Analysis of the Renewable Energy Assessment Programs RETScreen and System Advisor Model (SAM)

Wind Energy Model Predictions Comparison with Measured Operational Data

Sigurdur Oli Gudmundsson

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Civil Engineering

University of Washington

2013

Committee:
Timothy V. Larson
Joe P. Mahoney

Program Authorized to Offer Degree:
Civil & Environmental Engineering

University of Washington

Abstract

Analysis of the Renewable Energy Assessment Programs RETScreen and System Advisor Model (SAM)

Wind Energy Model Predictions Comparison with Measured Operational Data

Sigurdur Oli Gudmundsson

Chair of the Supervisory Committee:

Professor Joe P. Mahoney

Professor Timothy V. Larson

Department of Civil & Environmental Engineering

In this study, the wind energy modules of the renewable energy assessment programs RETScreen and System Advisor Model (SAM) were examined, and their predictions compared to measured operational data. Both of these programs have been used in teaching *energy infrastructure* at the University of Washington. It is of interest to see how well they perform, since validation and similar research have been limited to date. The programs have integrated and associated web-based weather databases and, therefore, a preliminary assessment can be performed in the absence of onsite wind speed measurements.

Operational data from a wind farm in the United States, which included electricity production and availability for a five-year period, as well as wind speed measurements from an onsite MET (meteorological) tower, were compared to the wind speed and AEP (Annual Energy Production) predictions of the models. Model predictions were made with and without accounting for energy losses. One standard deviation in predicted AEP and wind speed based on variation in the input parameter values was used as a measure of uncertainty. The wind farm is located in a complex topographical area, which increased the complexity of the comparison. The main conclusions, listed for each program, are the following:

RETScreen:

- The weather database associated with RETScreen has too coarse a spatial resolution to be accurate for a given site located in a complex topographical area. Low wind speeds obtained from the database (i.e. 25% - 32% lower than MET data from an onsite weather station), lead to an underestimation of the AEP in the range of [−34%; −45%], assuming no losses and [−47%; −56%], when accounting for losses.
- Using a wind resource map from NREL (National Renewable Energy Laboratory) gives a better estimate of the wind speed at the site, in the range of [−3.4%; +4.5%] difference compared to the MET data. Consequently, the AEP was predicted more accurately in the range of [+25%; −8%], assuming no losses and [+1%; −27%], when accounting for losses.
- For sites in complex terrain, it is recommended that NREL wind resource maps are used rather than the associated weather databases. However, this estimate should be considered to be very rough as the maps are given in increments of 0.5 m/s and the AEP is, therefore, predicted over a large range.

- It is recommended that the shape factor k and shear coefficient α are defined as ranges rather than single values based on how much impact the determination of those has on the predicted AEP.

SAM:

- Two weather files at locations closest to the existing wind farm were selected as representative of the wind farm and the AEP predictions were performed for both. The annual average wind speed was 6.73 ± 0.06 m/s and 7.21 ± 0.22 m/s respectively, compared to 6.93 m/s wind speed at the MET tower.
- For the closest site, the predicted average AEP is 13.3% higher compared to the average wind farm AEP and the range is [+32%; −2%] ignoring losses. When accounting for losses, the difference range is [+7%; −22%] and −8.7% when averages are compared (i.e. the average AEP in SAM has an 8.7% underestimation compared to the wind farm data).
- Based on this case study, the AEP predictions in SAM are quite good (in the range of roughly [+10% to −30%] compared to the wind farm data) and using only one weather file to represent a whole wind farm is appropriate for rough AEP estimation. However, based on only one case in this study, it is not possible to generalize about the accuracy of the program and further studies would need to be conducted.

One important limitation of this analysis is that the operational wind farm data and the SAM predictions do not cover the same period, resulting in uncertainty of the AEP comparison. However, it should also be noted that the predicted AEP from SAM does not vary significantly over the years when data was available. It is recommended that additional research will be conducted to eliminate this uncertainty. It would also be of interest to compare the models to operational data from a site in a flat terrain.

Table of Contents

List of Figures .... **iii**

List of Tables .... **vi**

List of Tables – Appendix .... **ix**

List of Variables and Abbreviations .... **xiii**
Abbreviations xiii
List of Variables xiv

Acknowledgements .... **xviii**

1 Introduction **1**

2 Theoretical Background **5**
2.1 The Power in the Wind 5
2.2 RETScreen 7
2.2.1 The Weather Database 9
2.2.2 Energy Calculation Algorithm 15
2.3 System Advisory Model 21
2.3.1 The Weather Database for the Wind Energy Module 23
2.3.2 Energy Calculation Algorithm 30
2.4 Validation and similar research 36
2.4.1 RETScreen 36
2.4.2 SAM 39
2.5 Summary 40

3 Methodology **44**
3.1 Wind Farm Data 44
3.2 RETScreen 47
3.2.1 Weather Data Determination 47
3.2.2 Shape Coefficient of the Weibull Distribution 48
3.2.3 Wind Shear Coefficient 50
3.3 SAM 55
3.3.1 Weather Data Determination 55
3.3.2 Turbine Layout 57
3.3.3 Wake Loss Calculations 58
3.4 Common Inputs for Both Models 59

3.4.1 Turbine Characteristics ... 59
3.4.2 Wind Farm Losses ... 60
3.4.3 Comparison with Wind Farm Data ... 64
3.5 Summary of Input Data for both Models ... 65
3.6 Limitations ... 66

4 Results ... 68
4.1 Wind Farm Data ... 68
4.1.1 Wind Speed ... 68
4.1.2 Availability ... 69
4.1.3 Energy production ... 69
4.2 RETScreen ... 71
4.2.1 Wind Speed ... 71
4.2.2 Predicted Energy Production ... 76
4.3 SAM ... 85
4.3.1 Wind Speed ... 85
4.3.2 Predicted Energy Production ... 91

5 Discussion ... 105
5.1 RETScreen ... 105
5.1.1 Wind Speed ... 105
5.1.2 Energy Predictions ... 107
5.1.3 Determination of Input Variables ... 110
5.2 SAM ... 112
5.2.1 Wind Speed ... 112
5.2.2 Energy Predictions ... 113
5.2.3 Determination of Input Variables ... 114

6 Summary and Conclusion ... 118

7 Bibliography ... 124

Appendix A – Methodology Additions ... 130

Appendix B – Energy Predictions ... 133
B.1 RETScreen ... 133
B.2 SAM ... 149

List of Figures

Figure 1 - Power curve for Vestas V80 - 1.8 MW Turbine. Edited from (RETScreen, 2013). 6

Figure 2 – Screenshot from RETScreen Plus, showing the integrated data locations in RETScreen for Washington State and part of Oregon, Idaho and Montana States. Source: (RETScreen, 2013d). 11

Figure 3 - Example of the weather file for Ottawa International Airport at Ontario in Canada. Source: (RETScreen Plus, 2013). 12

Figure 4 - The NASA database resolution. 13

Figure 5 – Summary of the weather databases associated with RETScreen. 14

Figure 6 – Three different scenarios of wind speed distribution, v = 5 m/s and k = 1.3, 2 and 3 respectively. 16

Figure 7 – Simplified summary of the energy algorithm in RETScreen. 20

Figure 8 - SAM's Model Structure. *Source:* (NREL, 2013e). 22

Figure 9 - Location of the U.S. Western and Eastern Wind Datasets. The red line roughly demarcates the western and eastern weather data sets. Source: (Super Teacher Worksheet, n.d.). 25

Figure 10 – How the weather file location lookup works for the WWDS. 28

Figure 11 - Selection options for the weather data in SAM. 29

Figure 12 – Simplification of the wind energy algorithm in SAM. 30

Figure 13 - Example of Turbine Layout Map in SAM. *Source:* (System Advisor Model Version 2013.9.20, 2013). 33

Figure 14 – Plan view of turbine one in the wake of turbine two. Source: (AWS Truepower, 2010). 36

Figure 15 – Vegetation similar to the one on the Wind Farm site. 45

Figure 16 – Location of weather files from the NASA database relevant to the wind farm. 48

Figure 17 – Weibull fit of the MET Tower data at the wind farm site using *XLSTAT*. 49

Figure 18 – Observed wind speed frequencies from the MET Tower data and theoretical Weibull distribution using *XLSTAT*. 50

Figure 19 - Shear Coefficients as a function of the hour of the day, for the sites examined in Smith et.al. (2002). 54

Figure 20 – SAM weather file location and the wind farm layout. 56

Figure 21 – The relevant weather files in SAM and the MET location. 56

Figure 22 – The relevant weather files in SAM and the Wind farm center location. 57

Figure 23 – The power curves from RETScreen and SAM for VESTAS V80-1.8MW 1A/2A. 59

Figure 24 – Average monthly and annual wind speeds from the MET Tower for the year 2011 68

Figure 25 – Average monthly availability 2007 – 2011, ± one standard deviation with y-axis from 95 – 100%. 69

Figure 26 – Average monthly production 2007 – 2011 ± one standard deviation. 70

Figure 27 – The difference *d*, between monthly wind speed in RETScreen (C1) and the MET tower data, for shear coefficients of $\alpha = 0.20$ and $\alpha = 0.25$. 73

Figure 28 – The difference *d*, between the annual average wind speed in RETScreen (C1) and the MET tower data in 2011, for shear coefficient of 0.20 - 0.25. 73

Figure 29 – The difference between monthly wind speed in RETScreen (C2) and the MET tower data in 2011 for shear coefficient of 0.20 and 0.25. 75

Figure 30 – The difference between the annual average wind speed in RETScreen (C2) and the MET tower data in 2011, for shear coefficient of 0.20 - 0.25. 75

Figure 31 – AEP [left axis] for k=1.7 and S4 and *d* the difference from wind farm AEP [right axis] as a function of wind shear coefficient from 0.20 – 0.25. 78

Figure 32 – AEP as a function of the shape factor k with α= 0.25 for loss scenario S4 i.e. assuming all losses. 79

Figure 33 – The difference *d* between the AEP predictions in RETScreen and the wind farm operational data as a function of the shape factor k with α = 0.25 for loss scenario S4 i.e. assuming all losses. The red lines indicate the range where k is commonly found. 79

Figure 34 – AEP [left axis] and difference *d* from wind farm AEP [right axis] as a function of wind shear coefficient from 0.20 – 0.25 for *S4*. 82

Figure 35 – AEP as a function of the shape factor k with α= 0.25 for loss scenario *S4*. 82

Figure 36 – Difference *d* between the AEP predictions and the wind farm operational data as a function of the shape factor k with α = 0.25 for S4. The red lines indicate the range where k is commonly found. 83

Figure 37 – Average wind speeds in SAM at location L1 over the three year period ±σ, compared to the MET tower wind speeds in 2011. 85

Figure 38 – Difference *d* between the SAM and MET wind speeds. 86

Figure 39 – Average wind speed in SAM at location L4 over the three year period ±σ, compared to the MET tower wind speed in 2011. 88

Figure 40 – Difference *d* between the SAM and MET average wind speeds. 88

Figure 41 – Average wind speed in SAM for 2004-2006 at L1 compared to the L4. 90

Figure 42 – Difference *d* between the average wind speeds at location L4 and L1. 90

Figure 43 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S1 ignoring losses. 93

Figure 44 – Difference between the average MEP for SAM and the operational data from the wind farm for S1, i.e. assuming no losses. 94

Figure 45 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S4 i.e. assuming all losses [Wakes, PA and 10% additional]. 94

Figure 46 – The difference *d* between the average MEP for SAM and the operational data from the wind farm for S4, i.e. assuming all losses [Wakes, PA and 10% additional]. 95

Figure 47 – AEP from SAM for all losses scenarios for 2004-2006 at location 1 compared with AEP from the wind farm. 96

Figure 48 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S1, i.e. assuming no losses. 100

Figure 49 – Difference *d* between the average MEP for SAM and the operational data from the wind farm for S1, i.e. assuming no losses. 100

Figure 50 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S4 i.e. assuming all losses [Wakes, PA and 10% additional]. 101

Figure 51 – Difference between the average MEP for SAM and the operational data from the wind farm for S4, i.e. assuming all losses [Wakes, PA and 10% additional]. 101

Figure 52 – AEP from SAM for all losses scenarios for 2004-2006 at location 4 compared with AEP from the wind farm. 102

List of Tables

Table 1 – Comparison of the AEP predictions in RETScreen and HOMER. Source: (RETScreen, 2005) 37

