ICELAND SCHOOL OF ENERGY
REYKJAVIK UNIVERSITY

Macro-Scale Multi Criteria Site Assessment for Wind Resource Development in Iceland

by

Michael Stephen Doheny

Thesis

Master of Science in Sustainable Energy Science

December 2015

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Michael Stephen Doheny

Thesis submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment
of the requirements for the degree of
Master of Science in **Sustainable Energy Science**
60 ECTS

December 2015

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ABSTRACT

The process of developing wind resources in a given region is subject to a variety of factors. A thorough understanding and adherence to such factors is paramount to the optimization of wind turbine site selection. This study identifies, analyzes and illustrates those factors which influence onshore wind resource development in Iceland by using geographic information systems (GIS) software. In addition, optimal sites for wind resource development are identified within the Snæfellsness region using the Pareto Frontier method and a cost-benefit analysis.

After consideration of developmental exclusion zones within the analysis, 56.3% of land area is highlighted as suitable for wind resource development within the Snæfellsness region. Among the 43 wind points examined, four points are recognized as most optimal using the Pareto Frontier method. Finally, a cost-benefit analysis is conducted to determine the most optimal site amongst those analyzed for development of an Enercon E44 turbine within the region. Calculations show an AEP yield of 3639.3 MWh´s for the most optimal site.

Further recommendations within this field include the development of more accurate macro-scale wind measurement models, and to develop overarching environmental impact assessment standards to encompass such factors into large-scale wind resource assessment processes.

Keywords: Wind turbines, wind resource optimization, multi criteria decision making, mapping, GIS

Fjölþætt, alhliða staðháttarmat fyrir uppbyggingu vindorku Íslandi

Michael Stephen Doheny

Desember 2015

ÁGRIP

Ferli þróunar á nýtingu vindorku á tilteknu svæði er háð ýmsum þáttum. Ítarlegur skilningur og fylgni á slíkum þáttum er lykilatriði við bestun á vali svæðis fyrir uppbyggingu vindhverfla. Rannsóknin ber kennsl á, greinir og lýsir þeim tilteknu þáttum sem hafa áhrif á onshore wind resource þróun með því að nota landfræðilegt upplýsingakerfi (e. geographic information system) (GIS). Þar að auki eru borin kennsl á ákjósanleg svæði á Snæfellsnesi fyrir þróun vindorku með því að nota aðferð Pareto Frontier sem og kostnaðarnytja greiningu (e. cost-benefit analysis).

Þegar búið er að taka tillit til þeirra svæða þar sem nýting vindorku kemur ekki til greina virðist 56,3% af landsvæði Snæfellsnes vera ákjósanlegur kostur fyrir nýtingu vindorku. Af þeim 43 þáttum sem skoðaðir voru, voru 4 þættir sem þóttu hagkvæmastir samkvæmt Pareto Frontier aðferðafræðinni. Að lokum var gerð kostnaðarnytja greining til að ákvarða hvaða staðsetning á tilteknu svæði væri hagkvæmust fyrir uppbyggingu á Enercon E44 vindhverflum. Útreikningar sýna að árleg raforkuframleiðsla (e. annual energy production) (AEP) yrði 3639.3 MWst á hagkvæmasta staðnum.

Tillögur að framtíðarrannsóknum á þessu sviði fela í sér þróun á nákvæmara, alhliða vindorkulíkani ásamt þróun á staðli fyrir umhverfismat á þeim þáttum sem taka þarf tillit til við þróun stórra vindorku verkefna.

Lykilorð: Vindhverfill, vindorku bestun, fjölþætt ákvarðanartaka, kortlagning, GIS

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LIST OF SYMBOLS AND ACRONYMS

AEP	Annual energy production	[MWh/year]
WPD	Wind power density	[W/m^2]
kWh	Kilowatt hour	[-]
MWh	Megawatt hour	[-]
kW	Kilowatt	[kJ/s]
MW	Megawatt	[mJ/s]
dB(a)	A-weighted decibel	[-]
LCoE	Levelized cost of electricity	[USD/MWh]
NPV	Net present value	[-]
EIA	Environmental impact assessment	[-]
HAWT	Horizontal axis wind turbine	[-]
VAWT	Vertical axis wind turbine	[-]
OEM	Original equipment manufacturer	[-]
O&M	Operations and maintenance	[-]
SCADA	Supervisory, control and data acquisition	[-]
USD	2015 United States Dollars	[$]
MISK	Million(s) of Icelandic Kronur	[-]
RSA	Rotor swept area	[m^2]
agl	Above ground-level	[m]
TSO	Transmission system operator	[-]
W_p	Power potential of the wind	[W/m^2]
$v(z)$	Wind speed at an elevation of z	[m/s]
α	Wind-shear coefficient	[dimensionless]
k	Weibull shape parameter	[dimensionless]
λ	Weibull scale parameter	[m/s]
$P(v)$	Power produced at a particular wind speed	[W]

1. INTRODUCTION

The following chapter provides a concise introduction into wind and wind power. Briefly discussed are global costs of wind generation, the current environment of electricity generation in Iceland, and ideas which lay the foundation of this thesis topic.

1.1. BACKGROUND

Technically a form of solar energy, wind resources are generated through the process of uneven solar heating on the surfaces of Earth (Tester et al., 2005). Coinciding with temperature difference comes a relative pressure difference, called a pressure gradient. Wind is the resulting effect of an areas pressure gradient as high pressure systems constantly move to low pressure areas in a continuous effort to reach an equilibrium state (Skinner and Murck, 2011).

Windmill development grew to prominence in 12th century Europe as development of the 'Dutch style' windmill spread (Tester et al., 2005). However, simple machines used to extract wind energy may date back as far as the BC era. The Persians were perhaps the first to discover that wind-harnessing machines could be used to exploit kinetic energy in the wind to produce mechanical energy, used to do useful work.

Modern day wind turbines harness wind resources by converting kinetic energy into mechanical energy via a rotor and then to electricity typically via a three-phase generator (EDF, 2015). Wind turbines consist of two primary types in relation to their axial rotor positioning, horizontal axis wind turbines (HAWT's) and vertical axis wind turbines (VAWT's), the former being the dominant technology type. Today, utility and commercial scale onshore wind turbine development projects, known as wind farms, consistently produce electricity at the same or lower levelized costs than conventional fossil fuel based electricity generation technologies (IRENA, 2015). In 2014, global average LCoE for onshore wind farms ranged between USD $0.06 - 0.09/kWh depending on region, with the best projects routinely generating electricity at rates as low as USD $0.05/kWh.

Iceland's current electricity generation mix consists of hydroelectric and geothermal resources which account for approximately 71% and 29% of the country's electricity generation, respectively (Orkustofnun, n.d.). In December 2012, two Enercon E44 wind turbines were erected by Landsvirkjun, the national power company, as part of a pilot project aimed at testing the feasibility of wind resource development within Iceland (“Landsvirkjun,” n.d.). The direct drive turbines each have a rated capacity of 900kW and operate within the Búrfell region approximately 100km east of Reykjavik. To date the pilot turbines have adequately demonstrated the potential for wind development within the country, each boasting an approximate 40% capacity factor. Comparatively, projects commissioned within the US in 2012 averaged a 33.4% CF for 2013 (IRENA, 2015).

In addition, the potential development of a high-voltage direct current (HVDC) cable interconnecting into the UK grid has been gaining traction over the past few years. After signing a Memorandum of Understanding in 2012, Icelandic parliament talks continued in 2014 over the feasibility and macroeconomic repercussions of such a project (“Raforkustrengur til Evrópu,” n.d.). Undoubtedly, the development of such a cable would necessitate the demand for further domestic electricity generation.

1.2. RESEARCH FOCUS

The focus of this project is to consider comprehensive methods in which wind power projects are assessed, considered and ultimately developed. The potential development of a wind power project could be considered a function of a multitude of factors, such as:

- Wind resources
- Environmental factors
- Social factors
- Site characteristics
- Risk factors
- Access to existing infrastructure

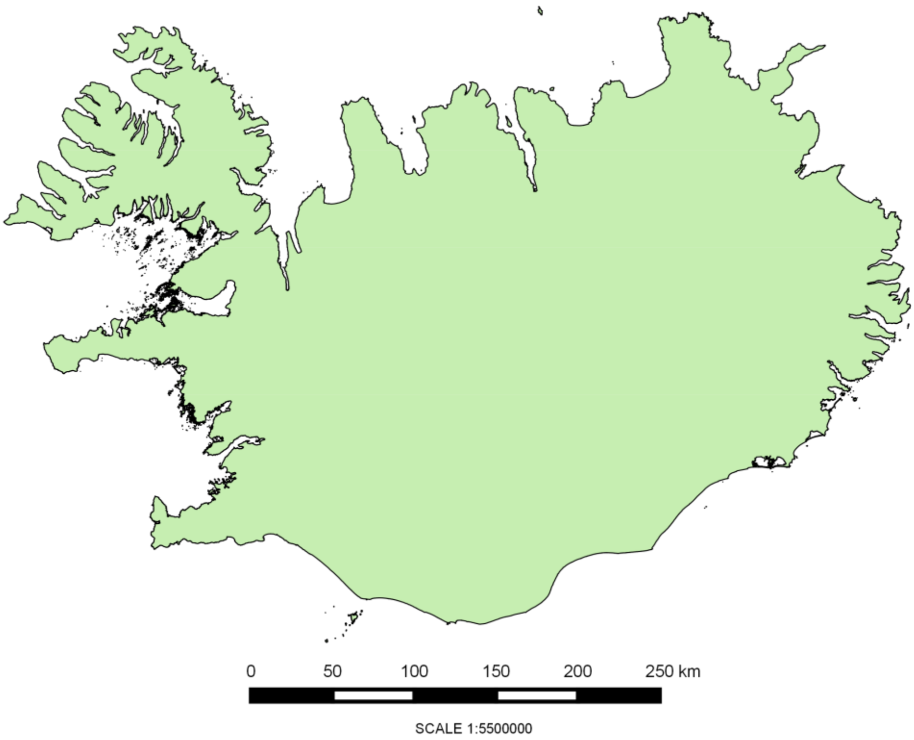

Figure 1: Shapefile map portraying Iceland in the graphic information systems software package, QGIS

Each of these variables can be considered and evaluated in a wind resource assessment for a given site. However, independent variable significance may become skewed when faced with multiple-criteria decision making, particularly in consideration of site feasibility amongst multiple locations. In order to gain a more comprehensive understanding of wind turbine site assessment, graphic information systems (GIS) software may be utilized within the scope of site analysis. GIS software may be further incorporated into an initial site assessment, providing useful insight on a site-specific, regional, or country-wide level.

1.3. AIM AND OBJECTIVES

The aim of this project is to produce GIS maps identifying those sites which might be considered optimal for wind resource development in Iceland. In addition, preliminary aims are to produce maps based on individual factors regarding wind development. Objectives for this project are to:

1) Identify and consider all relevant factors regarding wind resource development
2) Identify and evaluate individual factor rejection parameters
3) Develop single and dual-factor maps incorporating rejection parameters
4) Combine all factors maps to create a comprehensive wind development map
5) Recommend optimal site(s) for wind resource development

1.4. MOTIVATION

Motivation for this thesis is to continue expanding the understanding of wind resource development in Iceland. Over the past half-decade literature pertaining to Icelandic wind resource development has been produced frequently. In 2012, Helgasson examined 48 unique sites around Iceland to determine optimal turbine placement in terms of three factors, annual energy production (AEP), capacity factor (CF) and levelized cost of electricity (LCoE) (Helgason, 2012). This was done by considering and matching site specific wind resources with the power curves from 47 unique wind turbines, resulting in a singular highest AEP, highest CF and lowest LCoE turbine amongst all sites considered. In 2015, Perkin published findings from a case study focused on the optimization of wind turbine selection methods within the Búrfell region (Perkin et al., 2015). Using a genetic algorithm, Perkin was able to identify a hypothetical turbine which would produce 10.6% lower LCoE than the current Enercon E44 turbines operating at Búrfell.

1.5. OUTLINE OF THESIS

This section outlines the following chapters to come within this paper. Chapters to follow include a literature review, an explanation of research methods, and an expression of results, conclusions and appendices.

Within the literature review, those factors regarding wind resource assessment are encompassed and examined with regard to Icelandic implementation and policy. Described throughout are the relative impacts each factor has on wind resource development.

Within the research methods chapter, specific methods used in this paper are highlighted and described. The efficient frontier method is explained as well as logical processes used in the generation of this papers results. Furthermore, main arguments from each subchapter within the literature review are gathered, summarized, and expressed.

The results section encompasses two subchapters, developed maps and an analysis of the Snæfellsness peninsula. First, single and dual-factor maps generated by the author are illustrated to express the wide range of potential application pertaining to wind resource development within Iceland. Second, an efficient frontier and cost-benefit analysis are conducted in which specific sites are highlighted as optimal locations for wind resource development within the Snæfellsness region.

Lastly, conclusions are drawn which highlight the general advantages and disadvantages regarding the application of this methodology. Finally, suggestions for future work in this area are expressed and rationalized.

2. LITERATURE REVIEW

This chapter of the thesis is intended to achieve the aim of identifying and considering all relevant factors regarding wind resource development in Iceland.

2.1. TYPES OF FACTORS

As stated briefly throughout chapter sections 1.2-1.3, the aim of this project is to develop maps of Iceland encompassing all factors pertaining to wind resource development. Such factors considered within the scope of this project include wind resources, environmental issues, social factors, soil conditions, blade icing, and proximity to infrastructure such as transmission lines, substations, and roadways. Careful consideration was given towards each input variable and its relative impact on wind resource development. Resources which aided in this determination include the American Wind Energy Association's Wind Energy Siting Handbook, which is designed to 'inform wind energy developers and other interested parties about environmental siting issues relevant to land-based commercial-scale wind energy project development...' (AWEA, 2008). An individually-focused approach is taken throughout this chapter in which we consider each factor through comprehensive research of developmental 'best practices', referring to peer-reviewed publications, governmental regulations, and industry standards, where applicable.

2.2. DEVELOPMENTAL FACTORS

This section of chapter two is designed to encompass, review and analyze the critical developmental factors which contribute to wind resource development. Each variable is individually considered and critiqued in order to evaluate its relative influence regarding wind development in Iceland.

Key literature regarding wind resource development which influenced this work include the AWEA 'Wind energy siting handbook', the Búrfell case study by Perkin, the 2015 IRENA report on renewable power generation costs, the 'Wind turbine health impact study' developed by the Massachusetts Department of Public Health, the master's thesis 'Social acceptance of wind projects in Iceland' by Rútsson and the 'Wind energy potential of Iceland' by Nawri.

Briefly summarized in table 1 below is a compilation of factors which were identified and considered, as well as those resources which aided in their identification.

Table 1: Resources which aided in the identification of developmental factors

Factor	Identification Resources
Wind Resources	AWEA citing handbook, DWIA, Helgasson (2012), IRENA (2015)
Impacts on Tourism	AWEA citing handbook, DWIA, Ferdamalastofa tourism study, Frantal & Kunc (2011), Rutsson (2013)
Mitigation of Noise Pollution	AWEA citing handbook, DWIA, Frantal & Kunc (2011), GE, Haugen (2011), Mass. D.O.E., Nordman (2010)
Mitigation of Shadow Flicker	AWEA citing handbook, DWIA, Frantal & Kunc (2011), Haugen (2011), Mass. D.O.E., Nordman (2010), USNO
Environmental Factors	AWEA citing handbook, DWIA, Mass. D.O.E.
Distance to Transmission Infrastructure	AWEA citing handbook, IRENA (2015), OSHA
Distance to Roadways	AWEA citing handbook, IRENA (2015)
Soil Conditions	AWEA citing handbook, DWIA, Svensson (2010), Thein (1979)
Turbine Blade Icing	DWIA, Mass. D.O.E., Icewind project, Kraj & Bibaeu (2010)

2.2.1. WIND RESOURCES

As mentioned in section 1.1, surface wind is most commonly the resulting effect of pressure movement along an areas pressure gradient. Wind speed in a given area is influenced by the relative pressure gradient as well as variables such as height of measurement (meters agl), air density (kg/m^3), and surface roughness (m) (DWIA, 2015).

