Chapter 3 details the research design, data acquisition, data processing and sensitivity analysis. Chapter 4 details the suitability analysis, the attributes of a selected site and the return on investment of the selected site. Chapter 5 discusses possible implementations and limitations and details the conclusions that can be drawn from this thesis project.

Chapter 2 Background

When properly engineered and sited, wind turbine technology is an economically competitive alternative to carbon-based grid inputs (Blanco 2009; Hall and Klitgaard 2018). However, the caveat “if properly engineered and sited” is critical. Implementation complications include wind resource availability, regional economic costs, community concerns, grid integration issues and environmental concerns (Bishop and Miller 2007; Hall and Klitgaard 2018; DuVivier 2016; Horn, Arnett, and Kunz 2008; Wolsink 2000, 2007). Fortunately, Geographic Information Systems (GIS) can make use of multi-criteria site selection, a type of spatial Multi-Criteria Analysis (MCA) (Harrison 2012), that allows an analyst to incorporate diverse spatial inputs to analyze sometimes competing and nebulous criteria. The approach in this section is to investigate each criterion individually and then to investigate GIS-based multi-criteria site selection procedures.

The current renewable energy alternative to urban wind energy for Fort Worth is rural wind energy. According to the American Wind Energy Association (AWEA), there are 14,929 operating wind turbines with an installed wind capacity of over 29 gigawatts in Texas (AWEA 2019). These turbines that dot the Texas landscape on ranches and farms generate energy for urban centers like Fort Worth and can provide supplemental income to ranchers and farmers as well as good paying jobs for those that maintain this infrastructure. However, electrical demand can frequently outstrip the supply provided by these windfarms, leaving fossil fuels as the only current viable option to make up the shortfall in energy production. Potential energy production is further reduced because these windfarms are tens to hundreds of miles from the urban centers where their energy is utilized. This distance from urban centers decreases the net realized energy production due to energy loss in transmission (Mathew 2006).

2.1 Wind Resource Criteria

Knowing the availability of wind as a resource is pivotal in learning where to place turbines as well as how large and how high the turbines need to be off the ground. The NREL has published wind power classification maps for the U.S. at differing heights above ground (Figure 6). The NREL maps are used to identify regions of the country that would be appropriate for wind energy applications. However, because the aim of this research is to define the potential energy of winds in urban environments, the NREL wind resource maps are too coarse in terms of scale to be used to identify exact locations. This research instead used Meteorological Aerodrome Reports (METAR) and Remote Automated Weather Stations (RAWS). METARs report wind speed and direction data hourly in or near airports and therefore near population centers. METAR data has been shown to be satisfactory in conducting site analysis for micro wind turbines near Malaysian airports and therefore may be suitable for this research (Albani, Ibrahim and Hamzah 2013). METAR data can narrow down areas of interest (AOIs). However, airports are distributed across the landscape at random intervals and thus, there may not be sufficient numbers in some areas to adequately interpolate wind conditions throughout a city. Therefore, data gaps need to be filled in by other meteorological networks. Brown et al. (2011) describes the steps required to use RAWS networks to fill in the gaps.

It is important to use networks like those mentioned above to show the gradation of wind energy over the AOI for an entire year. The aggregation of the hourly wind speed data for a site is used to create a Weibull wind distribution curve. A Weibull wind distribution, like that shown in Figure 2, shows how much wind energy can be expected at a specific location over a period of time. Weibull distribution curves for all sites can be used to create a wind energy surface for the AOI to demonstrate the total energy distribution over the AOI. The wind resource map shown in

Figure 6 does not show any gradation over the Fort Worth, TX AOI but ranks the entire AOI as marginal. Furthermore, the map in Figure 6 does not show how wind speed is distributed over the course of a year. There could be large periods of time with little or no wind. Constant wind, regardless of speed, provides a reliable resource.

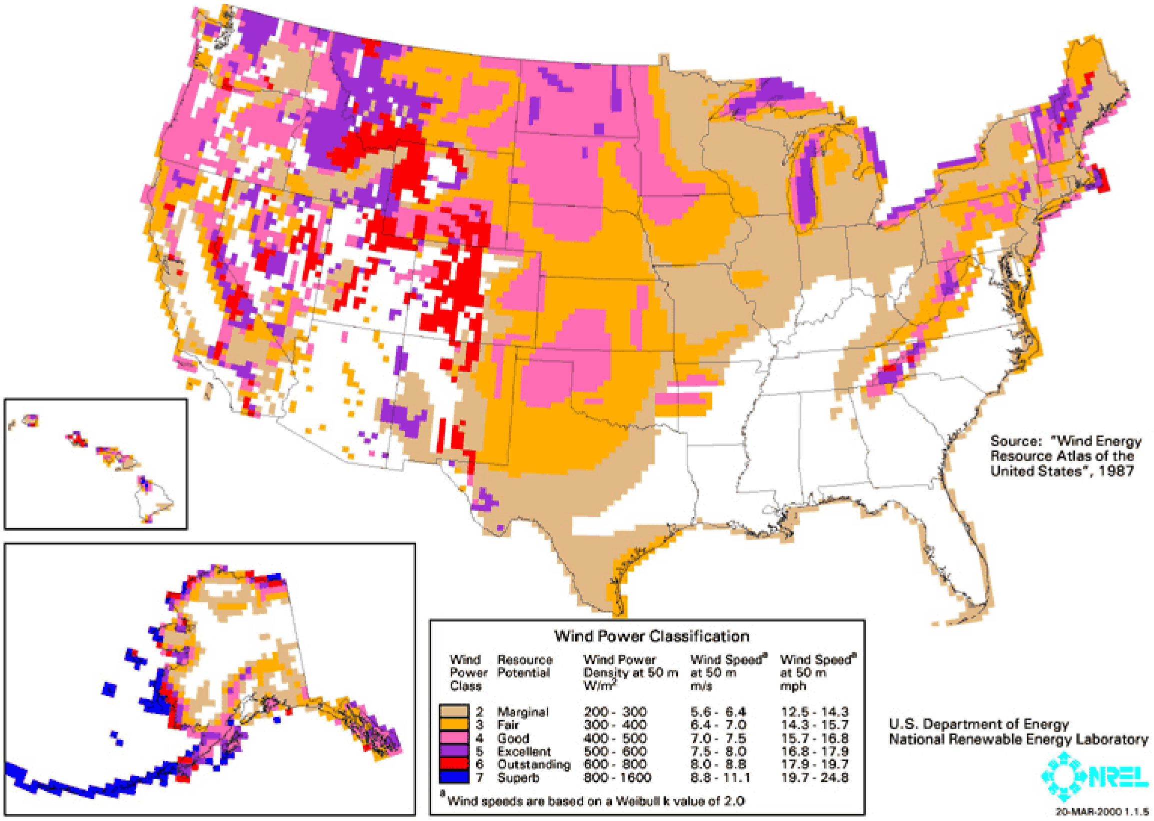


Figure 6: NREL wind resource map of the U.S. for 50 m above ground Source: NREL

2.2 Economic Criteria

Locating a turbine in a remote area can increase costs considerably due to the need for roads, transportation, and electrical connections. This gives urban wind turbine installations a distinct advantage over rural based installations. To gain an understanding of per unit cost estimates of an innovative volumetric turbine, the Wind Turbine Design Cost and Scaling Model provides a spreadsheet-type model that allows a user to input various parameters to approximate costs of an installation for a conventional wind turbine in a windfarm (Fingersh et al. 2006). An example of the resultant cost in this spreadsheet is illustrated in Table 1. Table 1 is an example of a resultant cost table for a 1.5 megawatt (MW) wind turbine using this spreadsheet model with 2002 estimated cost structure. Using this spreadsheet model, a user can input parameters specifying site and wind turbine requirements. The undetermined part of this research is the cost of an innovative wind turbine rotor with volumetric blades. It is beyond the scope of this research to specify the engineering and therefore actual manufactured cost of this component; however, it should be understood that it is a feat of engineering to understand the load requirements on the rotor as well as any supporting structure. It is not clear at this point what an engineered solution would cost the research will use rotor surface area as a proxy for true costs. When considering a return on investment (ROI), all costs, including maintenance costs, must be considered. Property costs due to purchase, lease, or easement could potentially be much greater in urban areas due to the higher demand for real estate. However, there are exceptions when it comes to highly depressed real estate such as unused industrial plants, abandoned grain elevators, oil or gas well sites, landfills, and brownfields. The U.S. Environmental Protection Agency (US EPA) designates a "brownfield" as a property whose expansion, redevelopment, or reuse may be hampered by the presence or potential presence of hazardous materials. These types of sites could be considered by residents as hazardous, ugly, and worthless. Finding a proper use for these types of sites could not only benefit the community, but they could also be considered by investors as economically viable.

In the early days of wind energy technology, turbines were too small and inefficient to contribute sufficient power to the grid to make them economically viable. However, over the last few decades there have been advances in turbine engineering and when coupled with GIS to properly site turbines, wind energy now has a return on investment comparable to that of fossil fuels (Blanco 2009; DuVivier 2016). However, the previous research is predicated on conventionally sited HAWTs. Fortunately, much of the economic analyses for traditional wind turbines are applicable to volumetric urban turbines. For this part of the analysis, costs would need to be added or subtracted where appropriate.

Table 1: Hypothetical cost estimate example in dollars

Machine rating (KWs)	1,500	
Rotor diameter (m)	70	
Hub height (m)	65	
Component	Component cost ($000)	As a %
<u>Turbine costs</u>		
Rotor	237	17
Drive train Nacelle	617	44
Controls	35	2
Tower	147	10
<u>Capital costs</u>		
Foundations	46	3
Transportation	50	4
Roads, civil work	79	6
Assembly & installation	38	3
Electrical connections	122	9
Engineering & permits	32	2
Total turbine	1,036	74
Total capital	367	26
Total	1,403	

Table 1 uses manufactured blade costs and specifications of turbine blades for a 60 m diameter rotor. Using this information, the cost per unit area can be calculated for the manufactured HAWT turbine blade. This cost can then be applied to the volumetric turbine rotor resulting in a net increase in cost due to the increase in surface area. With that said, however, there is an inherent strength in the hemispherical shape of the volumetric blade such that flexing inclinations will be considerably less and consequently less expensive materials and processes could be employed in the manufacture of the volumetric blade. This might produce a turbine blade that is comparable in price to the traditional HAWT. The possible need for a blade structure, perhaps made of carbon fiber and wire rope, to resist centrifugal forces as well as the possible need for extra strength in the supporting tower, might add to the costs of producing volumetric wind turbines.

There are four main factors that will govern the ROI in this analysis. The first is the amount of wind energy that is available over a typical year. The second factor is the capacity of the wind turbine to convert the wind energy into electricity. The third factor is the investment to pay for the cost of the turbine, installation, operation, and maintenance. The fourth is the market price of electricity in the area in which it operates.

2.3 Community Impact Criteria

A significant factor in siting utility-scaled wind turbines in urban environments is the impact of a unit on the surrounding community. Concerns include visual impairment of the landscape, noise, construction disruption, lower property values, health issues and those who would like the idea of renewable energy but are not willing to have a wind turbine sited near them. Wolsink (2000, 2007) investigated why people do not want wind turbines in their communities. This work presents a nuanced view of local opposition to wind turbines in which feelings of inequity and unfairness drive opposition. Jones and Eiser (2010) attempted to quantify opposition to wind farms near communities in the United Kingdom (UK). Their study tracked issues such as the despoiling of the landscape, noise, construction disruption, lowering property values, health issues and ecological concerns, reporting that visual impact to the landscape is the primary concern. Bishop and Miller (2007) examined visual impact to the scenery in their study. They used a computer program to quantify aesthetic assessments of scenery. The program showed scenes with moving wind turbines, static turbines, and no turbines. Their research team concluded that scenes without turbines were favored overall and scenes with moving turbines were favored over static turbines (Bishop and Miller 2007).

It is cost-prohibitive to quantify attitudinal concerns as numeric inputs in this type of analysis. However, property values depict the competition there is for a given property and ergo a proxy as to how much it is valued by the community. Property that is not likely to be devalued because of a turbine installation, or perhaps even enhanced, should be sought out as is the case in near unused industrial plants, abandoned grain elevators, landfills and brownfields.

Zoning restrictions are created by cities to represent the community's standards and values. If the community is accurately represented by the council, then zoning constraints can serve as *de jure* limitations imposed by community standards.

Last but not least, research into the not-in-my-backyard (NIMBY) phenomenon indicates that community buy-in to projects is extremely important. In many cases, it might be useful for nearby residents to actually *buy-in* to the project and receive part of the ROI (Nolden 2013). In countries such as Germany, The Netherlands, Denmark, and Australia community wind projects are common, and there are even a few community projects in the U.S. nowadays. These types of concerns should be addressed when a concrete proposal is introduced to the stakeholders in the community.

2.4 Grid Integration Criteria

Regardless of internal or external grid inputs, utility operators need to manage fluctuating demand. With renewable energy comprising an increasingly large percentage of electrical generation, these sources need to account for fluctuating generation as well. In non-urban applications, connections to the grid require installing substations, transformers, and high voltage lines at considerable cost to the project. The cost of integration in non-urban applications is spread across several turbines, thereby reducing the integration cost on a per turbine basis. The amount of energy produced by a rural wind farm can be a considerable input to an electrical grid and requires the utility to have carbon-based generation capacity equal to the wind generation input at the ready in the event that energy demand outstrips wind energy generation (Amin and Wollenberg 2005). Distributed intra-grid wind generation should help utility operators to improve their monitoring and control over their generation capacity.

Electrical connections to the power grid can require a capital expenditure and cost will vary depending on machine rating, the turbine's share of cables to the substation, and presumably how far the substation is from the turbine (Table 1). The distance to substation parameter is not explicitly expressed in the documentation for the NREL turbine costing model; however, it must be presumed that the NREL documentation, Fingersh et al. (2006), is referencing a wind farm's substation. A separate substation for a wind farm will impose a cost to grid operation all on its own. For an urban turbine installation, which will require a transformer but not necessarily a substation, cost to grid operation will be minimal.

In rural applications there are considerations for nearness to roads and towns. In an urban application those considerations are nullified. However, distance to a resource component is still useful in the analysis to determine the cost of grid integration.

2.5 Environmental Impact Criteria

The Trinity River runs through the city of Fort Worth, TX, and its tributaries include riparian, woodland, and grassland habitats. Ducks, geese, other birds, and Monarch butterflies pass through in Fort Worth on their seasonal migrations on the central flyway. North Texas is also home to bat species who make their home in wooded areas. Hale and Giggleman (2005) found in their report for the U.S. Fish and Wildlife Service (USFWS) that this AOI is also home to woodpeckers, chickadees, hawks and owls in the riparian woodland, emergent wetland, and upland woodland.

When considering the environmental impact of siting a wind turbine in an ecosystem that is home to birds and bats, which are harmed by wind turbines, it is necessary to reduce the impact these machines have on their habitats. There has been much research devoted to the impact wind farms have had on wildlife, primarily birds and bats. For example, Baerwald et al. (2008), identified the cause of bat fatalities near wind turbines by inspecting the ears of the dead bats. They suggest the cause is likely due to the pressure differential near the blade tips. The proposed volumetric wind turbine has blade tips which are curved in toward the incoming flow, which will minimize blade tip vortices. If this is the cause of bat deaths, as suggested by this study, bats are not likely to be harmed by flying near the proposed turbines. Horn et al. (2008) used infrared cameras to record the flights of bats at night near a wind farm. Images revealed that the bats were both trapped in blade tip vortices and struck by the blades. Volumetric blades are wider, which should present a larger target for a bat to echolocate. Everaert and Stienen (2007) studied bird colonies near wind turbines to quantify the incidence of fatalities due to the colony’s nearness to the wind turbines. The researchers concluded that wind turbines should not be located near breeding colonies of birds. The researchers did not identify whether birds were struck by the passing blades or if they flew into the stationary structure. Leddy et al. (1999) conducted a study near wind farms to find that there were fewer nesting birds near wind farms likely due to human disturbance.

Riparian buffers have been used in urban and suburban environments to mitigate the impacts on wildlife living near the built environment (Miltner et al. 2004). However, the one size fits all type of buffer scheme was shown by Kantartzis et al. (2006) to be insufficient to take into account the nuances of the interplay of the built environment and ecosystems. Furthermore, in this AOI there are areas with riparian buffers maintained by the U.S. Army Corps of Engineers (USACE) designed to create wetlands that mitigate runoff from impervious surfaces (Hale and Giggleman 2005). The riparian buffers mentioned are generally undertaken to protect against flooding; however, they also have the added benefit of preservation of river flora and fauna. Hale and Giggleman (2005) also identified riparian woodlands, emergent wetlands, grasslands and upland woodland habitats in this AOI that are home to birds and bats.

It is not sufficient to simply locate the habitats of wildlife that could be adversely affected by the siting of a wind turbine, it is also necessary to take measures to lessen the risk to these animals. Bohrer et al. (2013) sought to maximize turbine efficiency while minimizing wildlife impact for small-to medium-sized wind turbines. The researchers conducted population counts of birds around the Ohio State University (OSU) campus to determine bird densities and bird types and then created exclusion zones where turbines could not be sited (Bohrer et al. 2013). Hale and Giggleman (2005) provided evidence of the types of wildlife and their associated habitats that could be impacted by siting a wind turbine in or near these areas. The OSU study created an exclusion zone for areas on campus where there were high numbers of birds that could be impacted (Bohrer et al. 2013).

2.6 GIS Site Selection

GIS site suitability analysis is both an art and a science. Depending on the factors considered and the subjective weights and/or ranks of those factors, a researcher can produce incredibly different results (Qureshi et al. 1999). Each suitability analysis differs depending on the objective of the project, the researcher, the audience, the available data, and nature of the object or phenomenon being sited. In his thesis on Onshore Wind Power Systems (ONSWPS), Harrison (2012) gives a great deal of weight to proximity to urban centers, which is also the focus of the present thesis. Harrison (2012) also includes scaling factors for elevation, slope and aspect. Pohekar and Ramachandran (2004) explore a range of selection principles including weighed averages, priority settings, fuzzy principles, and combinations of these methods. Notably, they utilized weighted averages in a hierarchal approach for siting energy related resources such as solar, wind and thermal energy. Sanchez-Lozano et al. (2016) used a qualitative approach to site selection using a fuzzy multi-criteria decision method approach. While it was not included in this project, future research could benefit from incorporating qualitative data such as community attitudes might consider using a fuzzy multi-criteria approach.

Multi-Criteria Analysis (MCA) is a way of assessing the comparative influence of inputs to a decision and can incorporate binary (yes/no) evaluations, decisions which have multiple weighted influences that guides outcomes, and fuzzy logic where there could be many possible solutions to the same set of inputs (Qureshi et al. 1999). Harrison (2012), for example, used a four-stage weighted approach to MCA for finding suitable sites for onshore windfarms in the Pacific Northwest. The first stage, after deciding on the area and collecting the data, was to process non-feasible areas as exclusion zones. The second stage was to discover possible areas for inclusion. In the present thesis areas zoned as industrial, agricultural, or intensive commercial were possible areas for inclusion. The third stage was to evaluate suitability by combining the static criteria from the first two stages and introduce dynamic criteria. The fourth stage is the final evaluation wherein sensitivity analysis is performed. Sensitivity analysis changes the influence/weight of each of the criteria in an iterative process to discover how each of the influences impact outcomes.

Sensitivity analysis is a way of creating rigor in complex decision making, where each of the factors is explored to discover their influence. There can be several approaches to sensitivity analysis; however, there needs to be an initial assessment of the weights of all the dynamic criteria. This assessment should be based on critical factors.

Chapter 3 Methods

This project aimed to find optimal sites for innovative wind turbines within the City of Fort Worth Texas and determine the return on investment for a cost-effective wind turbine. There were five phases in this analysis. The first phase was to acquire, organize, evaluate, and process data. The second phase was to perform a weighted overlay analysis using the static inclusion/exclusion data and dynamic data to acquire results classified by suitability. The third phase was to perform sensitivity analysis to discover how each layer contributes to the results. The fourth phase was to validate results using 20 sites in the AOI deemed suitable for siting a utility-scaled turbine. After quantifying the weighted study, a site was selected to perform wind power and ROI calculations.

3.1 Data acquisition and processing

All of the data used for this thesis project was acquired from federal, state and municipal sources, with the exception of the test data for the volumetric turbine. All city related data was downloaded from The City of Fort Worth GIS website and these data were used to delineate the AOI, land use, inclusion, and exclusion zones. Two digital elevation model rasters (DEMs) were downloaded from the U.S. Geological Survey (USGS) and used to define the topographic surface. For wind data, the METAR data from area airports collected by the National Oceanic and Atmospheric Administration (NOAA) and the Texas Commission on Environmental Quality (TCEQ) was used. Electrical grid data was acquired from the Homeland Infrastructure Foundation-Level Data (HIFLD) website. Gas well data was acquired from the Texas Railroad Commission (TRC). Brownfields data were collected from the U.S. Environmental Protection Agency (EPA), and NREL wind power rating data were downloaded from the NREL website (Table 2).

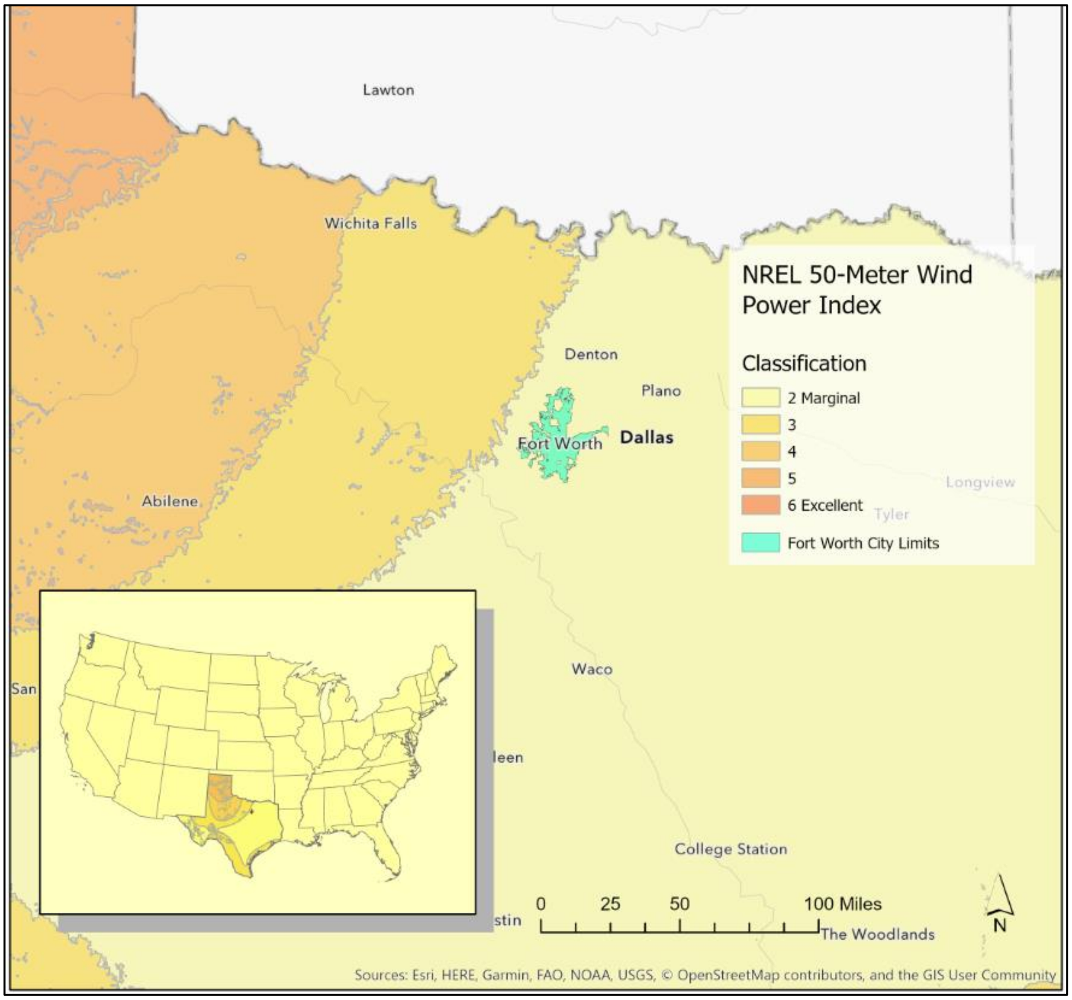
Table 2 Data sources

Data	Source	Type	Acquisition date
Brownfield sites	EPA	Text	Mar-2020
Electrical grid	HIFLD	Shapefiles	Dec-2019
Elevation rasters (DEMs)	USGS	Raster	Dec-2019
Gas well sites	TRC	Shapefiles	Mar-2020
METAR data	NOAA	Text	Dec-2019
Municipal data	City of Fort Worth	Shapefiles	Dec-2019
NREL power ranking	NREL	Raster	May-2019
Property values	City of Fort Worth	Shapefiles	Dec-2019
TCEQ wind data	TCEQ	Text	Dec-2019
Volumetric turbine test data	Researcher	Text	Mar-2013

3.1.1 NREL Wind Power Data

NREL wind resource maps for the U.S. at 50 m above the ground surface were used to find AOIs (see Figure 5). This map, based on current state-of-the-art wind turbines that are typically deployed at a hub height of 50 m above the ground, illustrates the fact that much of the U.S. is rated from good to marginal for wind energy. Moreover, most of the areas rated excellent to outstanding are found in relatively unpopulated areas. For the analysis, it would be relatively easy to find economically viable sites for turbines in areas rated in the excellent category, but in an effort to increase market penetration, the focus in this thesis was on areas rated in the marginal to good categories. Figure 7 below shows the NREL wind resource classification for the AOI.