Table 2 – Comparison of the AEP predictions in RETScreen and HOMER. Source: (RETScreen, 2005). 37

Table 3 – Comparison of RETscreen predictions against monitored data for Kotzebue, AK. Source: (RETScreen, 2005). 38

Table 4 - Summary of the key information about RETScreen and SAM. 41

Table 5 - Summary of the weather data used in RETScreen. 48

Table 6 - List of shear coefficients for similar topographical and vegetation conditions as at the wind farm site, from several different sources. 51

Table 7 - List of shear coefficients for several sites in the US. [1] (Firtin, Guler, & Akdag, 2011) and [2] (Smith, Randall, Malcolm, Kelley, & Smith, 2002). 52

Table 8 - Shear Coefficients for several sites in the US. (Gipe, 2004). 53

Table 9 - Shear coefficients based on wind data from SAM for location L1. 54

Table 10 - Shear coefficients based on wind data from SAM for location L4. 54

Table 11 – Summary of weather data used in SAM. 57

Table 12 – Typical values for several loss categories based on three different sources. 63

Table 13 – The Four Loss Scenarios of the study, S1 – S4. 64

Table 14 - Summary of input data for RETScreen and SAM. 66

Table 15 – Monthly production 2007 – 2011 for the wind farm as well as, monthly average, standard deviation and coefficient of variation. 70

Table 16 - Wind Speed [m/s] as a function of the shear coefficient at 67 m hub height and database values at 10 m measurement height for *C1*. 72

Table 17 - Wind Speed [m/s] as a function of the shear coefficient at 67 m hub height and database values at 10 m measurement height for C2. 74

Table 18 - Comparison of the weather cells in RETScreen, C1 and C2 and difference from the MET tower data. 76

Table 19 –RET Screen's AEP predictions for k=1.7 and k=2.0. Weather file C1 and turbine type 1A used. 77

Table 20 – The difference *d* between the RETScreen predictions and the wind farm data for C1 and 1A for k=1.7 and k=2.0. 77

Table 21 – The range of the difference *d* between RETScreen's predictions and wind farm data based on ±σ for the wind farm data. This is for k = 1.7 and 1A turbine in weather cell C1. 77

Table 22 - Percentage points difference between turbine type 1A and 2A for all loss scenarios. 80

Table 23 –RET Screen's AEP predictions for k=1.7 and k=2.0. Weather file *C2* and turbine type 1A used. 81

Table 24 – The difference *d* between the RETScreen predictions and the weather file C2 using 1A for k=1.7 and k=2.0. 81

Table 25 – The range of the difference *d* between RETScreen's predictions and wind farm data based on ±σ for the wind farm data. This is for k = 1.7 and 1A turbine in weather cell C2. 81

Table 26 - Percentage points difference between turbine type 1A and 2A for all loss scenarios. 83

Table 27 - Comparison of the AEP predictions for the two different weather cells, C1 and C2. 84

Table 28 - Comparison of the difference *d* of RETScreen predictions and wind farm data for the two weather files, C1 and C2 and k=1.7. 84

Table 29 – Monthly wind speeds from SAM at L1 for 2004, 2005, 2006 as well the three year average, standard deviation and coefficient of variation. 87

Table 30 – Difference *d* between SAM and the MET tower wind speeds. 87

Table 31 – Monthly wind speeds from SAM at L4 for 2004, 2005, 2006 as well the three year average, standard deviation and coefficient of variation. 89

Table 32 – Deviation in SAM from the MET tower data, average compared to average........ 89

Table 33 – Comparison of the wind speeds at L1 and L4. 90

Table 34 - Summary of results from SAM for L1, loss scenario S1 i.e. assuming no losses. 91

Table 35 – AEP predictions and wake losses of individual years as well as for the three years average for location L1. 92

Table 36 – Average MEP and AEP predictions in SAM for 2004-2006 for L1 for all loss scenarios. 92

Table 37 – The difference *d* between the wind farm and the SAM data for the four loss scenarios. 93

Table 38 - Summary of the AEP predictions from SAM for L1 and S1-S4 and comparison with the wind farm data. 96

Table 39 - Summary of results from SAM for L4, loss scenario S1 i.e. assuming no losses. 97

Table 40 – AEP and wake losses of individual years as well as for the three years average for location L4. 98

Table 41 – Average MEP and AEP from SAM for 2004-2006 for L1 for all loss scenarios. 99

Table 42 – The difference *d* between the wind farm and the SAM data for the four losses scenarios, average compared to average. 99

Table 43 - Summary of the AEP predictions from SAM for L1 and S1-S4 and comparison with SAM. 103

Table 44 - Comparison of SAM 2004 – 2006 average for both L1 and L4 and comparison with the wind farm data. 104

Table 45 - Comparison of the wind speeds used in RETScreen and the MET Data. 107

Table 46 - AEP [MWh] for 7.0 – 7.5 m/s wind speed at 80 meters, for α = 0.20, α = 0.25, and k = 1.7; 2.0 for all loss scenarios S1-S4. 108

Table 47 – The difference *d* between the wind farm average AEP compared to RETScreen AEP predictions. 108

Table 48 - The range of *d* for the AEP predictions using NREL's wind resource map. 108

Table 49 - RETScreen's AEP predictions using the MET tower data and the difference from the operational data in 2011. 110

Table 50 – Comparison of the four weather locations in SAM. 115

Table 51 – IDW information. 116

List of Tables – Appendix

Appendix - Table 1 - Wind Shear Exponent for several terrain types. Source: (The Engineering ToolBox, n.d.). 130

Appendix - Table 2 - Wind Shear Exponent for several terrain types. Source: (RETScreen, 2013d). 130

Appendix - Table 3 - Wind Shear Exponent for several terrain types. Source: (Brower, 2012). 131

Appendix - Table 4 – Shear coefficient for different topography and vegetation. Source: (Jain, 2011). 131

Appendix - Table 5 - Shear coefficient for different landscape types. Source: (Banuelos-Ruedas & Camacho, n.d.)........ 132

Appendix - Table 6 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S1, i.e. assuming no losses. Weather CELL1 was used. 133

Appendix - Table 7 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S2, i.e. accounting for availability and wake losses. Weather CELL1 was used. 134

Appendix - Table 8 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S3, i.e. accounting for availability, wake losses and 5% additional losses. Weather CELL1 was used. 135

Appendix - Table 9 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL1 was used. 136

Appendix - Table 10 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S1, i.e. assuming no losses. Weather CELL1 was used. 137

Appendix - Table 11 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S2, i.e. accounting for availability and wake losses. Weather CELL1 was used. 138

Appendix - Table 12 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S3, i.e. accounting for availability, wake losses and 5% additional losses. Weather CELL1 was used. 139

Appendix - Table 13 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL1 was used. 140

Appendix - Table 14 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S1, i.e. assuming no losses. Weather CELL2 was used. 141

Appendix - Table 15 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S2, i.e. accounting for availability and wake losses. Weather CELL2 was used. 142

Appendix - Table 16 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S3, i.e. accounting for availability, wake losses and 5% additional losses.. Weather CELL2 was used. 143

Appendix - Table 17 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S4, i.e. accounting for availability, wake losses and 10% additional losses.. Weather CELL2 was used. 144

Appendix - Table 18 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S1, i.e. assuming no losses. Weather CELL2 was used. 145

Appendix - Table 19 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S2, i.e. accounting for availability and wake losses. Weather CELL2 was used. 146

Appendix - Table 20 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S3, i.e. accounting for availability, wake losses and 5% additional losses.. Weather CELL2 was used. 147

Appendix - Table 21 – AEP as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL2 was used. 148

Appendix - Table 22 : SAM 2004 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 149

Appendix - Table 23 : Deviation for SAM in 2004 – L1. 149

Appendix - Table 24 : SAM 2005 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 150

Appendix - Table 25 : Deviation for SAM in 2005 – L1. 150

Appendix - Table 26 : SAM 2006 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 151

Appendix - Table 27 : Deviation for SAM in 2006 – L1. 151

Appendix - Table 28 : SAM 2004 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 152

Appendix - Table 29 : Deviation for SAM in 2004 – L4. 152

Appendix - Table 30 : SAM 2005 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 153

Appendix - Table 31 : Deviation for SAM in 2005 – L4. 153

Appendix - Table 32 : SAM 2006 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%). 154

Appendix - Table 33 : Deviation for SAM in 2006 – L4. 154

List of Variables and Abbreviations

Below is a summary of technical abbreviations and variables used in this document. Even though all of those are introduced and discussed when they appear in relevant sections, they are summarized here for the ease of the reader. Only technical abbreviations and abbreviations of relevant institutions etc. are listed here while commonly used ones in general text are left out. The list of variables includes the ones used in both text and formulas. The abbreviations and variables are listed alphabetically.

Abbreviations

a.g.l.	Above ground level.
a.s.l.	Above sea level.
AEP	Annual energy production.
CEE	Civil and Environmental Engineering.
CSV	Comma separated values (file format).
DOE	Department of Energy.
DSV	Delimited separated values (file format).
Eq.	Equation.
EWDS	Eastern Wind Data Set.
GEOS-n	Goddard Earth Observing System global assimilation model, n indicates the models version's number.
GHG	Greenhouse gas.
GMAO	Global Model and Assimilation Office.
GWh	Giga(10^9)-watt-hours.
IDW	Inverse distance weighting.

kWh	Kilo(10^3)-watt-hours.
MEP	Monthly energy production.
MET	Meteorological.
MWh	Mega(10^6)-watt-hours.
NREL	National Renewable Energy Laboratory.
RET	Renewable energy technologies.
SAM	System Advisor Model.
SSE	Surface meteorology and Solar Energy.
TI	Turbulence intensity.
UTM	Universal Transverse Mercator.
UW	University of Washington.
WRA	Wind resource assessment.
WRF	Weather research and forecasting.
WWDS	Western Wind Data Set.

List of Variables

$\alpha_{i,j}$	Wind shear coefficient, if calculated between two different heights it is then denoted by the two measurements heights in subscript, with the lower height (i) followed by the higher height (j).
δv	Speed deficit.
$\Gamma(n)$	The gamma function.
$\bar{\lambda}$	Average availability.
$\lambda_1 - \lambda_n$	Operational losses.
μ	Average.

ρ	Air density [kg/m^3].
ρ_0	1.225 kg/m^3 - Air density at sea level (z = 0) and 15°C. [kg/m^3].
σ	Standard deviation.
A	Cross sectional area.
a	Air density adjustment factor.
A_1	Cross sectional area of turbine T_1.
$A_{overlap}$	Overlapping cross sectional area of turbines $T_1$and T_2.
C	Scale factor in the Weibull distribution [m/s].
$C1$	Weather CELL 1 in RETScreen. - The closest weather cell to the wind farm.
$C2$	Weather CELL 2 in RETScreen. - The second closest weather cell to the wind farm.
C_H	Pressure coefficient.
C_L	Loss coefficient.
C_p	Power coefficient.
C_T	Temperature coefficient.
C_t	Trust coefficient.
C_v	Coefficient of variation.
D	Width of wake.
d	The difference between the measured values from the wind farm and the predicted values by SAM and RETScreen.
$\bar{E}$	Average energy production (Monthly or Annual).
E_D	Energy delivered to the grid. - RETScreen/SAM.
$E_{G,S}$	Gross energy production of a single turbine - RETScreen.

$E_{G,T}$	Gross energy production of the whole wind farm – RETScreen.
E_{hourly}	Hourly energy - SAM.
$\overline{E_{RET}}$	Average energy production predictions from RETScreen.
$\overline{E_{SAM}}$	Average energy production predictions from SAM.
E_U	Unadjusted energy (gross energy) – SAM.
$E_{\overline{V_0}}$	The annual energy output of a single turbine for an average wind speed $\overline{v_o}$ - RETScreen.
$\overline{E_{WF}}$	Average energy production for wind farm.
h_{data}	Height of measured data from a database.
h_i	Height i above ground level (a.g.l.).
k	Shape factor in the Weibull distribution.
l	Empirical decay constant used in the Park Model.
$L1$	Weather data location 1 in SAM - The closest one to the MET tower and the second closest to the Wind farm Center.
$L2$	Weather data location 2 in SAM.
$L3$	Weather data location 3 in SAM.
$L4$	Weather data location 4 in SAM - The closest one to the Wind farm Center.
p	Atmospheric pressure [Pa].
P	Power [W].
$p(v)$	Probability to have a wind speed v over a given time period according to the Weibull distribution.
P_x	Turbine power at wind speed x.
p_0	101.325 kPa - Pressure at 15°C and sea level (z=0) [Pa].