The European Wind Atlas (EWA) defines surface roughness as the height above ground level where theoretical wind speeds are zero. The EWA has developed guidelines for surface roughness classification on a linear scale ranging from class 0 to class 4 with classifications at every 0.5 interval. Corresponding with surface roughness classification are roughness lengths and generally corresponding landscape types. For example, roughness class 1 encompasses surface roughness lengths around 0.03m (agl) and consists of landscapes such as, "open agricultural areas without fences and hedgerows and very scattered buildings. Only softly rounded hills." (DWIA, 2015). Comparatively, surface class 3 encompasses roughness lengths around 0.4m (agl) and consists of landscapes such as, "Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain." (DWIA, 2015)

Wind resources may be measured and expressed in a variety of ways. Common methods of expression are calculations of average wind speed (AWS) and wind power density (WPD), or expression using a Weibull distribution. Average wind speed for a given area is typically expressed in a two parameter Weibull distribution (Weibull, 1951). The probability density function can be mathematically expressed as follows:

$$f(v:\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} \; e^{-\frac{v}{\lambda}^{k}} & ,v \geq 0 \\ 0 & ,v < 0 \end{cases} \tag{2.1}$$

Where:

v: Wind Speed (m/s)

λ: Scale Parameter

k: Shape Parameter

The purpose of such is to express the statistical relationship of wind speed frequency for a given area in a simplified manner. Moreover, wind speed distributions can typically be approximated by the Rayleigh distribution, which is equivalent to a Weibull distribution with a shape parameter of 2 (Papoulis and Pillai, 2001).

Given a site specific Weibull distribution, a number of calculations may be utilized to portray measures of local wind conditions. For example, Jamil explains that metrics such as wind energy density may be calculated given a Weibull distribution to determine kinetic power available per unit area (Jamil et al., 1995). Equation (3.2) illustrates the formula used to express average wind speeds given a Weibull distribution.

$$V = k\Gamma(1 + \frac{1}{\boldsymbol{\lambda}}) \tag{2.2}$$

Where:

$\mathbf{V}$: Average Wind Speed (m/s)
k: Weibull Shape Parameter
$\boldsymbol{\Gamma}$: Gamma Function
$\boldsymbol{\lambda}$: Weibull Scale Parameter

For this project, Weibull parameter data has been examined and collected from the Icelandic wind atlas. The raw data was then processed using a Matlab script to calculate AWS for each unit area. In 2014, Nawri published findings regarding the wind energy potential of Iceland (Nawri et al., 2014). The study, in conjunction with the Icelandic Meteorological Office (MET) and the Nordic IceWind Project, aimed to develop an accurate wind atlas for the country with the goal to “provide the first overview across the entire island of the statistics relevant to wind energy assessments.” (Nawri et al., 2014) Data utilized within the wind atlas was gathered from the Institute for Meteorological Research in Iceland spanning a period from 1995-2008.

The Icelandic wind atlas is comprised of 12462 data points, each of which express a unique Weibull curve for a given height (10, 25, 50, 100 & 200 meters), surface roughness (0.00, 0.03, 0.1, 0.4 & 1.5 meters) and wind direction (12-directional wind rose) (Icelandic MET Office, 2014). Using this data, approximately 3,740,000 unique Weibull curves may be produced and assessed throughout the country.

2.2.2. SOCIAL FACTORS

Social factors encompass those variables which relate to the social acceptance of wind turbines and wind resource development. Within the scope of social acceptance, such factors include turbine location (placement), noise output, shadow flicker and size (Rutsson, 2013).

In 2013, Rutsson conducted social acceptance surveys regarding wind farm development amongst Icelandic residents, as portrayed in table 2 (Rutsson, 2013). Of the three generation technologies considered (wind power, hydroelectric and geothermal generation), wind power garnered the highest level of social acceptance amongst survey participants, with nearly 75% of participants regarding wind development as either ‘very positive’ or ‘somewhat positive’.

In addition, survey participants were polled regarding what they believe to be the primary disadvantages of wind resource development; answers most frequently responded were concerns about visual influences, especially those impacting tourism, concerns regarding noise, potential harm to birds and shadow flicker.

Table 2: Frequency of 'very positive' or 'somewhat positive' views towards renewable electricity generation technologies in Iceland (Rutsson, 2013)

[%]	**Urban**	**Farm**	**Rural**	**Mean value**
Wind	71	77	76	74.7
Hydro	67	77	76	73.3
Geothermal	65	62	77	68

2.2.3. MITIGATION OF IMPACTS ON TOURISM

Tourism has experienced rapid expansion in Iceland over the past five years (Ferdamalastofa, 2015). The early 2000's experienced modest inclines and declines in annual tourist frequency. However, since 2010 the amount of tourists visiting the country has expanded quickly, increasing at a rate of nearly 20%, per annum, as illustrated in figure 2. Furthermore, in 2014 international visitors climbed to nearly one million, more than three times the amount of local residents within the country.

Figure 2: Annual tourism rates in Iceland (in thousands) (Ferdamalastofa, 2015)

The rapid growth of tourism in Iceland has led to large developments within the tourism and hospitality sectors. Unsurprisingly, the tourism industry has now topped both the aluminum and fishing industries as Iceland's top export, accounting for 27.9% of GDP in 2014. Table 3 illustrates the relative growth of the tourism sector over the past five years, both in terms of gross revenue growth and percentage (%) share of GDP.

Table 3: Iceland's tourism revenue and share of exports per year (Ferdamalastofa, 2015)

Year	**Export of goods and services (ISK billion)**	**Tourism (ISK billion)**	**Share of tourism**
2010	865,623	162,822	18.8%
2011	961,615	196,495	20.4%
2012	1,009,005	239,471	23.7%
2013	1,027,303	274,819	26.8%
2014	1,086,064	302,667	27.9%

Aesthetic impact mitigation of wind turbines on tourism has become a topic of concern for the Icelandic people, as Rutsson explains, "Most people are concerned about visual influences that a wind turbine or wind turbines might cause on the surroundings. Very strong views are that wind turbines should not be placed in unspoiled areas or anywhere where they could spoil a view, especially amongst tourists and people in tourism." (Rutsson, 2013).

Comparatively, in 2011 Frantal and Kunc explored the impacts of wind resource development on tourism in Czech Republic (Frantal and Kunc, 2011). As part of their study a survey was conducted amongst participants in two regions, one which recently had constructed a wind farm and another in the planning phase for construction. The survey compiled information from 156 participants, all of whom were tourists to the area. Table 4 shows participant responses in relation to a number of survey questions regarding local wind turbine implementation. Most notably, participants were asked whether or not they would prefer to visit an area with wind turbines, 84% of those polled answered they would like to visit such areas and only 6% would prefer not to. Furthermore, evidence suggests that wind parks may even be viewed and utilized as tourist attractions. 65% of participants polled answered that they would be interested in visiting a wind farm which had an information center.

Table 4: Wind turbine development survey conducted amongst inhabitants of the Moravian-Silesian and Krystofovy Hamry regions of Czech Republic (Frantal and Kunc, 2011)

Relative Frequencies of Responses to the WT Dilemma Statements

Statement/response [%]	Agreed	Hesitant	Disagreed
WT as a renewable energy source contribute positively to the protection of the environment	69	13	18
WT significantly affect the landscape character	27	5	68
If I knew that there are WT in a location *X* I would rather not visit the location	6	10	84
I would be interested in visiting the WT as long as there would be an information (excursion) center	65	8	27
WT can be effectively used to support the tourism development	35	30	35

Such empirical evidence suggests that the development of wind turbines should not impact tourism in a negative manner. Implementation and enforcement of a developmental exclusion zone surrounding existing tourist areas and attractions may suffice, as Rutsson explains, “If a suitable location for wind turbines would be in the vicinity of a tourist attraction, then most people would prefer that it would be placed in a way that it would cause as little disturbance as possible to the attraction, both in terms of visual disturbance, annoyances due to noise and disruption in the installation time.” (Rutsson, 2013)

Therefore, future implementation of wind resource development in Iceland must consider both the mitigation of negative tourist impacts, as well as the prospect of potentially developing tourist attractions (information centers) coinciding with wind farm projects.

2.2.4. Mitigation of Noise Impacts

Noises and sounds can be measured in terms of loudness (decibels) and frequency (hertz) (TET, n.d.). The most common method for measuring sound regarding human influence is to measure such sounds through an A-weighted decibel dB(a) filter. The dB(a) filter is used to most accurately represent those noises which fall within frequency ranges detectable by humans, as the filter is less sensitive to high and low frequencies which humans are unable to hear.

Modern wind turbines produce ambient noise levels ~100 dB(a) at their source (GE, 2014). However, at a distance of 500m from the turbine hub, noise produced falls <40dB(a); the recommended value set by the World Health Organization (WHO) and the point at which turbine noise is lost amongst typical ambient background noise such as wind and wildlife (Nordman, 2010).

In 2012, the Massachusetts Department of Environmental Protection and Public Health commissioned a report covering the potential health implications associated for those individuals and communities living near wind turbines (Ellenbogen et al., 2012). The report primarily covers the viability of health impacts associated with turbine noise emittance, shadow flicker and ice throw. The study finds, "Evidence regarding wind turbine noise and human health is limited. There is limited evidence of an association between wind turbine noise and both annoyance and sleep disruption…" (Ellenbogen et al., 2012). However, the panel recommends the adoption of a table encompassing German and Danish standards regarding best practices of nighttime sound emittance, as portrayed in table 5.

Table 5: Best practice night-time sound decibel levels, by area

***measured at 10 m above ground, outside of residence or location of concern (Ellenbogen et al., 2012)**

Land Use	Sound Pressure Level,
	dB(a) Nighttime Limits
Industrial	70
Commercial	50
Villages, mixed usage	45
Sparsely populated areas, 8 m/s wind*	44
Sparsely populated areas, 6 m/s wind*	42
Residential areas, 8 m/s wind*	39
Residential areas, 6 m/s wind*	37

In order to ensure adherence to best practice noise controls, a wind resource development exclusion zone should be placed 500m around all residential and commercial structures within the country. Such an exclusion zone ensures ambient noise levels <40dB(a) for all individuals and communities, and is encompassed and incorporated within the results section of this paper.

2.2.5. MITIGATION OF SHADOW FLICKER

Shadow flicker is the resulting visual effect produced by the rotation of wind turbine blades passing between the sun and an observer. The frequency of flickering oscillations is a function of rotor rotational speed and the number of turbine blades (Ellenbogen et al., 2012). The resulting 'flicker' effect is often cited as a chief concern amongst those residents living within shadow zones of wind turbines. Many countries have begun implementing policies to mitigate these effects on local residents; figure 3 portrays relative wind turbine setback zone parameters set by Germanic regions as well as various countries with specified policies regarding such (Haugen, 2011). Policy set in Scotland represented the highest upper value, in some cases requiring turbines be placed at least 2000 meters from towns. However, more typical values range between 500-1000 meters.

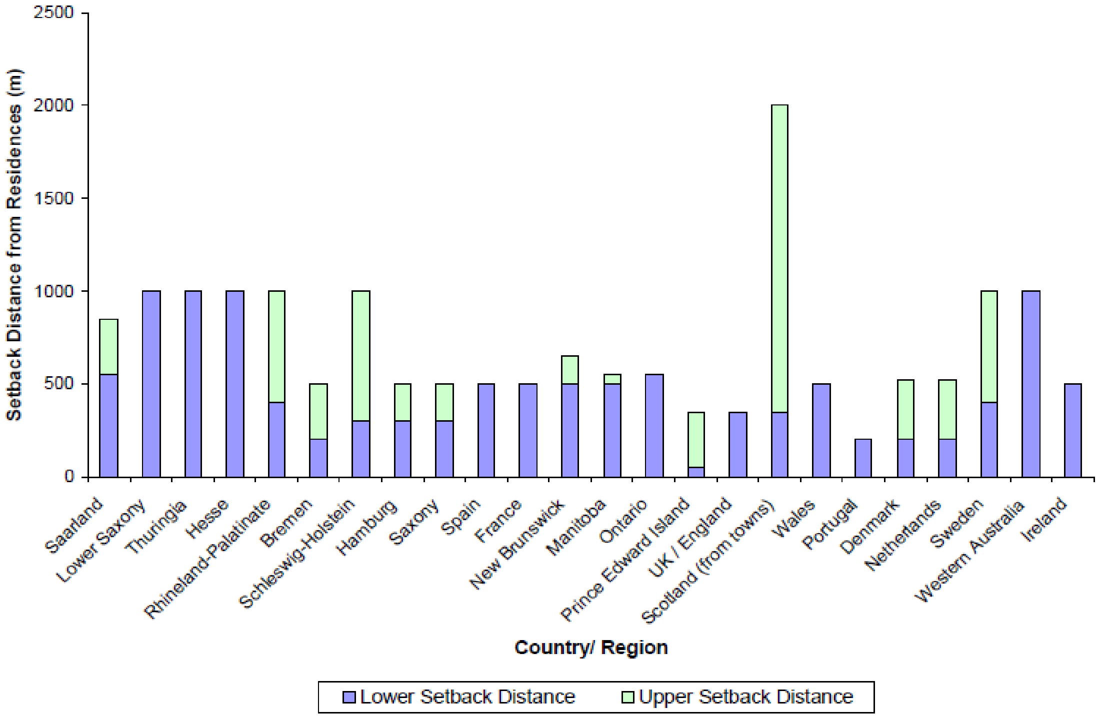

Figure 3: Wind turbine setback zone policies of German states and various countries (Haugen, 2011)

As the prospect of wind turbine development is still new to Iceland, the country has no formal regulations or standards in place concerning residential or commercial wind turbine setback zones. However, the turbine health impact study commissioned by the Massachusetts state government states, "shadow flicker is only present at distances of less than 1400 m from (a) turbine." (Ellenbogen et al., 2012).

Determination of a shadow flicker setback zone in Iceland is dependent on the altitude and azimuth of the sun (USNO, 2015). Altitude refers to the suns angle from the horizon, whereas azimuth refers to the relative angle from a reference point along the horizon. Shadow flicker setback zones are expressed as south-facing semicircles from all residential and commercial structure points within the country. This shape is chosen due to the suns altitude and azimuth in Iceland, which is predominantly south-facing and does not move past due east (90^{o}) or due west (270^{o}) at an altitude capable of generating shadow flicker.

In order to ensure comprehensive mitigation of shadow flicker effects to residents, turbine placement must not fall within any area 1400m to the south of residential or commercial structures. As such, a 1400 meter shadow flicker exclusion zone is applied throughout the results section of this paper.

2.2.6. CONSIDERATION OF EXISTING INFRASTRUCTURE

Wind power projects commonly rely on access to existing infrastructure throughout both the development process and operational phase (IRENA, 2015). Utilization of existing infrastructure including transmission lines, substations and roadways is often more timely and cost effective than the engineering, procurement, and construction of such.