The wind data are recorded by automated weather stations (AWS). These stations have integral validation fields which record the reliability of the measurements. METARs do not aggregate their readings and record readings below 1.5 m s^{-1} as “calm”. METAR readings are sometimes collected randomly with approximately one record per hour. The TCEQ network, on the other hand, collect readings several times per hour and reports an aggregated total for each hour. In the case of the METAR data, special processing was needed to aggregate totals for every hour in 2017, the year that the data were collected. Once both data sets were on the same temporal (hourly) scale, the data could be summarized to create Weibull curves for each site for the entire year. Because of the truncation of the METAR data at 1.5 m s^{-1} it was not possible to properly combine the two types of networks because the TCEQ stations reported wind below 1.5 m s^{-1} and the METARs reported “calm” during the same conditions. If this analysis had been for siting a typical HAWT turbine that does not start until at approximately 3 m s^{-1}, this data gap would not be significant. However, because the volumetric turbine can start at approximately 0.9 m s^{-1}, the data gap artificially creates a gap in production for the aggregated year.



Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

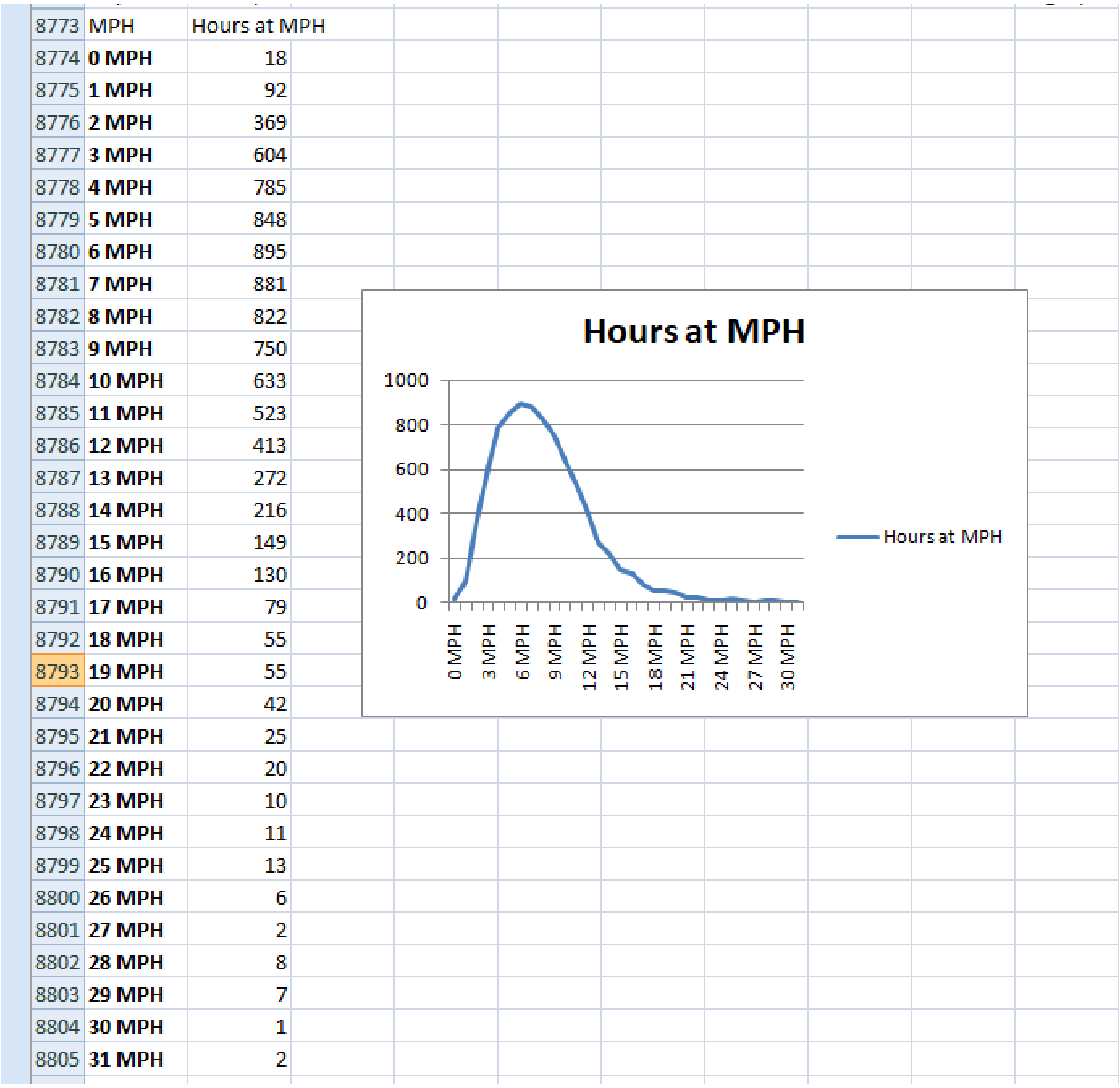
Figure 7: NREL 50 m wind power index map for Fort Worth, TX and surrounding areas

Both sources provided raw textual data that required processing to develop a viable wind energy surface. The data was downloaded and brought into a spreadsheet where it was examined for completeness, and unnecessary fields were eliminated. Table 3 shows the raw TCEQ data brought into Excel. This resultant spreadsheet was then summarized by hour. Figure 8 shows the summarized data for one TCEQ site. The summarized data were combined with the test data for the innovative turbine to yield a watt/hours curve as illustrated in Figure 4. Watt/hours were totaled for the year for each of the 25 sites in the study. The total was added to the location table that included geographic coordinates for each of the sites in the study.

Table 3: TCEQ raw textual data

State Cd	County Cd	Site ID	Parameter Cd	Dur Cd	Date	Time	Value
48	85	5	61101	1	20170101	12:00:00 AM	3.78833
48	85	5	61101	1	20170101	1:00:00 AM	3.38
48	85	5	61101	1	20170101	2:00:00 AM	3.48583
48	85	5	61101	1	20170101	3:00:00 AM	6.6175
48	85	5	61101	1	20170101	4:00:00 AM	3.82667
48	85	5	61101	1	20170101	5:00:00 AM	4.14917
48	85	5	61101	1	20170101	6:00:00 AM	4.0325
48	85	5	61101	1	20170101	7:00:00 AM	2.495
48	85	5	61101	1	20170101	8:00:00 AM	4.14333

The summarized data from the wind data tables were compiled into a site location table and imported into ArcGIS Pro as “Wind Monitoring Sites”. Feature Class copy was then used to create the table in the Thesis1 geodatabase and assigned the spatial reference NAD 1983 State Plane Texas North Central FIPS 4202 Feet. The ArcGIS Pro interpolation tool Empirical Bayesian Kriging (EBK) was used to create a Watt/Hours surface. EBK was chosen for its ability to handle non-stationary data and to interpolate over a wide area using a small number of inputs. A cell resolution of 100 ft was used and the search neighborhood used a standard circle with four sectors and a 45° offset which effectively aligned the data with the south to north predominant wind direction in this region of the country. Figure 9 shows the workflow used to create this surface.



8773	MPH	Hours at MPH
8774	**0 MPH**	18
8775	**1 MPH**	92
8776	**2 MPH**	369
8777	**3 MPH**	604
8778	**4 MPH**	785
8779	**5 MPH**	848
8780	**6 MPH**	895
8781	**7 MPH**	881
8782	**8 MPH**	822
8783	**9 MPH**	750
8784	**10 MPH**	633
8785	**11 MPH**	523
8786	**12 MPH**	413
8787	**13 MPH**	272
8788	**14 MPH**	216
8789	**15 MPH**	149
8790	**16 MPH**	130
8791	**17 MPH**	79
8792	**18 MPH**	55
8793	**19 MPH**	55
8794	**20 MPH**	42
8795	**21 MPH**	25
8796	**22 MPH**	20
8797	**23 MPH**	10
8798	**24 MPH**	11
8799	**25 MPH**	13
8800	**26 MPH**	6
8801	**27 MPH**	2
8802	**28 MPH**	8
8803	**29 MPH**	7
8804	**30 MPH**	1
8805	**31 MPH**	2

Figure 8: TCEQ wind data collected and graphed for site for one year

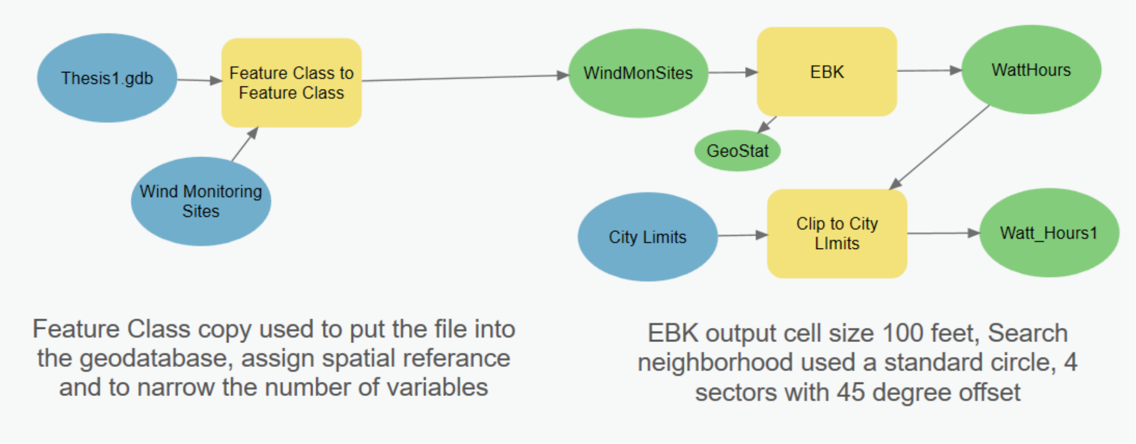


Figure 9: Model used to generate wind surface

The point data from the processing described above was used to interpolate a wind energy resource surface. Sites outside of the AOI were chosen to extend the interpolation past the AOI to reduce interpolation edge effects. The map shown in Figure 10 shows the resultant surface from the workflow shown in Figure 9. This surface is subsequently reclassified for the suitability analysis.

A complete years' worth of TCEQ hourly data for each station would include an entry for every hour of every day, or a total of 8,760 hours. This indicates that a simple row count will suffice to indicate completeness. The downloaded data from the TCEQ website was 24 hours short of 8,760 hours or 8,736 hours. Thus, the data can be considered complete, and they were used to calculate wind power using the following relationships:

$$\text{Power (Watts)} = \text{Torque (newton-meters)} \times \text{Speed (RPM)} / 9.5488 \qquad (1)$$

$$\text{Power (Horsepower)} = \text{Torque (lb-inch)} \times \text{Speed (RPM)} / 63{,}025 \qquad (2)$$

$$1\text{Watt} = 0.0013 \text{ Horsepower} \qquad (3)$$

$$1 \text{ Horsepower} = 745.6999 \text{ Watts} \qquad (4)$$

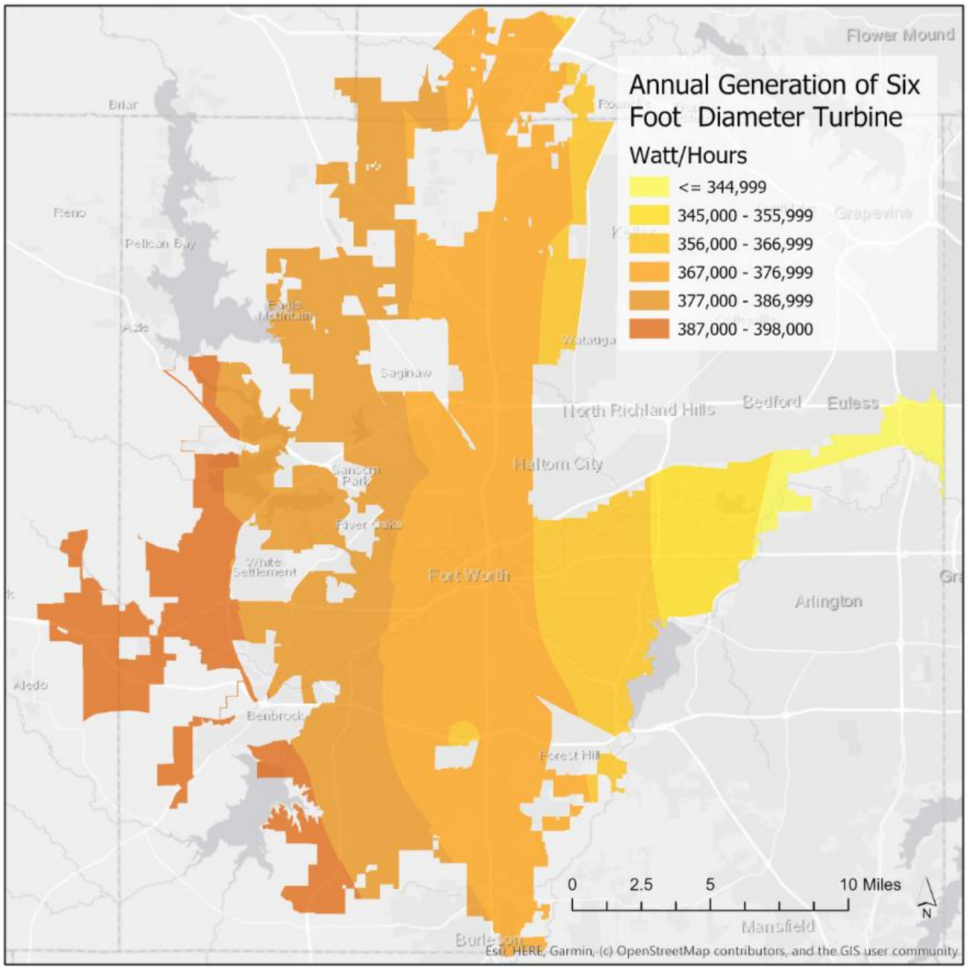


Figure 10: Wind resource surface

The theoretical wind power equation was calculated using:

$$P = \rho \pi d^2 v^3 / 8 \qquad (5)$$

where P = power (W); ρ = density of air (kg/m^3); A = windmill area perpendicular to the wind (m^2); v = wind speed (m/s); π = 3.14...; and d = windmill diameter (m).

Using the aforementioned equations, the actual wind power conversion for a windmill based on its efficiency was calculated using:

$$P_a = \xi \rho \pi d^2 v^3 / 8 \qquad (6)$$

where ξ = efficiency of the windmill (in general less than 0.4 - or 40%).

The actual available power from a windmill with a diameter of 1 m, and efficiency of 0.2 (20%) with wind velocity 10 meters/second, can be calculated as:

$$P_a = (0.2)\ (1.2\ \text{kg/m}^3)\ \pi\ (1\ \text{m})^2\ (10\ \text{m s-}^1)^3\ /\ 8 = 94.2\ \text{W} \tag{7}$$

The aforementioned equations assume we know the efficiency of a wind turbine at a given wind speed. However, what is important is that wind power is based primarily on the “swept area” or diameter of the rotor. Because this is an area calculation, doubling the diameter quadruples the area and therefore quadruples the energy capture at any given wind speed.

Testing the energy conversion of a wind turbine is tricky because an increase or decrease in wind speed does not instantly result in a change in energy conversion due to inertia. This is the case whether testing with an electrical generator or testing with a mechanical dynamometer. To have the data regress to the mean and therefore reflect the wind-speed to power-conversion relationship, as many measurements as possible were taken. Regardless of the effort, the wind blows at its own frequency that may have resulted in an understatement of the power conversion potential at higher wind speeds.

The power curve of the volumetric wind turbine shown in Figure 4 is used to define how much energy can be derived over the course of a year at a given site. This was used to interpolate wind power capture over the entire area. Wind speed was averaged into miles per hour divisions and then the averages were multiplied by the wattage associated with wind speed in the power curve for the innovative wind turbine, resulting in a watts/hour curve for the site. Each wind speed segment in the watts/hour curve were added together to show the net result of potential energy collection for the year in watt/hours.

Wind speed increases with elevation above ground at any given point. To extrapolate the wind speed at a given height, the Vertical Wind Profile – Logarithmic Law which extrapolates wind speed at one height based on the wind speed at a different height was used and is appropriate for calculating wind speeds at heights down to 10 m:

$$v_2 = v_1 . \frac{\ln\left(\frac{z_2 - d}{z_0}\right)}{\ln\left(\frac{z_{1-d}}{z_0}\right)} \tag{8}$$

where v_2 = mean wind speed at height z_2 in (m s^{-1}); v_1 = mean wind speed at height z_1 in (m s^{-1}); z_2 = height (m); d = zero plane displacement (m); z_0 = surface roughness (m); and z_1 height (m). An online calculator for the Vertical Wind Profile – Logarithmic Law can be found at https://www.fxsolver.com/ (last accessed 29 November 2020).

3.1.2 Elevation

Elevation data was used to quantify local fluctuations in wind power potential. This project used USGS 1/3 arc-second DEMs. Two were needed to capture the entire city. All project rasters, were projected into NAD 1983 State Plane Texas North Central FIPS 4202 Feet. Cell size was resampled to 100 ft and snapped to a project raster. These rasters were then added to a mosaic dataset and then clipped to the Fort Worth City limits. Figure 11 illustrates the process used to prepare the elevation data and Figure 12 illustrates elevation data before classification. After the initial processing of elevation data, the raster was reclassified into nine classes, with class 9 representing the highest elevation and being the most favorable, and class 1 being the lowest and consequently the least favorable. Figure 13 shows a map of the resultant reclassification.

Nine classes were chosen for all the layers in the suitability analysis to show a smooth color gradient between highly and least suitable. This gradient reduced the number of arbitrary breaks that occur when suitability studies use five or fewer classes. Furthermore, there is an inherent flexibility in siting wind turbines in that marginal obstacles in siting an economically viable wind turbine can be overcome by taller towers and larger rotor diameters.