$R_{specific}$	The ideal gas coefficient $R_{specific} = 287.058\, J/(Kg \cdot K)$.
$S1$	Loss scenario 1. Gross energy production, all losses neglected.
$S2$	Loss scenario 2. Accounting for wake losses and availability.
$S3$	Loss scenario 3. Same as $S2$ with additional 5% losses.
$S4$	Loss scenario 4. Same as $S2$ with additional 5% losses.
T	Temperature [K].
T_0	273.1 K - Temperature at 15°C and sea level (z=0) [K].
T_1	Turbine 1.
T_2	Turbine 2.
TI	Turbulence intensity.
v, x	Wind speed [m/s].
$\bar{v}, \bar{x}$	Average wind speed over the measured or defined period [m/s].
Z_j	Height above sea level (a.s.l.) and at ground level.

Acknowledgements

Several people have made the work of this study possible and their contribution is highly appreciated. Thanks to: *The Valle Scholarship and Exchange Program* for making my time at the University of Washington possible and given me this once in a lifetime opportunity, special thanks to *Dayna Cole* for all of her support during my time at UW. My advisors, Prof. *Timothy V. Larson* and Prof. *Joe P. Mahoney,* for their great mentoring, and support during the work of this study. *Tom Le* for proofreading the thesis. At last but not least, greatest thanks to *Idunn Elfa Bolladottir,* for her endless patience, support, motivation and help during my time at UW. Especially during the period of this study.

1 Introduction

The installed capacity of wind power has been increasing substantially world-wide and is estimated to be around 318 GW at the end of 2013, compared to roughly 200 GW at the end of 2012 (WWEA, 2013). In the United States, over 13 GW were added to the grid in 2012 which is close to double the wind capacity developed in 2011, and since the year 2000, the cumulative installed wind energy capacity has increased more than 22-fold in the country (U.S. Department of Energy , 2013). This rapid increase over the last decade can be attributed to improvement in technology, such as bigger turbines and increased capacity, reduced cost and government incentives to renewable energy technologies.

The discipline of estimating the strength of wind resources is called Wind Resource Assessment (**WRA**). The first step is usually a preliminary assessment or prospecting where publicly available wind resource maps and data are used, usually resulting in a rough financial assessment to determine the viability of the project. If that is promising, the next step would be to conduct on-site wind measurements where data is collected, usually over one to two years (Jain, 2011). Based on these measurements the wind speed is then estimated at the whole project site using a wind flow models such as *WAsP*. At last, the turbine layout is determined in a practice called micro-modeling. Several programs can be used in this phase and are commercially used in the industry such as; GL Garrad Hassan's *Wind Farmer*, ReSoft's *Wind Farm* EMD International's *WindPro*, and AWS Truepower's openWind etc. (Brower, 2012).

In this study, two programs, **RETScreen** and the System Advisor Model (**SAM**) which both are freeware, were examined. The programs have integrated weather databases and a preliminary assessment can be performed in the absence of on-site wind measurements. Annual energy production (**AEP**) predictions can therefore, be performed based on user defined input variables. The programs have different spatial coverage. SAM which was created by the National Renewable Energy Laboratory (**NREL**) in 2005 has integrated, and web-based weather data coverage for the United States while RETScreen, which was created over 15 years by CanmetENERGY research center in Vareenes Canada, has a global coverage. As might be expected, the spatial resolution of RETScreen is way coarser than in SAM. While RETScreen was created for pre-feasibility assessments, the main purpose of SAM is to facilitate decision making in the renewable energy. On top of the prediction models in the programs, they also have financial models, i.e. assessment of financial viability can be conducted. The prediction model has however, to be accurate enough to build reliable financial assessment which can be used in decision making. Since RETScreen and SAM are freeware, it is known that these models are limited compared to commercially used models in the industry. Therefore, interest was to quantify the limitations and margin of error that can be expected in the AEP when those are used.

Operational data over a five year period from a wind farm located in the western part of the US was available for comparing to the models, this included operational and availability data for five year period, as well as on-site wind speed measurements. This gives a unique opportunity to compare the predictions of these models to actual measured data. The wind farm is located in a complex topographical area which adds complexity to the comparison. As will be shown in the study, the validation of these models and knowledge about how well they can be used in the decision making or pre-feasibility phase of such projects is relatively limited, which makes this interesting research topic.

The main reason for carrying out this study is that these programs have been used in teaching at the University of Washington in classes on *energy infrastructure*. They are used to establish theoretical knowledge for students new to the renewable energy industry about technologies such as wind and solar power. It is hoped by performing this research that a better knowledge of these programs will be established, and their potentials based on a comparison with real operational data. Also, by digging into the theoretical background behind the programs it is hoped that this study can serve as a reference guide to the wind energy module in the programs and benefit the *CEE-588 Energy Infrastructure and The Environment* class, which is taught at the University of Washington.

The AEP predictions in the programs were compared to the operational data from the wind farm and wind speeds from the databases compared to the on-site measurements. The following three research questions will be answered in the study:

1. How well do RETScreen and SAM predict the annual energy production for a Wind Farm located in a mountainous environment compared with measured operational data?
2. How well do the weather databases associated with RETScreen and SAM compare with measured data for a specific location in a mountainous environment?
3. What are the main input variables that have to be defined when the AEP predictions are calculated, and what must be considered when those are chosen?

Therefore, the main purpose of the study is to: *Quantify the accuracy of the programs and the level of uncertainty that can be expected when those are used based on a comparison with real operational data, and lastly create a reference guide for the CEE-588 class at UW*. This document is organized as follows:

Chapter 2 – Theoretical Background: The theoretical background of the study is established. Comprehensive discussion is about the weather databases associated with the models and the algorithm that it uses in the energy calculations is listed as well as the validation efforts of the programs to date.

Chapter 3 - Methodology: Describes comprehensively the methodology that was used in this research, how the weather data, user defined values, and input data for AEP calculations were determined and which assumptions were made.

Chapter 4 – Results: The results of the research are listed most in form of graphs and tables with numerical information being minimal, but listed as necessary. Comprehensive numerical background data can be found in **Appendix**.

Chapter 5 - Discussion: The results from **Chapter 4** are analyzed and discussed.

Chapter 6 – Summary and Conclusion: This chapter is a summary of the study and main conclusions from the study are established, and recommendations for future research are made.

Appendix A-E: This report has several appendixes as a lot of numerical data was created during the study. The data is referenced in relevant sections of the report as needed. This is a supplement to inform the reader better if needed without having an overwhelming amount of numerical data in the body of the report.

2 Theoretical Background

This chapter establishes the theoretical background of the study. The first section is a brief discussion about the power in the wind and how it is defined for wind turbines. Then both RETScreen and SAM are discussed in depth, starting with a brief general discussion of each program, followed by a detailed discussion about the wind energy module. The weather databases associated with the models and the algorithms that are used in the energy calculations are described. In **Section 2.4** the prior validations of the programs are discussed and lastly, **Section 2.5** summarizes the key-features of the programs and compares them as appropriate.

2.1 The Power in the Wind

For an ideal rotor with the cross-sectional area A, the available power P in the wind can be calculated according to:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \qquad \textbf{(Eq. 2-1)}$$

where ρ is the air density and v is the wind speed at a given time. Even though this is the theoretical available power, there is a limitation on how much power a rotor can extract from the wind. This is defined as the power coefficient C_p:

$$C_p = \frac{Max\ Power\ Extracted}{Power\ Availible}. \qquad \textbf{(Eq. 2-2)}$$

C_p varies based on turbine type but the maximum value based on both Betz limit and the rotor disk theory is 59.3% (Jain, 2011). Therefore **(Eq. 2-1)**, can be rewritten to account for C_p and becomes:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_P. \qquad \textbf{(Eq. 2-3)}$$

For a wind turbine, the power at a given wind speed is defined by the so-called *power curve*. This is a key performance indicator of a turbine and is provided by its manufacturer. A power curve for a VESTAS V80 – 1.8MW turbine is shown on **Figure 1** below, as an example. The power curve indicates the power of the turbine as wind speeds increase and is defined by three speed related parameters. The *cut-in speed* is when the turbine starts producing energy which is most commonly at 3 to 5 m/s. The second parameter is the *rated speed* at which the rated power of the turbine is reached and is most commonly found to be at 11.5-15 m/s. The *cut-out-speed* is when the turbine is shut down and stops producing energy and is most generally at around 25 m/s (Jain, 2011). For the power curve given on **Figure 1**, these are 4 m/s, 15 m/s and 25 m/s respectively (Vestas, 2005). Therefore, once the turbine has reached its rated capacity of 1,800 kW at 15 m/s, it keeps the same rated power even though the wind speed increases until it reaches the cut-out speed at 25 m/s.

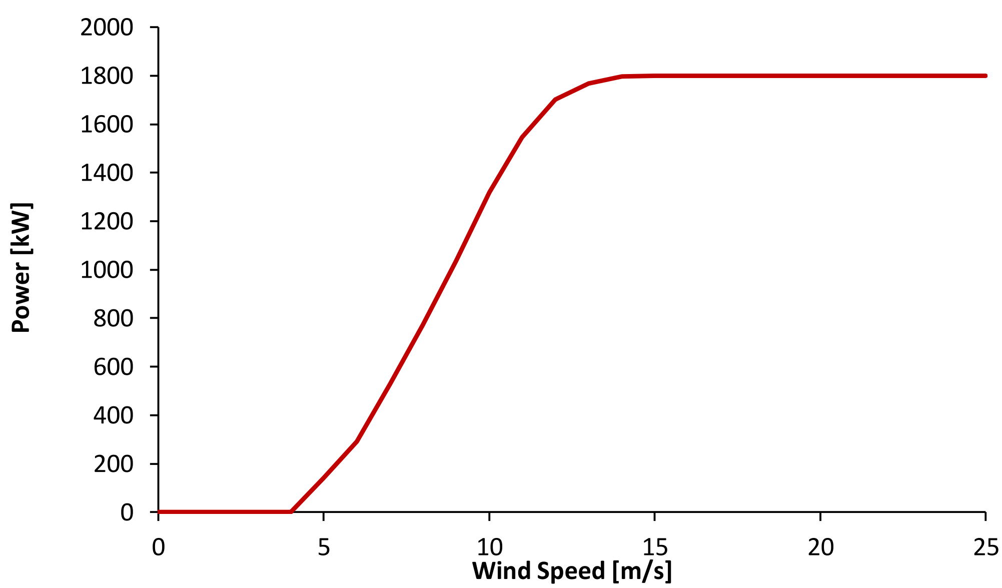


Figure 1 - Power curve for Vestas V80 - 1.8 MW Turbine. Edited from (RETScreen, 2013).

The power curve in **Figure 1** is given at standard air density of 1.225 kg/m^3. Most often the power curves are given over a range of air densities and adjusted to account for meteorological conditions on site. Referring to **(Eq. 2-3)** it is clear that since the wind speed is cubed, it is the most important variable in the energy estimation for a given wind turbine while the relationship between the power and air density is linear. The energy estimation is therefore very dependent on an accurate estimate of the wind speed on site. Even though the estimated energy output is not as sensitive to the air density, it should still be estimated as properly as possible. The air density depends on the pressure, temperature and relative humidity (Jain, 2011). There are several ways to estimate the air density at a given site and the ideal gas law for dry air is commonly used:

$$\rho = \frac{p}{R_{specific} \cdot T} \qquad \textbf{(Eq. 2-4)}$$

where R is the ideal gas coefficient, and T and p are the temperature and pressure respectively. The humidity is often excluded from adjustments to the air density as it has shown to have relatively small impact compared to other parameters.

2.2 RETScreen

RETScreen Software Suite is a decision support tool for renewable energy technologies (RETs). It is developed and maintained by CanmetENERGY research center in Vareenes, Canada in corporation with a large network of experts from the industry, government and academia (RETScreen, 2013d). It includes two programs: *RETScreen Plus* and *RETScreen*. RETScreen Plus is “energy management software tool that allows project owners to easily verify the ongoing energy performance of their facilities” (RETScreen, 2012a) while RETScreen is “an Excel-based clean energy project analysis software tool that helps decision makers quickly and inexpensively determine the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects” (RETScreen, 2013c). The main purpose of the software is to create recognized methodology to use in assessment of clean energy technology implementation at the preliminary feasibility stage in a fast, accurate and inexpensive way (RETScreen, 2005).