Table 6 illustrates the average capital cost breakdowns for onshore and offshore wind farms in developed countries (IRENA, 2015). The wind turbine category includes the cost of the turbine, logistics such as shipping to site, and installation. Grid connection includes all costs associated with interconnection into existing grid infrastructure such as cabling and new substations (if required). Construction costs encompass those pertaining to the building of roadways or other associated infrastructure. Finally, ‘other capital’ refers to capital expenditure allocated towards consultancy services, licensing costs, SCADA and monitoring systems.

Table 6: Capital cost breakdown for onshore and offshore wind farms in developed countries (IRENA, 2015)

Cost share of:	Onshore (%)	Offshore (%)
Wind turbine	64-84	30-50
Grid connection	9-14	15-30
Construction	4-10	15-25
Other Capital	4-10	8-30

2.2.7. TRANSMISSION LINES & SUBSTATIONS

Transmission lines and substations are critical infrastructure components utilized in the electricity distribution process. Transmission lines are designed to carry electric current at a specified voltage across an area; whereas primary functions of substations include voltage regulation between generation and transmission, topological control, and AC/DC transformation (OSHA, n.d.). Major transmission lines and substations throughout the country are owned and operated by Landsnet, Iceland's transmission system operator (TSO). Landsnet operates 72 substations along 3,169km of transmission lines with voltage capacities ranging from 33kV to 220kV (Landsnet, 2012). Figure 4 illustrates the layout of the transmission and substation infrastructure owned and operated by Landsnet as of 2010.

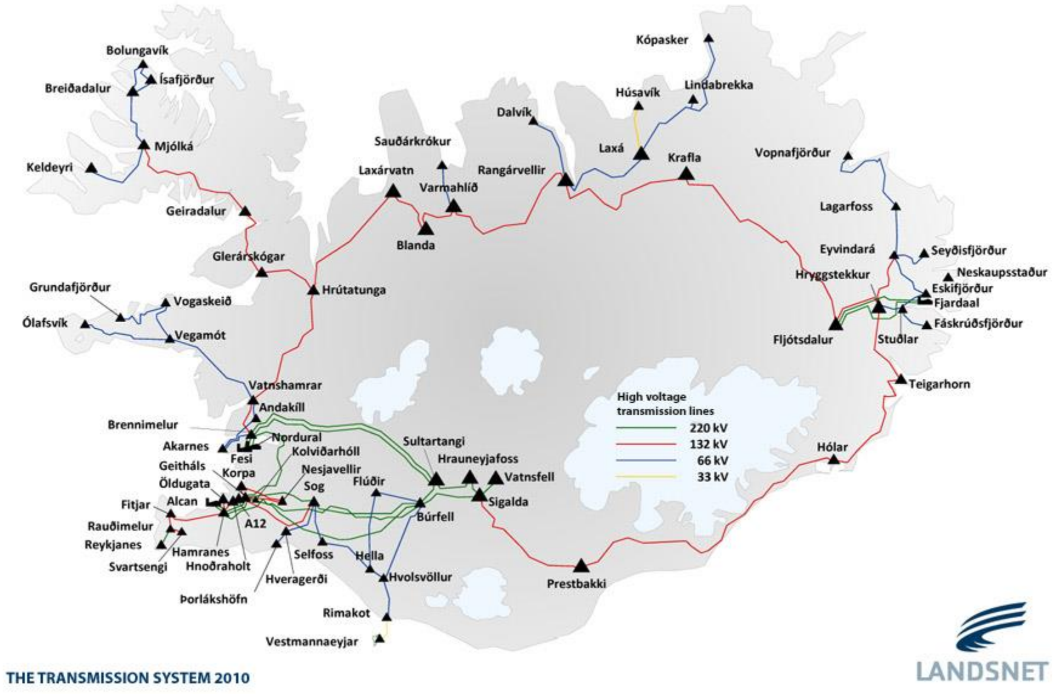

Figure 4: The Icelandic transmission system operated by Landsnet (Landsnet, 2012)

In 2013, an article was published in the magazine, ‘Electric Light & Power’ comparing installation costs of overhead and underground transmission lines (Alonso and Greenwell, 2013). The article highlighted typical installation costs in the United States of $285,000/mile (~$177,000/km) of 69kV overhead transmission line and $390,000/mile (~$242,000/km) of 138kV transmission line. Comparatively, proprietary information retrieved in Iceland illustrates installed line costs of approximately 40MISK/km (~$308,000/km) of 132kV transmission line (Confidential, 2015).

2.2.8. ROADWAYS

A similar developmental consideration as transmission infrastructure, access to existing roadway infrastructure is a factor which influences the feasibility of developing wind resources in a specified location. During the construction phase of a wind farm, access roads are necessary to facilitating safe and secure turbine delivery to site (AWEA, 2008). Proprietary information accessed in Iceland portrays that construction of single-wide roads cost approximately 10-15MISK (~$77,000-115,000 USD) per kilometer (Confidential, 2015). In comparison, installed costs of transmission infrastructure are approximately 3-4 times greater per kilometer than costs associated with the construction of new roadways.

2.3. ADDITIONAL CONSIDERATIONS

This chapter encompasses those factors pertaining to wind resource development which are excluded from the analysis portion of this project. Such variables are critical factors regarding developmental feasibility. However, each require site-specific assessment and cannot be easily assessed on an aggregated scale such as a country-wide assessment. Factors included within this chapter subsection are environmental factors, the examination of local soil conditions, and risk factors associated with turbine blade icing.

2.3.1. ENVIRONMENTAL FACTORS

Environmental factors regarding wind resource development fall primarily on concerns of impact mitigation to local ecology. Potential impacts on local flora and fauna populations must be carefully reviewed, assessed and considered. Typically this is done through an Environmental Impact Assessment (EIA) as part of the permitting process prior to any development (AWEA, 2008). Many countries have guidelines on how EIAs are to be structured and conducted. In the US, for example, the National Environmental Policy Act (NEPA) regulates and necessitates the thorough preparation of development of EIAs for such projects as wind farms, assessing any impacts to the local environment prior to the developmental phase.

The CIA World Factbook is a continuously updated catalogue of relevant country-specific information, including “information on the history, people, government, economy, energy, geography, communications, transportation, military, and transnational issues (of each country)…” (CIA, 2015). The CIA Factbook describes the landscape of Iceland as primarily homogenous and harsh with approximately 103,000km^2 of land area (CIA, 2015). Land area is broken down into three main segments, agricultural land (18.7%), forested land (0.3%) and wasteland (81%), as portrayed in figure 5.

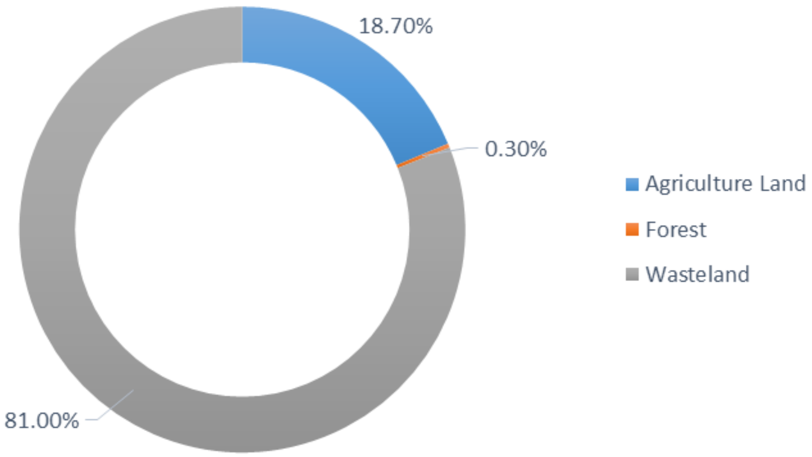

Figure 5: Primary land types in Iceland (CIA, 2015)

Prior to development of any potential wind farm, an adequate and locally focused EIA must be conducted to account for any potential impacts within a specific region. Particular issues pertaining to wind resource development include such impacts as those to migratory bird species, disturbance or displacement of local flora, disturbance or displacement of land-based fauna (mammals, reptiles, amphibians, etc…), aesthetic impacts, and cultural disturbances.

2.3.2. SOIL CONDITIONS

Following turbine site selection, local soil conditions must be evaluated and analyzed to determine ideal wind turbine foundation types. In general, soil textures may fall into a mixture of one of three predominant categories, clay, sand or silt (Thien, 1979). Prior to the construction phase, subsurface soil must be collected in order to determine an ideal foundational type. Common methods of soil extraction include rotary drilling, percussion drilling, and wash boring (Das, 2007). Figure 6 illustrates a cross-sectional imagine comprising of various types of soil particulates including sands, gravels, and silts. Proper soil condition classification and monitoring is essential for turbine foundation selection.

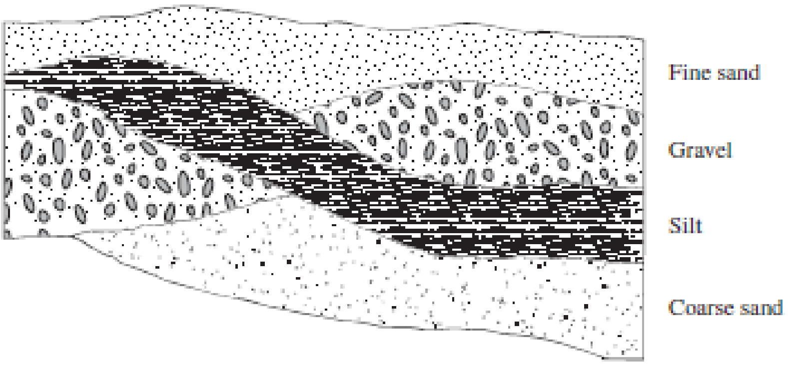

Figure 6: Cross section of various soil particulates (Das, 2007)

Ample turbine foundational types and methods of development exist, however, modern onshore wind turbine foundations fall into one of two distinct sub-categories, spread foundations and piled foundations (Svensson, 2010).

Spread foundations, also known as slab foundations are designed to evenly distribute structural weight across the base of the foundation (Svensson, 2010). Such foundations often consist of reinforced concrete and are characteristically of cylindrical geometry. Typically, such foundations are utilized in stiff, less elastic soil conditions.

When surface soil conditions are not suitable for spread foundations, piled foundations are utilized in order to reach higher quality (stiff & inelastic) soil at depth or bedrock. Figure 7 demonstrates common examples of spread and piled foundations.

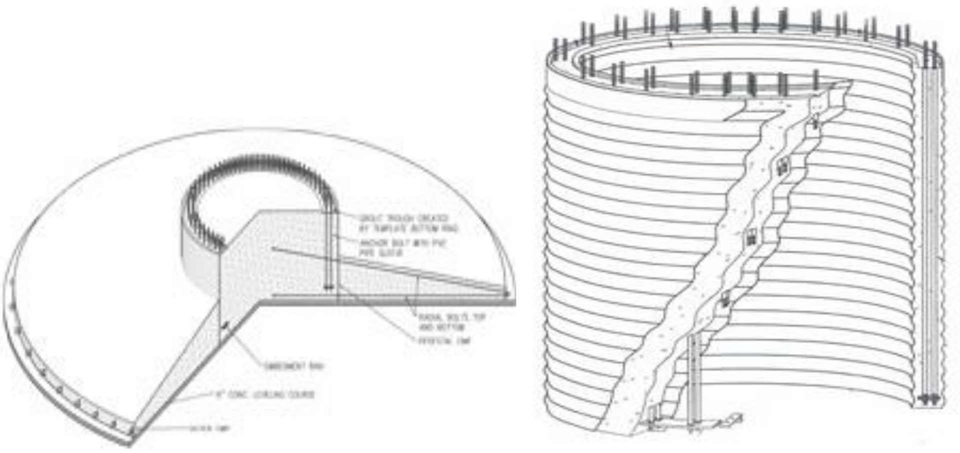

Figure 7: Spread (left) and piled (right) foundations commonly used for wind turbines

Due to the importance and acute nature of localized site assessments of soil conditions, this factor has been left out of the analysis portion of this paper.

2.3.3. TURBINE BLADE ICING

Wind resource development within colder climates are subject to the additional risk factor of wind turbine blade icing (Kraj and Bibaeu, 2010). As such, an icing event can occur in any climate which experiences freezing temperatures and can hinder turbine efficiencies and even lead to turbine downtime. Such events can be classified into distinct icing stages, providing information useful to the development of mitigation strategies. Moreover, blade icing reduces the safety of wind turbine operations due to conditions such as ice-throw, an event in which chunks or sheets of ice are cast from the turbine blades (Ellenbogen et al., 2012).

The Icewind project is a workgroup developed between Iceland and Sweden, aimed at addressing many of the issues associated with wind resource development in colder climates (IceWind, 2015). In partnership with industry players such as Landsvirkjun, Landsnet, Vestas and Oceaneering, the Icewind project consists of four workgroups focused on the topics of turbine blade icing, wind power in Iceland, offshore forecasting of O&M, and energy transmission systems. As part of the turbine blade icing workgroup, an icing atlas is currently in development, “The final objective is development of an engineering tool for production loss calculation of large wind turbine installations in northern latitudes.” (IceWind, 2015). However, until such a development is complete, blade icing forecasting must be done on a site specific level to ensure greater accuracy of estimates.

2.4. EFFICIENT FRONTIER METHOD

The efficient frontier method was first developed and introduced by Harry Markowitz in 1952 and remains relevant today as a concept firmly grounded in modern portfolio theory (Markowitz, 1952). The concept was originally used within the realm of finance to correlate implied risk with implied return (Investopedia, 2015). This method, however, is also utilized in a variety of applications with the purpose of analyzing optimization strategies.

Pertaining to wind resource assessment and optimization, illustrated graphically below is the correlation of infrastructure costs (transmission and roadways) on the x-axis and wind resources (AWS) on the y-axis, as portrayed in figure 8.

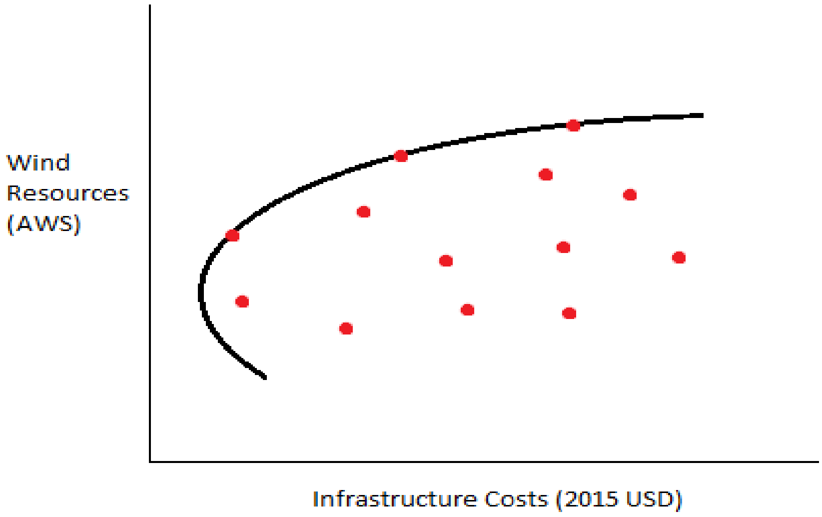

Figure 8: Efficient frontier method illustrating optimal wind resource development selection criteria

Such a graph illustrates the most optimal site(s) for development along the efficient curve, as every alternative below and to the right of a given site has higher infrastructure cost and less optimal wind resources.

3. RESEARCH METHODS

Methods used throughout this study involve the analysis of global best practices and the application of such to the Icelandic wind developmental framework. Listed below in table 7 are those factors compiled and deemed most critical to wind resource development in Iceland. This table summarizes key findings for each factor examined throughout the literature review as well as whether they are included in the following efficient frontier analysis.