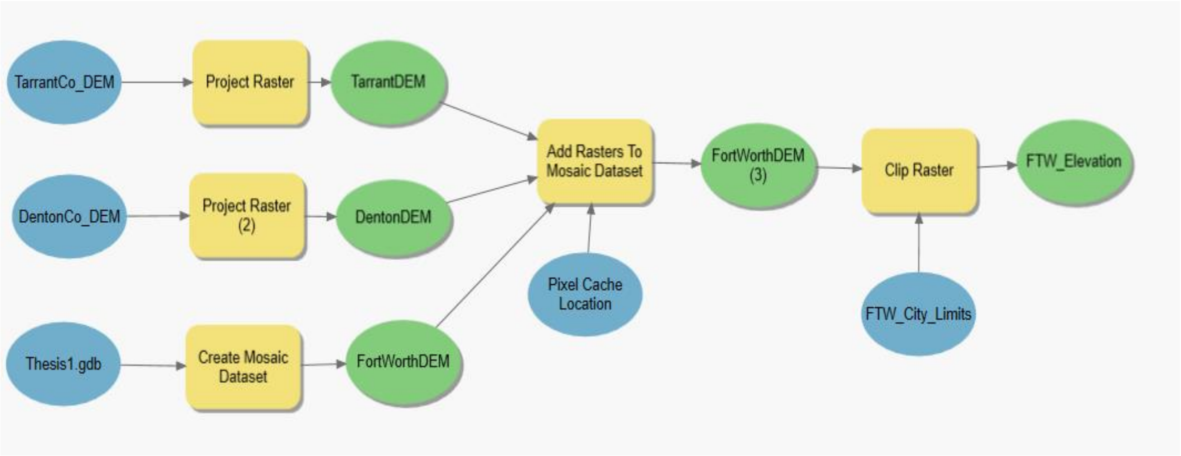


Figure 11: Model of data process used to prepare elevation data

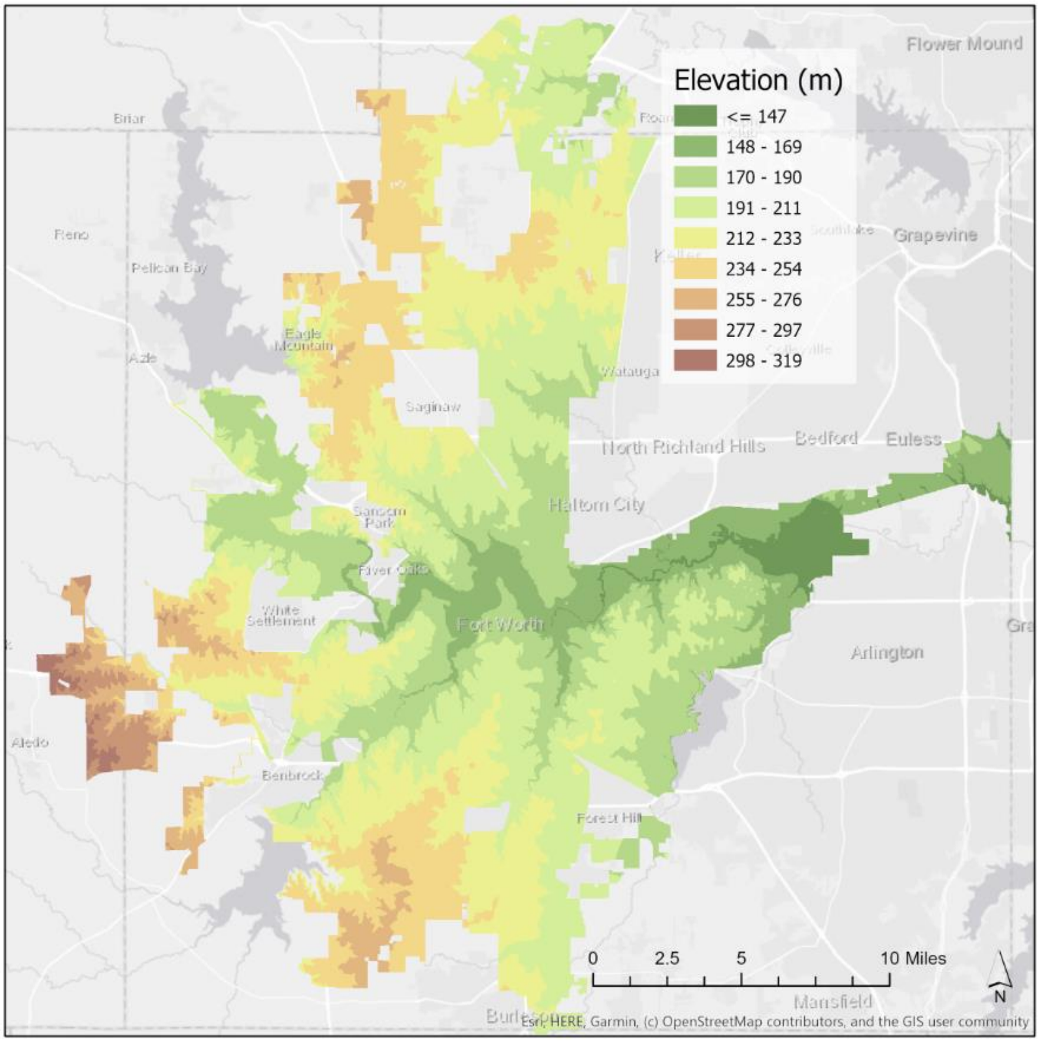
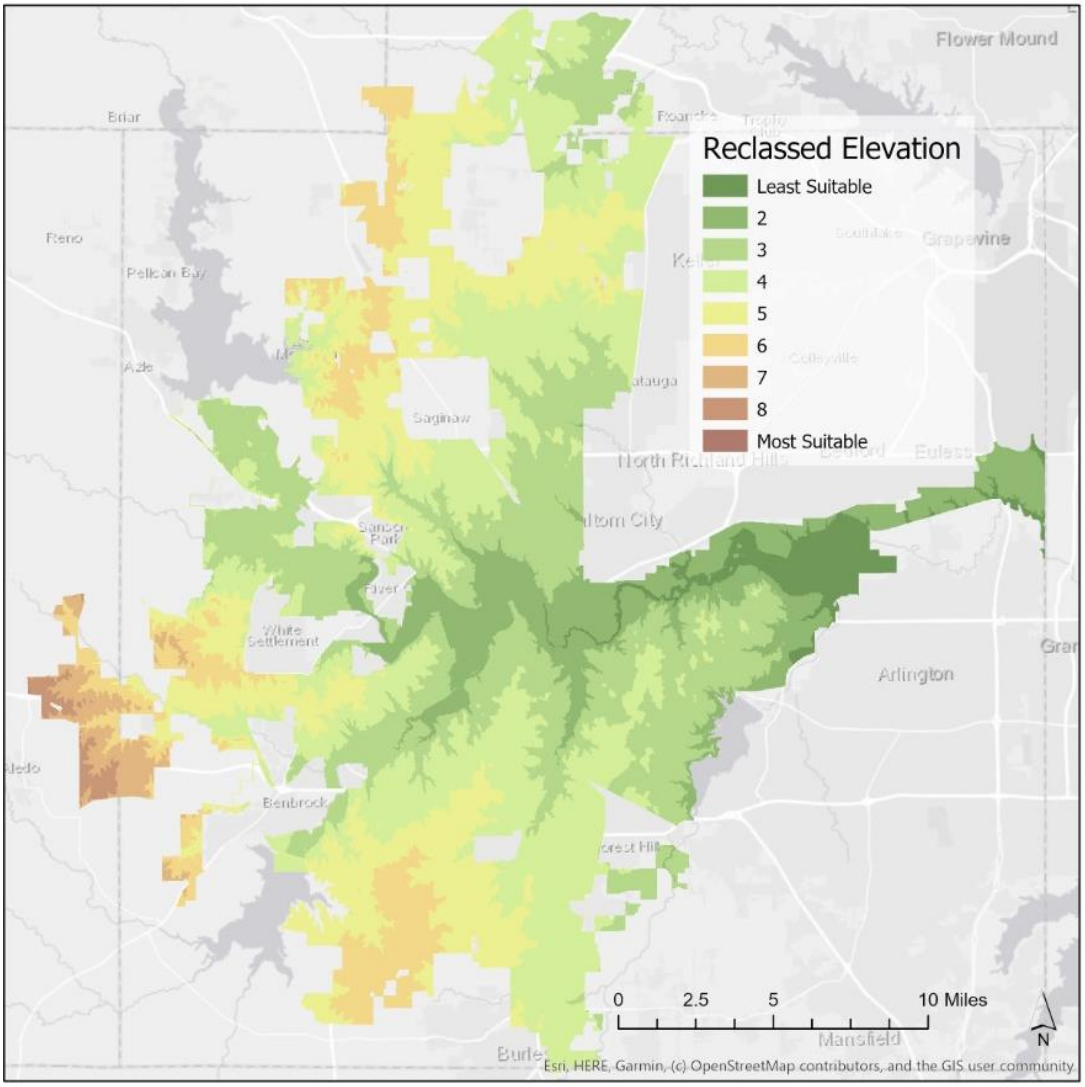


Figure 12: Fort Worth, TX elevation raster



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

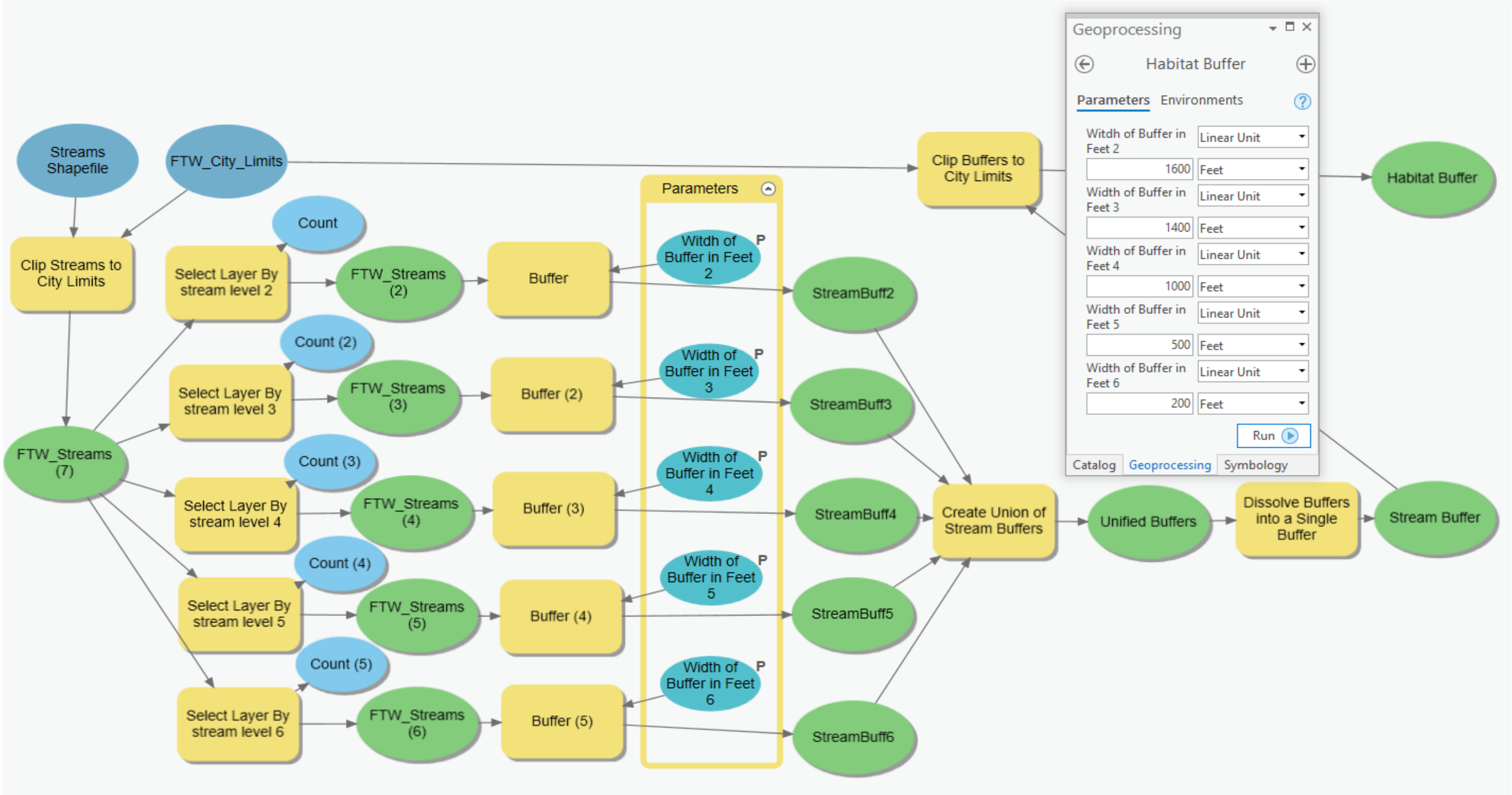
Figure 13: Map of reclassified elevation

Although slope and aspect are logical inputs to this type of study, after processing the exclusion data in the AOI, the maximum slope of the terrain in the included areas was 5.21° with a mean slope of 0.38° and therefore slope could not be said to play a significant role. Similarly, because of the relatively flat terrain within the included areas of the AOI aspect is not a significant influence as well. However, once a site has been selected, terrain plays a role when considering the surface roughness attribute in the Vertical Wind Profile – Logarithmic Law.

3.1.3 Environmental Concerns, Exclusion Criteria

Environmental data is used as exclusionary data in the first phase of the MCA. As mentioned in Chapter 2, the Trinity River and its tributaries possess riparian, woodland and grassland habitats. These habitats are home to birds and bats that might be harmed by a wind turbine and therefore stream buffers based on stream level are applied to streams in the AOI. Birds inhabit both riverine and wooded areas. Bats typically inhabit wooded areas and there are wooded areas that border the rivers and streams in this AOI. It is possible that bats may be able to echolocate the hemispherical wind turbines and thus the risk to them may prove to be minimal. Nonetheless, riparian buffers were applied in the wooded areas along rivers and streams to preserve this area for habitat preservation.

Because the rivers and streams in this AOI are adjacent to both the built environment and wildlife habitats a simple stream level buffering that only considers one or the other cannot be used. To create this type of buffer an iterative approach was used to define the exclusion buffers to encompass wetlands, riparian, and riparian woodlands for habitat preservation (Figure 14). Figure 15 shows an exclusion buffer around rivers and streams to eliminate areas of habitat as siting opportunities. This buffer serves as an exclusion because all cells within the buffered area were excluded from consideration. Figure 15 also shows the major reservoirs and their associated buffers in the area that were treated as exclusion areas as well. The workflow reproduced in Figure 14 was customized for this AOI based on stream level, with stream level 2 being the highest stream level in the AOI and level 6 being the lowest. An iterative process was used to build buffers around the streams wherein a buffer width was chosen for a stream level and then inspected to see if the buffer was sized large enough to incorporate the green space surrounding the channel. If the buffer was too small the size was increased and if too large,



Habitat Buffer

Witdh of Buffer in Feet 2: 1600 Feet

Width of Buffer in Feet 3: 1400 Feet

Width of Buffer in Feet 4: 1000 Feet

Width of Buffer in Feet 5: 500 Feet

Width of Buffer in Feet 6: 200 Feet

Figure 14: Parameterized model used to create habitat buffers

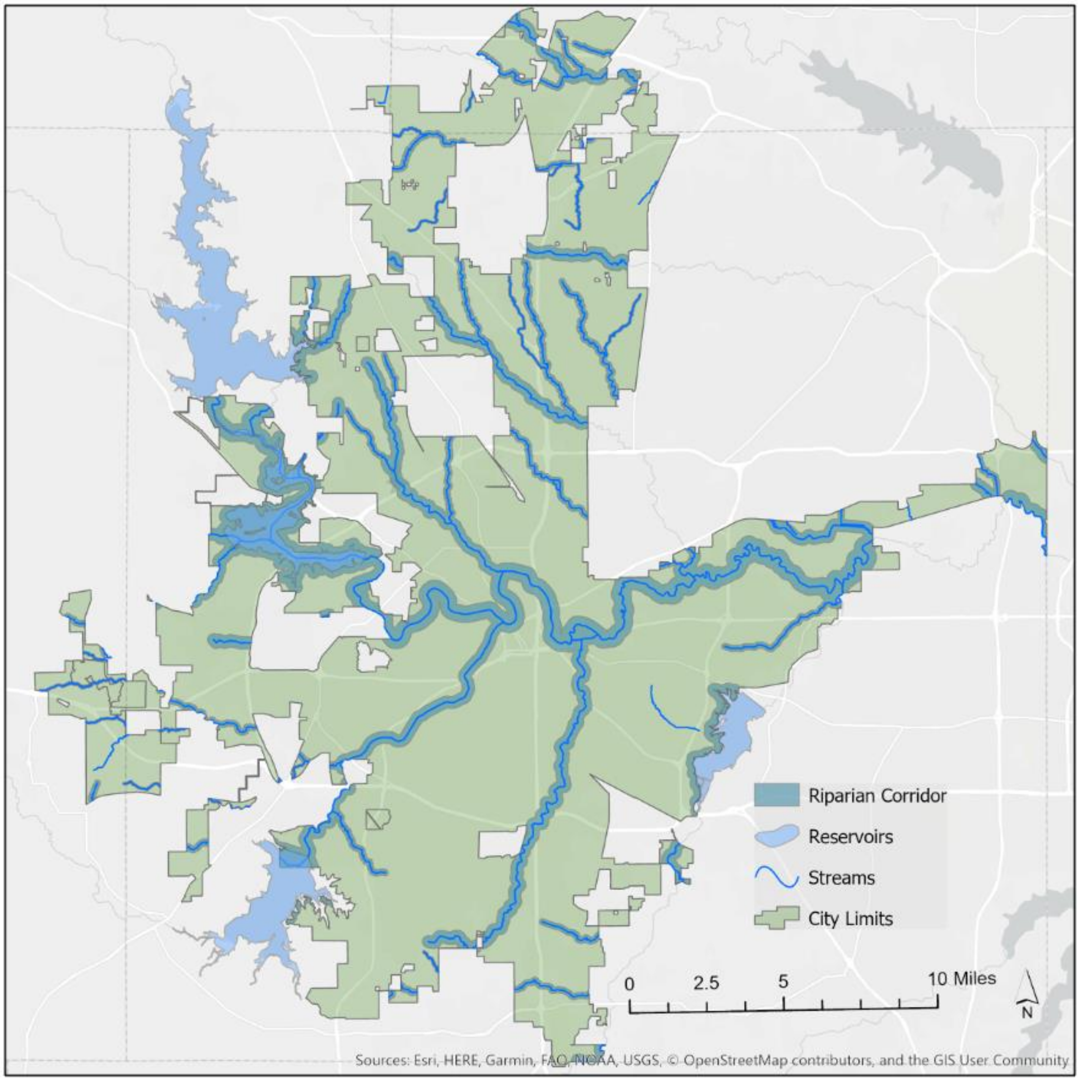


Figure 15: Map of habitat buffers and other sensitive areas

incorporating a significant amount of developed land, it was decreased. Therefore, a parameterized model was created so the iterations could be accomplished rapidly. There is no one correct methodology for conducting this process.

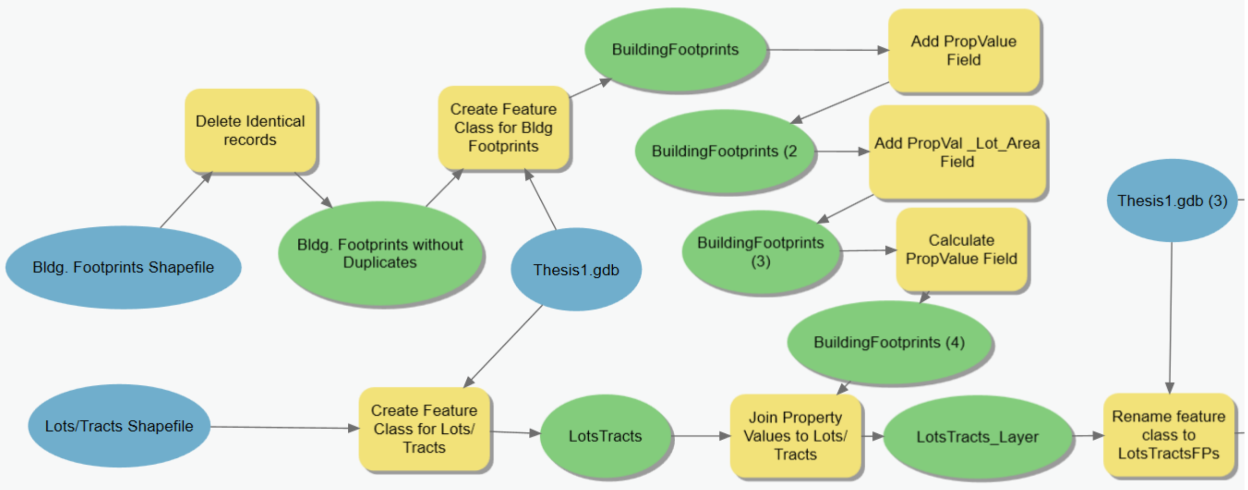
It is notable that in this AOI, private residential property surrounds most of the reservoir edges. This residential land use creates a *de facto* reservoir buffer. However, the reservoirs were buffered to 300 m to encompass areas that might not be encompassed by residential property.

3.1.4 Economic/Property Values, Dynamic Criteria

Local economic criteria can include such factors such as property values, cost of electricity, cost of alternative grid inputs, the monetary value of state and local incentives, and the cost of an appropriately sized turbine. All of the abovementioned factors except property values were deferred until after a site is selected and therefore not considered for the work at hand. In this part of the analysis, property values assessed by the Tarrant County Appraisal District (TAD) were used to calculate a cost surface. Unfortunately, the City of Fort Worth did not provide appraisal values in the neighboring Parker County on the west side of the city and therefore this part of the city was excluded from this analysis. The process depicted in Figure 19 joined the data of the City of Fort Worth's Building Footprints layer with the Lots and Tracts layer to create a property value field normalized by lot area to give a value/cost per square foot for each lot. The subsequent combined feature class was then used as input to EBK to create the cost surface. After trying several parameters, a smooth circular search neighborhood with a smoothing factor of 1 and a search radius of 5,000 feet was used in the EBK tool, which reflected the gradient of the data in the AOI. Figure 19 shows the model for processing the property cost data.

Even though the surface produced by the process shown in Figure 16 showed some expected variability, there were anomalous areas of extremely high values. These extremely high values caused the interpolation to predict some negative values for nearby properties. Upon closer inspection of the data, a property's valuation for an entire campus of lots was assigned to each lot in the campus. From TAD's perspective, it makes sense to assign a tax valuation for a campus of properties owned by a single taxpayer. However, the practice of assigning a campus's value to each lot in the campus causes problems for spatial interpolation. One solution to this problem would have been to manipulate the records by merging all the lots of a suspected campus into a single multi-part polygon, and then applying the valuation to the entire merged polygon. However, invoking Tobler’s First Law of Geography, the property values of individual lots in these campuses should mirror those of the campuses; therefore, the solution taken was to simply delete the records and allow the interpolation to fill in the gaps.

Figure 17 shows the resultant surface. The CBD is clearly shown in red at the center of the city, and low-income areas that are prevalent in the southeast are also clearly visible. This surface was reclassified into nine classes and the resultant classified surface is shown in Figure 18. Blue areas have less cost and are more suitable, while yellow-to-red areas have more cost and are less suitable.



Continued Below

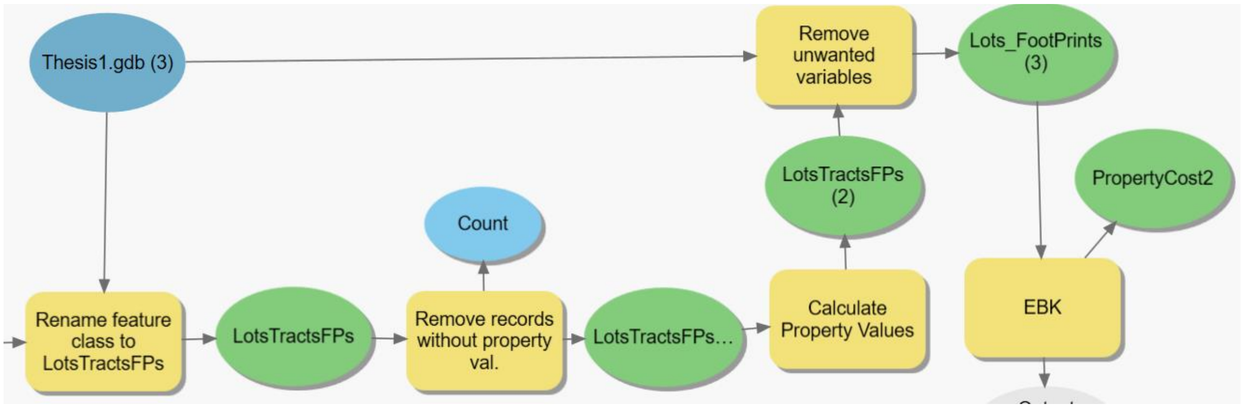


Figure 16: Model used to remove duplicate data, join property values to lots, assign property cost, and remove records without property values

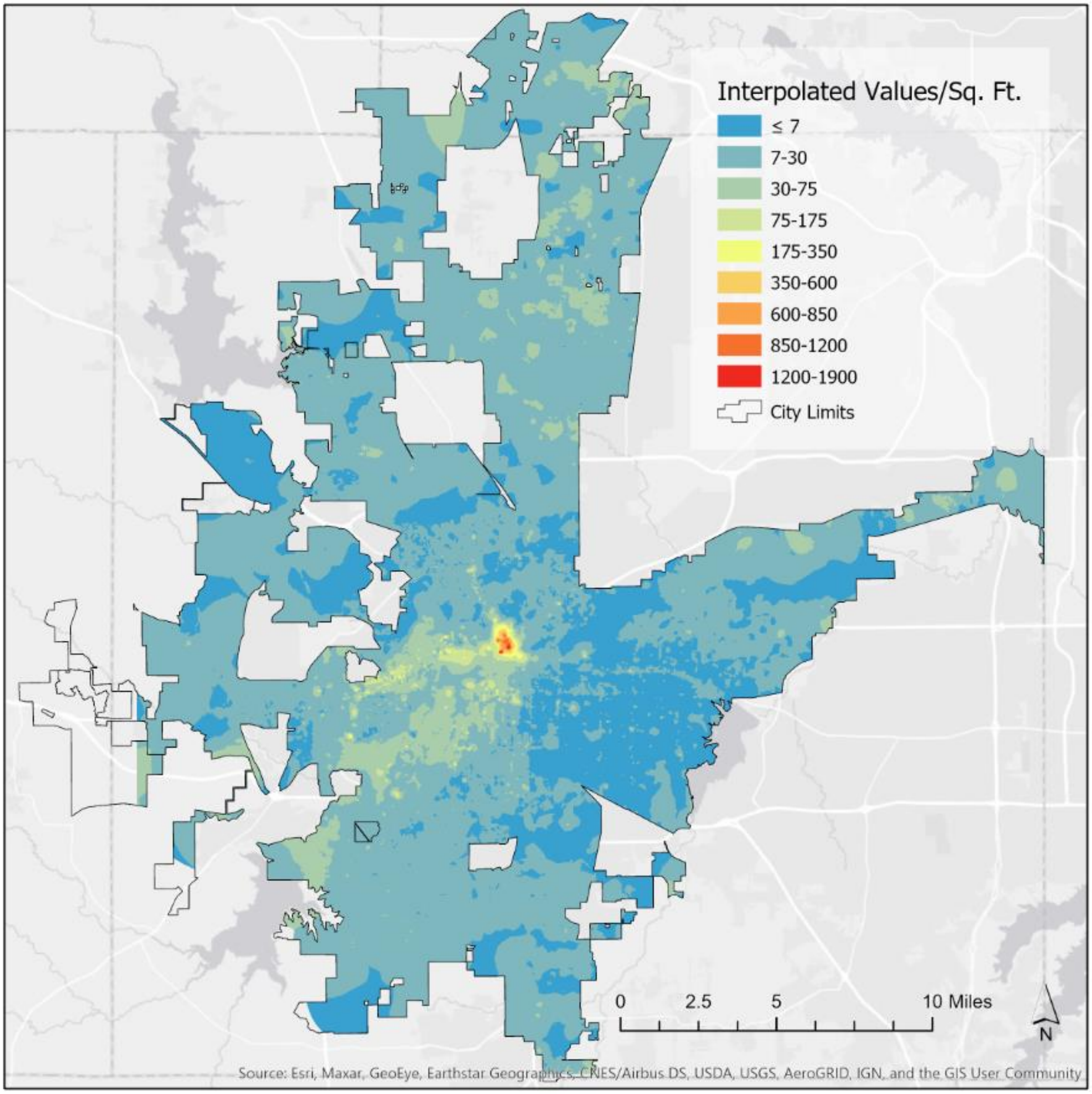


Figure 17: Resultant interpolated property values given hypothetical relationship between property values and appropriateness of siting wind turbines

.