RETScreen is able to model renewable energy electricity technologies such as *wind power, solar power, small hydro power, biomass combustion technologies* as well as renewable energy heating and cooling technologies like *biomass heating, solar air heating, solar water heating, passive solar heating, and ground-source heat pump technologies* (RETScreen, 2005). The program is built up as a five step analysis, each located on separate Excel sheet. Prior to the first step, the user identifies site conditions and selects the right climate data. Several weather and product databases are integrated in the software to minimize the user data input and a comprehensive help manual also gives a range of values for many inputs. Each step of the model is shortly explained below:

1. **Energy Model:** The user determines the physical equipment of the project and calculates the energy output based on the climate data selected and various user defined inputs.

2. **Cost Analysis:** Several cost items are evaluated such as implementation, operational and maintenance cost as an input for the financial analysis.

3. **Emission Analysis:** The reduction in greenhouse gas (GHG) emission is calculated compared to selected conventional technology based on integrated emission factors. (Optional).

4. **Financial Analysis:** Financial analysis parameters such as the inflation rate, project life and debt ratio are determined to estimate values such as the rate on investment and payback period.

5. **Risk and Sensitivity Analysis:** Allows the user to evaluate how the uncertainty in the estimates of various key parameters may affect the financial viability of a given project (optional) (RETScreen, 2013d).

Even though the main purpose of the software is pre-feasibility analysis of projects and helping project developers estimate if their project makes financial sense or not (go/no-go decision), the energy model needs to be accurate enough to build reliable financial assessment. Inaccurate energy prediction will lead to a financial assessment that decisions cannot be based on. In this study, the energy model of the software is being examined and therefore further discussion about other models is not provided.

RETScreen was not only designed for project analysis but also provides useful information about renewable energy technologies, and there is an extensive educational data associated with the software, case studies and examples with solutions, online training material as well as textbook with over 450 pages of content (RETScreen, 2005). The book includes content about the theoretical background of the different modules in RETScreen, the algorithms that are used in each module, as well as general information about the different technologies. The software is available in 36 languages free of charge online and has to-date been downloaded over 350,000 times world-wide as well being integrated in curriculum by several universities (RETScreen, 2013f).

2.2.1 The Weather Database

The climate database that is associated with RETScreen and is relevant for the wind energy module is dual: ground monitoring stations data which is integrated in the software and NASA satellite data which can be obtained from the web. Both dataset include the same information which is; latitude, longitude and elevation of the data point and monthly and annual average values for *air temperature, relative humidity, daily solar radiation (horizontal), atmospheric pressure, wind speed, earth temperature and heating/cooling degree-days* (RETScreen, 2013a). The climate parameters that are needed for energy calculations in RETScreen are monthly or annual average values for wind speed, temperature and pressure.

The ground monitoring database which is integrated into the software includes data for around 6,700 sites worldwide (RETscreen, 2013b), most often measured at airport locations with anemometers at 10 m height (RETScreen, 2013d). Additionally some of the NASA data has also been integrated into the RETScreen Software. This is data for populated areas where ground station values were not available. The source of the data is always identified in the weather file. The ground based observations are based on measured data for approximately a 30 year period (1961 – 1990) obtained from over 20 different sources, which e.g. are *The National Climatic Data Center and National Renewable Energy Laboratory* and *The World Meteorological Organization* (RETScreen, 2005). If the user requests data for specific latitude and longitude, it is good to use the RETScreen Plus where all the data points are listed on a map, and the distance from the requested point to the closest data location is shown, which can be very convenient. A screenshot from RETScreen Plus showing a map of the data points available in Washington State, as well as part of Oregon, Montana and Idaho States can be seen on **Figure 2** and an example of a weather file for Ottawa International Airport at Ontario in Canada can be seen on **Figure 3**.

The online weather database is a satellite-derived meteorological data from the NASA Surface meteorology and Solar Energy (**SSE**) dataset. The data has been prepared on the same format as the ground station data and can simply by copied to RETScreen. The SSE dataset was formulated from various other datasets. The monthly average wind speed is based on a 10 year period from July 1983 through June 1993 and is based upon the NASA's Global Model and Assimilation Office (**GMAO**) and the Goddard Earth Observing System global assimilation model version 1 (**GEOS-1**).

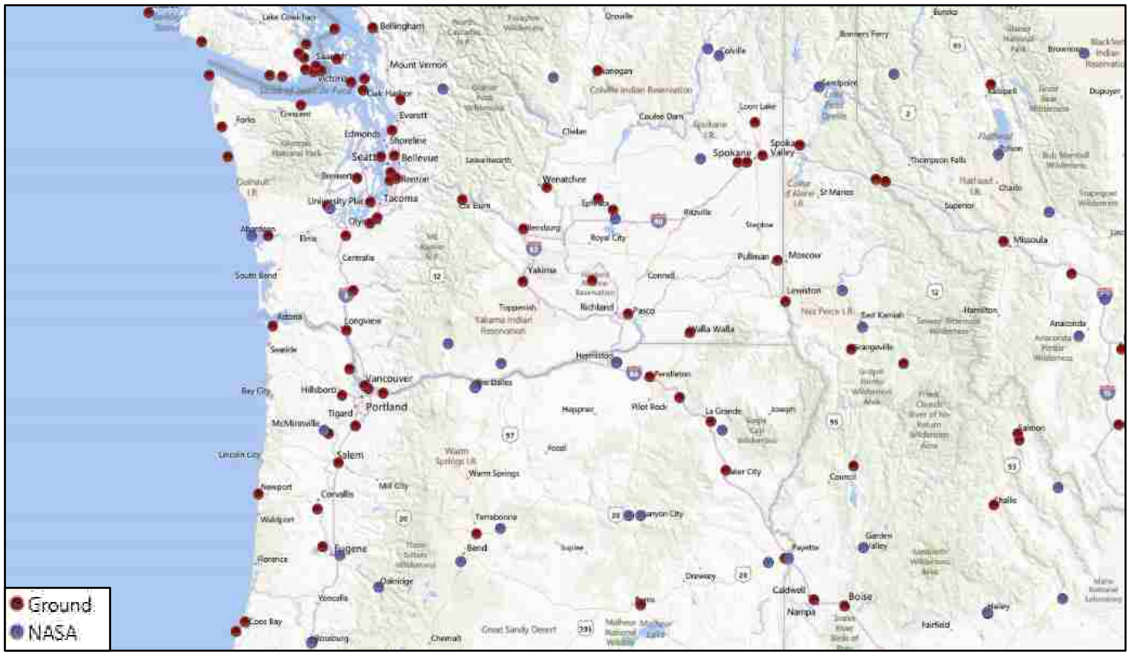
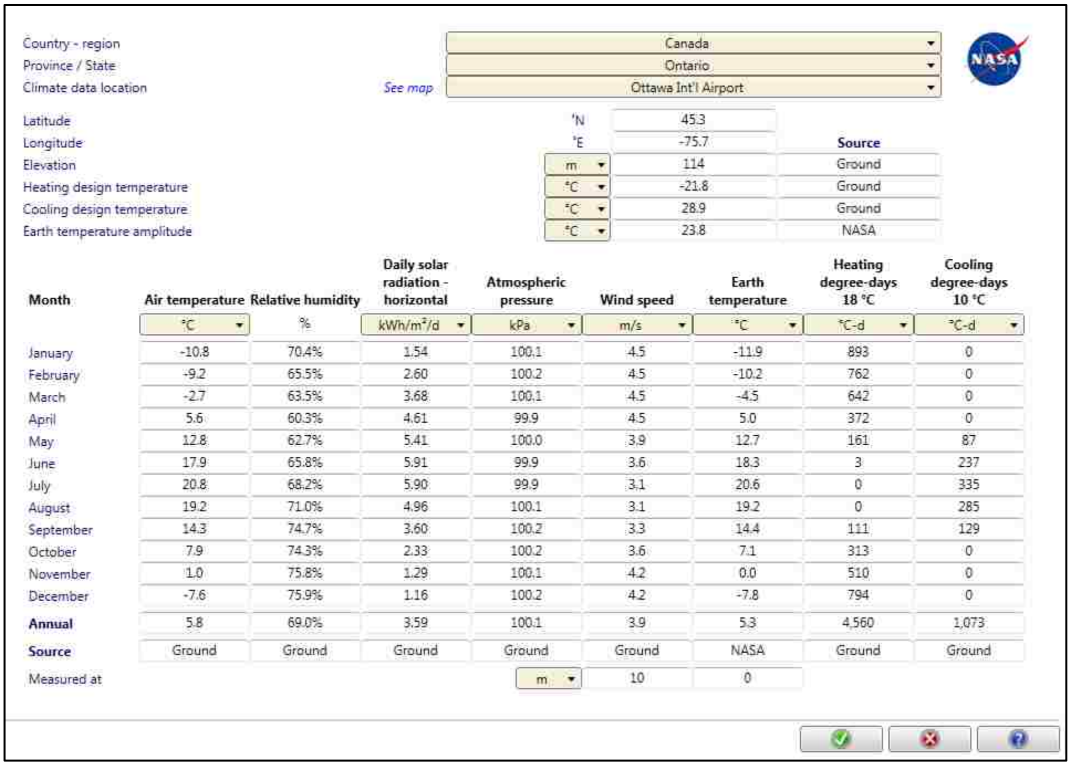


Figure 2 – Screenshot from RETScreen Plus, showing the integrated data locations in RETScreen for Washington State and part of Oregon, Idaho and Montana States. Source: (RETScreen, 2013d).



Country - region: Canada
Province / State: Ontario
Climate data location: Ottawa Int'l Airport (See map)

	Unit		Source
Latitude	°N	45.3	
Longitude	°E	-75.7	
Elevation	m	114	Ground
Heating design temperature	°C	-21.8	Ground
Cooling design temperature	°C	28.9	Ground
Earth temperature amplitude	°C	23.8	NASA

Month	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	-10.8	70.4%	1.54	100.1	4.5	-11.9	893	0
February	-9.2	65.5%	2.60	100.2	4.5	-10.2	762	0
March	-2.7	63.5%	3.68	100.1	4.5	-4.5	642	0
April	5.6	60.3%	4.61	99.9	4.5	5.0	372	0
May	12.8	62.7%	5.41	100.0	3.9	12.7	161	87
June	17.9	65.8%	5.91	99.9	3.6	18.3	3	237
July	20.8	68.2%	5.90	99.9	3.1	20.6	0	335
August	19.2	71.0%	4.96	100.1	3.1	19.2	0	285
September	14.3	74.7%	3.60	100.2	3.3	14.4	111	129
October	7.9	74.3%	2.33	100.2	3.6	7.1	313	0
November	1.0	75.8%	1.29	100.1	4.2	0.0	510	0
December	-7.6	75.9%	1.16	100.2	4.2	-7.8	794	0
Annual	5.8	69.0%	3.59	100.1	3.9	5.3	4,560	1,073
Source	Ground	Ground	Ground	Ground	Ground	NASA	Ground	Ground
Measured at				m	10	0		

Figure 3 - Example of the weather file for Ottawa International Airport at Ontario in Canada. Source: (RETScreen Plus, 2013).