Table 7: Summary of key findings for each factor examined

Factor	Included in Analysis?	Accept/Reject Criteria
Wind Resources	Yes	Efficient frontier analysis, value based on AWS bin value
Social Factors:	-	-
Tourism	Yes	Accept/reject criteria based on established exclusion zones
Noise Pollution		
Shadow Flicker		
Environmental Factors	No	Site-specific EIA necessary
Transmission Infrastructure	Yes	Efficient frontier analysis, lower cost at closer proximity to site *X*
Roadways	Yes	Efficient frontier analysis, lower cost at closer proximity to site *X*
Soil Conditions	No	Micro-citing consideration
Turbine Blade Icing	No	Insufficient information/ Site specific

Throughout the analysis, each site assessed is processed through a rejection criteria pertaining to whether they fall outside of predetermined exclusion zones. If site 'X' is located within exclusion zones, the area is rejected and not considered for development. If site 'X' is located outside of exclusion zones an efficient frontier analysis is conducted regarding the areas' factor properties pertaining to wind resources, distance to transmission lines and distance to roadways. Upon consideration of acceptable sites, locations are plotted and compared in terms of their efficient frontier rank. Finally, optimal sites for wind resource development are recognized and recommended. The logical progression of this analysis is illustrated through a flow chart shown in figure 9.

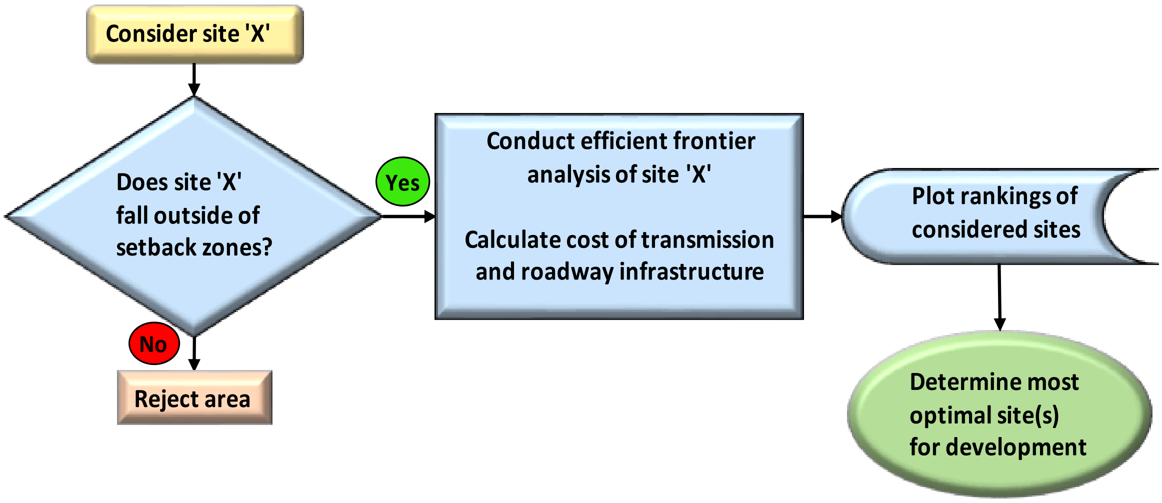

Figure 9: Flow chart of wind site consideration and classification process

4. RESULTS

4.1. SINGLE AND DUAL-FACTOR MAPS

This section includes all maps developed and generated by the author. The aim of such are to illustrate those relevant factors pertaining to wind resource development in a method which is clear, concise and easily interpreted on a macro-scale.

For the purpose of this study, the AWS of each area throughout Iceland was calculated by considering each directional average wind velocity and calculating the weighted average wind speed. To do so, two assumptions were made. First, it was assumed that 50m (agl) is the ideal height consideration amongst options available. Second, the surface roughness class 1 (0.03m) is assumed and applied to all points within the country. Figure 10 portrays the average wind speeds in Iceland given the assumed values of 50m height (agl) and roughness class 1 (0.03m). The color scale ranges from greens to yellows to reds. Areas with green color schemes have the lowest AWS and areas in red have the highest AWS.

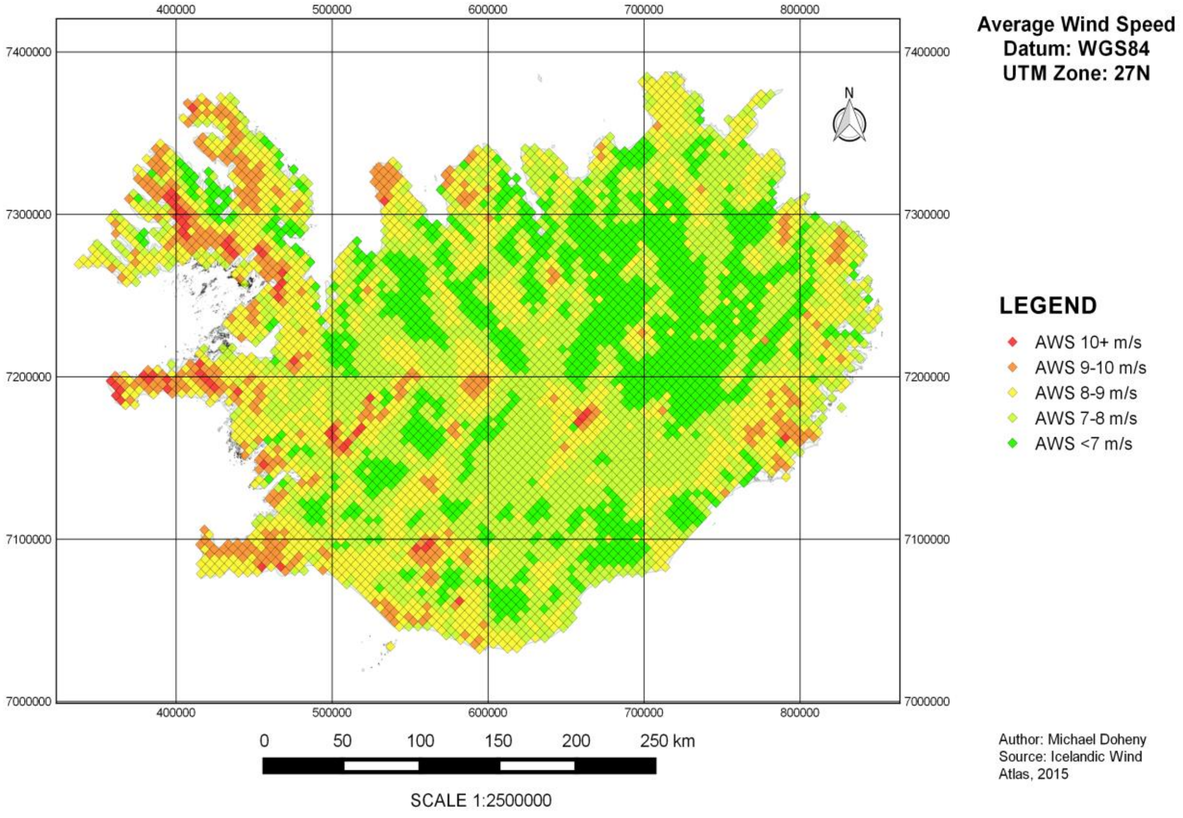

Figure 10: Average Wind Speeds in Iceland at 50m (agl) height and 0.03m surface roughness

Overall, AWS values ranged between 4.79 m/s and 11.55m/s and were placed within five wind resource bins, as portrayed in the frequency distribution in figure 11. Illustrated below are similar characteristics to a Weibull distribution, in which the three lowest value bins cumulatively comprise of most of the sites around the country (93.7%); whereas the two highest value bins contain a small cumulative percentage (6.3%) of the sites examined throughout Iceland.

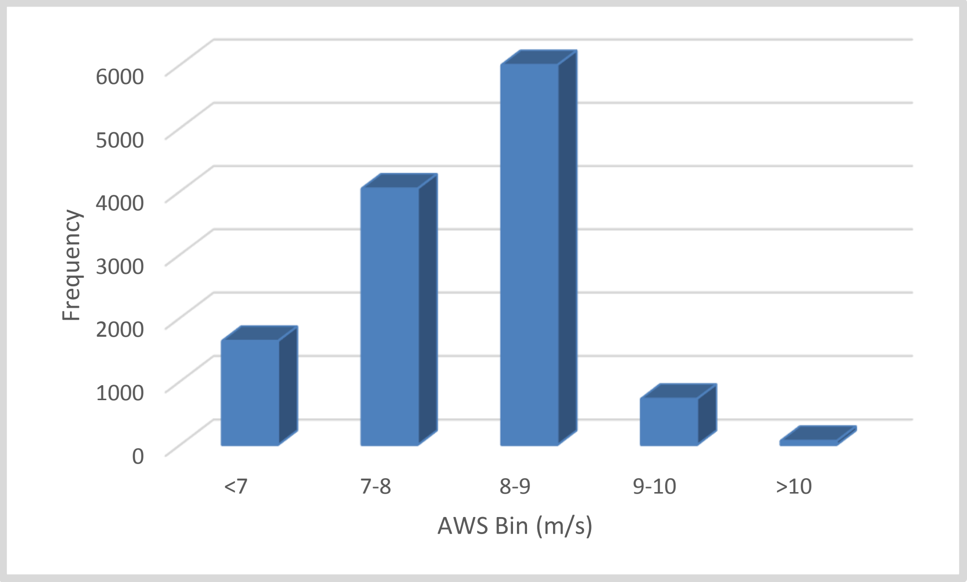

Figure 11: AWS frequency distribution in Iceland per wind speed bin

To add perspective, the city of Chicago in the US is known as the ‘windy city’. However, 2014 data provided from the Chicago MET office demonstrates an annual average wind speed of 7.21m/s at a height of 25.9m a.g.l. approximately 4.4km offshore in the Chicago Bay (Chicago MET, 2015); a wind speed which would be considered a lower value compared to the Icelandic data analyzed.

Figure 12 portrays the existing transmission line (ranging from 33-220kV) and substation infrastructure throughout Iceland. Development of wind resources within relative proximity of existing transmission infrastructure is paramount to controlling installed costs, as discussed throughout chapter’s 2.2.6.-2.2.8.

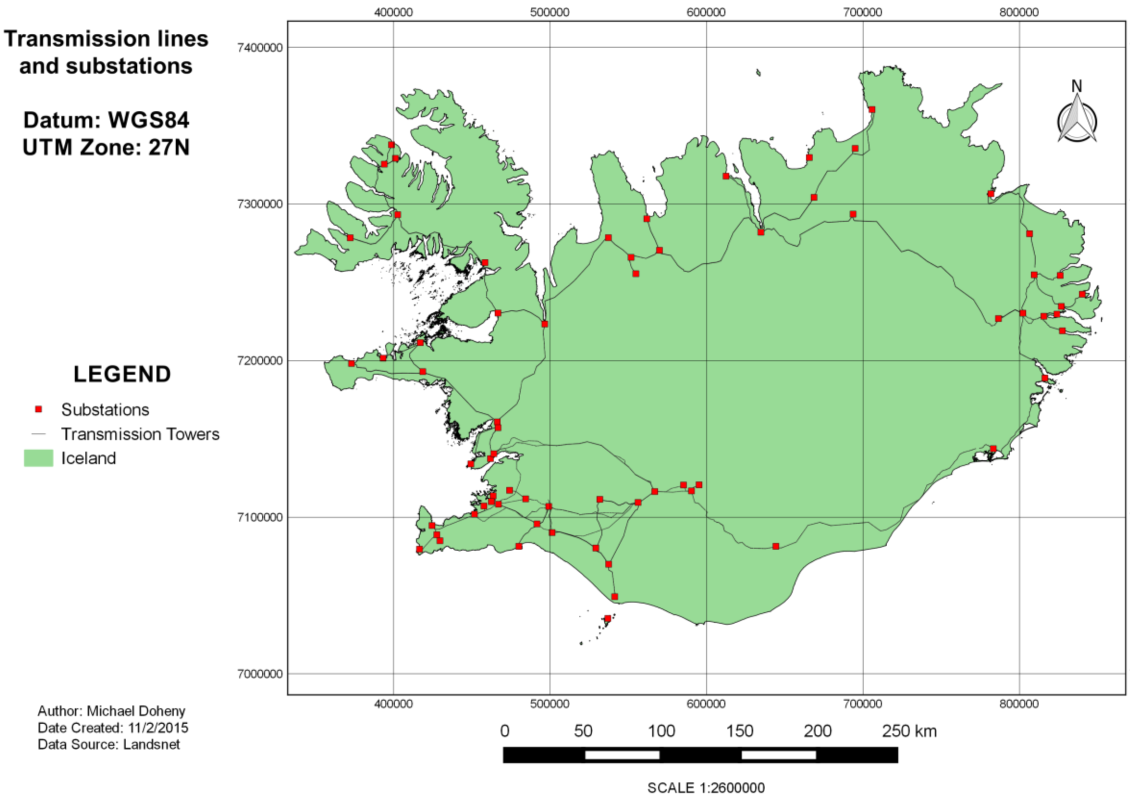

Figure 12: Existing transmission and substation infrastructure throughout Iceland

Figure 13 illustrates glaciers and protected conservation areas present in Iceland. Shapefiles were provided by Landmælingar Island, the National Land Survey of Iceland. Conservation areas such as Skaftafell, þingvellir, Ásbyrgi, Vatnajökull National Park and Snæfellsness National Park are excluded from wind development consideration, as they are areas which experience high volumes of tourism and contain natural or historical significance. Additionally, Iceland's glaciers such as Vatnajökull, Snæfellsjökull, Eyjafjallajökull, Langjökull, Tungafellsjökull and Hofsjökull are regarded as conservation areas in this regard. Around all conservation and glacial boarders a 1 km buffer area will be applied as an additional exclusion zone, as a means of minimising noise and aesthetic impacts on tourist activities.