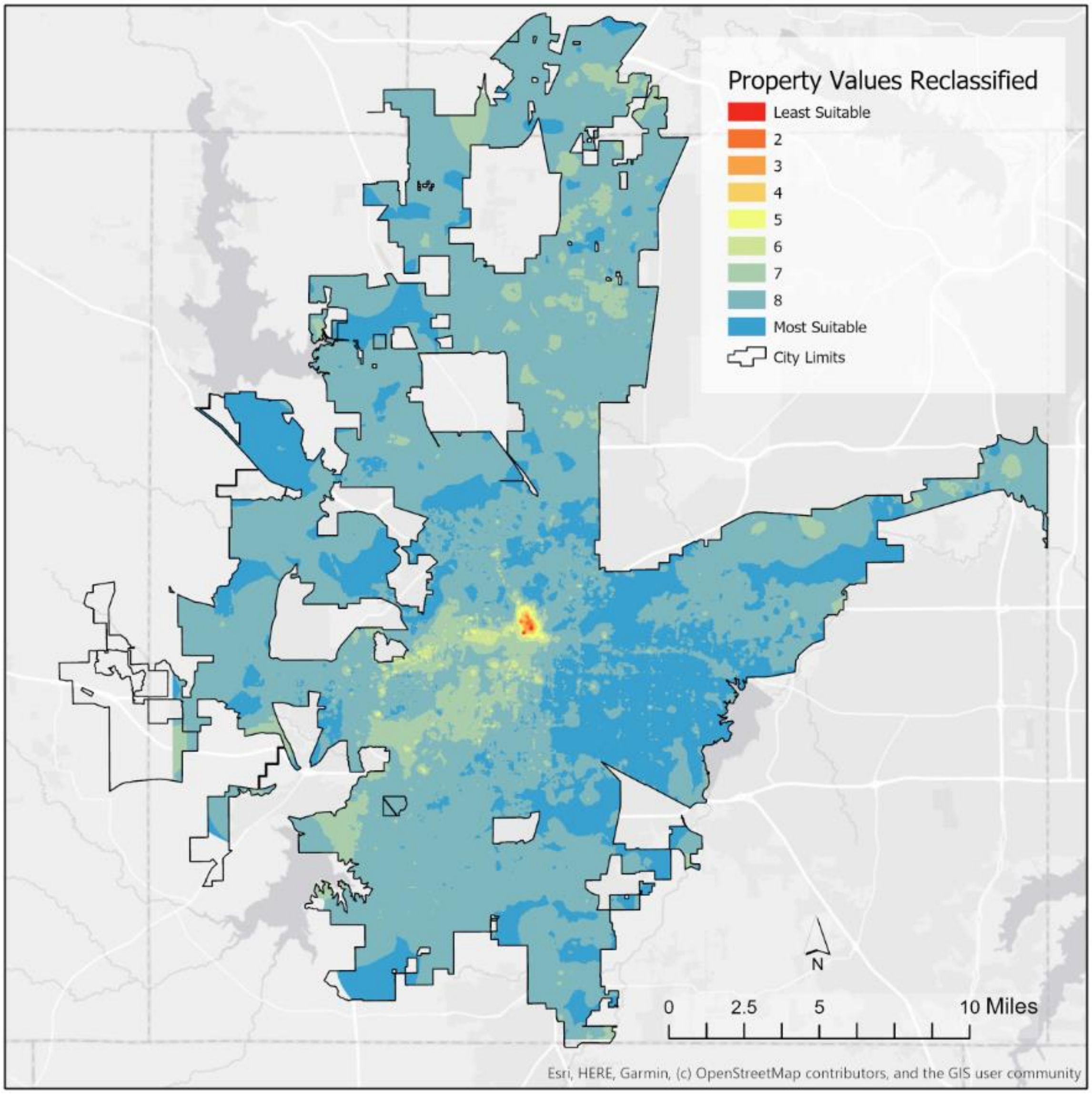


Figure 18: Property cost surface given hypothetical relationship between property values and wind power capture

3.1.5 Community Concerns, Exclusion Criteria

The City of Fort Worth has created several community-related layers that are useful in defining community concerns and possible interest in renewable energy projects. These layers include zoning restrictions, neighborhood organizations, neighborhood alliances, local historic areas and growth centers. The information found in these layers are helpful in determining where a utility scaled wind turbine can be sited, and which communities might have interest or concerns with any forthcoming proposal.

It is beyond the scope of this study to conduct a survey to find where in this AOI people would be most amenable to the siting of a wind turbine in their neighborhood. However, if this innovation proved to be viable, then surveys should be conducted to ascertain areas of receptivity and resistance to siting in a neighborhood. In lieu of conducting a survey, zoning restrictions are used as a proxy for receptivity and resistance. As an argument for using zoning it could be said that the city council in Fort Worth, which oversees the zoning restrictions and variances, are duly elected officials and represent the people in their district and therefore zoning restrictions are proxies for attitudinal concerns in that district.

Zoning is stationary data that serves as both inclusion and exclusion criteria in phase one, processing of exclusion areas and phase two, processing of inclusion areas for the MCA. Local zoning regulations were used to determine whether it would be advisable or legal to site a turbine without a zoning variance. These zones do not address wind turbines *per se*, but some address height restrictions specifically around airports and the CBD while others give guidance as to the intended uses for the area. Each of the 94 city zone types was inspected for possible use. Six zones possessed sufficiently similar uses to make them worthy candidates for inclusion in the siting criteria: agriculture, intensive commercial, light industrial, medium industrial, heavy industrial and planned development. The two most problematic of these are intensive commercial because the properties tend to be high value real estate, and planned development because it is unclear what the development is planned for. Some of the planned development was not only planned but built and the zoning map data has clearly not kept up with the change in status.

The workflow used to create the combined exclusion feature to remove unusable areas from consideration and extract said exclusions from the zones deemed suitable (Figure 19). Some of these zones are what the City of Fort Worth calls overlay zones. The overlay zone types supersede the underlying zones and can encompass large swaths of real estate. These zones are prominent features of area airports but can also include neighborhoods and historic districts. Overlay districts can overlay any of the six zone types included in the analysis and therefore their footprints need to be extracted from the inclusion zone layers along with the exclusion layer for habitat preservation. Figure 20 shows the overlay zones, habitat preservation areas, reservoirs and zoning classes used to remove areas from consideration during the first phase of the MCA.

Other exclusion criteria covered areas that are too small to be considered for a utility-scaled wind turbine and the neighborhood organization layer. The latter was used to examine where and how the extracted zones were located with respect to residential neighborhoods. The neighborhood organization layer included mostly residential property but there were also commercial and industrial components to consider as well. Because of the multi-use nature of some of these neighborhoods a simple residential buffer could not be employed. Instead, each neighborhood was examined as to how the included zone was located with respect to adjacent building types.

Phase two of this MCA comprised the processing of inclusion criteria that delineated zones considered suitable for siting (Figure 21). However, given the exigencies of the project, not all zones shown will be retained. Zones in Parker County to the west were excluded due to the lack of property cost data. The results were further limited by removing areas that were too small to site a utility scaled wind turbine or zones that were too close to residential structures. This reduction is illustrated in Figure 22. Comparing this map to that in Figure 21 show how these exclusions removed a large amount of real estate from consideration in the analysis. Figure 22 represents the output for phase three of the MCA, the combining of the two inputs from the previous two phases, to create a surface for possible sites to be used in the final stage.

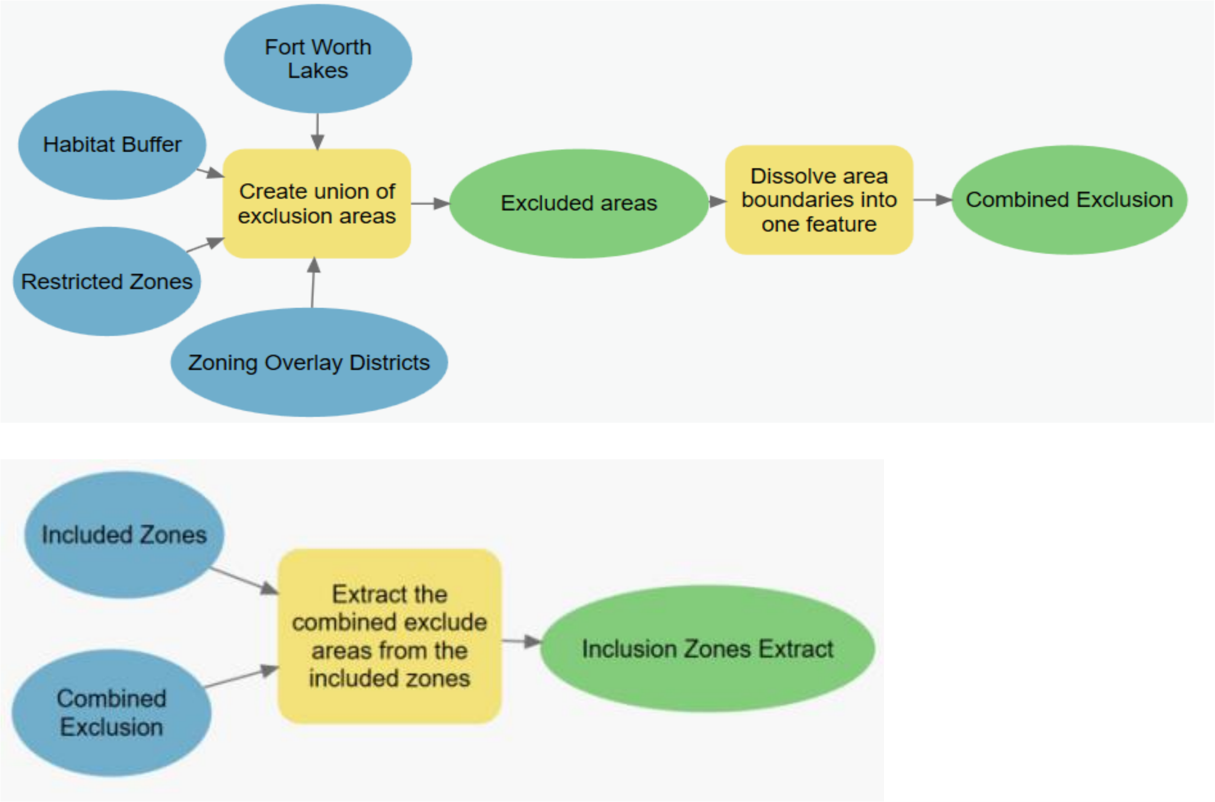


Figure 19: Used to create the combined exclusion feature class and extract the exclusions from the zones deemed suitable

Other community concerns may be harder to quantify but are no less critical in the successful siting of a new and perhaps extremely large wind turbine. Unhappy residents have derailed many of what otherwise would be considered successful renewable energy installations.

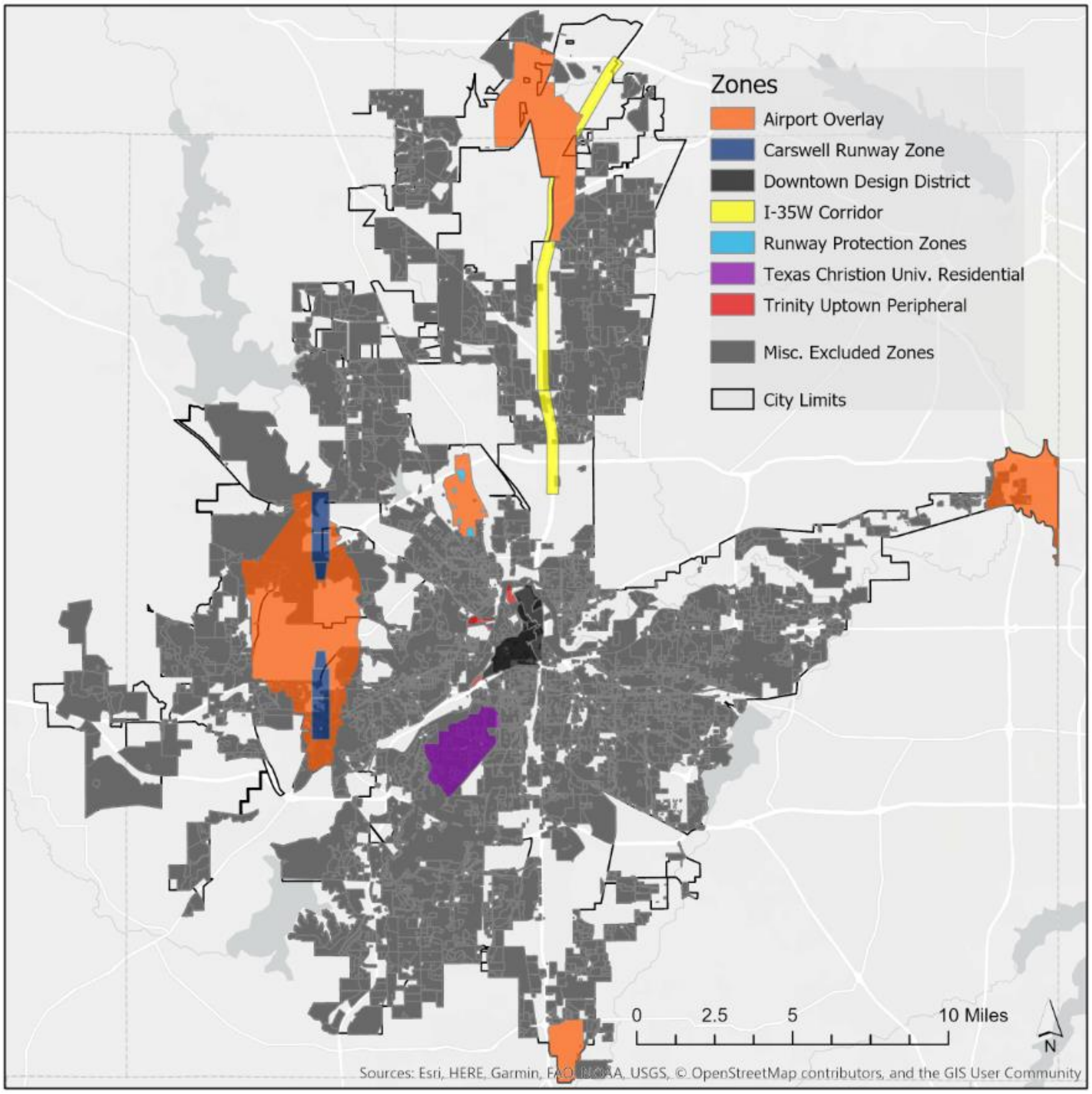
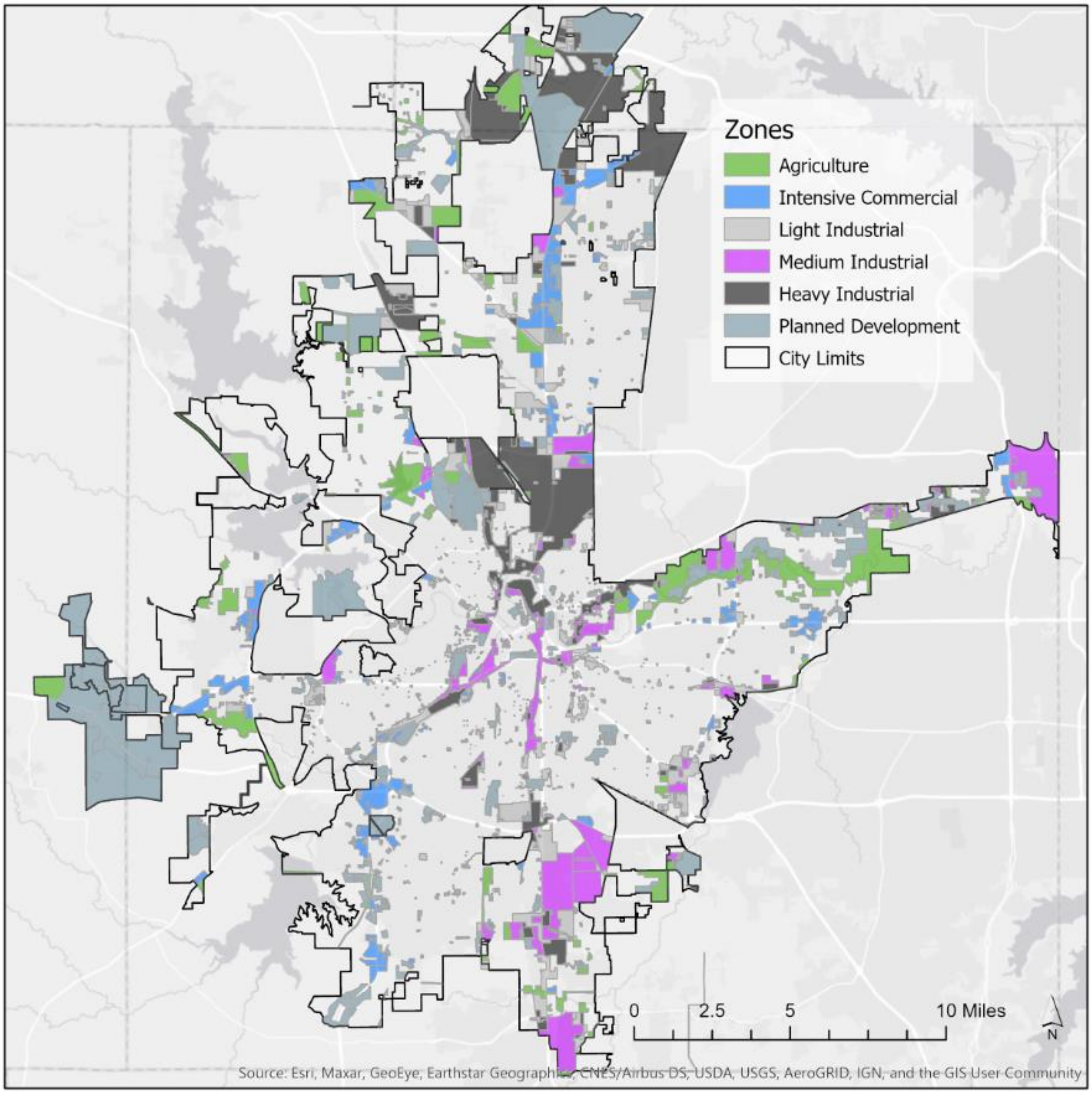


Figure 20: Fort Worth exclusion zone map

3.1.6 Grid Integration, Dynamic Criteria

Figure 23 shows the workflow used to create the distance to substation raster. A similar process was used to create the distance to transmission lines raster. The inputs to these two processes are shown in the map in Figure 24. It should be noted that features outside the city limits were included because in some cases substations and transmission lines outside of the AOI will prove to be closer than those inside for sites located along the borders of the AOI. Not shown is the



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 21: Zoning map of types of zones included in the study

service area polygon which extends past the boundaries of this map. Service areas are important to identify cost of electrical service and service provider. This analysis uses the Euclidean distance (nearness) to substations and transmission lines as a weighted factor in determining siting. The two distance rasters, distance to transmission lines and distance to substation, was subsequently reclassified into nine classes.