The other meteorological parameters used in RETScreen are calculated or based on parameters in NASA/GMAO GEOS version 4 (**GEOS-4**) and span 22 years of data, from July 1, 1983 through June 30, 2005 (NASA, 2013). The data is available for the whole globe but in a coarse 1° by 1° spatial resolution (RETScreen, 2005). Each degree of latitude is relatively constant or approximately 69 miles (≈ 110 km), however the size of one degree of longitude varies based on the location on the globe, at a latitude of 45° a degree of longitude is approximately 49 miles (≈ 80 km) while at the equator it is approximately 69 miles (≈ 110 km) (National Atlas, 2013). The data is available through a web interface at *NASA* (2008). The user inputs latitude and longitude of requested site and the data relevant to that location will be found and new dataset is given at every whole degree. An example to explain how this works is shown on **Figure 4.** If the user request data for *Location 1* it will get the same data as

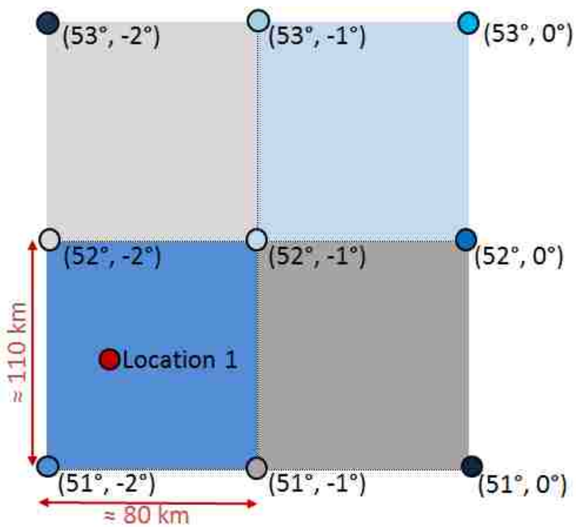


Figure 4 - The NASA database resolution.

if data for (51°,-2°) would have been obtained (blue cell on **Figure 4**). If however data for (52°,-2°) would be requested a new data set would be given that would be representative for that cell (light gray cell on **Figure 4**). Information about where exactly the data is collected in each cell is not available. Since new data file is given on the whole degree, it is thought unlikely that the data was collected there, and more likely that it is collected on the half degree i.e. in the middle of each cell, this however could not be confirmed.

The web based NASA data provides more coverage than the ground site measurements and can be a valuable resource and sometimes the only one for isolated and remote locations (RETScreen, 2005). However because of the coarse resolution of the data it "may be insufficient to catch local peculiarities of the climate; natural or human (urban affect) microclimates are not taken into account, and the SSE data alone is not appropriate where there are large topographic features within a cell of the grid" (RETScreen, 2005, p. INTRO.44). Furthermore it has been found that for wind speed the SSE values are:

> …usually lower than measurements in mountain regions where localized accelerated flow may occur at passes, ridge lines or mountain peaks. One-degree resolution wind data is not an accurate predictor of local condition in regions with significant topography variation or complex water/land boundaries (NASA, 2013, p. 38).

Wind speed is very sensitive to the spatial resolution while e.g. insolation is ideally suited to the 1° by 1° resolution and higher resolution would have negligible effects on the energy analysis (RETScreen, 2005). Further discussion about how the data set was created, its validations and limitations are outside the scope of this report but can however be found in *NASA* (2013) and *Suarez etc.* (2005).

Since RETScreen only requires average monthly or even annual wind speed data it is possible to use data from wind resource maps that have been created e.g. by NREL for the whole US. These maps do not have pressure or temperature data, but that could be obtained from other source. Since the wind resources maps are given in increments of 0.5 m/s this will always be rather rough estimate, as will be further discussed in **Chapter 5**. A summary of the weather databases associated with RETScreen are listed on **Figure 5** below.

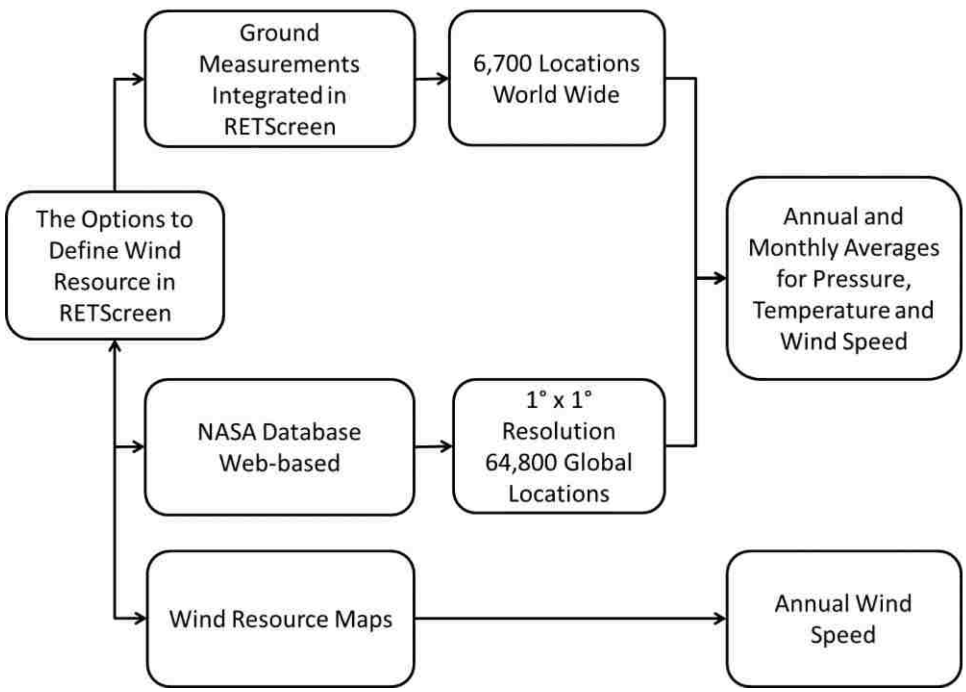


Figure 5 – Summary of the weather databases associated with RETScreen.

2.2.2 Energy Calculation Algorithm

The RETScreen energy model for the wind power module requires wind speed, atmospheric pressure and temperature for the energy output calculations. Only monthly and annual average wind speed data is available in the climate databases associated with RETScreen. Since the wind speed can vary significantly during a given period, using only the average speed in the energy calculations is inaccurate. It is, therefore, necessary to estimate how the wind speed is distributed.

Wind Speed Distribution

The distribution of the wind speed in RETScreen is calculated using a Weibull probability density function. The function is used to express what the probability $p(v)$ is to have wind speed v over a given time period according to:

$$p(v) = \left(\frac{k}{C}\right)\left(\frac{v}{C}\right)^{k-1} \exp\left[-\left(\frac{v}{C}\right)^{k}\right] \quad \textbf{(Eq. 2-5)}$$

where k and C are the shape and scale factor of the distribution. **(Eq. 2-5)** holds while $v \geq 0, k > 1$ and $C > 0$. C is calculated value and a function of both the average wind speed $\bar{v}$ and k, and is defined as (RETScreen, 2005):

$$C = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \quad \textbf{(Eq. 2-6)}$$

Where $\Gamma(n)$ is the gamma function which is an extension of the factorial function ($n!$) but shifted down by 1. If n is a positive integer it is defined as:

$$\Gamma(n) = (n-1)! \quad \textbf{(Eq. 2-7)}$$

while for complex numbers larger than zero it is (Weisstein, n.d.):

$$\Gamma(t) = \int_0^{\infty} x^{t-1}\, e^{-x}\, dx \quad \textbf{(Eq. 2-8)}$$

While C is a calculated value the user has to define the shape factor of the Weibull distribution i.e. the k value. It is important to understand the effect that the determination of this factor can have on the energy output predictions. Higher k means that the height of the curve increases, this results in a narrower distribution that has a smaller tail and the probability at higher speeds decreases. If two wind speed distributions with the same $\bar{v}$ have different k values e.g. $k = 1.3$ and $k = 2$ the first case will likely result in higher estimated energy output than the latter one (Jain, 2011). Common k values are on the range 1 – 3, with 2 often being used as the default value (RETScreen, 2005). **Figure 6** shows three different scenarios of a Weibull distributed wind speed with the average wind speed as 5 m/s and k as 1.3, 2 and 3 respectively. As can be seen when k increases the probability of higher wind speeds decreases and consequently the energy output.

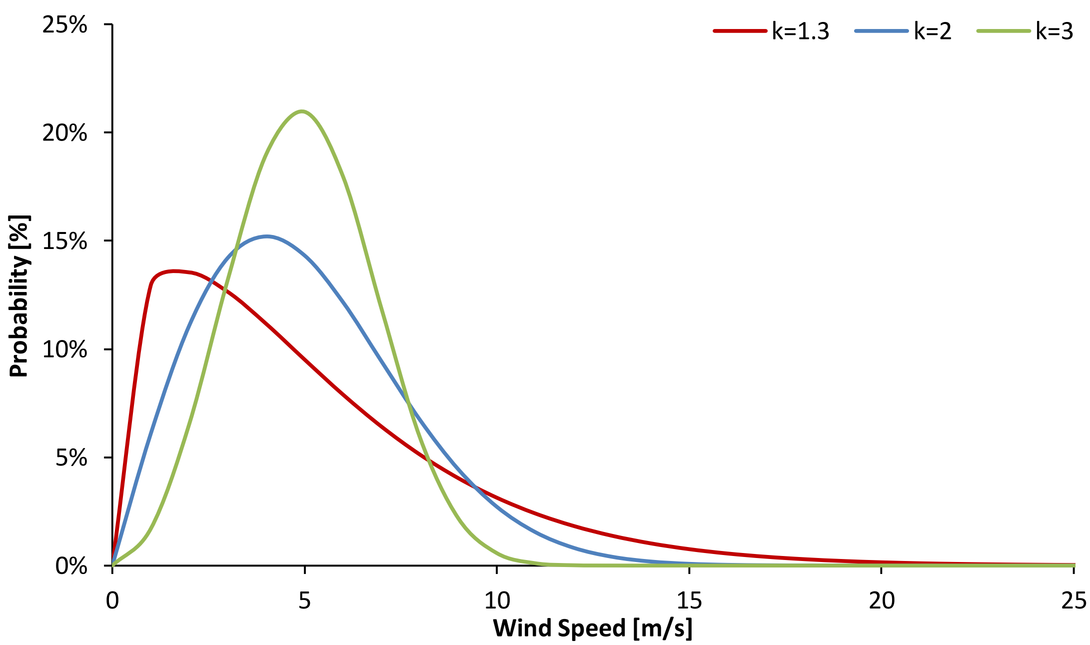


Figure 6 – Three different scenarios of wind speed distribution, $\bar{v}$ = 5 m/s and k = 1.3, 2 and 3 respectively.

The Weibull distribution is widely used in wind energy engineering as it has shown to fit the distribution of mean wind speed for range of sites (RETScreen, 2005 and Jain, 2011). It is important to know that this is not always the case and at best a rough estimate of the wind distribution at a given site, and will never replace on-site measured wind data (Brower, 2012). Therefore, using distribution like Weibull instead of measured data is always a limitation. Further discussion about the selection of appropriate shape factor for a given site is listed in **Section 3.2.3.**

Energy Output Estimation

To estimate the energy output, the physical characteristic of the wind farm must be determined (i.e. what turbines to use and its hub height). Integrated in RETScreen is a comprehensive selection of commercially used wind turbines from several established manufacturers in the wind energy industry, or the user can define its characteristics. Once the turbine is selected, its power and energy curve is generated by the model. In RETScreen, the power curves are defined from 0 m/s to 25 m/s with the increment of 1 m/s. The annual energy output of a single turbine for an average wind speed $\overline{v_0}$ is calculated by:

$$E_{\overline{v_0}} = 8760 \cdot \sum_{x=0}^{25} P_x \cdot p(x) \qquad \textbf{(Eq. 2-9)}$$

where P_x is the turbine power at the wind speed x and $p(x)$ the probability of the wind occurring according to the prior defined Weibull distribution. It is summed over the wind speeds from 0 to 25 m/s and 8,760 is multiplied to the sum to account for the hours in a year, by this the annual energy production for a single turbine has been calculated. The monthly energy is calculated in the same way, by multiplying the sum by the number of hours in each month. An energy curve for annual energy wind speeds ranging from 3 – 15 m/s has also been calculated according to **(Eq. 2-9)** and is integrated into RETScreen for each turbine type (RETScreen, 2005).

Wind speed increases usually significantly with height above the ground. The wind speed data from the weather databases that are associated with RETScreen are measured at a lower height (most often 10 m) than the turbine hub height, to calculate the wind speed at hub height the power law is used:

$$\bar{v} = \overline{v_{data}} \cdot \left(\frac{h}{h_{data}}\right)^{\alpha}. \quad \textbf{(Eq. 2-10)}$$

Where $\bar{v}$ is the average wind speed at hub height h, $\overline{v_{data}}$ is the wind speed at measurement height h_{data}, obtained from the weather database. The last variable α is the shear coefficient which expresses how the wind speed varies with height above the ground (RETScreen, 2005). The value of α is affected by two factors; the topography and land cover (vegetation) at site. Lower value (leading to lower wind speed increment with height) indicates flat terrain with low vegetation while higher values indicate more complex terrain. The coefficient commonly varies from 0.1 – 0.4 and has to be defined by the user (RETScreen, 2013d). In **Section 3.2.3**, the selection process of the shear coefficient as well as typical values based on the terrain and vegetation from case studies for several sites in the US are discussed. Once the wind speed at hub height is calculated the annual energy can be predicted by simply interpolating the energy curve between $\bar{v}$ and $\overline{v_0}$ (RETScreen, 2005).