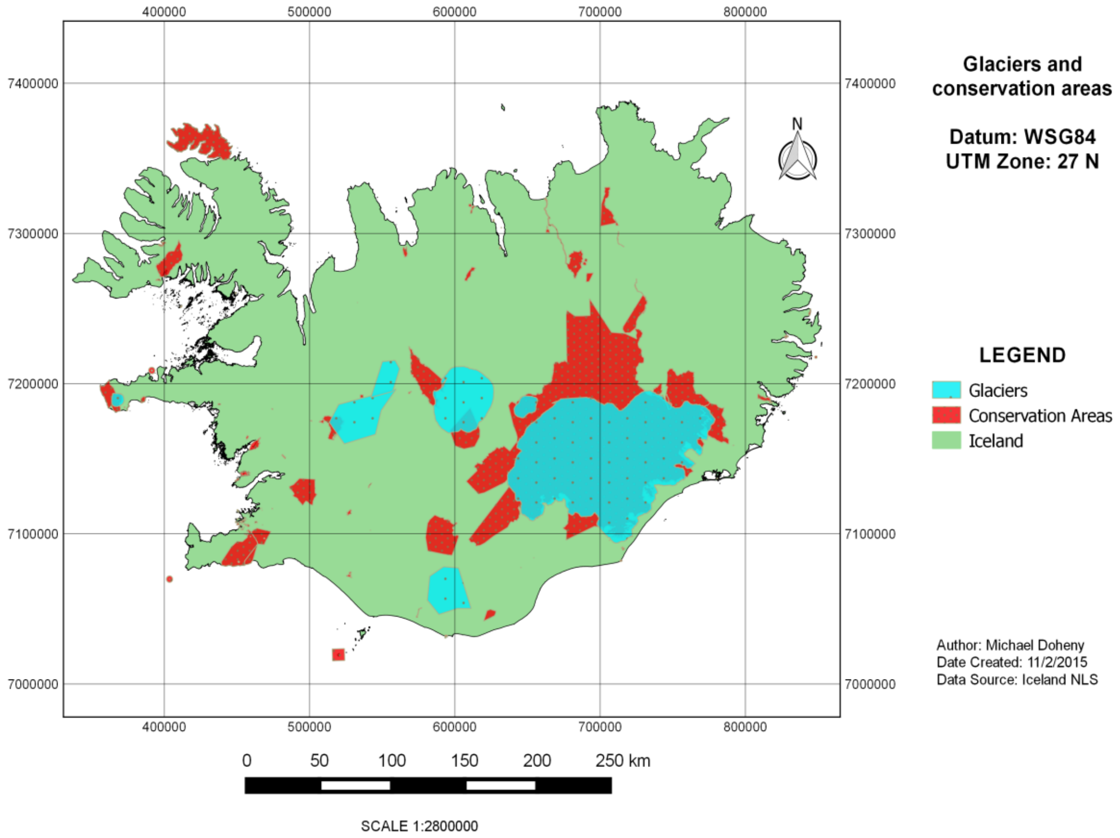

Figure 13: Glacier systems and protected conservation areas in Iceland

Figure 14 portrays all residential and commercial structure points throughout Iceland. Each of the 20,536 structure points include a 500m wind turbine exclusion zone to ensure no level of noise pollution is experienced by local residents and communities, as discussed in chapter 2.2.4., a value recommended by the WHO. At this range, noise produced by the turbines is entirely lost amongst ambient outdoor noise (<40dBa). After assessment of those areas with overlapping noise pollution exclusion zones, roughly 5,325km^2 (~5.17%) of the country faces exclusion of potential wind resource development due to this factor.

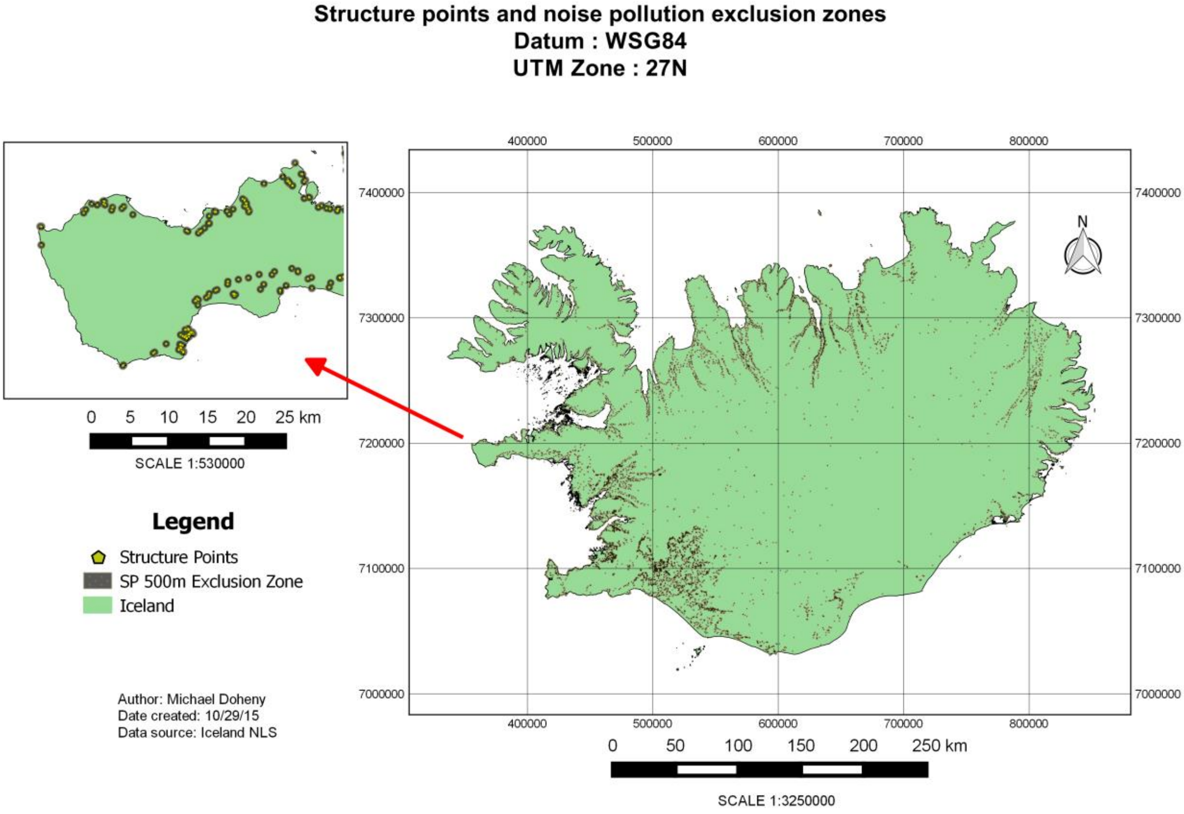

Figure 14: Structure points with 500m wind turbine noise pollution exclusion zone

Illustrated in figure 15 is the implementation of a shadow flicker exclusion zone to the 20,536 structure points throughout the country. In addition to the noise pollution exclusion zone mentioned in figure 14, such zones are semi-circles which face due south and extend 1400 meters in radius. The purpose of such is to conservatively mitigate any potential for shadow flicker effects to Icelandic residents, as discussed throughout chapter 2.2.5.

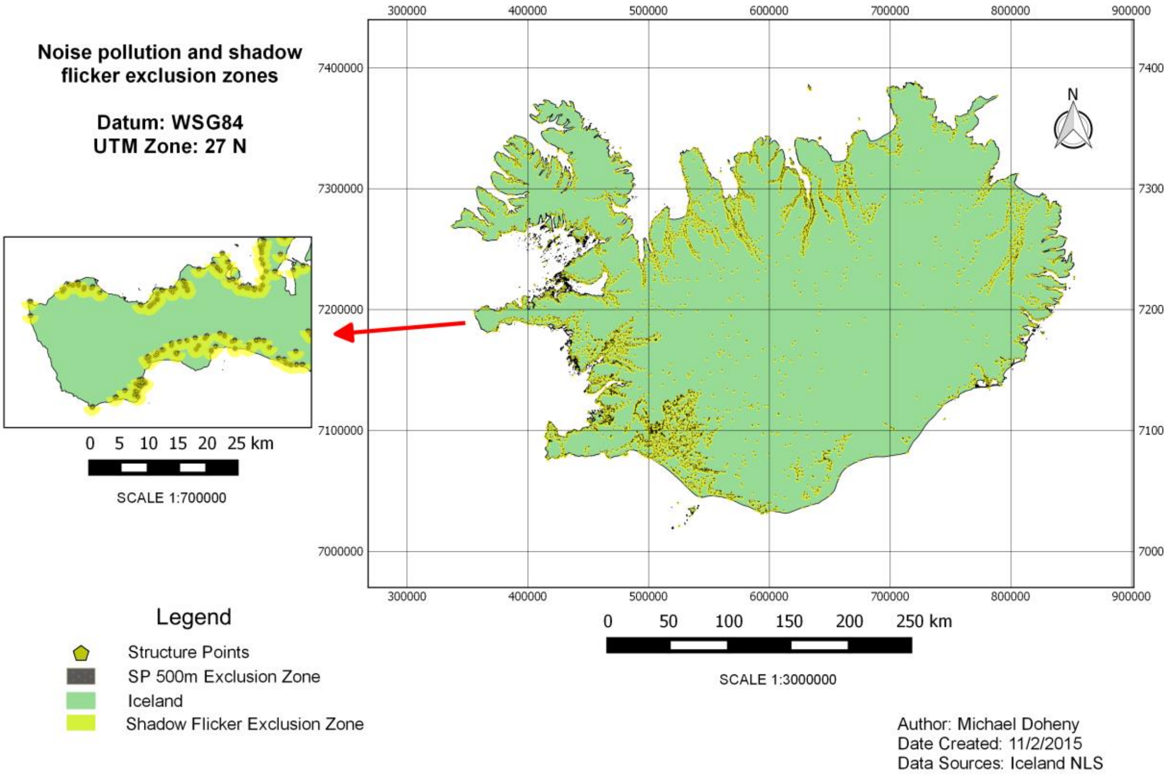

Figure 15: Shadow flicker exclusion zone (semi-circle) around all residential and commercial structures

4.2. ANALYSIS OF SNÆFELLSNESS PENINSULA

In this chapter an efficient frontier analysis in conducted of the wind resources throughout the Snæfellsness peninsula. The area analyzed encompasses the entire land area west of Alftafjördur, located in the eastern region of Snæfellsness. Throughout the region, a total of 72 wind resource data points were examined, as portrayed in figure 16.

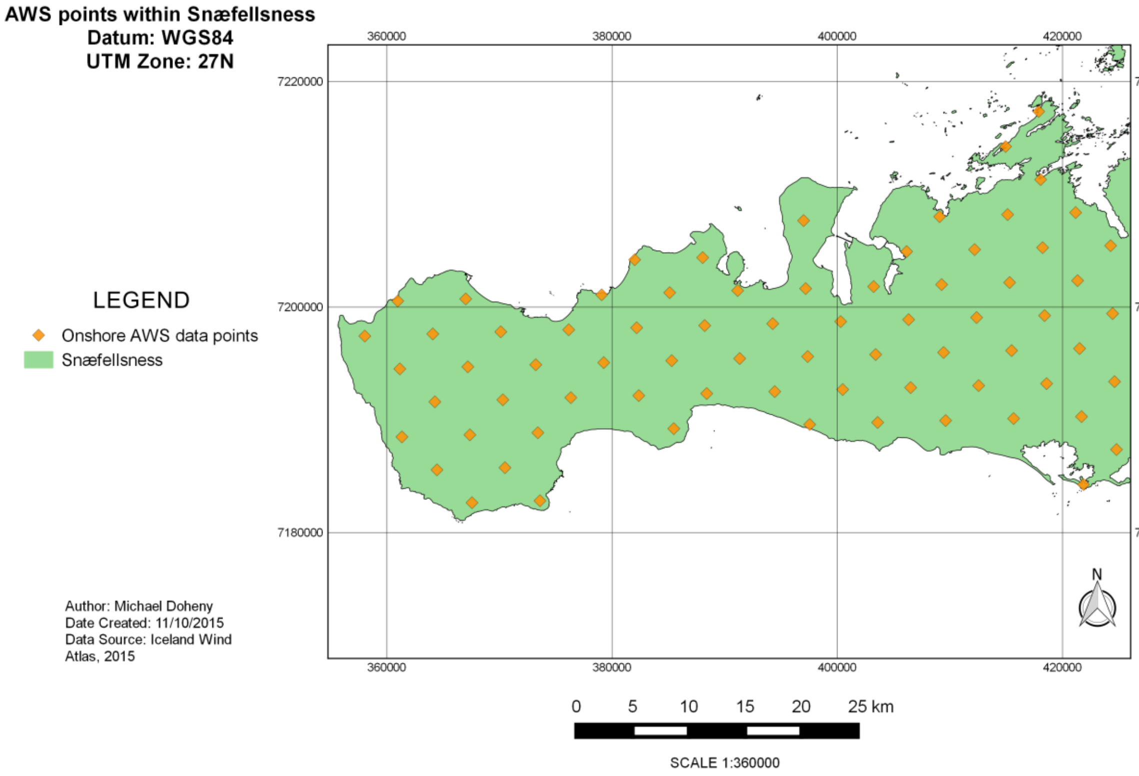

Figure 16: Land area and AWS data points examined within the Snæfellsness region

Table 8 demonstates those factors assessed throughout this analysis. The total land area analyzed spans 1260km^2; of which, 14.19% accounts for conservation areas, 4.92% for glaciers, 26.58% for shadow flicker exclusion zones and 8.72% for noise pollution exclusion zones, on an individualized basis. It is important to note that many exclusion zones overlap, thus the cumulative land area excluded from developmental consideration is expressed in column four. For example, the total land area occupied by glaciers within the Snæfellsness region account for approximately 62.01km^2, however, much of this area also falls within the boundaries of national conservation areas, as portrayed in figure 17.

Table 8: Factors examined and analyzed within the Snæfellsness region

	Locations	Area (km^2)	Percent of Region	Cumulative Percent (Including Overlap)
Snæfellsness peninsula	-	1260.00	-	-
Conservation areas	4	178.75	14.19%	14.19%
Glacier areas	1	62.01	4.92%	15.05%
Structure points	389	-	-	-
Shadow flicker exclusion	389	334.95	26.58%	41.63%
Noise pollution	389	109.81	8.72%	43.70%
Transmission lines	-	-	-	-

After consideration of all excluded zones, approximately 56.3% of the region is deemed suitable for wind resource development. Figure 17 portrays those areas which have been excluded from consideration within the Snæfellsness peninsula due to exclusion zones pertaining to each factor.

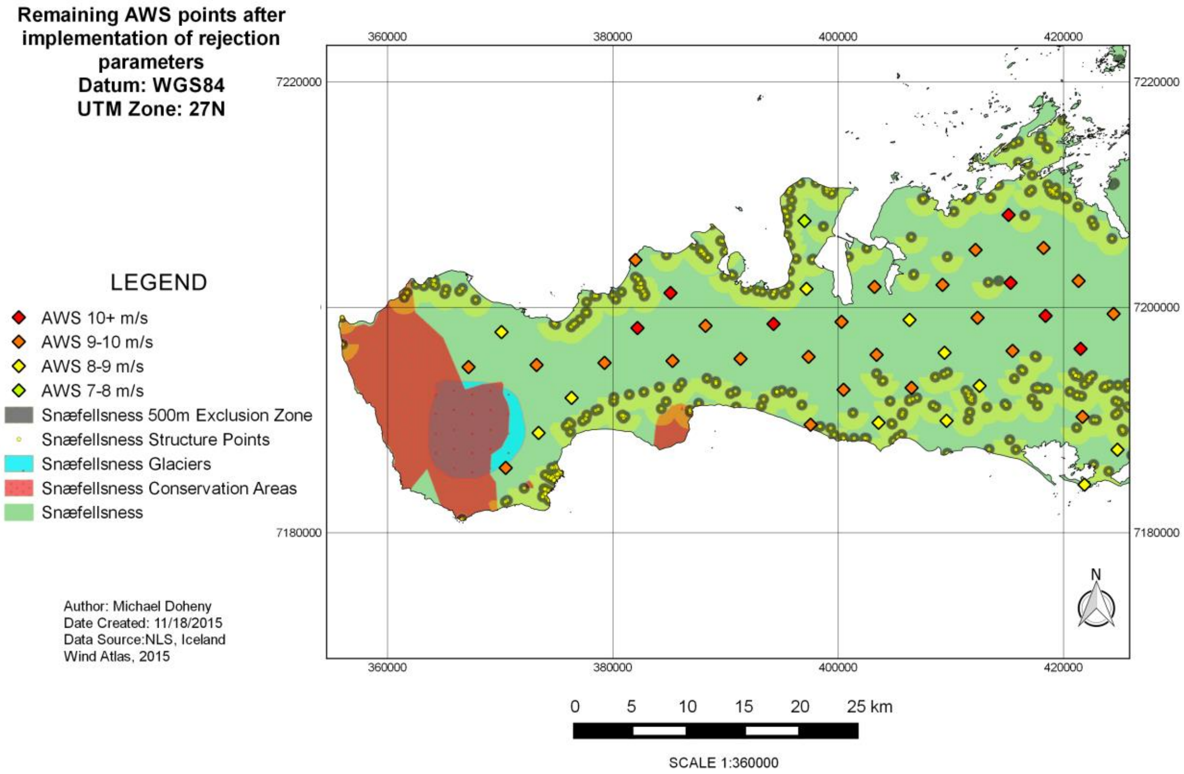

Figure 17: Snæfellsness exclusion zones and remaining wind locations

After following the rejection parameter methodology expressed in figure 9, elimination of those wind resource points which fall within exclusion zones left 43 wind points remaining for analysis within the efficient frontier method. Figure 18 portrays those remaining wind points which fall outside of predetermined exclusion zones, along with existing transmission and roadway infrastructure within the region.