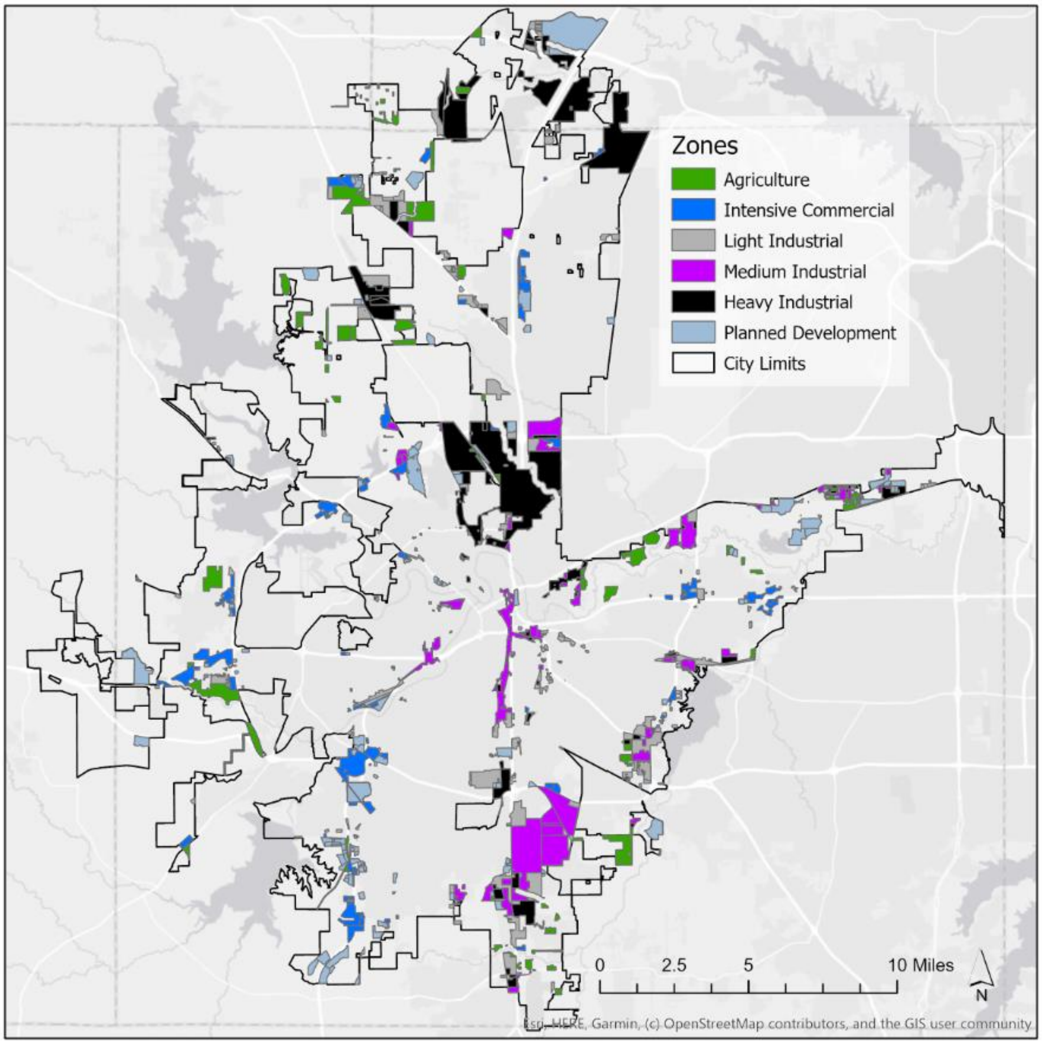


Figure 22: Fort Worth exclusion zone map

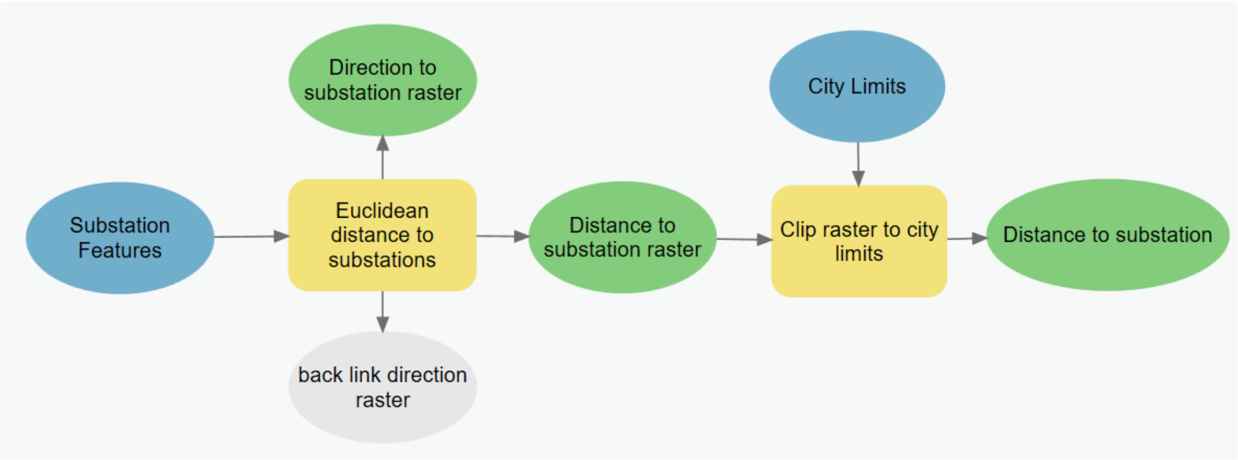


Figure 23: Data processing workflow to estimate distance to substation

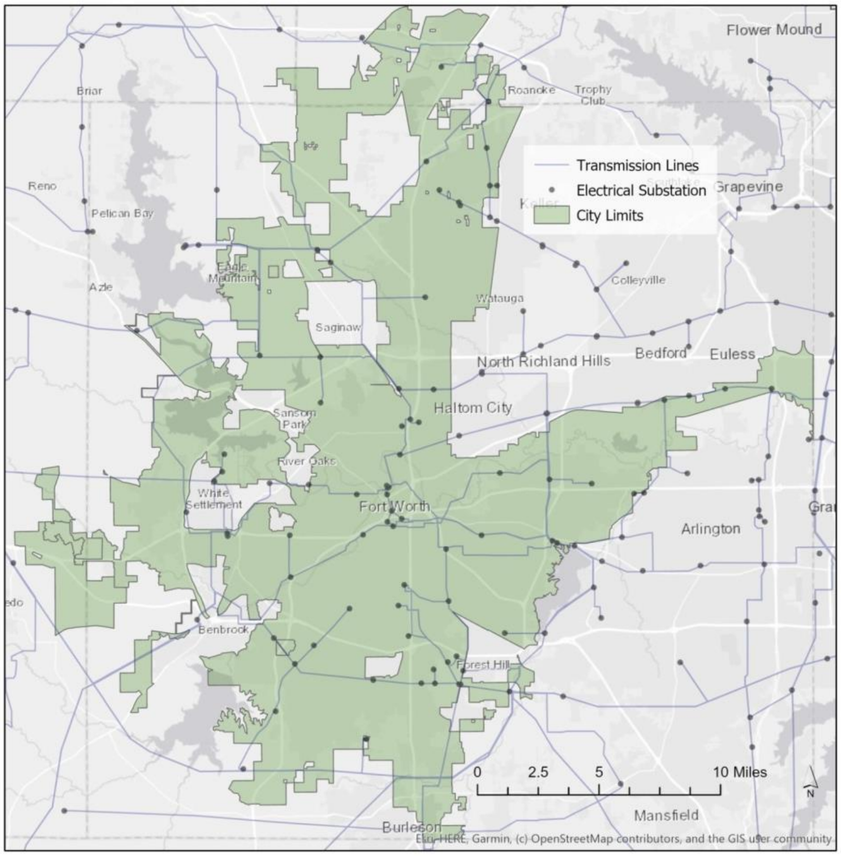


Figure 24: The Fort Worth electrical grid used as input to create the distance to transmission lines and distance to substation rasters

3.1.7 Siting Foci

Siting foci are considered sites where there is a long term or even permanent deterrent for non-residential type uses. Retired landfills, derelict grain elevators, EPA brownfields, and gas wells are considered "siting foci" for this analysis. Siting foci were not considered in the MCA initially, but instead are used as determining factors for siting *on* one of these sites. Each of these types of sites has advantages and disadvantages for siting a windmill, but any future commercial or residential development without considerable effort and expense to ameliorate the limitations will be unlikely. This therefore presents a niche opportunity for a utility like a wind turbine.

A retired landfill is unlikely to be used for anything in the future but does create a site elevated over the surrounding terrain which will create a positive vertical wind profile for siting a wind turbine. The downside is that to use these sites to install large vertical structures like wind turbines, piers need to be drilled through the fill and into solid substrate (bedrock) which increases installation cost. Furthermore, the site could possibly pose a toxic hazard to installation or maintenance crews and this hazard would need to be ameliorated.

Abandoned grain elevators can also provide a positive vertical wind profile for locating a wind turbine, and the solid structure and load carrying capacity are additional positive attributes. However, grain elevators in this area have a long history. Some are owned by historically prominent families who may use them as tax hedges instead of a revenue stream. Even if this is not the case, some of these structures have been decommissioned for decades which makes them targets for vandalism and decay. Renovation would need to be undertaken to make these sites suitable for this alternate use.

EPA brownfields are typically areas where toxicity has been found and the EPA pays incentives to developers to restore the property to future commercial use; however, these incentives may not be available for innovative wind turbines. Furthermore, the incentive may be sufficient to clean the area of the toxic compounds but may not pose enough of an incentive to make the installation of a wind turbine economically viable without some other *raison d'être.*

Fracking for natural gas began in earnest about fifteen years ago in this AOI. There are now hundreds of gas wells within the City of Fort Worth. These wells are expected to have a productive life of between ten and forty years. After they are retired, they can still leak gas and the ground surrounding them can leach out toxic chemicals making their future use for any other type of development questionable. The energy companies who drilled these wells sought to find areas that were suitable for siting an industrial application, or, where residents were unlikely to object too strenuously, and therefore a reasonable amount of siting groundwork has been completed. One possible downside is that natural gas production may be incompatible from a safety perspective with electrical generation.

Railroads are not considered siting foci, but they come into play when considering how to transport large components and equipment to an installation site. It is convenient that many of the inclusion zones have nearby railroads, sidings, and rail yards. This is a byproduct of the types of zones selected (primarily industrial) for siting. It is also a byproduct of Fort Worth being a regional rail hub throughout most of its history. Currently, the BNSF and the UP have large operations within the city. The TRE operates a link between Fort Worth and Dallas that had been part of the now defunct Rock Island Railroad. There is a small rail line, the FWWR that runs freight to various railroad sidings throughout the city and into Grapevine, TX. It is also convenient that electric utilities use railroad easements to install equipment such as substations and transmission lines. It is unclear how much weight to give railroads as a resource because they will be useful in the transporting of components but will not likely play a role in daily operations. Figure 25 is a map of siting foci. The gas well locations were provided by the Texas Railroad Commission and the brownfield locations were provided by the EPA.

3.1.7 Ground Truth Sites (Sites Deemed Suitable)

To validate the results of the MCA, 20 sites were selected that are deemed good sites in which to locate a utility-scaled wind turbine in the AOI. These sites were located within inclusion zones and near siting foci and a safe distance from residential properties. In addition, measurements were taken to determine if there was space for siting a utility-scaled wind turbine in these locations.

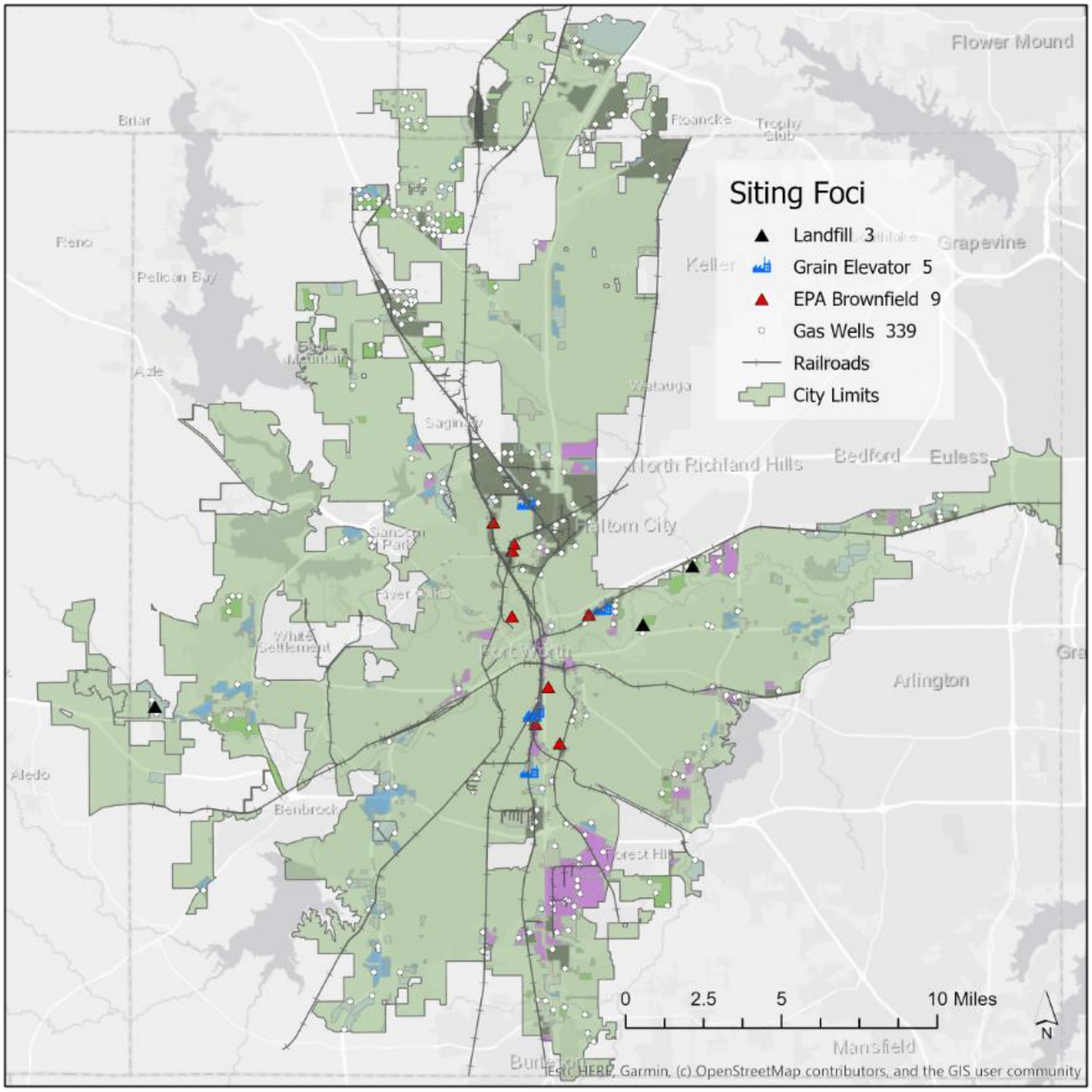


Figure 25: Map of siting foci

Sites were found throughout the AOI but more sites on the westside of the AOI were selected than on the eastside because of more favorable wind conditions. One decommissioned grain elevator was used as well as three closed landfills. The remainder of the sites were near gas wells (Figure 26).

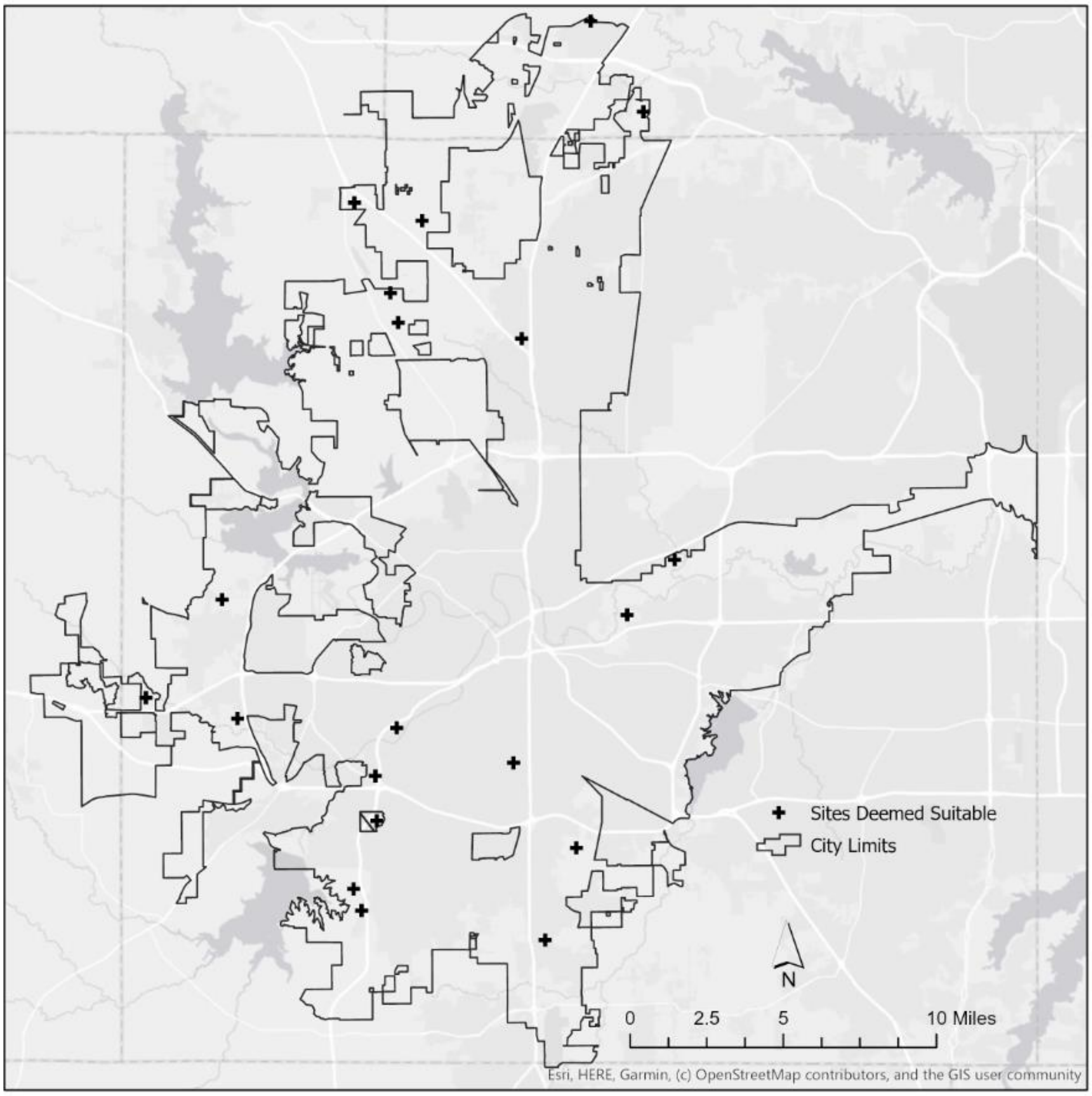


Figure 26: Sites selected to ground truth results

3.2 Sensitivity Analysis, Phase 4

Because this study primarily sought to quantify economic viability, information that was deemed to impact productivity and economic costs were weighted heaviest. The interpolated wind power layer provides an east to west gradient with the western side of the city possessing the highest wind power. The diminished wind on the east could be overcome with larger turbines if wind generation on the east side were needed to increase generation output. However, due to the increase in size, the wind turbine on the east side of the city would be more expensive to build but could in fact generate the same output of the smaller turbines on the west side. The same could be said about variability in elevation, in that a higher tower and larger diameter could be employed to equalize the viability of sites across the area. Property costs are not only a way to find the least cost property, but they could also be used as a proxy for community concerns, in that the higher the property value the more likely it will be that an installation will have a negative effect on those values. Distance to the electrical infrastructure components, transmission lines and substations, are more ambiguous. Are they a cost to the project or are they primarily a cost to the electrical service utility? The electrical service utility will undoubtedly be maintaining the connections to the turbine so it could be considered their cost. However, the distance to the electrical grid can impose a production cost to operations, in that there will be a voltage drop over distance and therefore an impact on electrical production.

The process for conducting this sensitivity analysis was to run a first best guess weighted overlay based on the above priorities. The results of this overlay were then analyzed for cell distribution and how much agreement there was with the sites deemed suitable. Subsequent runs were then generated to determine what influence the different inputs have on the outcome. Based on these analyses a final run was conducted. The results for runs 2-4 demonstrate the influences that the different layers have on results. However, many more iterations of the weighted overlay technique were conducted on this data in attempts to fine tune results. Furthermore, the sensitivity analysis was not exclusively based on how much agreement there is with the sites deemed suitable because it skewed cells towards the highest suitability ranking with no real basis for this bias. Therefore, analyses were added to show the distribution of cell values in the results. Results that were skewed away from a normal distribution were discarded.

3.2.1 Sensitivity Analysis: First Run

Property values were considered the most important contributor to this study due to its dual role as cost provider and community influence. Also, the highest property valuations could have a *de facto* veto effect on whether a turbine could be sited on a candidate site. Wind power data were considered second in importance because of impact on productivity. Next, elevation was weighted third. Both wind and elevation data possess a common trend in that values are higher to the west and, ergo, lower to the east. The electrical infrastructure components of distance to substation and distance to transmission lines were weighted fourth and fifth. The constraints as mentioned above are quantified in the initial weighting hierarchy for the first run of the sensitivity analysis as described in Table 4. The first run of the weighted overlay produced a normal distribution of cell values with a mean suitability of 6 (Figure 27). Of the 20 sites deemed suitable, there were two with a suitability classification of 8, there were seven with a suitability classification of 7, there were 10 with a suitability classification of 6, and one with a suitability classification of 5 (Figure 28).

Table 4: Weights for first run

Layer	Weight (as %)
Property values	45
Wind resource	25
Elevation	15
Distance to substation	10
Distance to transmission lines	5

3.2.2 Sensitivity Analysis Second Run.

The results of the first run shows that the east to west gradient noted in the wind and elevation data influenced the results in the weighted overlay study. Property values are also visually identifiable. It was not clear by the first run what influence if any the distance to grid rasters had

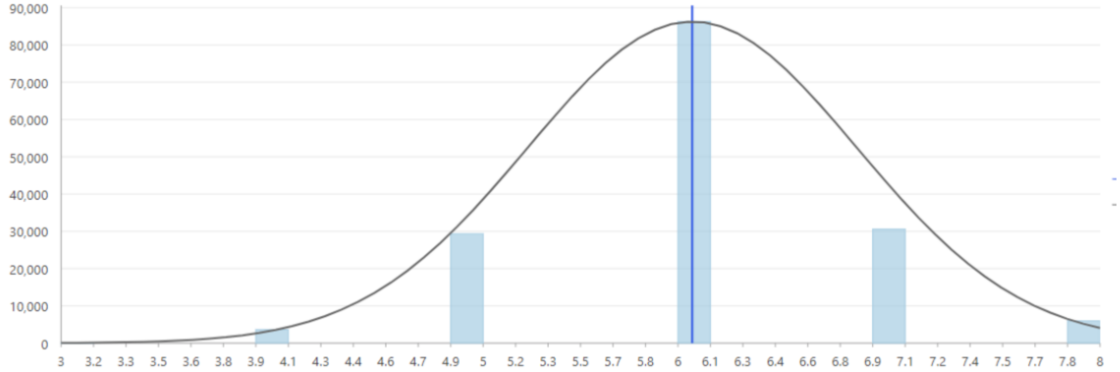
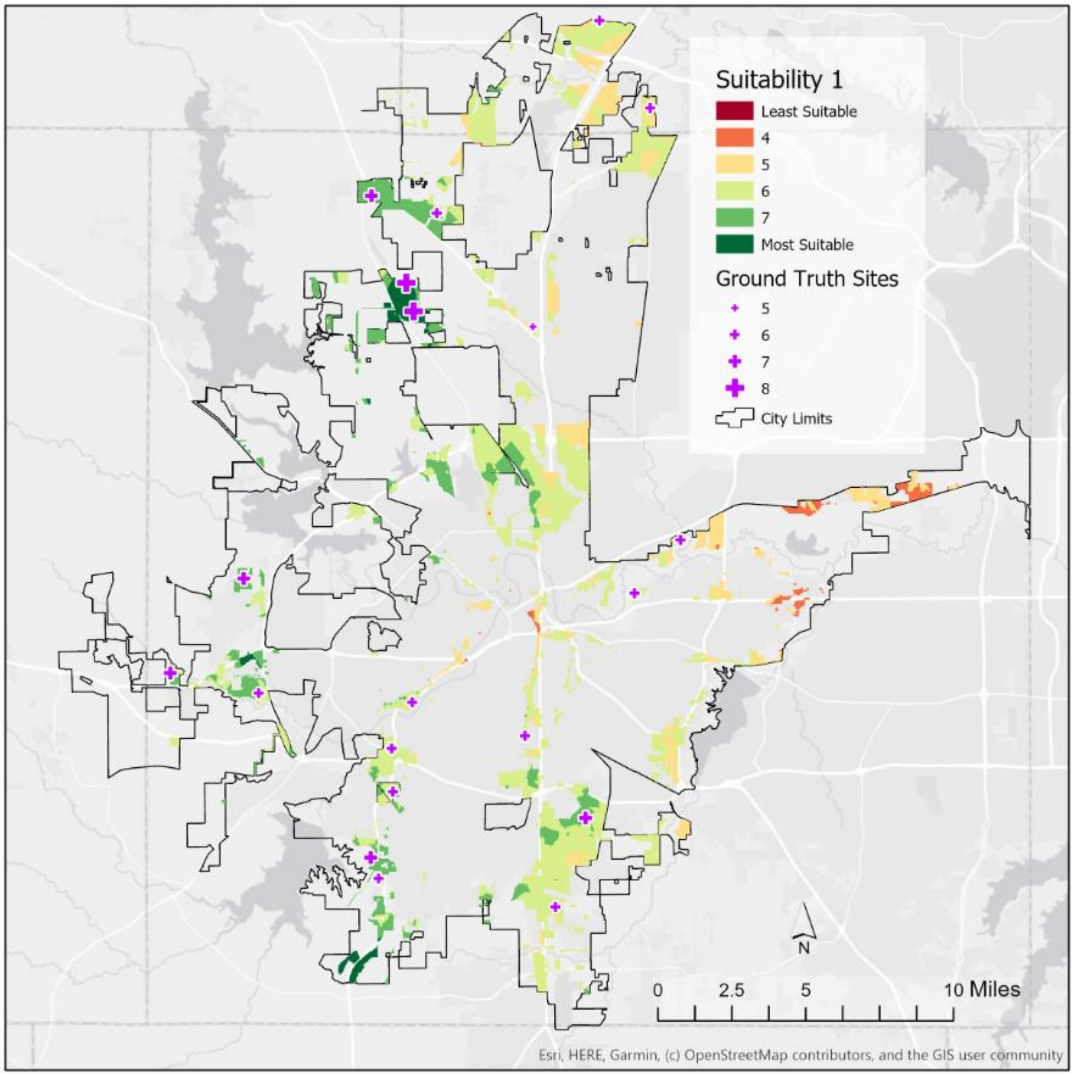


Figure 27: Cell value distribution for first run, with a mean suitability score of 6



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 28: First run of the weighted overlay sensitivity analysis.

on the result. The second run used a uniform weighting schema as shown in Table 5. This schema was used to discover what advantages or disadvantages an evenly weighted analysis has.