As the power curves are defined for turbine performance at sea level, at standard atmospheric pressure p_0 of 101.3 kPa and standard atmospheric temperature T_0 of 288.1 K, it is necessary to account for both the pressure and temperature at site. This is defined as the gross energy production for a single turbine $E_{G,S}$ i.e. the estimated energy production before any losses are accounted for, $E_{G,S}$ is defined as:

$$E_{G,S} = E_U \cdot c_H \cdot c_T \qquad \textbf{(Eq. 2-11)}$$

Where c_H is the pressure coefficient and c_T is the temperature coefficient defined as:

$$c_H = \frac{p}{p_0} \qquad \textbf{(Eq. 2-12)}$$

$$c_T = \frac{T_0}{T} \qquad \textbf{(Eq. 2-13)}$$

Where T and p are the annual average ambient temperature and atmospheric pressure both obtained from the weather database. Still the energy output has only been calculated for a single turbine. The user defines the number of wind turbines in the wind farm and to calculate the energy output of the whole farm ($E_{G,T}$) the energy output of a single turbine $E_{G,S}$ is simply multiplied by the number of turbines n in the farm according to:

$$E_{G,T} = E_{G,S} \cdot n. \qquad \textbf{(Eq. 2-14)}$$

At last the energy delivered to the grid E_D is defined as:

$$E_D = E_{G,T} \cdot c_L \qquad \textbf{(Eq. 2-15)}$$

where $c_L$is the loss coefficient defined as:

$$c_L = (1 - \lambda_1) \cdot (1 - \lambda_2) \cdot \ldots \cdot (1 - \lambda_n) \qquad \textbf{(Eq. 2-16)}$$

The gross energy is therefore adjusted in the end by accounting for various operational losses ($\lambda_1 - \lambda_n$) that can be expected in a wind farm. In RETScreen four loss categories are defined; *array losses, airfoil soiling and icing losses, downtime losses and miscellaneous losses* (RETScreen, 2005). Operational losses in wind farms and how they were determined will be further discussed in **Chapter 3**. Simplified summary of the wind energy algorithm in RETScreen can be found on **Figure 7** below.

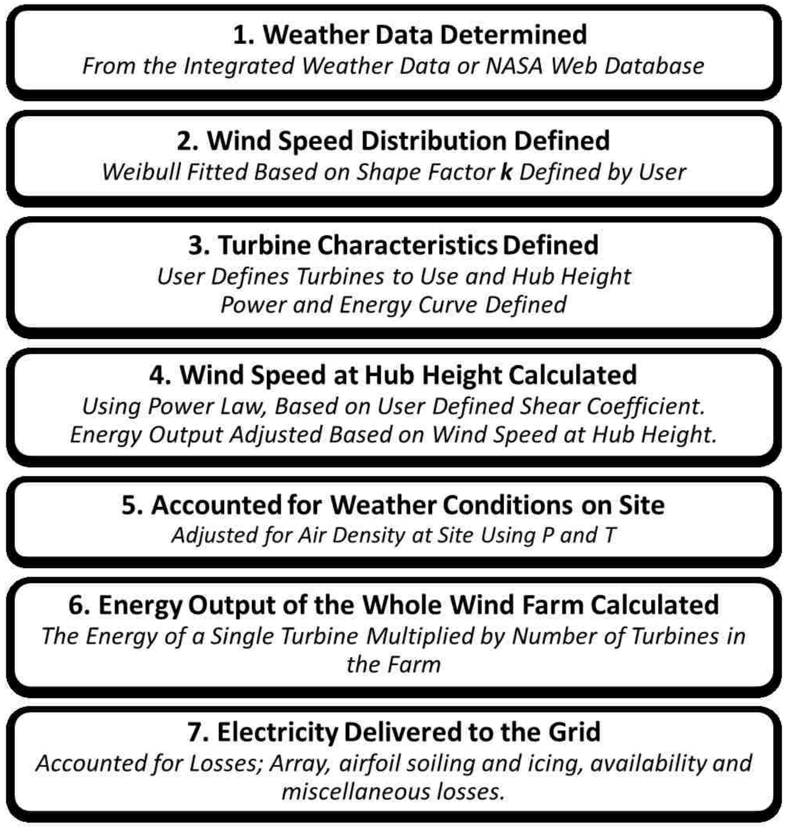


Figure 7 – Simplified summary of the energy algorithm in RETScreen.

The RETScreen software has indeed three calculation methods, called method 1, 2 and 3 respectively. The first is a very rough estimate and will not be discussed here, in the second the annual average values for wind speed, temperature and pressure are used to calculate the AEP. In the third method, monthly average values for winds speed, temperature and pressure are used, and the Weibull distribution is done for each month as well as the pressure and temperature adjustments according to **(Eq. 2-11).** By using the last mentioned both monthly and annual energy output is calculated.

2.3 System Advisory Model

The *System Advisory Model* (SAM) was designed for professionals and researchers involved in the renewable energy industry to facilitate decision making. It was developed in collaboration between the National Renewable Energy Laboratory **(NREL)** and *Sandia National Laboratories* in 2005. Its initial purpose was for internal use in U.S. Department of Energy's **(DOE)** *Solar Energy Technologies Program* as a decision tool while looking for opportunities of improvements in solar technology. Originally it only had the ability to model solar power related technologies and was at that time called the *Solar Advisor Model*. In 2007, the model was made publically available and in 2010 the name changed to System Advisor Model to reflect that several other renewable energy technologies had been added to the software (NREL, 2013e). In the current version of SAM launched in September 2013 (SAM 2013.9.20) the following technologies can be modeled; *Photovoltaic, Concentrating Solar Power, Generic System, Solar Water Heating, Wind Power, Geothermal* and *Biomass Power* (System Advisor Model Version 2013.9.20, 2013).

SAM has both performance and financial models to estimate the energy production and cost of a given project. Different algorithms are used based on the technology selected. To run the performance model, resource data describing both the weather conditions and the energy resource at the project location is required as well as information about the physical components or equipment of the energy system. Integrated in SAM are several databases that include equipment and performance data and coefficients for system component. Meteorological data is also integrated in SAM, but the user can also download those from linked databases on the internet or create the file using own data. The databases are most commonly available for locations in the U.S. The financial model uses the results from the performance model to calculate the financial viability of the proposed project based on inputs from the user regarding financial options and costs of its components such as installation cost, operation and maintenance cost, debt type, interest rates, incentives and electricity costs (NREL, 2013e). The financial model is therefore dependent on the performance model and poorly structured performance model will result in inaccurate and unreliable financial prediction that unlikely are useable in any decision making. Several analysis options are also available to better address the effects of inputs and variables such as *statistical*, *sensitivity* and *parametric* analysis which helps when comprehensive analysis is performed. SAM also has its own scripting language called *SamUL*. This allows users to write their own commands or program inside SAM, as well data exchange with Excel is made convenient (NREL, 2013e). An overview of the model structure can be seen on **Figure 8** below.

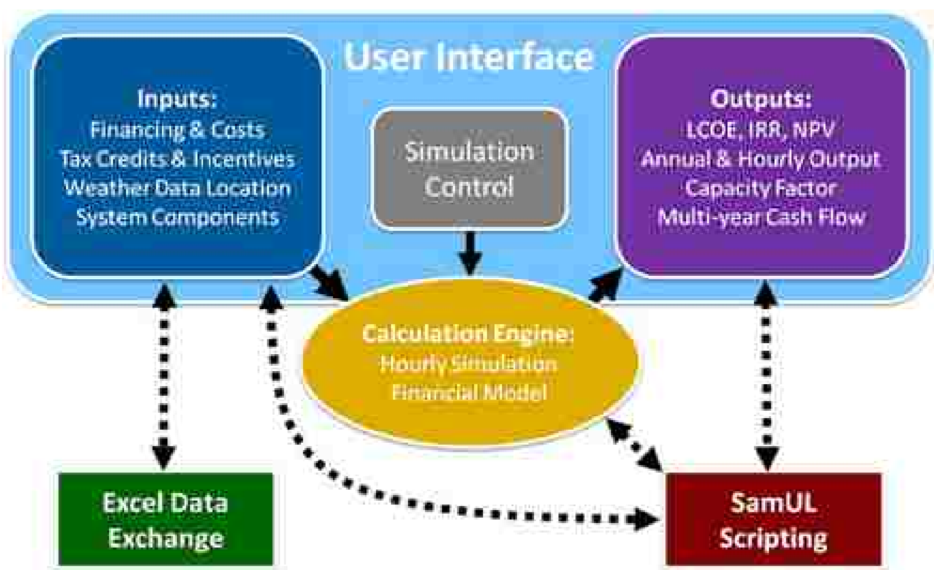


Figure 8 - SAM's Model Structure. *Source:* (NREL, 2013e).

To date SAM is used for program planning and grant programs by the U.S. DOE, NREL and Sandia. The software has also been downloaded by over 35,000 individuals which include manufacturers, project developers, academic researchers and policy makers (NREL, 2013e). The usage of the software is described by the software's developers as follows:

> Manufactures are using the model to evaluate the impact of efficiency improvements or cost reduction in their productions on the cost of energy from installed systems. Project developers use SAM to evaluate different system configurations to maximize earnings from electricity sales. Policy makers and designers use the model to experiment with different incentive structures (NREL, 2013e, p.17).

Based on the user support forum, see *Gilman* (2013), and the development history of the software it is clear that the solar technology module has been developed the most. It also seems to be the most used technology module by users. This is not a surprise since it was the reason for the software being developed in the first place. In the newest version of SAM additions to the wind module of the software allow user-defined turbine layout as well as commercially used wake models were added which makes the wind module more advanced.

2.3.1 The Weather Database for the Wind Energy Module

There are two options in SAM to define the wind resource which are using the *wind resource characteristics* option and the *wind resource by location* option. The prior allows the user to put in average annual wind speed at 50 m above ground level (a.g.l.) and use the Weibull distribution to represent the annual wind distribution (user defines k value, as discussed in **Section 2.2.2** above). If the latter is used, there are two sources of weather files that can be used, the first one is called *representative typical wind data files* which are integrated in the software and the second is using the *location lookup* option which downloads weather files via SAM from an online database (System Advisor Model Version 2013.9.20, 2013).

Representative Typical Wind Data

The *Representative typical wind data files* which are integrated into SAM were made for NREL by the company AWS Truepower. The wind data files are available for 39 locations in the US and have the following name format: *State Region-Terrain Description*. For example, the file *AR Northwestern-Flat Lands.srw* is a representative file for a site in the Northwestern part of Arizona where the topography is flat terrain. Eight Different terrain types are defined in the SAM help file using Google Earth images as a reference (NREL, 2013e). Each file represents data for typical year and includes the following; wind speed and direction, temperature and pressure data at 50, 80,110 and 140 m a.g.l. as well as the elevation height of the data point (System Advisor Model Version 2013.9.20, 2013). The data is created from multi-year data set to best represent typical 12 months for the region over a long time period. Information about how these weather files were created, e.g. over which time period and roughly for what area they were collected are not available. The description of each file is also very general and that only 39 files are used to represent locations over the whole US is a limitation. These files are describes to be "appropriate for preliminary studies to explore the feasibility of potential project or for policy studies" (NREL, 2013e, p.77) however the user should use them with caution and make sure it is appropriate for the user's analysis.

Location Lookup

The *location lookup* option in SAM can be used to access weather data that is stored on a web-based database. The user can type in an address, zip code or latitude and longitude to access these weather files that then will be downloaded to SAM (NREL, 2013e). There are two different databases that will be accessed based on the location selected, *Eastern Wind Dataset (EWDS)* and the *Western Wind Dataset (WWDS),* the 100° W longitude roughly demarcates the two data-sets which cover the eastern and western part of the US respectively, as can be seen on **Figure 9** below. Both databases contain modeled data for the years 2004, 2005 and 2006 and were created as a part of comprehensive studies conducted by NREL.