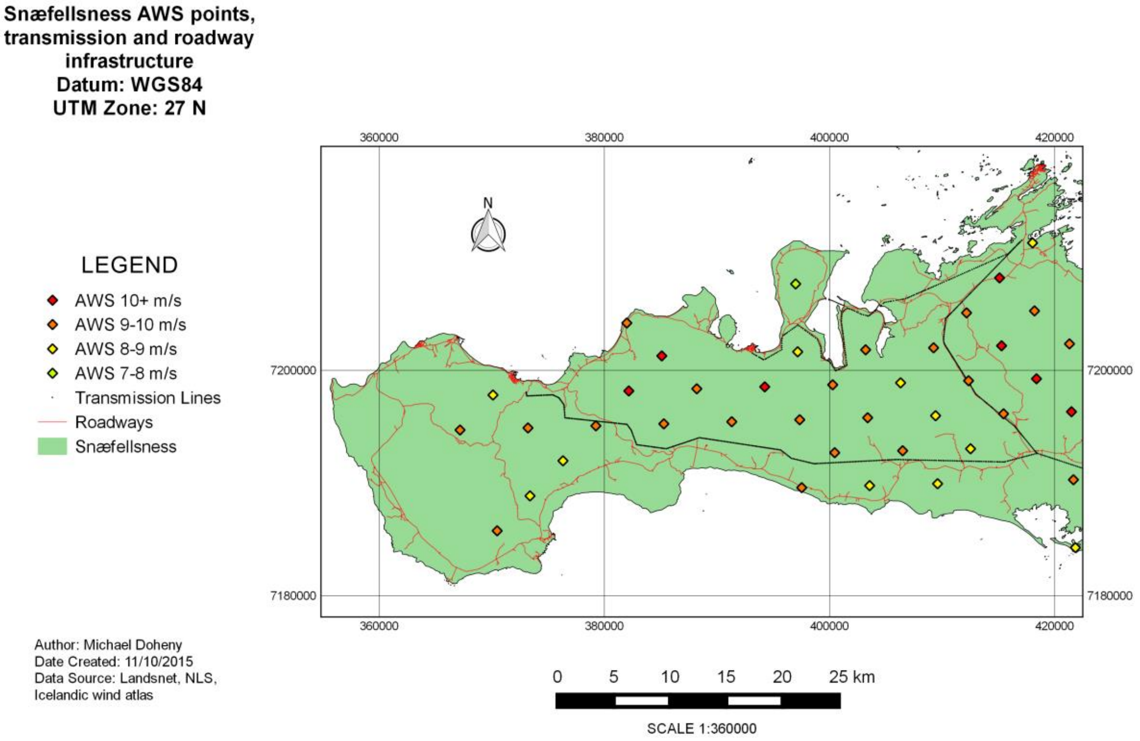

Figure 18: AWS points, transmission and roadway infrastructure within the Snæfellsness region

As mentioned in chapter 2.4, AWS and infrastructure costs can be graphically represented within an efficient frontier analysis. Utilization of this method facilitates the determination of those site which have the most optimal characteristics for wind resource development. Plotted in figure 19 are wind resources (AWS) and estimated infrastructure costs (2015 USD) of the remaining 43 sites assessed throughout the Snæfellsness region.

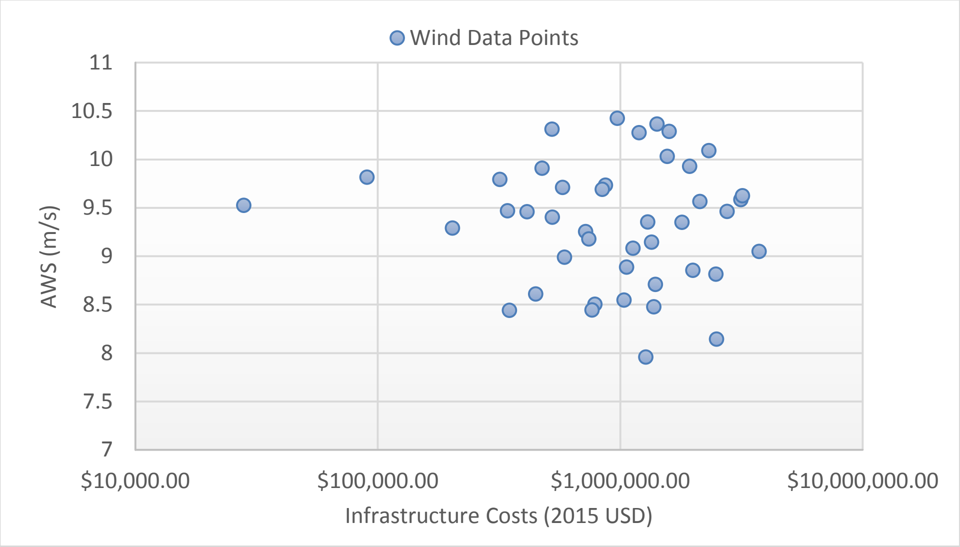

Figure 19: Efficient frontier analysis of 43 examined sites throughout Snæfellsness peninsula

Cost estimations for infrastructure include cost information for transmission lines and roadways as detailed in chapters 2.2.7. and 2.2.8., respectively. In addition, roadway costs were estimated to be $96,000/km, the median value of the cost range expressed in chapter 2.2.8.

Highlighted below in figure 20 are results expressing the four most optimal sites for wind resource development within the Snæfellsness peninsula. Each highlighted site along the Pareto Frontier is more ideal than those alternatives which fall below and to the right, as site characteristics are such that they possess both stronger wind resources and lower infrastructure costs. Further data pertaining to these sites can be found in appendix A.

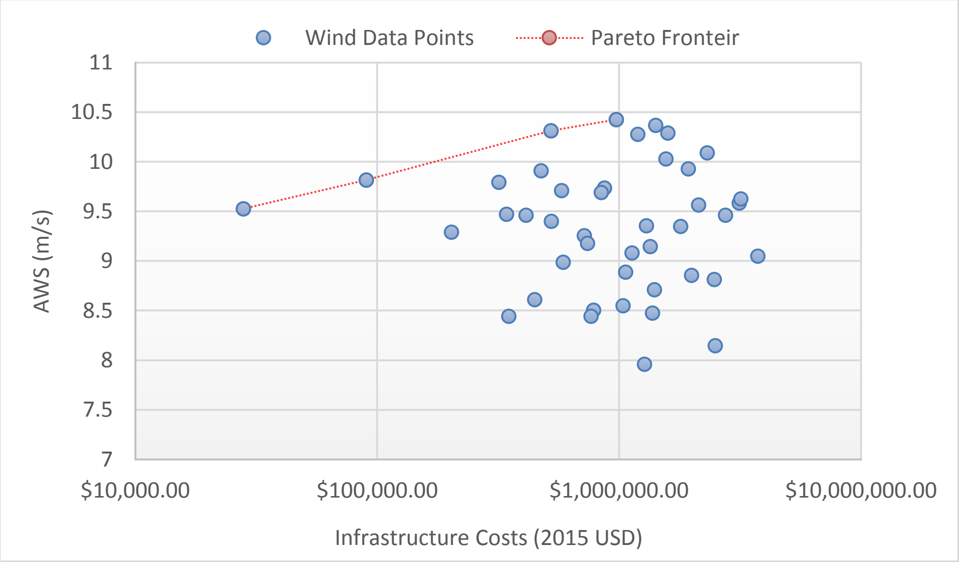

Figure 20: Four sites highlighted along the Pareto Frontier within the Snæfellsness region

Illustrated below in figure 21 are results expressing the four most optimal sites for wind resource development within the Snæfellsness peninsula. For simplicity throughout the remainder of this analysis the sites have been numbered from 1-4, corresponding from lowest to highest estimated infrastructure cost, and are referred to as such.

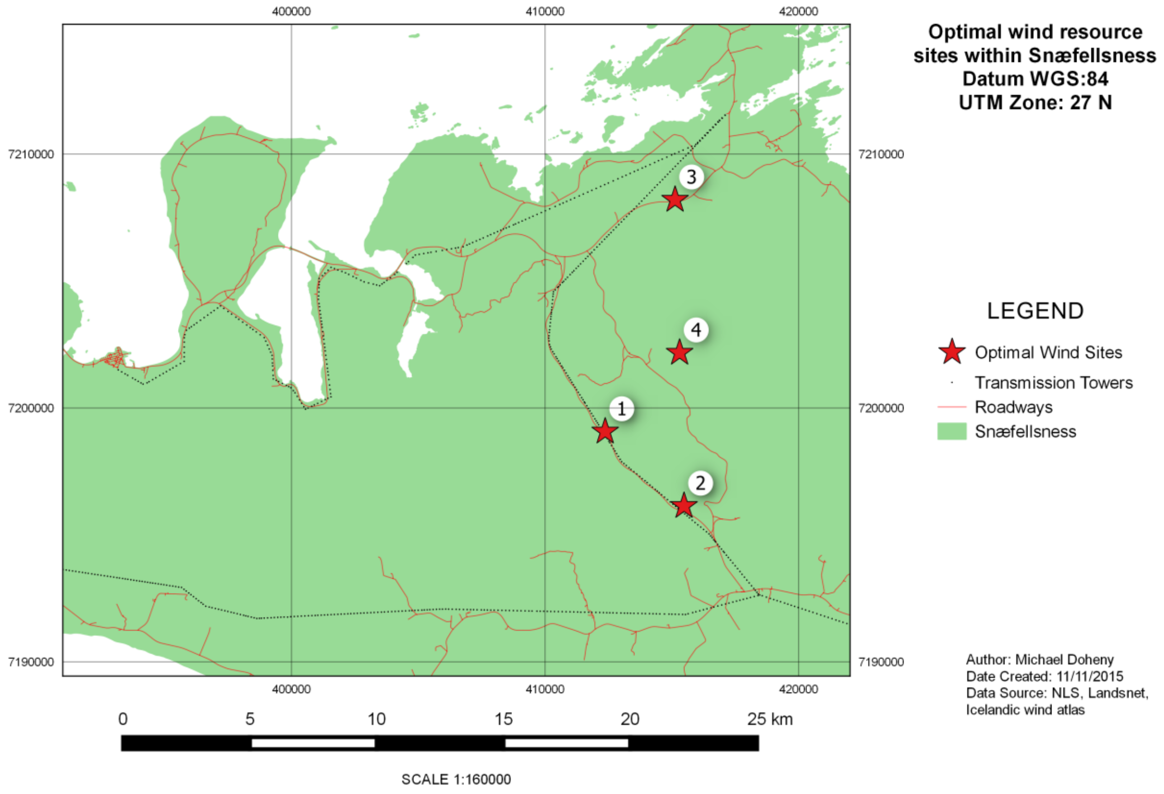

Figure 21: Pareto Frontier sites for wind resource development within the Snæfellsness peninsula

Having determined four sites for wind resource development, an assessment of annual energy production (AEP) for a given wind turbine may be calculated. Such an assessment provides further understanding of wind resource variance amongst each location by quantifying each sites Weibull curve in terms of MWh´s produced on an annual basis. Figure 22 illustrates the AEP for each site utilizing two methods; first by calculating electricity production using the power curve of an Enercon E44 wind turbine, and second by calculating the theoretical maximum wind energy potential using Betz Limit and the same RSA as the Enercon E44. Detailed information regarding these calculations can be found in appendix B.

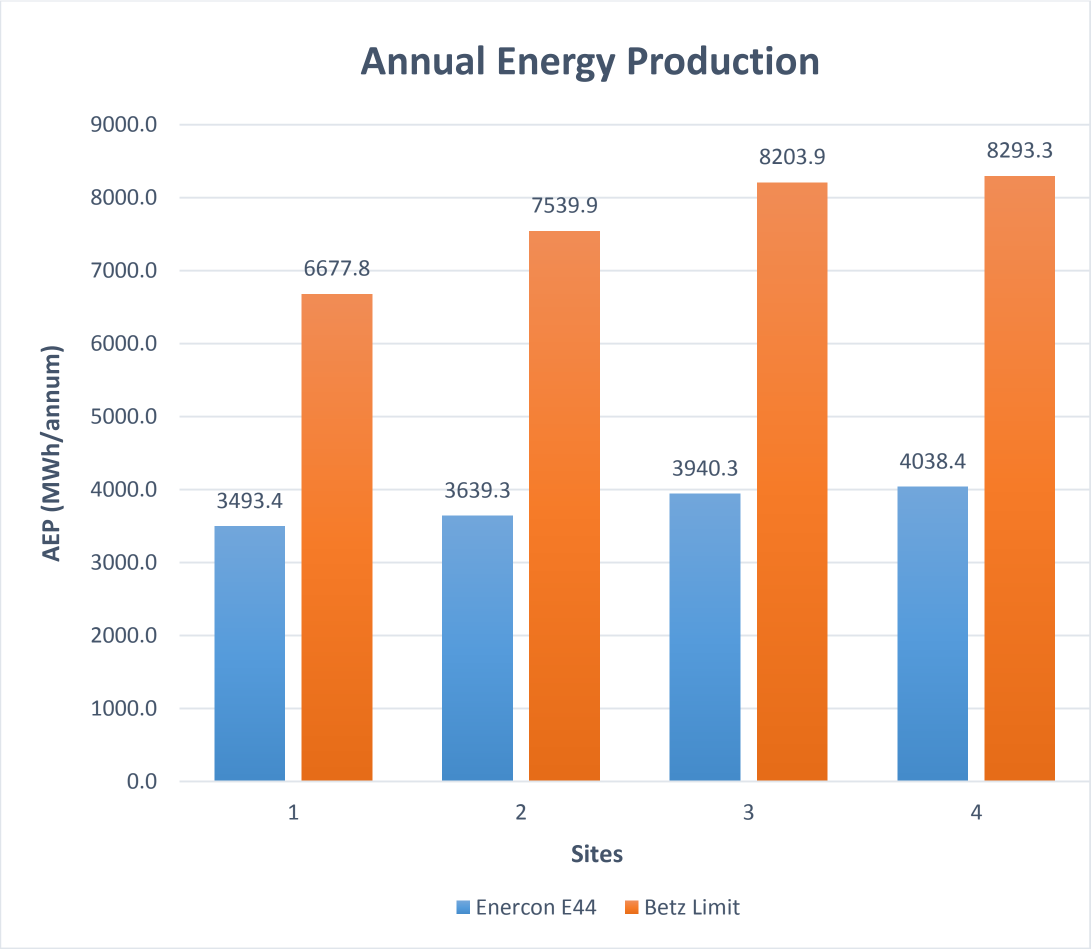

Figure 22: Calculation of AEP at each of the four sites assessed in Snæfellsness

Unsurprisingly, site four, which possesses the highest AWS value of its peer group, demonstrated the highest AEP yield for both methods. In the first method the AEP of an Enercon E44 turbine placed at site four would produce 4038MWh´s per annum, a 2.49% higher yield than the next best alternative. In the second method AEP is calculated using Betz Limit; again, site four possesses the highest theoretical maximum wind energy potential at 8293MWh´s per annum.