Table 5: Weights for second run

Layer	Weight (as %)
Property values	20
Wind resource	20
Elevation	20
Distance to substation	20
Distance to transmission lines	20

The cell distribution of the second run was shifted to higher values and hence one rank on the low end was dropped compared to that of the first run. Also, the cell distribution was skewed to the right side (Figure 29). Of the 20 sites deemed suitable, there were three with a suitability classification of 8, eight with a suitability classification of 7, and nine with a suitability classification of 6 (Figure 30).

Overall, this run proved less useful in determining sites to place a wind turbine over the first run. Because the distance to electrical grid layers were weighted equally, it doubled the influence of grid components. This electrical grid bias is shown by classification of areas on the outskirts of the city that are much less suitable than areas in the center of the city where grid components are concentrated, this is the case despite the fact that land is more expensive and more heavily developed in the city’s center. On the positive side, the relative unsuitability of the areas in the east of the city due to low wind and elevation in that part of the city can be observed in this run.

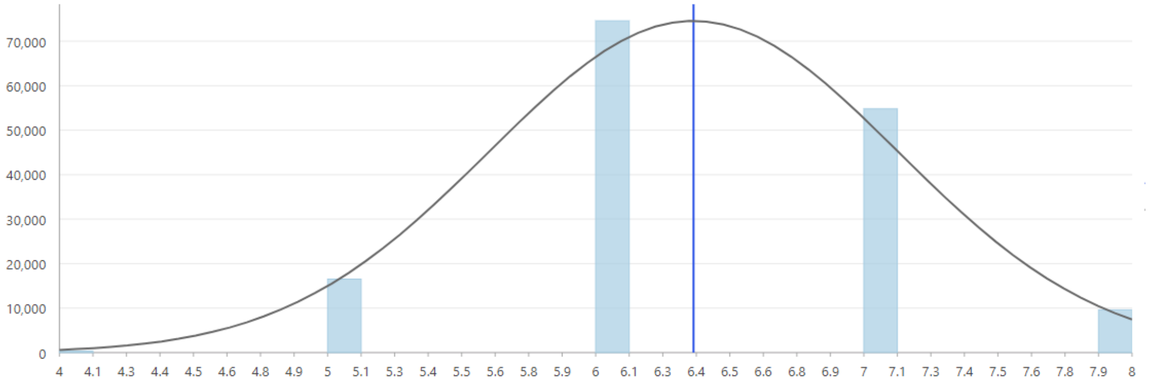
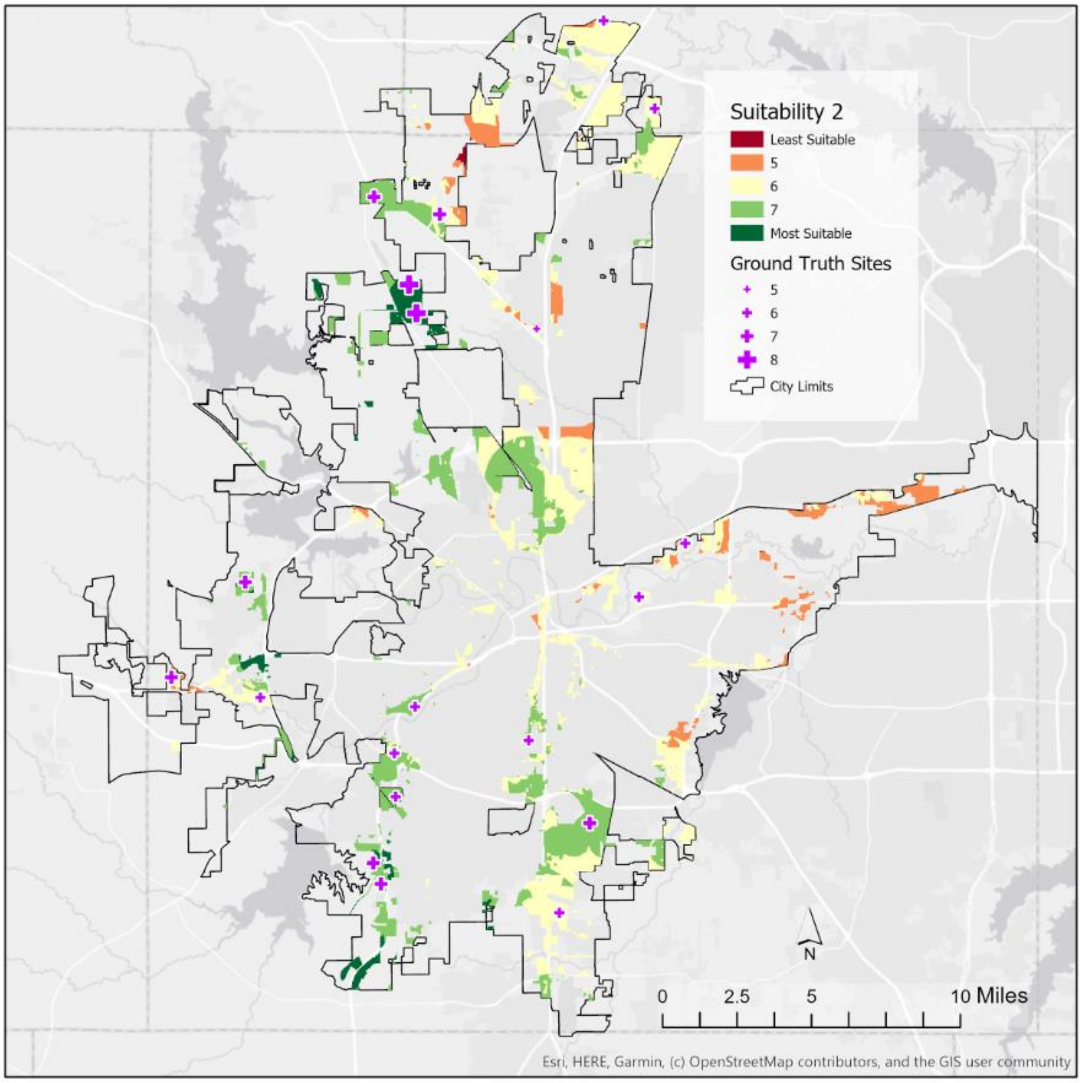


Figure 29: Cell value distribution for second run, with a mean suitability score of 6.4



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 30: Second run of the weighted overlay sensitivity analysis

3.2.3 Sensitivity Analysis: Third Run

The third run was created to better identify the electrical grid components in the analysis. The two components, distance to substation and distance to transmission lines, were weighted at 50% each and the other three inputs were zeroed out as illustrated in Table 6. The cell distribution of the third run was shifted to higher values and skewed right, with 9, the highest classification in the study, proving to be the mode in the distribution (Figure 31). Of the 20 sites deemed suitable, there were nine with a suitability classification of 9, there were four with a suitability classification of 7, and there were three with a suitability classification of 6, there was one with a suitability classification of 5, and one with a suitability classification of 2 (Figure 32).

The results of the third run shown in Figure 32 illustrate the fact that grid resources tend to be better in the center of the city than in the sparsely populated north and west portions of the AOI. The areas near the CBD have transmission lines or substations in proximity. Overall, there was a great deal of variability in the distance to grid components within the AOI. This fact may not be of great concern because it was in the most densely populated portions of the city where electrical lines are omnipresent and in low-density development, grid components are sparse. Electrical generation in the sparsely populated outskirts means that electricity will need to travel further to reach customers. Sites in the middle of the city will be closer to customers and therefore electricity will not need to be transmitted as far.

Table 6: Weights for third run

Layer	Weight (as %)
Property values	0
Wind resource	0
Elevation	0
Distance to substation	50
Distance to transmission lines	50

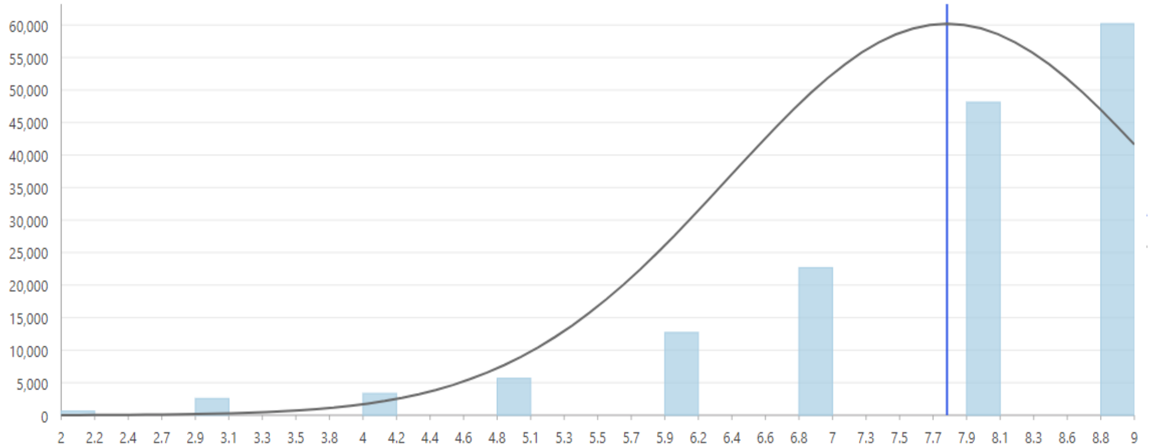


Figure 31: Cell value distribution for third run, with a mean suitability score of 7.8

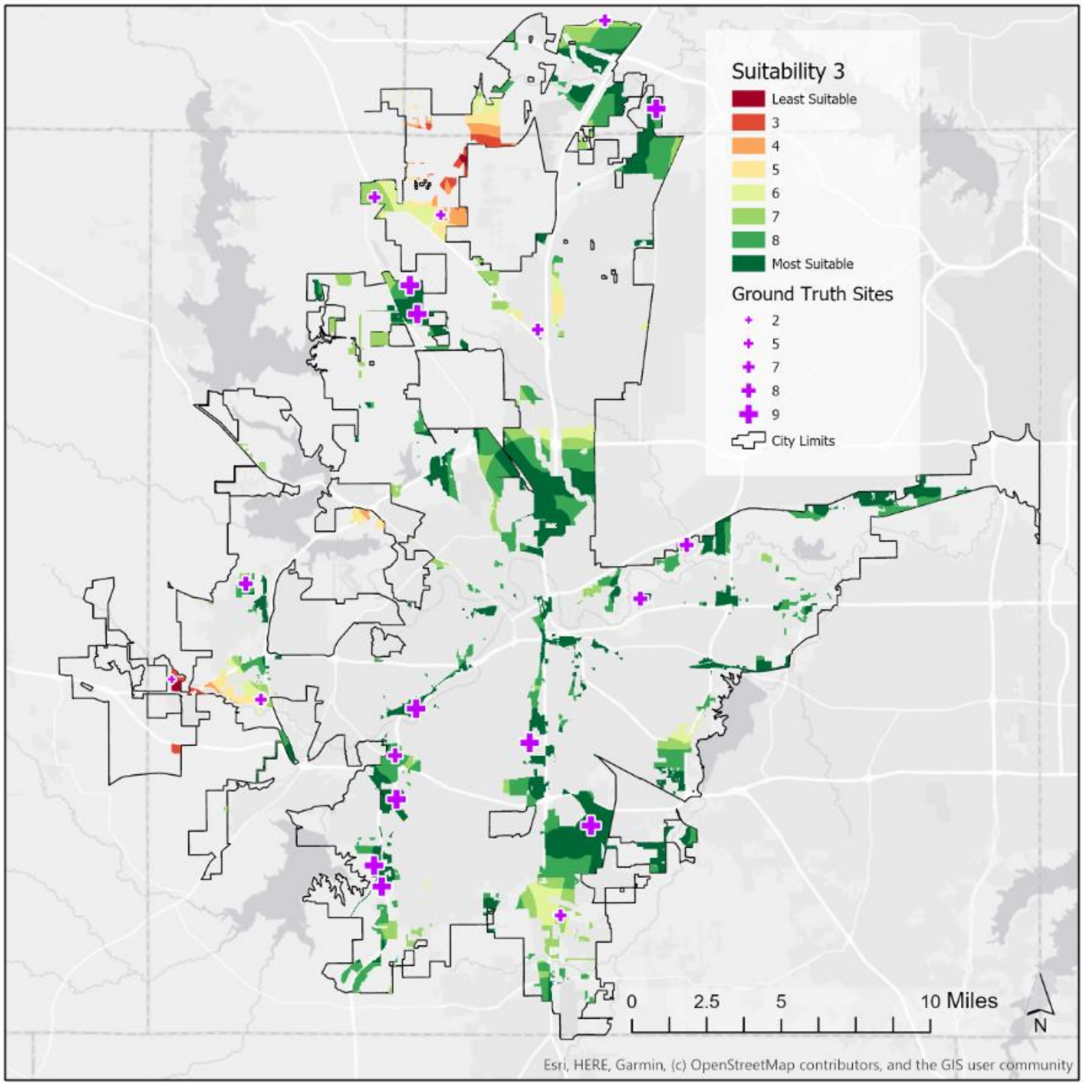


Figure 32: Third run of the weighted overlay sensitivity analysis

3.2.4 Sensitivity Analysis: Fourth Run

The elevation and wind resource data has an east-to-west trend in data values. To explore what influence this east-to-west gradient has in this analysis, elevation and wind resources were isolated in the fourth run (Table 7). This run showed a relatively flat cell distribution with a mean of 5.6 and a mode of 5 demonstrating a shift to lower values compared with the previous runs (Figure 33). Of the 20 sites deemed suitable, there were five with a suitability classification of 8, there were five with a suitability classification of 7, there were three with a suitability classification of 6, there were four with a suitability classification of 5, and two with a suitability classification of 3 (Figure 34). The 20 sites are well-distributed in this run due to the effort made to find sites throughout the AOI, including sites on the east side.

Table 7 Weights for fourth run

Layer	Weight (as %)
Property values	0
Wind resource	50
Elevation	50
Distance to substations	0
Distance to transmission lines	0

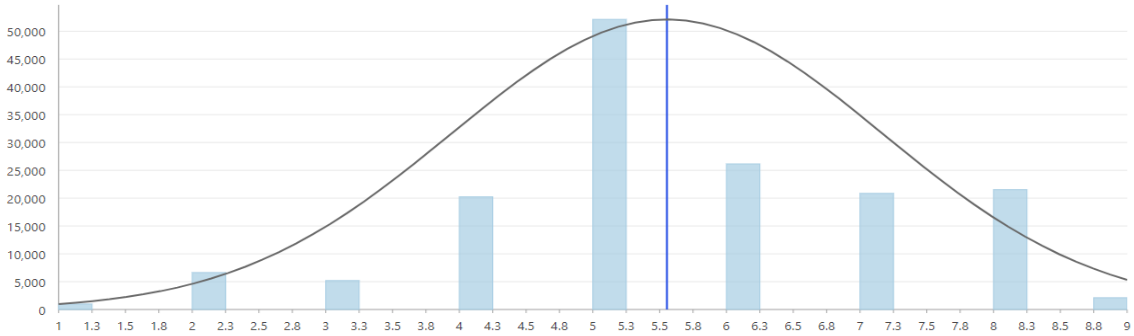


Figure 33: Cell value distribution for fourth run, with a mean suitability score of 5.6

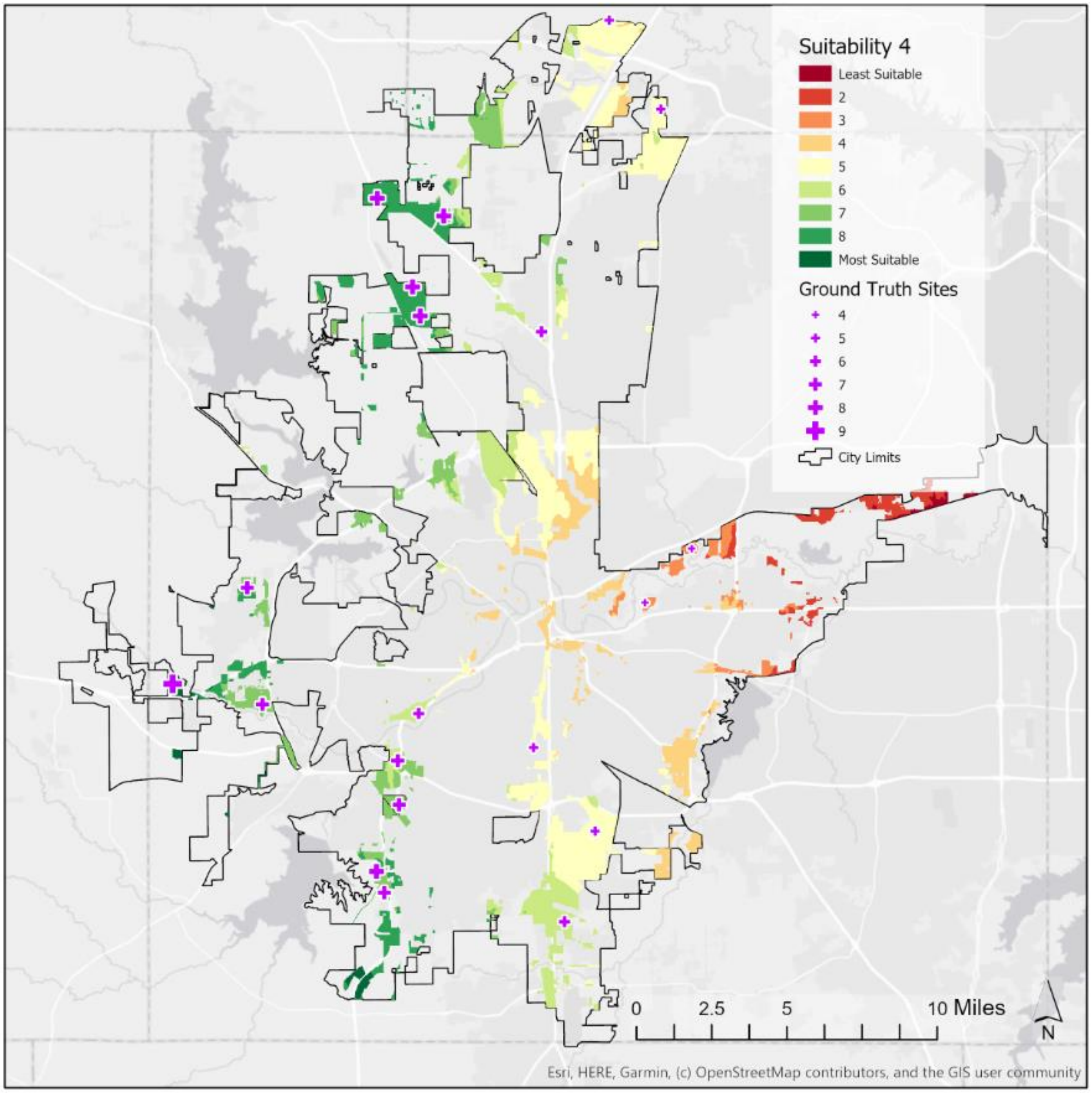


Figure 34: Fourth run of the weighted overlay sensitivity analysis

3.2.5 Sensitivity Analysis: Summarization

The first run featured a hierarchical weighting schema which appeared to show more accurate results than did the schema with equal weights used in the second run, in that grid influences made sites in the center of the city appear more suitable than would be expected given wind, elevation and property values in that area. The subsequent runs were conducted to discover the underlying influence of the distance to grid components and the influences of wind and elevation. The third run that was used to determine distance to grid influence, skewed the results to high values and consequently more ground truth sites were in high values as well. Although this run was only intended to discover the influence of grid inputs, it is an illustration of why it is necessary to understand the distribution of the cells in the output. If this sensitivity analysis were only an exercise in confirming ground truth sites, then this run with the largest amount of most suitable area, would work well. However, the ground truth site ranked 2, unsuitable, is an outlier that should cause further investigation in to why a site deemed suitable pre-analysis could subsequently be deemed unsuitable post analysis. In this case it is because the only influence is nearness to grid without taking into consideration, wind, elevation, and property cost. The fourth run conducted to understand wind and elevation influence, showed a rather flat cell distribution and a decrease in mean suitability compared with all the other runs.

Given the trends in the data, it is relatively easy to manipulate the results to some expected outcome, but not without skewing the cell distribution. For example, the perceived suitability in the center of the city can be improved by increasing the influence of the electrical grid inputs and/or by decreasing the weight for property costs, or the perceived suitability of sites on the east side of the city could be improved by decreasing the influence of wind and elevation. The 20 sites deemed suitable initially to measure the validity of the results were picked from all quadrants of the city to remove this sort of bias inherent in the data. With that said, after much experimentation, there was no discernable improvement in cell distribution, agreement with ground truth sites, or overall cell values from that of the first run.

Chapter 4 Results

This chapter will show the geographic distribution of cell values for the suitability analysis along with four detailed maps of the suitability analysis in areas of the city where ground truth sites were located, and perform ROI calculations for a selected site. The selected site provided a unique opportunity within the central part of the city. However, two sites in the north of the AOI showed consistently good results in all the sensitivity analyses, and exceptionally large turbines could be sited could be placed at these sites due to the lack of development. This would provide a greater ROI. However, this is a study to find the bounds of what is possible in this AOI and therefore, the site selected with some limitations, is more appropriate.