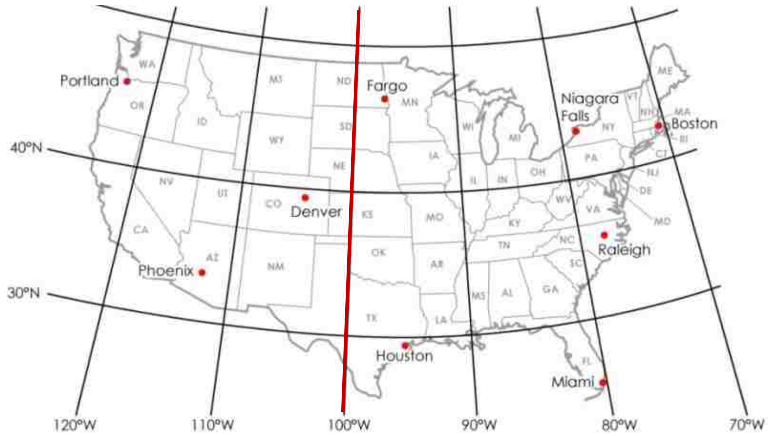


Figure 9 - Location of the U.S. Western and Eastern Wind Datasets. The red line roughly demarcates the western and eastern weather data sets. Source: (Super Teacher Worksheet, n.d.).

The EWDS was created for the purpose of use in the *Eastern Wind Integration and Transmission Study* which was conducted by NREL to "examine the impacts of 20-30% wind energy penetration on the power system of the Eastern Interconnect of the United States" (NREL, 2013b). The study which was completed in 2010 addressed the technical issues related to higher ratio of wind energy on the transmission grid. To be able to model the impacts of increased wind energy on the grid the EWDS, a modeled time series of wind speed and potential power output was created (NREL, 2013b). The data was originally created at approximately 2 km spatial and 10 minutes temporal resolution for the three year period (EnerNex Corporation, 2011). The dataset was created by oversight and assistance from NREL by AWS Truepower by using the MASS mesoscale model (NREL, 2013c). The wind speed series were used to estimate power output of synthetic wind farms using composite turbine power curves. Wind speed maps of the study as well as 10 years of speed distributions previously computed by AWS Truepower were used to determined probable wind plant locations, resulting in a final list of 1,326 sites with the total of 580 GW power output, the size of each output point varied from 5 km^2 to 160 km^2 where each output point capacity ranged from 100 MW to 1435 MW (NREL, 2013c) and (NREL, 2012a). The methodology used in the modeling as well as inputs used etc. is out of the scope of this report but is explained in depth in *Brower* (2010). The data-set for these 1,326 sites can be accessed in SAM, list of all the sites, location by state and latitude and longitude of the data points can be found on *NREL* (2013d). Each data point includes hourly wind speed values at 80 and 100 meters but no other meteorological data. This is insufficient for the wind energy calculations in SAM, which on top of wind speed requires wind direction (if wake models used), ambient temperature and atmospheric pressure. The user has therefore to define monthly wind direction, yearly temperature and pressure values (System Advisor Model Version 2013.9.20, 2013). The missing data could potentially be obtained from different source e.g. from a nearby airport and adjusted to account for elevation changes between site and the airport. In (NREL, 2013e) it is stated that even though the wind power model uses both the temperature and pressure in its energy calculations these have relatively small impacts on the results compared to the wind speed as discussed in **Section 2.1** earlier. Even though the data-set is rather coarse it however represents locations which were thought to be the mostly likely to see installed wind power plants in the upcoming years and should therefore be at promising locations for new wind power plants in the US. The incompleteness of the weather data in the EWDS is however clearly a limitation and increases the uncertainty of the assessment at a given site. When the user requests data from the EWDS for a specific location SAM will find the dataset closest to the requested location and give a rough distance between the requested location and the nearest resource data site (System Advisor Model Version 2013.9.20, 2013).

The WWDS was created for NREL for the *Western Wind and Solar Integration Study* which was conducted to explore the question "Can we integrate large amounts of wind and solar energy into the electric power system of the West?" In the first phase, finished in 2010, the benefits and challenges associated with the integration of up to 35% of wind and solar energy to the transmission system in the western US were examined (NREL, 2013f). To be able to model the increased wind energy on the grid, synthetic wind energy project data was created like for the EWDS. The data was modeled using Weather Research and Forecasting (**WRF**) mesoscale model by the company 3TIER with oversight and assistance from NREL (3TIER, 2010). The modeled data was sampled temporally every 10 minutes and spatially every arc-minute or roughly 2 km[1] which resulted in 1.2 million grid points for the whole study area. Comparison of the model to measured data has shown that it is more accurate in simple topography (flat or rolling terrain) and less in more complex topography (canyons, mountains, terrain with sharp features) as expected (NREL, 2012b). For specific areas the model accuracy is described as:

> East of the Rocky Mountains, the model appears to work well, with some underestimation of the resource during the warm season. West of the Rocky Mountains, in downslope acceleration areas, the model may overestimate downslope winds. In thermally driven areas (Altamont, Solano, Columbia Gorge, Stateline/Vansycle, Ellensburg/Columbia River), the model may underestimate winds, especially in the summer. To accurately model complex terrain, the model must be specifically tuned to that location, ideally using on-site data (NREL, 2012b).

It was decided that each grid point could be potential wind project rather than modeling each synthetic project as a unit like for the EWDS. Each grid point (2 x 2 km^2) was estimated to hold 10 Vestas V90 3-MW turbines representing a 30-MW project. Then sites from the 1.2 million data points were selected to represent 900 GW wind energy projects using multi-phase selection algorithm in conjunction with NREL to estimate the most feasible areas for wind power development. This resulted in 32,043 sites which represented 960 GW of wind energy

---

[1] One arc-minute is not constant and varies based on the location on the globe, what projection is used and so forth. 1 arc-minute of latitude remains nearly constant, while the arc-minute of longitude varies. At the equator they are almost equal or 1 nautical mile (1852.2) m , therefore the cell size is assumed to be roughly 2 km x 2 km (ESRI, n.d.).

projects (NREL, 2012b). Web database interface was created for the public to access the data which can be found on *NREL* (n.d.c).

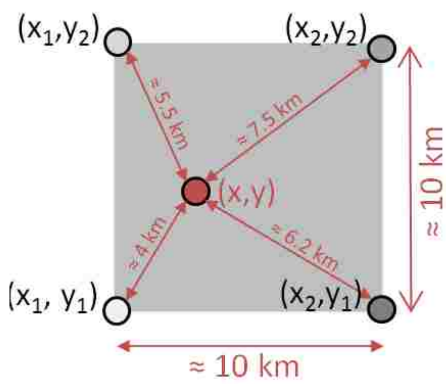


Figure 10 – How the weather file location lookup works for the WWDS.

The data that is available for downloading to SAM is however not these 32,043 output points like with the EWDS prior mentioned. It is instead roughly a five times more coarse spatial grid than the original 1.2 million data-point grid or a roughly 10 x 10 km spatial resolution over the whole study area or 192,000 data points (sampled every 0.083° or roughly 5 arc minutes). The reason that the SAM data is at a lower resolution than the original data has to do with server storage (Paul Gilman, e-mail communication, 2013). For each data-point the hourly data is included: *Atmospheric pressure* at ground level, *wind speed*, *wind direction* and *ambient temperature* at 10, 20, 50, 100 and 200 meters height. This data-set includes all the required information for the energy calculation in SAM. Each data-point is identified by latitude, longitude and elevation. When the user requests data for a given location, SAM will find the weather file closest to the requested location, one 10 x 10 km^2 cell is shown on **Figure 10** as an example. If the user request data for site at location (x,y) it will get the modeled data at (x_1,y_1) since that site is closest to the requested location.

The dataset is not said to be designed to represent accurate wind speeds or power output for a particular site nor to be used for sole basis for project investment (NREL, 2012b). Currently 3TIER is modeling data for NREL for the whole US at 2 km spatial and 5 minutes temporal resolution for the year 2007 – 2011 to update the national wind integration dataset (3TIER, 2012), whether or not this data will be accessible in SAM is unknown.

Creating Weather File From Own Data

At last it must also be noted that the user can create its own weather files and use in SAM. The weather file format that is used for the wind energy module is called **SRW**. It is a comma-delimited (.srw) format, special weather file format only used in the wind power module in SAM (NREL, 2013e). Comma-delimited is a format system which store two-dimensional arrays of data using delimiters such as commas or tabs to separate the values in each row (Wikipedia, 2013). Simple spreadsheet programs such as Excel can be used to edit and prepare data to use in SAM, it is therefore relatively simple if data is available to prepare it on the proper format. The options for the weather data selection in SAM are summarized on **Figure 11** below.

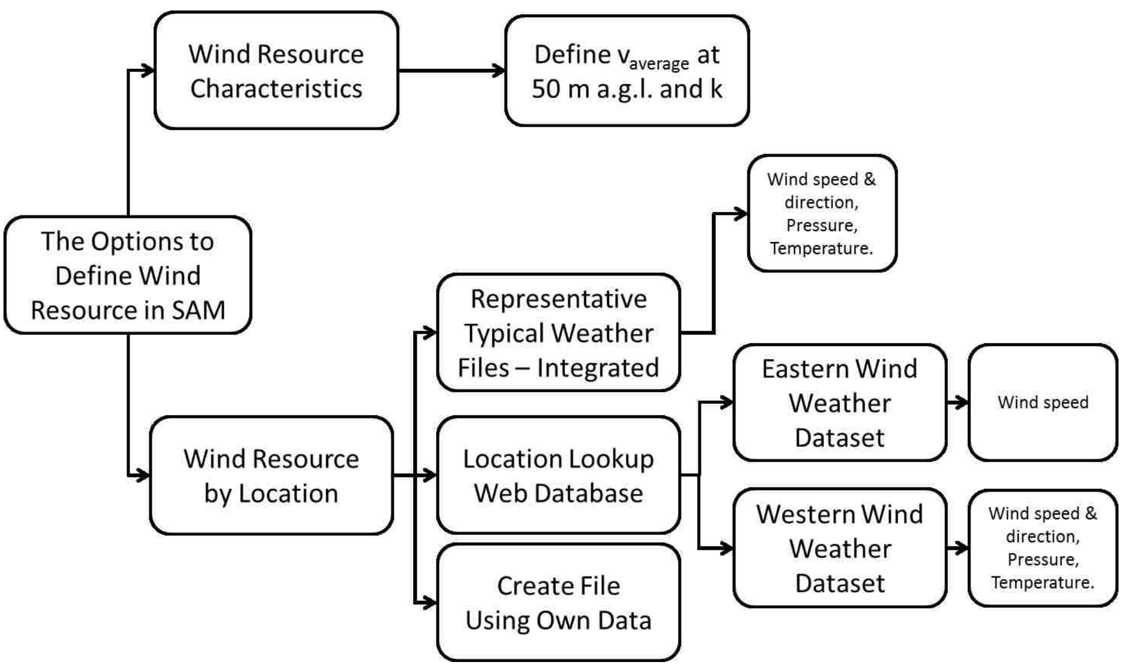


Figure 11 - Selection options for the weather data in SAM.

2.3.2 Energy Calculation Algorithm[2]

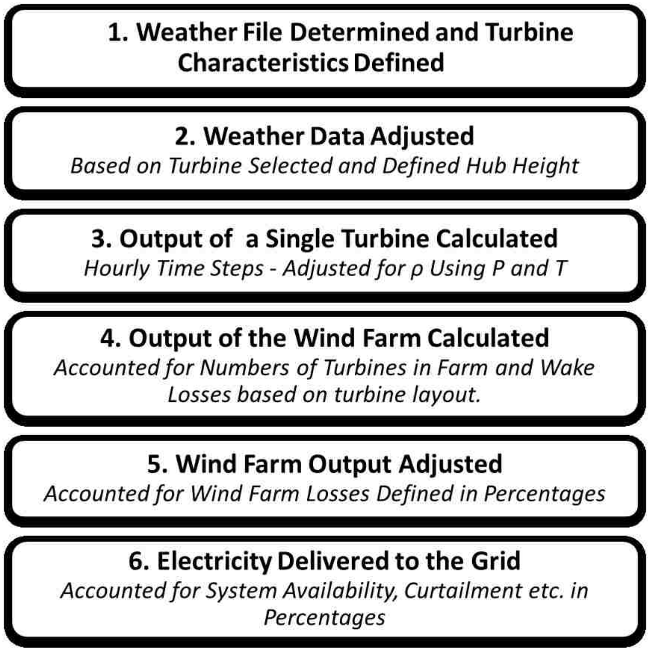


Figure 12 – Simplification of the wind energy algorithm in SAM.