While site four demonstrates the highest energy yields, marginal increase in electricity generation may not outweigh the marginal cost of additional infrastructure attributed to each site. In order to determine the most optimal site, a cost-benefit analysis must be conducted to calculate the marginal cost or benefit of incremental electricity generation relative to incremental infrastructure costs. Demonstrated for each site in figure 23 are the estimated discounted revenues, infrastructure costs and net present value of cash flows for an Enercon E44 over an assumed 20 year lifetime; for more detailed information refer to appendix C.

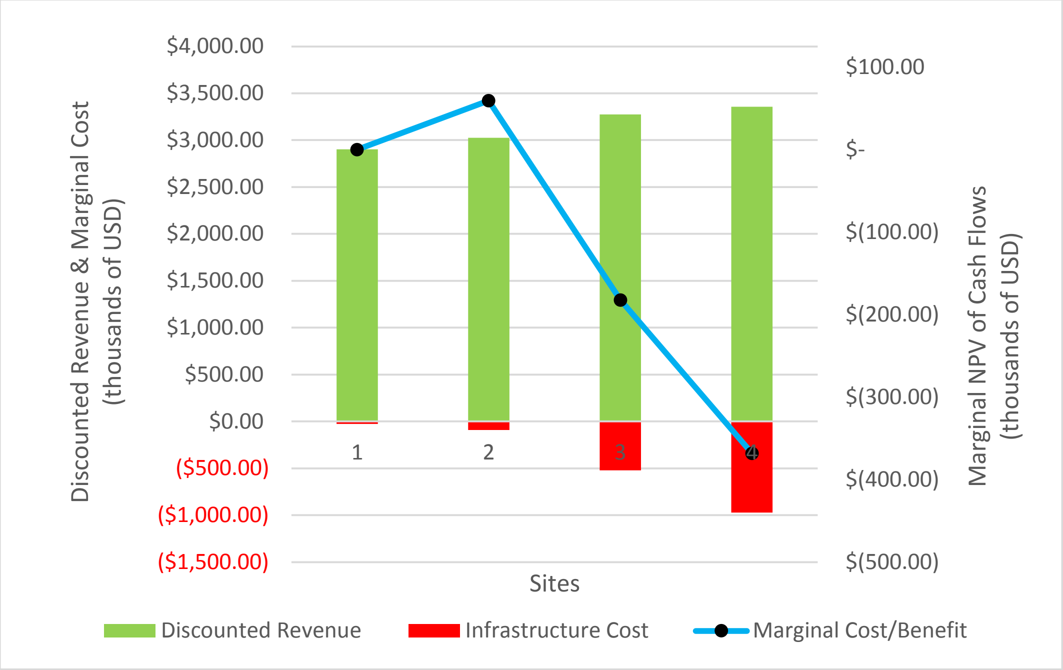

Figure 23: Discounted revenue, infrastructure costs and marginal cost/benefit of turbine development amongst sites

As illustrated, discounted revenues and infrastructure costs are plotted with a stacked bar graph on the primary y-axis; whereas marginal NPV of cash flows are plotted with stacked line on the secondary y-axis. Marginal NPV of CF increases correspondingly in comparison from site one to site two, indicating a greater increase in discounted revenues than the increase in infrastructure costs over the lifetime of the wind turbine. However, in comparison to sites three and four, marginal NPV falls indicating the cost of infrastructure is greater than the benefit of incrementally greater revenues.

Therefore, in regards to the development of a single Enercon E44 wind turbine, site two is considered most optimal demonstrating the greatest NPV.

4. CONCLUSIONS

As opportunities for wind resource development within Iceland grow, the utilization of methods to determine optimal sites become paramount. The methodology expressed throughout this paper may be utilized as a technique to determine optimal site selection on a macro-scale as part of a feasibility analysis. Social well-being is ensured through the application of developmental exclusion zones regarding such factors as impact mitigation on tourism, noise pollution and shadow flicker; while both an efficient frontier and cost-benefit analysis ensure optimal site selection in terms of maximizing marginal benefits (NPV of cash flows) associated with wind resource development in a given site.

Areas to be further addressed in future work include improving methods used to ensure accurate wind measurement techniques, development and inclusion of turbine blade icing risk factors, and the development of overarching EIA standards for wind resource development which might be applied in Iceland on a macro-scale.

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6. APPENDICES

Appendix A: Sites considered for wind resource development within the Snæfellsness region

This table represents those sites within Snæfellsness peninsula which passed the initial rejection criteria and were plotted within an efficient frontier analysis. The four highlighted sites are those chosen as most optimal due to site specific wind resources and infrastructure costs, as highlighted in the Pareto Frontier analysis.

					(meters)		(meters)		
10+	ID	long	Lat	AWS	Dist. to road	Cost of road	Dist. to transmission	Cost of Transmission	Total Infrastructure Cost
	6151	-23.4293	64.9158	10.28944621	2213	$ 212,448.00	4464	$ 1,374,912.00	$ 1,587,360.00
	5971	-22.6573	64.8819	10.27744861	2830	$ 271,680.00	2990	$ 920,920.00	$ 1,192,600.00
	6156	-22.7919	64.9329	10.42545304	2627	$ 252,192.00	2338	$ 720,104.00	$ 972,296.00
	6057	-23.4886	64.8869	10.03014318	1857	$ 178,272.00	4491	$ 1,383,228.00	$ 1,561,500.00
	6059	-23.234	64.8942	10.09038394	2292	$ 220,032.00	6799	$ 2,094,092.00	$ 2,314,124.00
	6063	-22.7246	64.9074	10.36663549	1217	$ 116,832.00	4220	$ 1,299,760.00	$ 1,416,592.00
	6342	-22.7993	64.9869	10.31331434	73	$ 7,008.00	1674	$ 515,592.00	$ 522,600.00

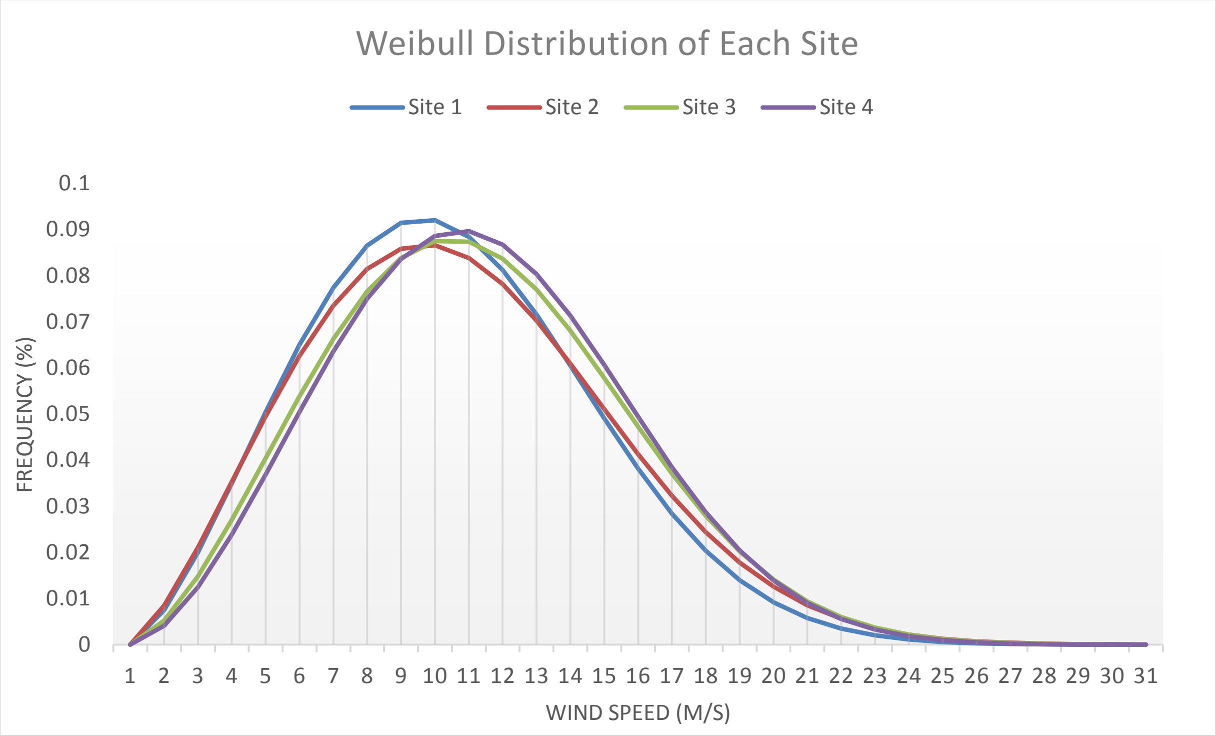
					(meters)		(meters)		
9-10	ID	long	Lat	AWS	Dist. to road	Cost of road	Dist. to transmission	Cost of Transmission	Total Infrastructure Cost
	5683	-23.7241	64.7713	9.048823423	1353	$ 129,888.00	11712	$ 3,607,296.00	$ 3,737,184.00
	5781	-23.1582	64.815	9.254627121	116	$ 11,136.00	2295	$ 706,860.00	$ 717,996.00
	5785	-22.6503	64.8278	9.909540166	1035	$ 99,360.00	1221	$ 376,068.00	$ 475,428.00
	5874	-23.0987	64.8437	9.709557473	3232	$ 310,272.00	867	$ 267,036.00	$ 577,308.00
	5875	-22.9716	64.847	9.470599035	1022	$ 98,112.00	792	$ 243,936.00	$ 342,048.00
	5962	-23.8017	64.8502	9.566215389	780	$ 74,880.00	6665	$ 2,052,820.00	$ 2,127,700.00
	5963	-23.6747	64.8542	9.082083749	2611	$ 250,656.00	2848	$ 877,184.00	$ 1,127,840.00
	5964	-23.5477	64.8581	9.290769094	759	$ 72,864.00	422	$ 129,976.00	$ 202,840.00
	5965	-23.4206	64.8618	9.73546312	2127	$ 204,192.00	2157	$ 664,356.00	$ 868,548.00
	5966	-23.2935	64.8655	9.690423717	2938	$ 282,048.00	1820	$ 560,560.00	$ 842,608.00
	5967	-23.1663	64.869	9.354123208	3328	$ 319,488.00	3172	$ 976,976.00	$ 1,296,464.00
	5968	-23.0391	64.8724	9.146488616	1662	$ 159,552.00	3839	$ 1,182,412.00	$ 1,341,964.00
	5970	-22.7846	64.8788	9.816708429	210	$ 20,160.00	227	$ 69,916.00	$ 90,076.00
	6058	-23.3613	64.8907	9.350383698	4676	$ 448,896.00	4363	$ 1,343,804.00	$ 1,792,700.00
	6060	-23.1067	64.8977	9.401888321	1401	$ 134,496.00	1266	$ 389,928.00	$ 524,424.00
	6062	-22.852	64.9043	9.526396087	38	$ 3,648.00	79	$ 24,332.00	$ 27,980.00
	6064	-22.5971	64.9104	9.584726447	5987	$ 574,752.00	8312	$ 2,560,096.00	$ 3,134,848.00
	6154	-23.047	64.9264	9.179591032	1864	$ 178,944.00	1823	$ 561,484.00	$ 740,428.00
	6155	-22.9195	64.9297	9.460364491	989	$ 94,944.00	1029	$ 316,932.00	$ 411,876.00
	6157	-22.6644	64.9359	9.625715297	5151	$ 494,496.00	8736	$ 2,690,688.00	$ 3,185,184.00
	6243	-23.4974	64.9409	9.46195912	34	$ 3,264.00	8924	$ 2,748,592.00	$ 2,751,856.00
	6248	-22.8595	64.9583	9.793443029	191	$ 18,336.00	974	$ 299,992.00	$ 318,328.00
	6249	-22.7318	64.9614	9.927792844	3318	$ 318,528.00	5233	$ 1,611,764.00	$ 1,930,292.00

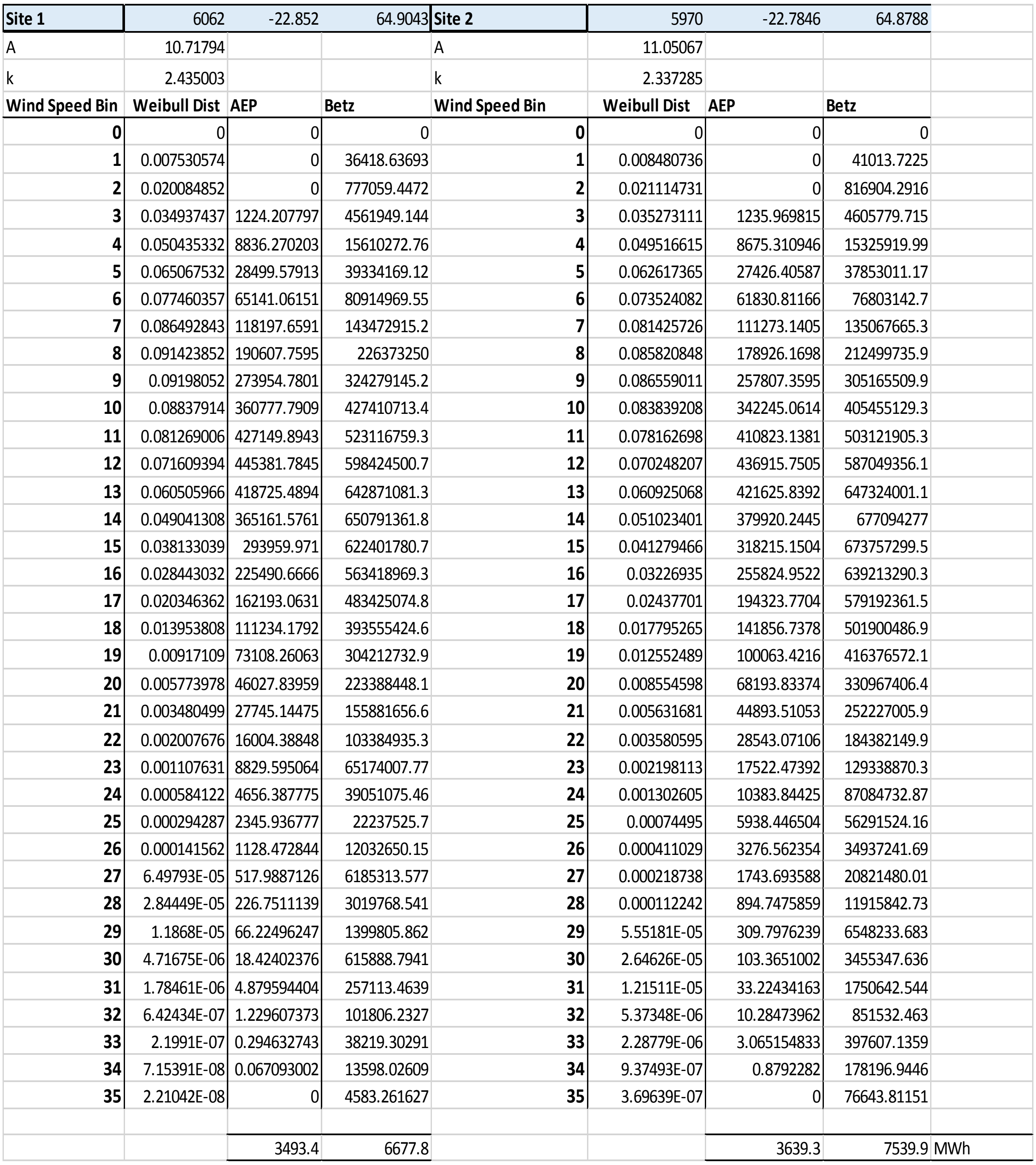
					(meters)		(meters)		
8-9	ID	long	Lat	AWS	Dist. to road	Cost of road	Dist. to transmission	Cost of Transmission	Total Infrastructure Cost
	5599	-22.6433	64.7738	8.145406207	2541	$ 243,936.00	7298	$ 2,247,784.00	$ 2,491,720.00
	5692	-22.5834	64.8023	8.548788123	1100	$ 105,600.00	3019	$ 929,852.00	$ 1,035,452.00
	5777	-23.6655	64.8002	8.813692147	1358	$ 130,368.00	7607	$ 2,342,956.00	$ 2,473,324.00
	5782	-23.0313	64.8184	8.504838729	1178	$ 113,088.00	2179	$ 671,132.00	$ 784,220.00
	5783	-22.9043	64.8216	8.443131276	1340	$ 128,640.00	2061	$ 634,788.00	$ 763,428.00
	5870	-23.6066	64.8292	8.476226562	1977	$ 189,792.00	3835	$ 1,181,180.00	$ 1,370,972.00
	5876	-22.8445	64.8502	8.609913832	1110	$ 106,560.00	1104	$ 340,032.00	$ 446,592.00
	5969	-22.9119	64.8757	8.710155467	1768	$ 169,728.00	3980	$ 1,225,840.00	$ 1,395,568.00
	6055	-23.7429	64.8792	8.888347409	1545	$ 148,320.00	2965	$ 913,220.00	$ 1,061,540.00
	6061	-22.9794	64.901	8.856104782	4099	$ 393,504.00	5181	$ 1,595,748.00	$ 1,989,252.00
	6153	-23.1745	64.923	8.988808302	1558	$ 149,568.00	1421	$ 437,668.00	$ 587,236.00
	6435	-22.739	65.0155	8.442780722	488	$ 46,848.00	981	$ 302,148.00	$ 348,996.00