4.1 Suitability Analysis Results

The graduated hierarchy described in the first run of the sensitivity analysis produced the best results overall; therefore, the parameters for the final weighted suitability study are like those of the first run (Table 8). Compared to the first run of the sensitivity analysis, 5% more weight was given to property values and 5% less to wind resource. This change was made to shift cells to higher values but interestingly this modification had no appreciable effect. Like the results of the first run, the cells in this study reflect a normal distribution centered on a mean suitability value of 6 (Figure 35). The suitability values of the 20 ground truth sites varied from 5 (one site) to 6 (10 sites), 7 (seven sites), and 8 (two sites) (Figure 36). Efforts were made to shift the distribution to the right to optimize the results. But regardless of the weights that were assigned to the layers in the overlay, the results converged on a value of 6 when a normal distribution was achieved.

Table 8: Final weights for the suitability study

Layer	Weight (as %)
Property values	50
Wind resource	20
Elevation	15
Distance to substations	10
Distance to transmission lines	5

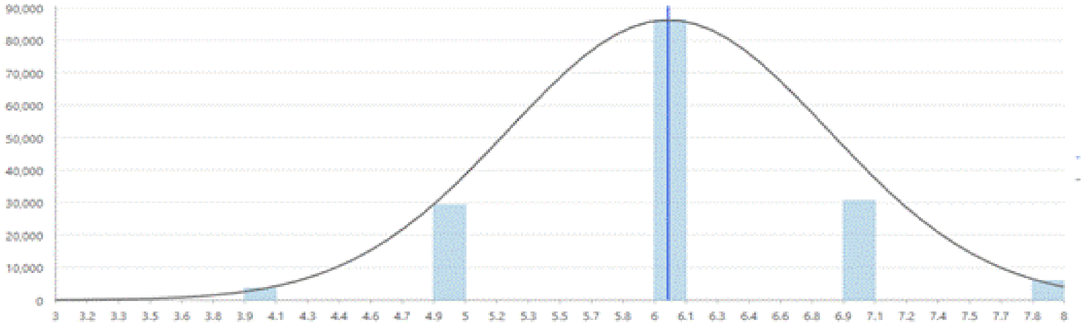


Figure 35: Final suitability study cell distribution

To validate the sites that are ranked as highly suitable a closer examination of the areas was undertaken. In many cases there are areas that were chosen as suitable that had incompatible uses and structures, such as freeway easements, which would limit the siting of turbines. However, there often was nearby places that could be deemed highly suitable. Figures 37-40 shows four different areas with several areas with suitability scores ranging from 6 to 8. Most of these areas are undeveloped and could potentially be used for many purposes. However, there are many gas wells that pose limitations to future development and hence, these locations could be seen as an opportunity for siting a wind turbine. These gas wells show up on these maps as white colored rectangular patches. Figure 37 describes an area in north Fort Worth that has two ground truth sites with gas wells in the most suitable classification. One site is zoned for light industry, and the other site is zoned for heavy industry. The two ground truthed sites in this map were consistently classified as most suitable throughout the sensitivity analysis.

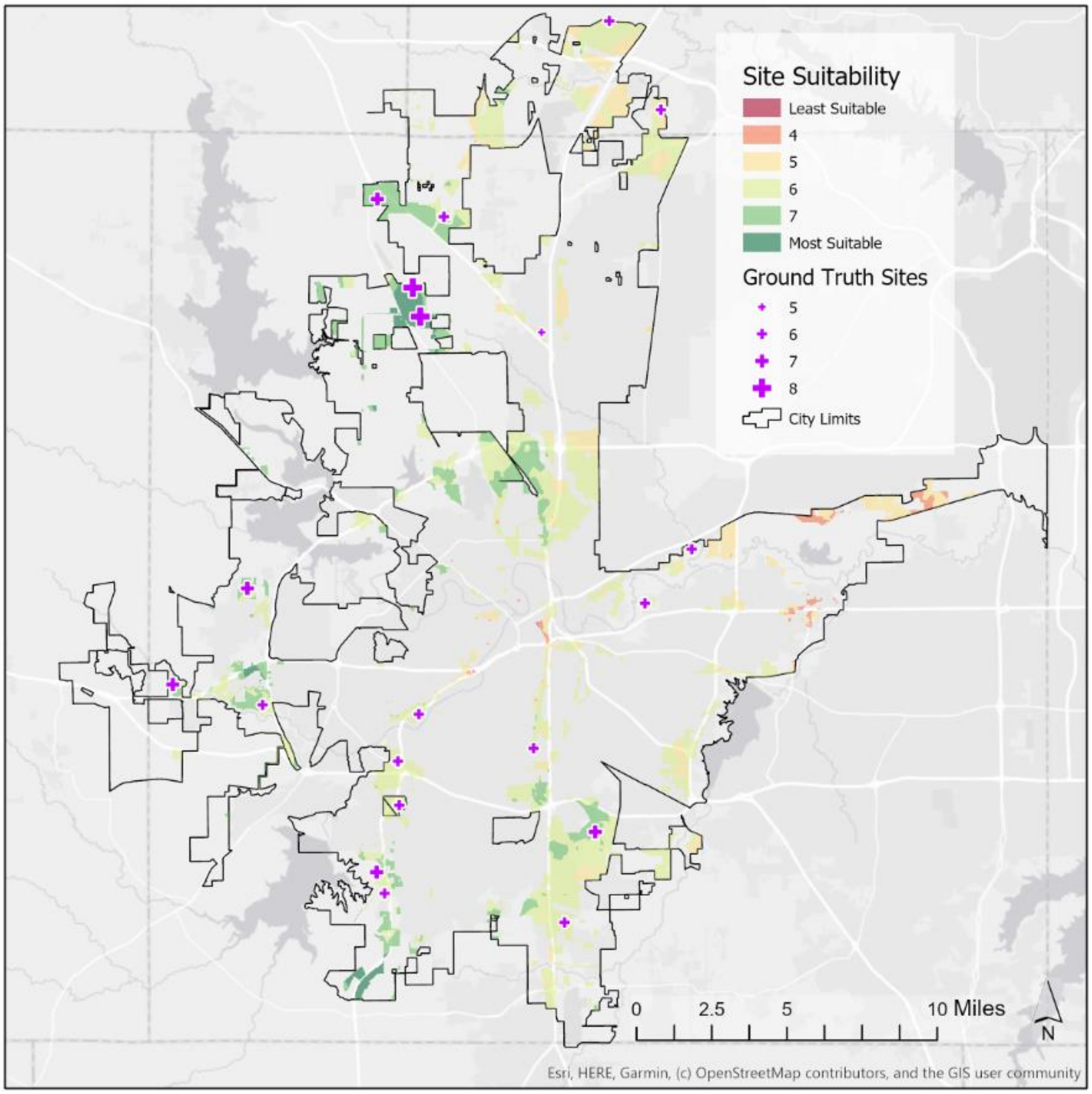


Figure 36: Geographic distribution of cells for site suitability with ground truth sites

Because of higher wind and elevation values, it was not surprising that the areas in the western side of the AOI have high suitability ratings. Figure 38 shows an area near the western boundary of the AOI. The cells in this map have suitability scores ranging from 6 to 8. However, due to a relative lack of electrical infrastructure, the distance to grid layers decreased values from what otherwise would be the highest in the area. Two of the ground truth sites have a suitability ranking of 7, and one has a suitability ranking of 6.

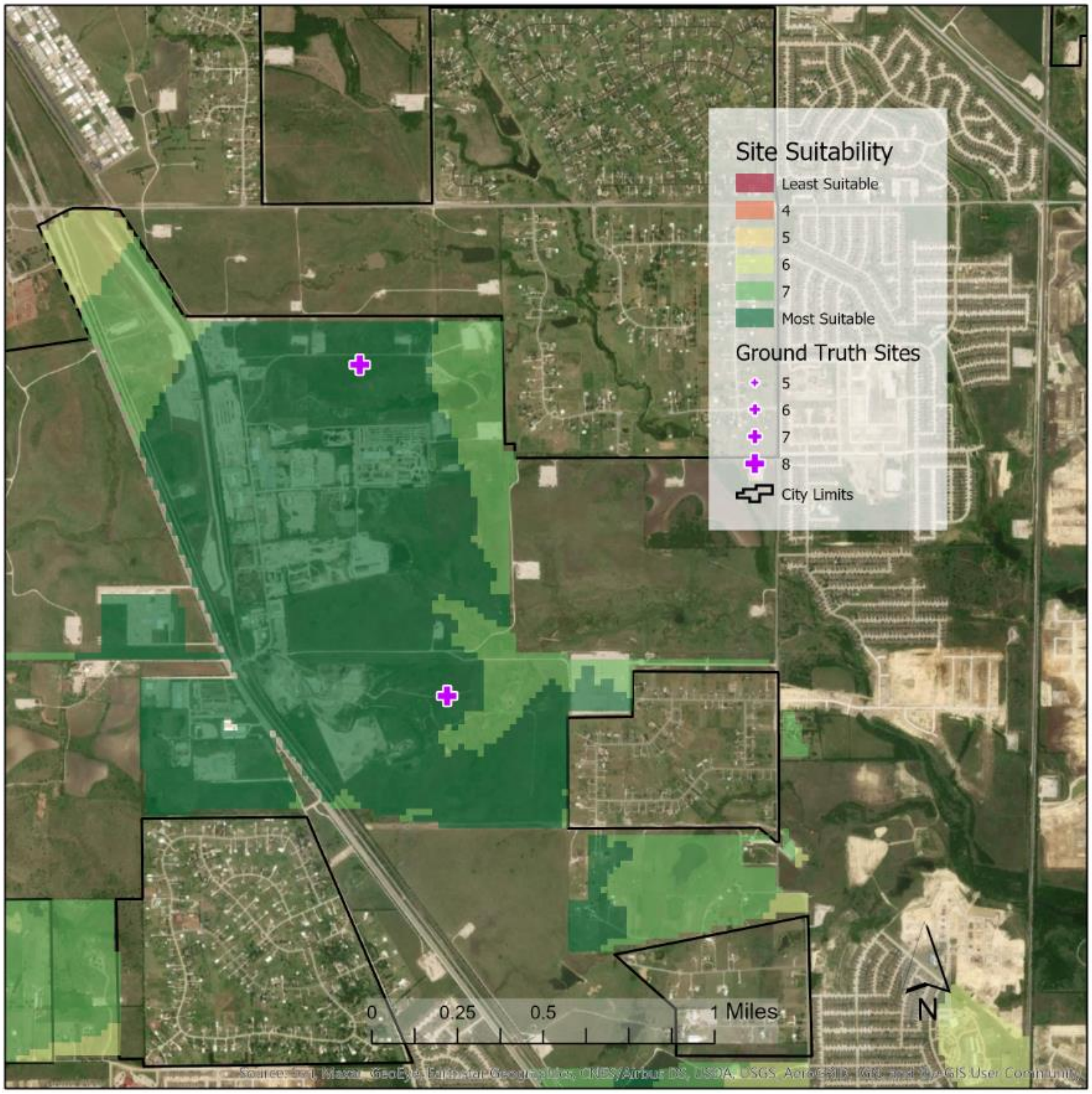


Figure 37: Geographic distribution of cells with site suitability values ranging from 6 to 8 and ground truth sites in north Fort Worth

The ground truth sites in the southside of the AOI shown in Figure 39 were chosen to find sites that were in a more developed area of town. The suitability scores of the cells in this map ranged from 4 to 7. Two of the ground truth sites in this map have a suitability ranking of 7, and three have a suitability ranking of 6.

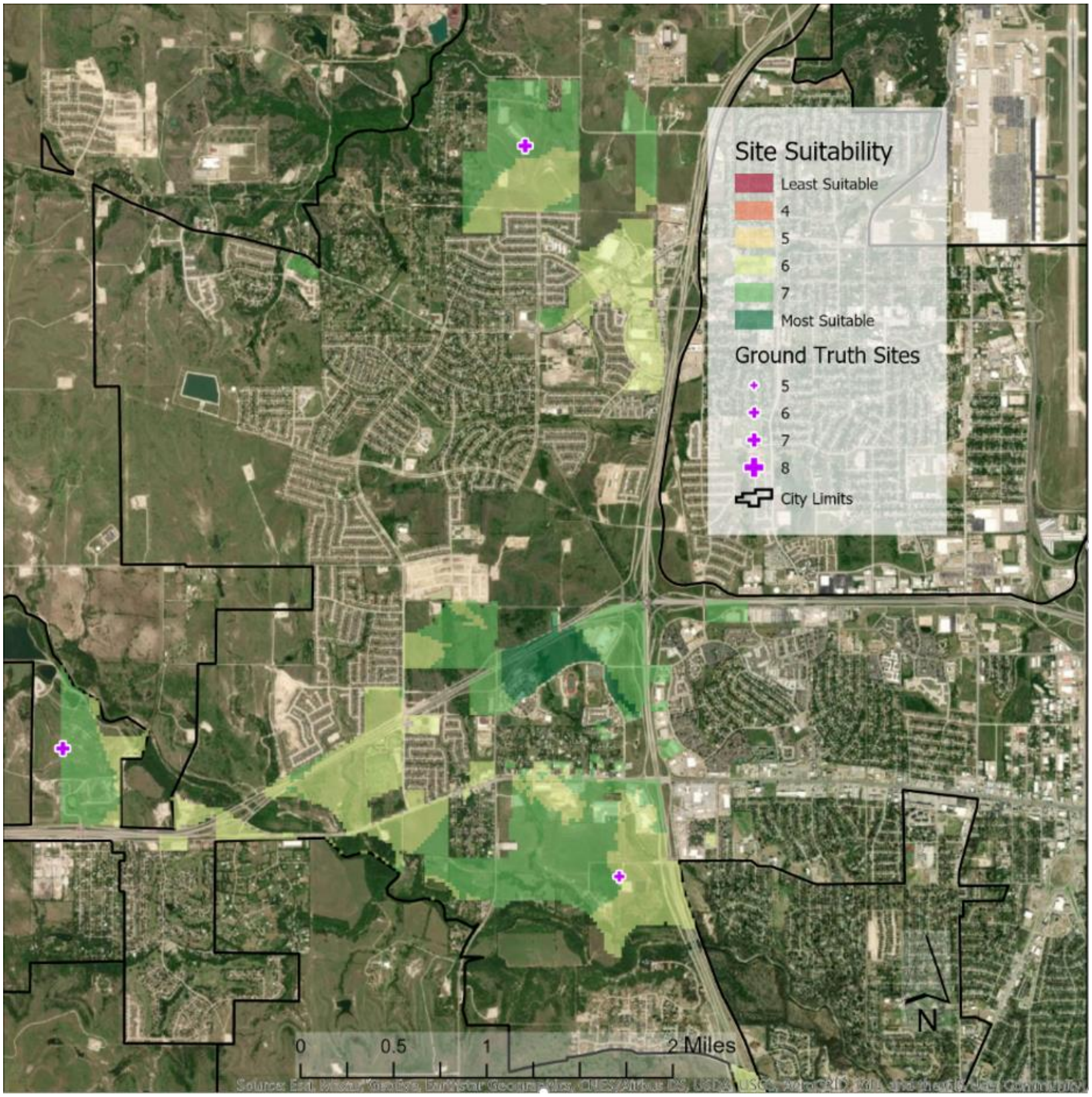


Figure 38: Geographic distribution of cells with site suitability values ranging from 6 to 8 and ground truth sites in far west Fort Worth

The area on the east side is not very suitable due to low elevation and low wind resource. However, there are two closed landfills that were used for ground truth sites with site suitability scores of 6. The area shown in Figure 40 is rated from 4 to 6 in terms of site suitability. As mentioned earlier, this side of the AOI is lower in elevation and there is not as much wind energy. This would require a larger application to capture the same energy as on the west side.

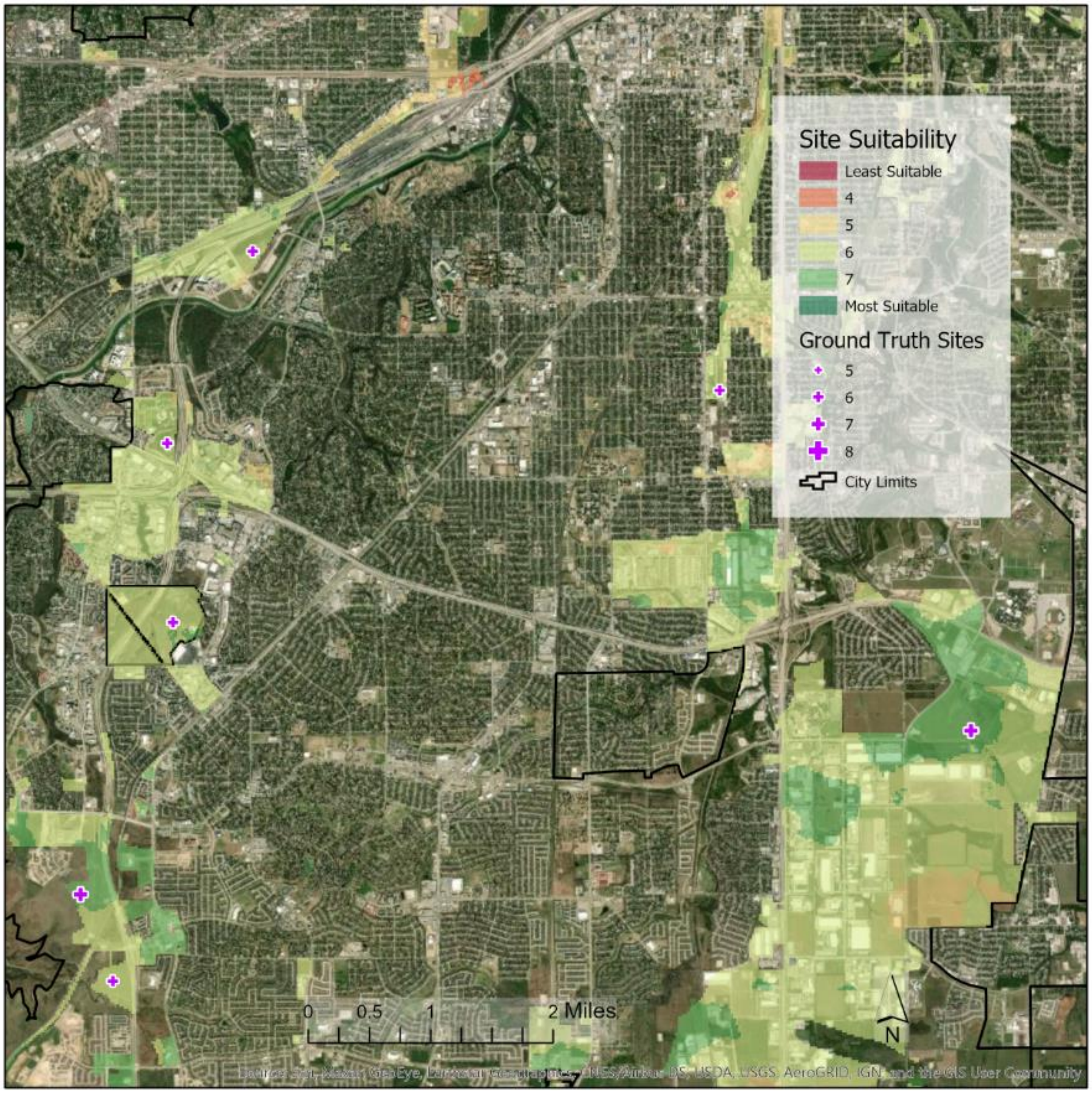


Figure 39: Geographic distribution of cells with site suitability values ranging from 4 to 7 and ground truth sites in south Fort Worth

4.2 Selected Site

To discover the viability of sites that had limitations on turbine size, an abandoned grain elevator located at 3700 Alice Street on the near south side with a suitability score of 6 was chosen to conduct the ROI part of this analysis. This site is in the central part of the city, has a railroad siding on site that would aid in the transportation of large components, and has recently been

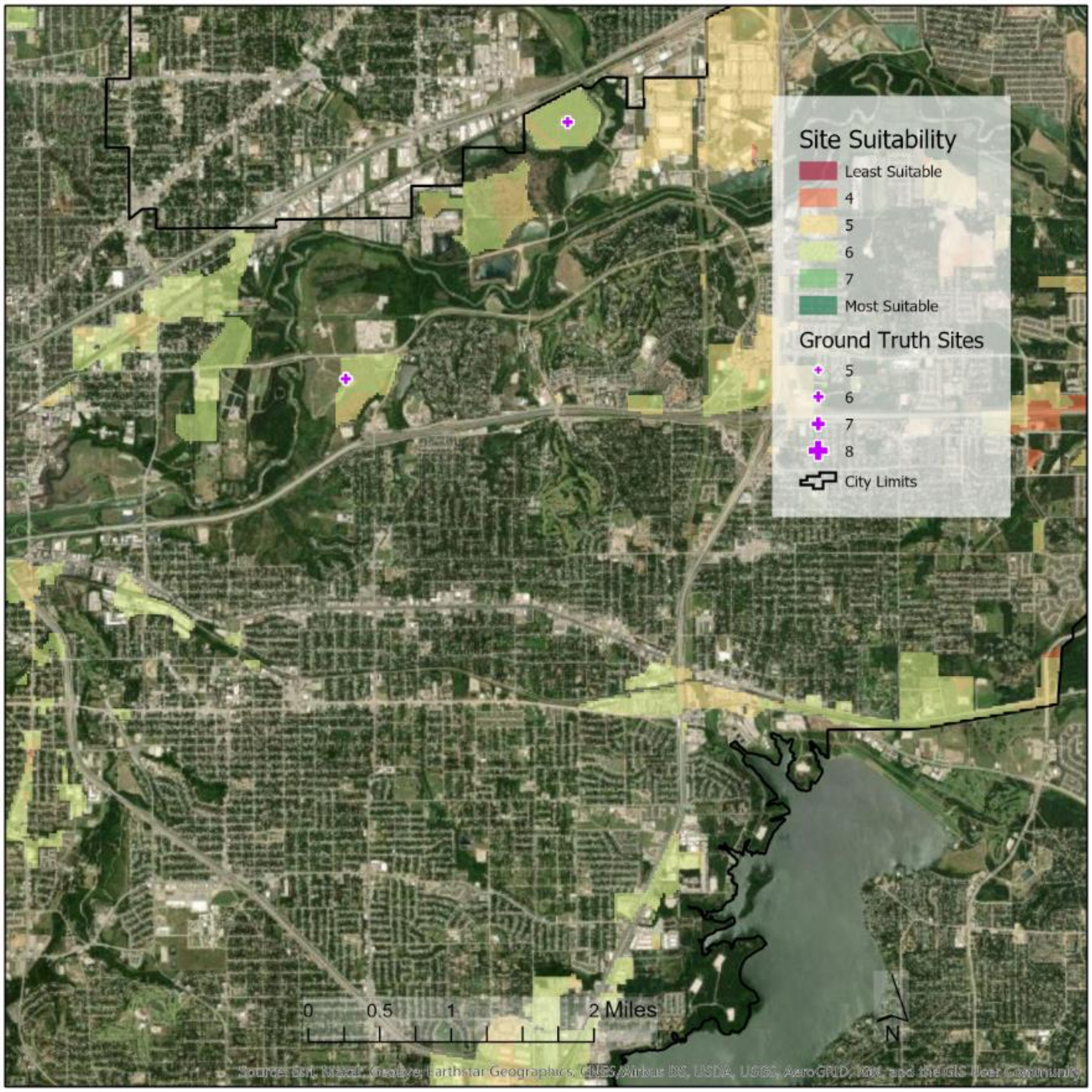


Figure 40: Geographic distribution of cells with site suitability values ranging from 4 to 6 and ground truth sites in east Fort Worth

cited for an EPA grant. Figure 41 shows the suitability map for this site. The suitability score of 6 is not as high as some of the sites in this study, especially those shown in Figure 37, but the railroad infrastructure, EPA grant and high vertical profile could make this site more economical than the suitability ranking suggests.

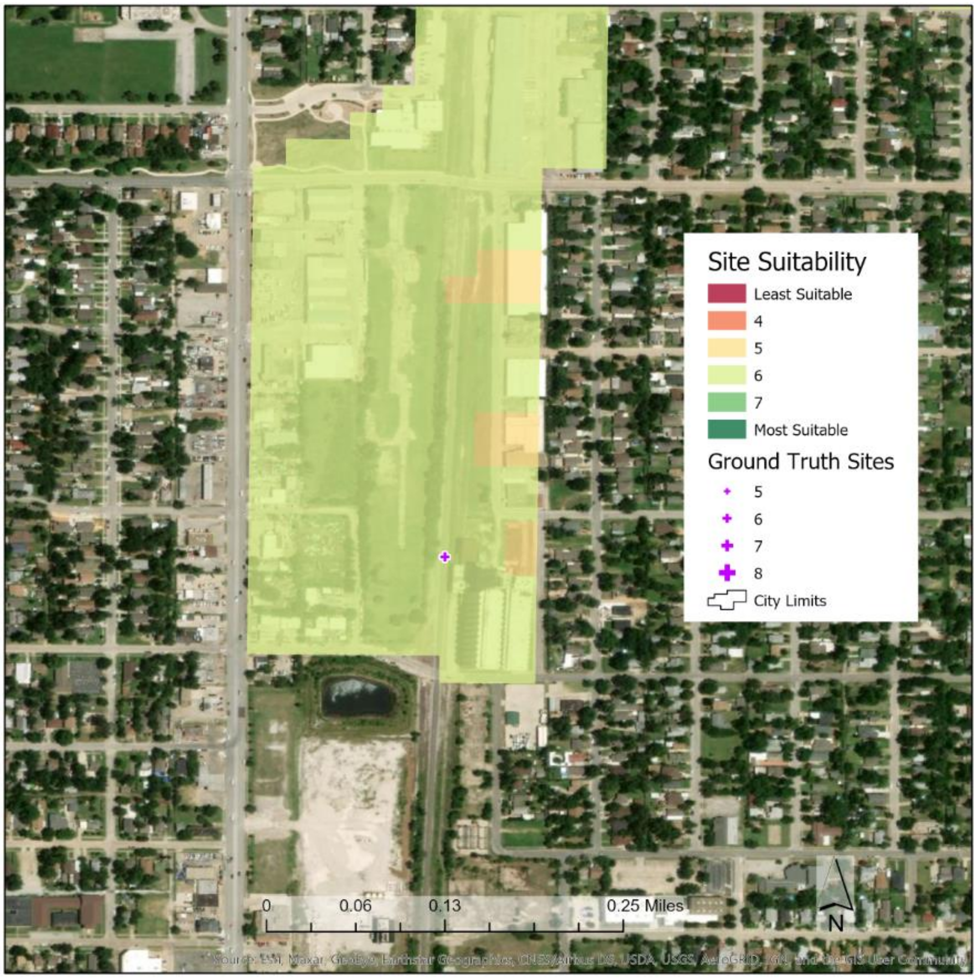


Figure 41: Geographic distribution of cells of selected site with site suitability values ranging from 5 to 6 at near southside grain elevator

This structure has been a feature of the landscape since the 1920s. It was likely a lone outpost on the southside until the 1940s when there was a post war building boom in this area. Figure 42 shows the grain elevator complex when it was new in 1928 and in 2020. Nowadays, there is clear evidence of deterioration on the structure. There are obvious efforts to paint over the graffiti at the bottom. There is still graffiti at the top many of the windows are broken. An in-person investigation revealed that the site has become an established dumpsite. To make matters worse, a few years ago there was a fatal accident at the complex. The EPA awarded the city of Fort Worth a $300,000 Brownfields Assessment Coalition Grant to investigate how to ameliorate the hazard this area poses to the community. This grant is for assessment only and not for cleanup or demolition. The EPA provides cleanup assistance under EPA's Multipurpose, Cleanup, and Revolving Loan Fund (RLF) Grants, for which this site may be eligible (US EPA 2016). The range of possibilities for this type of grant include site cleanup, demolition, or revitalization. Under the multipurpose RLF, there is a community involvement requirement that could be used to advance the idea of a wind turbine component to the surrounding community. This site with its EPA assessment grant and the potential for EPA revitalization funding makes this site the most intriguing.

Figure 42: Alice Street grain elevators, left circa 1928, right circa 2020

4.3 Return on Investment Calculation

Even though a site is selected through the MCA discussed in the previous chapter, the selection process is somewhat artificial unless the siting of an innovative wind turbine provides a positive ROI. Thus, an ROI was performed on the Alice Street Grain Elevator location, which was identified through the weighted overlay process as one of the most promising potential sites.

It is well known by meteorologists that wind increases with elevation (Taylor, 1916; Tennekes 1973). This is why utility-scaled wind turbines have become so tall. In order to assess a wind turbine mounted on a 100 ft, or 30 m grain elevator the wind at the hub height of the turbine needs to be calculated. This analysis assumes a 1-Mw rated turbine with a 60 m diameter. A 60 m diameter means that each blade extends 30 m from the hub. For clearance purposes, the supporting tower needs to be 35 to 40 m. This tower height in combination with the height of the grain elevator provides a hub height of aproximattly 60 to 70 m. Even though these structures were built to hold hundreds of tons of grain and could support any size of turbine, the 60 m size was chosen because there are houses located across the street on the east side of this property. Because these neighbors are so close, a fall zone equal to the total height of the turbine was used. It is wise to minimize the aspect of a large rotating structure that the neighbors might fear would break and fall into their property.

4.3.1 ROI inputs

In order to find the available wind resource at the 60 m hub height for this proposed wind turbine, the wind speed at 60 m will be extrapolated based on the wind speed at a nearby air monitoring station (Figure 43). Figure 43 shows a TCEQ wind monitoring site near the grain elevator that is being assessed for ROI. The right side of Figure 44, displays the average annual wind speed for this site to be 8.3 mph, or 3.71 m s^{-1}. Also shown on the right side of Figure 44, is the watt/hours that a 6 foot turbine would generate at this site over the course of a year, 426 kilowatt/hour (Kwh). The tower on this site which holds the wind meter is 15 m tall.

The vertical wind profile logarithmic law (Equation 9) was used to calculate wind speed as follows:

$$v_2 = v_1 . \frac{\ln\left(\frac{z_2 - d}{z_0}\right)}{\ln\left(\frac{z_{1-d}}{z_0}\right)} \qquad (9)$$

where v_2 is the resultant velocity (6.31 m s^{-1}), v_1 is the initial velocity at a nearby air monitoring site (3.71 m s^{-1}), d is the surface level displacement (6 m), z_0 is the roughness coefficient (0.7 m), z_1 is the height of measurement (15 m), and z_2 is the target height (60 m). Established vertical wind profile tables were

Fort Worth Joe B. Rushing Road

WindMonSites - Fort Worth Joe B. Rushing

OBJECTID	7
AQS Code	484391065
SiteCode	1065
Site Name	Fort Worth Joe B. Rushing Road
Street Address	2525 Joe B. Rushing Road
City	Fort Worth
County	TARRANT
Latitude	32.672406
Longitude	-97.291178
Elevation	99999
CalmHours	10
AvgMPH	8.3
AvgDir	178
Wattage	426015
Hours	8736

97.2911702°W 32.6723999°N

Figure 43: TCEQ wind monitoring site near the Alice Street grain elevators.

used to validate the speed differential. However, it should be noted this calculation is typically not used in urban environments due to turbulence and heat island effects.

Based on the above calculation, the estimated average wind speed at the 60 m hub height at the Alice Street elevators is 6.31 m s^{-1}. At that windspeed the estimated efficiency for the proposed turbine is 21%. The density of air fluctuates but it is typically in the 1.2 kg m^{-3} range in Fort Worth. Using Equation (6) and substituting the values above into the equation reveals the watts output of a 60 m turbine, at this site, with an average wind speed of 6.31 m s^{-1} is:

$$(0.21 \text{ efficiency})\ (1.2 \text{ kg/m}^3)\ \pi\ (60 \text{ m})^2\ (6.31 \text{ m s-}^1)^3 / 8 = 89{,}505.76 \text{ W} \tag{10}$$

Therefore, at this site a 60 m wind turbine can capture an average of 89,505.76 W throughout the year. However, what is missing is the temporal component, namely hours. To find Watt/Hours or Megawatt/Hours (MWH) the previous result was multiplied by the number of hours in a year:

$$(89{,}505.76)\ (8{,}760) = 784{,}070{,}494.50 \text{ W or } 784 \text{ MWH per year} \tag{11}$$

The cost of electricity in this area in 2020 is about 10 cents per Kilowatt/hour (KWH), which yields an approximate electrical generation revenue of $78,400 per year for this turbine. The Producers Price Index (PPI) estimates turbine costs for the year 2019 to have been approximately $700,000 per 1-Mw turbine rating. To account for the difference in conformation from the traditional HAWT, to the volumetric, there is an additional charge added to the cost of the volumetric turbine based on the proportional surface area difference in the two blade types. The increased surface area of the volumetric blades, which is about five times of that of a HAWT, increases the turbine cost by approximately $400,000 and the total price of a 1-Mw volumetric turbine from $700,000 for the HAWT to $1,100,000 for the volumetric. However, as previously noted, the hemispherical blades have an inherent strength that should enable less expensive materials and methods of production to be used in manufacture, compared with the typical HAWT blades. The volumetric blade could conceivably be manufactured by automated processes that make the blades more price competitive. The life span of a typical turbine is 20 to 25 years. At $78,000 per year, pay back of principal would happen in the first quarter of year 15 if the cost of electricity remains constant over that period. Total revenue would come to $1,950,000.

The grain elevator site was selected for the ROI calculation because, serendipitously, it has been selected by the EPA as a brownfield site, and a grant for revitalization (or clean-up) y be awarded in the foreseeable future. This creates a hypothetical opportunity to use an EPA grant to eliminate the cost of site cleanup as a line item in the cost of a wind turbine project, or, possibly could be used to help fund or even fully fund the project under the umbrella of community revitalization. The call by the EPA for community involvement in such a project would give the project an opportunity to discuss the positive aspects of having a wind turbine near them. Community buy-in to renewable energy projects has been shown in other studies to be essential to the success of a project (Wolsink 2000, 2007). Figure 44 is a Google Earth visualization of what a 60-m diameter volumetric turbine would look like mounted to the Alice Street grain elevators.

In the bottom left of this image is a power substation that is no longer in use. This substation could conceivably be put back into use if needed. This image also shows a gas well site on the other side of the railroad tracks that could also be used for siting a turbine given the property cost and wind profile of this area. This gas well site was, zoned in the exclusion criteria, as obviously been changed into a property type that is now suitable for industrial applications and the zoning map does not reflect the change.

Figure 44: 3D visualization of a 60 m volumetric turbine mounted on grain elevators at the selected site

Chapter 5 Discussion and Conclusions

The present analysis was undertaken to answer the question of whether sites could be found within an urban environment for utility-scaled wind turbines and provide a return on investment. The AOI for this study, the City of Fort Worth, might seem an unlikely candidate for such a project because of its entrenched history of petroleum exploration, relatively low electrical energy costs and NREL marginal wind resource designation. However, the presence of significant industrial zones, functional encumbrances to land development (i.e. gas wells), railway infrastructure, relatively low property costs, areas of sparse to moderate land development, and constant wind creates an environment where utility-scaled wind turbines should be able to be sited within an urban region. Figure 25 shows that there could be hundreds of sites within the city that may be suitable for siting a large wind turbine simply because those sites would be unsuitable for much else. This hypothetical intra-grid wind farm, if built, could be a major contributor to the Fort Worth electrical grid providing renewable energy as well as local employment.

5.1 Discussion

Urban wind energy generation could work in conjunction with rural windfarms to create a more complete renewable energy infrastructure. In the hypothetical Fort Worth urban windfarm that is suggested above there would be minimal transmission loss, local job creation, and intra-grid turbine control. The ideal implementation of an urban windfarm would have excess wind generation capacity. Turbines could be brought on-line by grid operators in the event of a surge in demand by virtue of the fact there is an almost constant supply of wind in this AOI as illustrated in Figure 2. This wind energy potential can best be utilized by an innovative wind turbine that can capture wind energy potential below 3 $m\ s^{-1}$ as illustrated in Figure 4. A traditional turbine could also be utilized in the urban environment, but it would need to be much taller and larger for this function. This increase in size will likely come with increased costs, community objections, and environmental risks.

While public opposition to windfarms was not quantified in this study, there is reason to think that residents will oppose large, visually intrusive wind turbines. However, the City of Fort Worth possesses characteristics that makes this hypothetical urban windfarm a possibility. In particular, the derelict grain elevators identified in this study give reason to believe that opposition to green technology will diminish over time. Most of these derelict elevators were built in the 1920s on what then was the outskirts of the city and it is doubtful that many questioned their need or location. The city grew up around them and once they were decommissioned, few of these large industrial structures have been demolished. Figure 42 shows two photographs of the Alice Street grain elevators on the south side. The photograph on the left was taken when the complex was almost new and shows the railroads that serviced the elevator in the foreground. There was little development surrounding this structure when it was new, and the city grew up around it. This suggests that a large intrusive structure may not be an impediment to property development given that the community has endured the presence of grain elevators thus far. It takes little imagination to realize that if a grain elevator, communication tower, or large water tower can be incorporated into the city landscape, then a utility-scaled wind turbine should be able to exist within the urban landscape as well.

The financial aspects of this project indicate that a turbine can be sized and sited to be economically viable in an urban environment, the key factor being how large and how high off the ground. Other spatial factors that impact economic viability are property cost, nearness to grid which impacts the amount of usable generation, and the local cost of labor for construction, operation, and maintenance.

5.2 Conclusions and Future Work

This research found that a utility-scaled wind turbine may be successfully and economically sited within an urban environment if care is taken to exclude property where there are competing interests. A way to eliminate competing interests is to find areas where other types of development are impeded by toxicity or abandonment. As mentioned above, the AOI in this study possesses these attributes and others as well, such as areas with sparse to medium urban land development, industrial and railroad infrastructure, relatively low property values and constant wind. These attributes are key to the successful siting of a utility-scaled wind turbine in an urban landscape.

The chosen grain elevator site had a significant limitation in that the property is adjacent to a residential neighborhood that was assumed to restrict the size of the diameter by forcing the imposition of a “fall zone” requirement. There are areas in the “most suitable” portions of the AOI where this fall zone requirement is non-existent; therefore, any sized turbine could be considered and therefore a larger return on investment might be realized.

This project quantifies the output of a wind turbine with volumetric blades and identified opportunities in an urban environment where its low-speed wind energy capture characteristics could be utilized. However, there are considerable unknowns and further research needs to be conducted to verify the output of a working prototype of a volumetric wind turbine and delineate the efficacy of using the urban and other environments where wind power has previously not been considered a viable option.

There are many unexplored fluid capture possibilities that a volumetric turbine, which can be oriented in any direction within a flow, could exploit. For example, Figure 45 located in the Appendix is a visualization of a 250 m crossflow vertically oriented turbine sited on a landfill. This type of application has the advantage of simplicity and with a turbine of this size could act as its own flywheel and could generate electricity continuously. Figure 46 shows two such turbines on closed landfills on the east side. Another possible application could be deployed in oceans to capture tidal energy because of the low flow energy capture capability of volumetrics and their capacity to be deployed in any orientation to a flow.

References

Albani, A., Bin Ibrahim, M.Z., and Hamzah, M.H.M. 2013. "Assessment of Wind Energy Potential based on METAR data in Malaysia." *International Journal of Renewable Energy Research* 3(4): 959-968.

Amin, M., and Wollenberg, B.F. 2005. "Toward a Smart Grid." *IEEE Power and Energy Magazine*, 3(5): 34-41.

Baerwald, E.F., D'Amours, G.H., Klug, B.J., and Barclay, R.M.R. 2008. "Barotrauma is a Significant Cause of Bat Fatalities at Wind Turbines." *Current Biology* 18(16): R605-R696.

AWEA (American Wind Energy Association). 2019. "Wind Energy in Texas 2019." https://www.awea.org/Awea/media/Resources/StateFactSheets/Texas.pdf

Bishop, I.D., and Miller, D.R. 2007. "Visual Assessment of Off-Shore Wind Turbines: The Influence of Distance, Contrast, Movement and Social Variables." *Renewable Energy* 32(5): 814-831.

Blanco, M.I. 2009. "The Economics of Wind Energy." *Renewable and Sustainable Energy Reviews* 13(6-7): 1372-1382.

Bohrer, G., Zhu, K., Jones, R.L., and Curtis, P.S. 2013. "Optimizing Wind Power Generation while Minimizing Wildlife Impacts in an Urban Area." *PloS ONE* 8(2): e56036.

Brown, T.J., Horel, J.D., McCurdy, G.D., and Fearon, M.G. 2011. *"What is the Appropriate RAWS."* Reno, NV: Program for Climate, Ecosystem and Fire Applications, Desert Research Institute.

Carter, M., Shepherd, J.M., Burian, S., and Jeyachandran, I. 2012. "Integration of Lidar Data into a Coupled Mesoscale–Land Surface Model: A Theoretical Assessment of Sensitivity of Urban–Coastal Mesoscale Circulations to Urban Canopy Parameters." *Journal of Atmospheric and Oceanic Technology* 29(3): 328-346.

DuVivier, K.K. 2015. *"Wind Power Growing Pains."* Denver, CO: University of Denver Legal Studies Research Paper No. 16-02.

Everaert, J., and Stienen, E. 2007. "Impact of Wind Turbines on Birds in Zeebrugge (Belgium)." *Biodiversity and Conservation* 16(12): 3345-3359.

Fingersh, L.J., Hand, M.M., and Laxson, A.S. 2006. *"Wind Turbine Design Cost and Scaling Model."* Golden, CO: National Renewable Energy Laboratory.

Equanalysis, U.G. 2020 "Vertical Wind Profile Logarithmic Law." https://fxsolver.com/browse/formulas/Vertical+Wind+Profile+-+Logarithmic+Law

Hall, C.A.S., and Klitgaard, K. 2018. *"Energy and the Wealth of Nations."* Cham, Switzerland: Springer.

Hale, C.S., and Giggleman, C. 2005. *"Fish and Wildlife Coordination Act Report."* Albuquerque, NM: United States Fish and Wildlife Service.

Harrison, J.D. 2012. “Onshore Wind Power Systems (ONSWPS): A GIS-Based Tool for Preliminary Site-Suitability Analysis (Unpublished M.S. Thesis).” University of Southern California, Los Angeles, CA.

Horn, J.W., Arnett, E.B., and Kunz, T.H. 2008. "Behavioral Responses of Bats to Operating Wind Turbines." *Journal of Wildlife Management* 72(1): 123-132.

Jones, C.R. and Eiser, J.R. 2010. "Understanding ‘Local’ Opposition to Wind Development in the UK: How Big is a Backyard?" *Energy Policy* 38(6): 3106-3117.

Kantartzis, A., Gregory Varras, G., Panagiota, K., Koutsikou, M., Papadopoulou, A., and Gogolou, C. 2006. *"Greenway Planning and Management of Urban Riparian Corridors: The Alternative Basis for an Integrated System of Urban Green Spaces. Case Study: Riparian Corridors in the City of Igoumenitsa, Greece."* Epirus, Greece: Department of Floriculture and Landscape Architecture Technological Educational Institute of Epirus.

Kim, T.-S., Park, K.-A., and Moon, W.-I. 2010. "Wind Vector Retrieval from SIR-C SAR Data off the East Coast of Korea." *Journal of the Korean Earth Science Society* 31(5): 475-487.

Leddy, K.L., Higgins, K.F., and Naugle, D.E. 1999. "Effects of Wind Turbines on Upland Nesting Birds in Conservation Reserve Program Grasslands." *The Wilson Bulletin* 111(1): 100-104.

Li, L., Gong, J., and Zhou, J. 2014. "Spatial Interpolation of Fine Particulate Matter Concentrations using the Shortest Wind-Field Path Distance." *PloS ONE* 9(5): e96111.

Lussana, C., Salvati, M.R., Pellegrini, U., and Uboldi, F. 2009. "Efficient High-Resolution 3-D Interpolation of Meteorological Variables for Operational Use." *Advances in Science and Research* 3(1): 105-112.

Mathew, S. 2006. *“Wind Energy: Fundamentals, Resource Analysis and Economics.”* Berlin, Germany: Springer.

Miltner, R.J., White, D., and Yoder, C. 2004. "The Biotic Integrity of Streams in Urban and Suburbanizing Landscapes." *Landscape and Urban Planning* 69(1): 87-100.

Nolden, C. 2013. "Governing Community energy: Feed-in Tariffs and the Development of Community Wind Energy Schemes in the United Kingdom and Germany." *Energy Policy* 63: 543-552.

Pohekar, S.D., and Ramachandran, M. 2004. "Application of Multi-Criteria Decision Making to Sustainable Energy planning: A Review." *Renewable and Sustainable Energy Reviews* 8(4): 365-381.

Qureshi, M. E., Harrison, S.R., and Wegener, M.K. 1999. "Validation of Multicriteria Analysis Models." *Agricultural Systems* 62(2): 105-116.

Sánchez-Lozano, J.M., García-Cascales, M.S., and Lamata, M.T. 2016. "GIS-Based Onshore Wind Farm Site Selection using Fuzzy Multi-Criteria Decision Making Methods. Evaluating the Case of Southeastern Spain." *Applied Energy* 171: 86-102.

Taylor, G. I. 1916. "Skin Friction of the Wind on the Earth's Surface." *Royal Society of London Publishing 92(637)*: 196-199.

Tennekes, H. 1973. "The Logarithmic Wind Profile." *Journal of Atmospheric Sciences* 30: 234-238.

Wolsink, M. 2000. "Wind Power and the NIMBY-Myth: Institutional Capacity and the Limited Significance of Public Support." *Renewable Energy* 21(1): 49-64.

Wolsink, M. 2007. "Wind Power Implementation: The Nature of Public Attitudes: Equity and Fairness Instead of 'Backyard Motives'." *Renewable and Sustainable Energy Reviews* 11(6): 1188-1207.

U. S. Environmental Protection Agency. 2017. *"Climate Change Impacts."* https://19january2017snapshot.epa.gov/climate-impacts/international-climate-impacts_.html

"U. S. Environmental Protection Agency. 2018. *"EPA Brownfields Assessment Grants Assessment Coalitions."* https://www.epa.gov/sites/production/files/2020-03/documents/epa_assessment_coalitions.pdf

Yang, Z., Liu, Y., and Li, C. 2011. "Interpolation of Missing Wind Data Based on ANFIS." *Renewable Energy* 36(3): 993-998.

Appendix

Visualizations:

A turbine of the scale envisioned below, would be in constant motion in this AOI due to the amount of wind in the area and the momentum/inertia of the application. Note the water tower adjacent to the residential neighborhood in the foreground and the communication tower on the left.

Figure 46: 250 M diameter vertically oriented turbine near I 30

Figure 47: Overview of two landfills