7-8	ID	long	Lat	AWS	Dist. to road	Cost of road	Dist. to transmission	Cost of Transmission	Total Infrastructure Cost
	6339	-23.1827	64.977	7.959570335	1545	$ 148,320.00	3647	$ 1,123,276.00	$ 1,271,596.00

Appendix B: Weibull distributions & AEP calculation data

Illustrated in appendix B are figures illustrating graphically the Weibull distributions for each of the four sites considered within Snæfellsness, calculations for each sites' theoretical maximum energy potential and energy yield given the implementation of an Enercon E44.





Site 1	6062	-22.852	64.9043	Site 2	5970	-22.7846	64.8788	
A	10.71794			A	11.05067			
k	2.435003			k	2.337285			
Wind Speed Bin	**Weibull Dist**	**AEP**	**Betz**	**Wind Speed Bin**	**Weibull Dist**	**AEP**	**Betz**	
0	0	0	0	**0**	0	0	0	
1	0.007530574	0	36418.63693	**1**	0.008480736	0	41013.7225	
2	0.020084852	0	777059.4472	**2**	0.021114731	0	816904.2916	
3	0.034937437	1224.207797	4561949.144	**3**	0.035273111	1235.969815	4605779.715	
4	0.050435332	8836.270203	15610272.76	**4**	0.049516615	8675.310946	15325919.99	
5	0.065067532	28499.57913	39334169.12	**5**	0.062617365	27426.40587	37853011.17	
6	0.077460357	65141.06151	80914969.55	**6**	0.073524082	61830.81166	76803142.7	
7	0.086492843	118197.6591	143472915.2	**7**	0.081425726	111273.1405	135067665.3	
8	0.091423852	190607.7595	226373250	**8**	0.085820848	178926.1698	212499735.9	
9	0.09198052	273954.7801	324279145.2	**9**	0.086559011	257807.3595	305165509.9	
10	0.08837914	360777.7909	427410713.4	**10**	0.083839208	342245.0614	405455129.3	
11	0.081269006	427149.8943	523116759.3	**11**	0.078162698	410823.1381	503121905.3	
12	0.071609394	445381.7845	598424500.7	**12**	0.070248207	436915.7505	587049356.1	
13	0.060505966	418725.4894	642871081.3	**13**	0.060925068	421625.8392	647324001.1	
14	0.049041308	365161.5761	650791361.8	**14**	0.051023401	379920.2445	677094277	
15	0.038133039	293959.971	622401780.7	**15**	0.041279466	318215.1504	673757299.5	
16	0.028443032	225490.6666	563418969.3	**16**	0.03226935	255824.9522	639213290.3	
17	0.020346362	162193.0631	483425074.8	**17**	0.02437701	194323.7704	579192361.5	
18	0.013953808	111234.1792	393555424.6	**18**	0.017795265	141856.7378	501900486.9	
19	0.00917109	73108.26063	304212732.9	**19**	0.012552489	100063.4216	416376572.1	
20	0.005773978	46027.83959	223388448.1	**20**	0.008554598	68193.83374	330967406.4	
21	0.003480499	27745.14475	155881656.6	**21**	0.005631681	44893.51053	252227005.9	
22	0.002007676	16004.38848	103384935.3	**22**	0.003580595	28543.07106	184382149.9	
23	0.001107631	8829.595064	65174007.77	**23**	0.002198113	17522.47392	129338870.3	
24	0.000584122	4656.387775	39051075.46	**24**	0.001302605	10383.84425	87084732.87	
25	0.000294287	2345.936777	22237525.7	**25**	0.00074495	5938.446504	56291524.16	
26	0.000141562	1128.472844	12032650.15	**26**	0.000411029	3276.562354	34937241.69	
27	6.49793E-05	517.9887126	6185313.577	**27**	0.000218738	1743.693588	20821480.01	
28	2.84449E-05	226.7511139	3019768.541	**28**	0.000112242	894.7475859	11915842.73	
29	1.1868E-05	66.22496247	1399805.862	**29**	5.55181E-05	309.7976239	6548233.683	
30	4.71675E-06	18.42402376	615888.7941	**30**	2.64626E-05	103.3651002	3455347.636	
31	1.78461E-06	4.879594404	257113.4639	**31**	1.21511E-05	33.22434163	1750642.544	
32	6.42434E-07	1.229607373	101806.2327	**32**	5.37348E-06	10.28473962	851532.463	
33	2.1991E-07	0.294632743	38219.30291	**33**	2.28779E-06	3.065154833	397607.1359	
34	7.15391E-08	0.067093002	13598.02609	**34**	9.37493E-07	0.8792282	178196.9446	
35	2.21042E-08	0	4583.261627	**35**	3.69639E-07	0	76643.81151	
		3493.4	6677.8			3639.3	7539.9	MWh

Site 3	6342	-22.7993	64.9869	**Site 4**	6156	-22.7919	64.9329	
A	11.56923			A	11.7071			
k	2.522302			k	2.626276			
Wind Speed Bin	**Weibull Dist**	**AEP**	**Betz**	**Wind Spee**	**Weibull Dist**	**AEP**	**Betz**	
0	0	0	0	**0**	0	0	0	
1	0.005235026	0	25317.1322	**1**	0.004098441	0	19820.49	
2	0.014889891	0	576072.5	**2**	0.012550594	0	485567.8	
3	0.027021858	946.846	3528373.9	**3**	0.023827161	834.9037	3111227	
4	0.040413604	7080.46	12508441	**4**	0.036858364	6457.585	11408056	
5	0.05389232	23604.8	32578608.2	**5**	0.050526379	22130.55	30543853	
6	0.066298815	55754.7	69255639.8	**6**	0.063640111	53518.79	66478362	
7	0.076563804	104629	127002787	**7**	0.075014865	102512.3	1.24E+08	
8	0.083816649	174748	207537168	**8**	0.083598311	174292.4	2.07E+08	
9	0.087489009	260577	308444234	**9**	0.088606507	263905.6	3.12E+08	
10	0.087385507	356722	422605401	**10**	0.0896363	365909.7	4.33E+08	
11	0.083702373	439940	538779991	**11**	0.086725039	455826.8	5.58E+08	
12	0.076986923	478828	643363371	**12**	0.080339652	499680.5	6.71E+08	
13	0.068044326	470894	722965556	**13**	0.071293595	493380.2	7.57E+08	
14	0.057810117	430454	767155826	**14**	0.060607961	451286.9	8.04E+08	
15	0.04721412	363964	770621835	**15**	0.049346872	380405.2	8.05E+08	
16	0.037061907	293819	734147522	**16**	0.038462587	304923.7	7.62E+08	
17	0.027953708	222836	664173931	**17**	0.028681106	228634.3	6.81E+08	
18	0.02025014	161426	571138149	**18**	0.020446126	162988.3	5.77E+08	
19	0.0140825	112260	467128330	**19**	0.013922769	110986.7	4.62E+08	
20	0.009396256	74903.2	363530171	**20**	0.009048018	72127.18	3.5E+08	
21	0.006011652	47922.5	269244827	**21**	0.005606443	44692.32	2.51E+08	
22	0.003685724	29381.1	189795736	**22**	0.00330906	26378.5	1.7E+08	
23	0.002163997	17250.5	127331490	**23**	0.001858535	14815.5	1.09E+08	
24	0.001215913	9692.77	81289027.8	**24**	0.0009923	7910.221	66339547	
25	0.000653374	5208.43	49371607.9	**25**	0.000503121	4010.681	38017916	
26	0.00033553	2674.71	28519803.5	**26**	0.000241995	1929.086	20569411	
27	0.000164553	1311.75	15663596.9	**27**	0.000110303	879.2925	10499649	
28	7.7015E-05	613.933	8176079.22	**28**	4.75949E-05	379.4073	5052774	
29	3.43744E-05	191.813	4054381.21	**29**	1.94207E-05	108.3699	2290628	
30	1.46209E-05	57.1106	1909124.66	**30**	7.4859E-06	29.24057	977470.3	
31	5.92225E-06	16.193	853233.262	**31**	2.72295E-06	7.445261	392302.4	
32	2.28278E-06	4.3692	361750.971	**32**	9.33678E-07	1.787041	147959.4	
33	8.36758E-07	1.12108	145424.417	**33**	3.0148E-07	0.40392	52395.82	
34	2.91467E-07	0.27335	55401.5373	**34**	9.15744E-08	0.085883	17406.3	
35	9.64117E-08	0	19990.7589	**35**	2.61391E-08	0	5419.882	
		3940.3	8203.9			4038.4	8293.3	MWh

	ID	Long	Lat	NNN	NNE	ENE	EEE	ESE	SSE	SSS	SSW	WSW	WWW	WNW	NNW	
Site 1	6062	-22.852	64.9043													
			A	9.9	12.16	14.7	10.31	9.74	10.51	11.37	11.41	10.58	7.35	7.46	6.42	
			k	2.319	2.53	3.545	2.632	2.627	2.011	2.317	2.681	2.174	2.036	2.05	1.787	
			%	0.118	0.098	0.131	0.031	0.09	0.193	0.112	0.056	0.034	0.012	0.037	0.089	
				1.1682	1.19168	1.9257	0.31961	0.8766	2.02843	1.27344	0.63896	0.35972	0.0882	0.27602	0.57138	10.71794
				0.273642	0.24794	0.464395	0.081592	0.23643	0.388123	0.259504	0.150136	0.073916	0.024432	0.07585	0.159043	2.435003
	ID	Long	Lat	NNN	NNE	ENE	EEE	ESE	SSE	SSS	SSW	WSW	WWW	WNW	NNW	
Site 2	5970	-22.7846	64.8788													
			A	10.26	13.74	15.44	8.95	9.1	10.84	10.66	10.63	9.44	6.79	6.09	7.46	
			k	2.013	2.376	3.311	2.302	2.314	2.127	2.206	2.093	1.846	2.02	1.612	2.117	
			%	0.113	0.148	0.147	0.076	0.107	0.104	0.092	0.06	0.045	0.02	0.021	0.067	
				1.15938	2.03352	2.26968	0.6802	0.9737	1.12736	0.98072	0.6378	0.4248	0.1358	0.12789	0.49982	11.05067
				0.227469	0.351648	0.486717	0.174952	0.247598	0.221208	0.202952	0.12558	0.08307	0.0404	0.033852	0.141839	2.337285
	ID	Long	Lat	NNN	NNE	ENE	EEE	ESE	SSE	SSS	SSW	WSW	WWW	WNW	NNW	
Site 3	6342	-22.7993	64.9869													
			A	9.29	11.18	9.8	8.78	10.14	15.21	17.76	13.38	10.24	8.42	4.87	6.23	
			k	2.091	2.545	2.432	3.419	3.358	2.103	2.394	2.395	1.765	1.643	1.272	1.426	
			%	0.027	0.092	0.092	0.134	0.143	0.076	0.146	0.126	0.07	0.037	0.037	0.019	
				0.25083	1.02856	0.9016	1.17652	1.45002	1.15596	2.59296	1.68588	0.7168	0.31154	0.18019	0.11837	11.56923
				0.056457	0.23414	0.223744	0.458146	0.480194	0.159828	0.349524	0.30177	0.12355	0.060791	0.047064	0.027094	2.522302
	ID	Long	Lat	NNN	NNE	ENE	EEE	ESE	SSE	SSS	SSW	WSW	WWW	WNW	NNW	
Site 4	6156	-22.7919	64.9329													
			A	9.34	11.53	12.84	12.43	11.01	13.85	12.29	11.36	10.04	7.86	6.65	5.97	
			k	1.949	2.783	3.48	3.747	2.341	2.543	2.202	2.374	1.866	2.016	1.787	1.529	
			%	0.057	0.122	0.147	0.1	0.036	0.14	0.191	0.094	0.034	0.027	0.025	0.028	
				0.53238	1.40666	1.88748	1.243	0.39636	1.939	2.34739	1.06784	0.34136	0.21222	0.16625	0.16716	11.7071
				0.111093	0.339526	0.51156	0.3747	0.084276	0.35602	0.420582	0.223156	0.063444	0.054432	0.044675	0.042812	2.626276

Appendix C: Cost estimations and data

Estimations calculated given the following assumptions:

- 5% discount rate
- $60/MWh utility electricity rate
- 95% turbine utilization (efficiency & availability)
- 50m turbine hub height (exclusion of vertical extrapolation)

		Site 1	Site 2	Site 3	Site 4	
	AEP	3677.2	3830.8	4147.7	4250.9	MWh
	year 0	$ (27,980.00)	$ (90,076.00)	$ (522,600.00)	$ (972,296.00)	
NPV of Revenue	Year 20	$2,904,179.58	$3,025,489.82	$3,275,771.15	$3,357,276.46	

(All monetary terms in 2015 USD)	***Site 1***	***Site 2***	***Site 3***	***Site 4***
Electricity Generation (MWh over 20 years)	73544	76616	82954	85018
20-Yr. Discounted Revenue	$2,904,179.58	$3,025,489.82	$3,275,771.15	$3,357,276.46
Marginal Increase in 20-Yr. Revenue	0	$121,310.23	$250,281.33	$81,505.31
Infrastructure Cost	$ (27,980.00)	$ (90,076.00)	$ (522,600.00)	$ (972,296.00)
Marginal Increase in Infrastructure Cost	0	$ (62,096.00)	$ (432,524.00)	$ (449,696.00)
Marginal Benefit/Cost	$ -	$59,214.23	$ (182,242.67)	$ (368,190.69)