If the weather resource was defined using the *characteristics options* by defining the annual average wind speed at 50 m and the shape factor k, SAM uses the Weibull distribution for the energy output calculations. This option is only available for one turbine and no adjustments are made to the air density resulting in the entire hourly time step being identical for the energy output calculations. If the wind resource is however defined using the *wind resource by location,* hourly wind speed, wind direction, ambient temperature and atmosphere pressure data is required so the energy output of a wind project can be calculated. The calculations are done in hourly time steps which are then summed up to represent the AEP of the project. A simplified overview of the algorithm can be seen on **Figure 12.** Following is a step by step description of the algorithm used for the energy output calculations.

1. **Wind Resource File and Turbine Characteristics Defined**

Once the wind resource file has been selected to represent the meteorological data at site the user defines the physical equipment in the wind farm i.e. the turbines. For that are two options, either the turbine can be selected from SAM's turbine library which includes turbine data from manufactures in the industry or the user can define the turbine characteristics

[2] Note that mathimatical expression in this section has mostly be developed by the author, the algorithm is not express this way in the SAM help reference. The mathimatical expression is based on the discussion from (NREL, 2013e) and the authors interpretation.

manually, both options are used to access the power curve for the chosen turbine. The user also defines the hub height of the turbine as well as shear coefficient if applicable (System Advisor Model Version 2013.9.20, 2013).

2. Weather Data Adjusted to account for the Hub Height

The wind data is adjusted to account for the difference between the wind resource data height and the hub height of the turbines. If wind speed data is available at more than one measurement height and the turbine hub height falls between the minimum and maximum wind speed measurement height, SAM looks for the measurement height closest to the hub height. If it finds a perfect match it uses that, otherwise it uses the measurement heights at either side of the hub height and estimates the wind speed at hub height using linear interpolation. For the wind direction, SAM uses interpolation if the two measurements heights differ by less than 90° but otherwise uses the data at the measurement height closest to the hub height (System Advisor Model Version 2013.9.20, 2013).

If wind data is however only available at one measurement height, or the turbine hub height is above the maximum or below the minimum measurement height in the file the shear coefficient is used to calculated the hourly wind speed at hub height v_{hub} according to **(Eq. 2-10)**.

3. Output of single turbine calculated

The hourly wind speed at hub height is used to estimate the hourly energy using the turbine power curve as shown on **Figure 1**. The power curve represents the turbine's performance at $\rho_0 = 1.225\ kg/m^3$ i.e. standard conditions. To account for changes in the air density at the project site the air density adjustment factor a is calculated according to:

$$a = \frac{\rho}{\rho_0} \quad \textbf{(Eq. 2-17)}$$

Where ρ is the air density at the project's site calculated using the ideal gas law according to **(Eq. 2-4)**. Where $R_{specific} = 287.058\, J/(Kg \cdot K)$ is the gas constant and p and T are obtained from weather data file (NREL, 2013e). Then the energy at each hour is calculated according to:

$$E_{hourly} = a_i \cdot P_{v_i} \quad \textbf{(Eq. 2-18)}$$

Where P_{v_i} is the power output of the turbine at wind speed v at hour i.

4. Output of the Wind Farm Calculated

The user has the option to account for the size of the system in two ways, either only to calculate the output for one wind turbine or specify the turbine layout for a wind farm. There are two ways to specify the turbine layout, either by using integrated turbine layout forms in SAM, which are square, rectangle or parallelogram or defining the turbine layout using a Comma-Separated-Value **(CSV)** file. The first option can be rather limited as the wind farm is likely to follow more irregular shape than the integrated layout forms allow. The latter option allows the user to input the layout of the wind farm by creating a comma separated list of X and Y coordinates in meters, this can easily be done using spreadsheet programs like Excel (Tom Ferguson, software developer at NREL, e-mail communication, 2013). The number of wind turbines can be anywhere on the range from 1-300. An example of a turbine layout of 64 turbines in SAM can be seen on **Figure 13** below. Once the turbine layout has been defined, the next step is to identify which model to use to calculate wake losses. Wake effects is an important issue in wind farm design, turbines located upwind can reduce the wind speed that downwind turbines will attain. The impact of the wind speed deficit can last as long as $20D$ in the wake of the rotor, where D is the diameter of the rotor of a given turbine (Jain, 2011). The wake models use, wind speed and direction data from the weather files as well as the turbine layout information and calculate the effects from upwind turbines on downwind turbines. SAM offers three different wake models, *Simple Wake Model* (the Pat Quinlan model), the *Eddy-Viscosity Model* and the *Park Model (WAsP)* (NREL, 2013e). The latter two are commercially used in professional WRA programs the algorithm used in SAM is the same as found in the openWind model (Tom Ferguson, software developer at NREL, e-mail conversation, 2013). In this study, the Park Model was used and therefore the other models are not discussed further here, however information about the Simple Wake Model can be found in *Quinlan* (M.S., 1996) and about the Eddy-Viscosity in *AWS Truepower (2010)* and *Brower (2012).* The reason for the selection of the Park Model will be discussed in **Section 3.3.3** but the theory behind the Park Model is discussed at the end of this section. The wake models in SAM do not account for topographical information and therefore assume that the wind farm is located on a flat surface which is a major limitation.

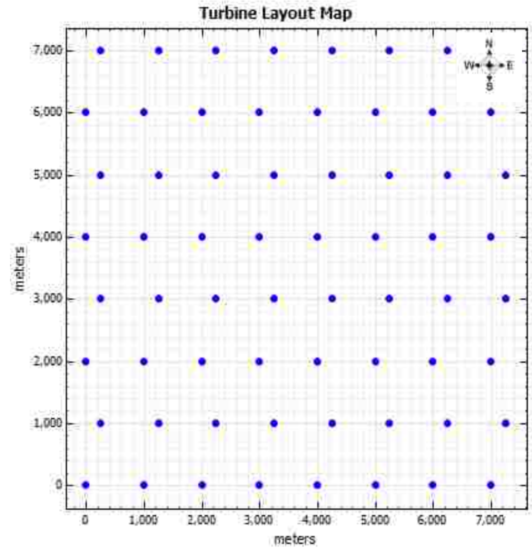


Figure 13 - Example of Turbine Layout Map in SAM. *Source:* (System Advisor Model Version 2013.9.20, 2013).

By using the wake models, the hourly wind speed is adjusted for each of the n turbines in the wind farm based on wind direction and free flow wind speed of upwind turbines. The total unadjusted (before accounting for losses) AEP (E_U) can be calculated according to:

$$E_U = \sum_{i=1}^{8760} \sum_{j=1}^{n} a_i \cdot P_{v_{i,j}}$$ **(Eq. 2-19)**

That is the hourly energy is calculated for each turbine based on the power curve at wind speed $v_{i,j}$ at hour i for all of the n, turbines and then adjusted using a at each hour. This is then summed up for each turbine over the 8760 hours in the year. The MEP for each month is calculated by summing up of the hours in each month.

5. Wind Farm Output Adjusted

Once all of the inputs have been defined and E_U has been calculated the last steps are to account for losses that can by experienced in wind farms for several reasons. This is done in two separate steps in SAM. Firstly the user can identify what is called *Wind Farm Losses* (λ_1) which are defined as "expected losses in the wind farm's electrical output as a percentage of the wind farm's total output. Use this factor to account for wiring, transformer or other losses" (NREL, 2013e, p. 376). Is defined by the user and is inserted in percentages. Mathematically this can be expressed as the energy delivered (E_D) as (NREL, 2013e):

$$E_D = E_U \cdot (1 - \lambda_1)$$ **(Eq. 2-20)**

6. Electricity Delivered to the Grid Calculated

At last the electricity to the grid E_C is calculated accounting for availability, curtailment and other factors that were not accounted for in λ_1 above. This is done by adjusting the system output in percentages of annual output (λ_2), this can be defined specially for different hours of the day or month of the year. Therefore the total energy delivered to the grid is:

$$E_C = E_U \cdot (1 - \lambda_1) \cdot \lambda_2$$ **(Eq. 2-21)**

A detailed discussion about losses in wind farms and how they were determined in this research is found in **Section 3.4.2**.

The Park Model

The Park Model has been used to estimate the effects of the wakes in wind farms for decades. It was originally used in the WAsP software and has since been implemented in most commercial wind design programs. To characterize the wakes, two parameters are defined; the width of the wake D and the speed deficit δv relative to the free-stream speed of the upwind turbine. It is assumed that D is initially equal to the rotor diameter of the turbine and has a linear growth with distance downwind and is defined as: (Brower, 2012)

$$D(x) = D_0 \cdot (1 + 2lx) \qquad \textbf{(Eq. 2-22)}$$

Where D_0 is the rotor diameter of a given upwind turbine T_0 (in meters), l is empirical decay constant, defined by the user, which determines the linear rate of expansion of the wake and x represent the distant from the rotor to next turbine downwind and is expressed in rotor diameters (this can be seen on **Figure 14**). Park assumes that the wind flow follows the terrain and the combined speed deficit at a downwind turbine (T_1) is given by (AWS Truepower, 2010):

$$\delta V_{01} = V_0 \cdot \left(1 - \sqrt{1 - C_t}\right) \cdot \left(\frac{D_0}{D_0 + 2lX_{01}}\right)^2 \cdot \frac{A_{overlap}}{A_1} \qquad \textbf{(Eq. 2-23)}$$

Where C_t is a trust coefficient of the turbine which is given by manufacturers for a given turbine and is a function of the wind speed. V_0 is the unaffected wind speed at the turbine T_0 upwind and $A_{overlap}$ and A_1 are the cross sectional area as seen on **Figure 14**.

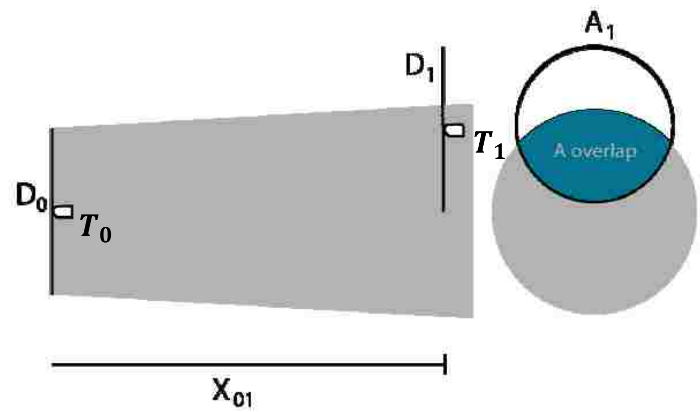


Figure 14 – Plan view of turbine one in the wake of turbine two. Source: (AWS Truepower, 2010).

Then the wind speed at the T_1 is simply the free-stream at T_0 minus δV_{01}. In the case where more than one upwind turbine has overlapping wakes, the largest single wake deficit is used (AWS Truepower, 2010).

2.4 Validation and similar research

The validation of the programs to date has been rather limited, below the main validation efforts for each program are listed.

2.4.1 RETScreen

In (RETScreen, 2005) it reads that all of the module in RETScreen provide reliable results since all of the models have been validated by third-party experts, the validation efforts are listed in the RETScreen textbook. The textbook covers three validation examples, first there are two cases where RETScreen is compared to the hourly simulation program HOMER from NREL, and secondly comparison with monitored data from an operating wind farm. Both are covered below. All of the following discussion is from (RETScreen, 2005).

Comparison with hourly simulation model

RETScreen predictions were compared to HOMER, an hourly simulation and optimization model for electric power systems such as wind power, further information about HOMER can be found at (HOMER Energy, n.d.). Two comparison efforts were performed, for a small and a large wind farm. The small wind farm has 10 turbines with total capacity of 500 kW and is based on a real wind power project in Kotzebue, Alaska. User-defined input parameters were selected to be as comparable as possible between the two models and detailed discussion about them can be found in (RETScreen, 2005). As seen in **Table 1** the comparison between the gross AEP predictions from the two models is very good and only 1.1% difference was observed.

Table 1 – Comparison of the AEP predictions in RETScreen and HOMER. Source: (RETScreen, 2005)

RETScreen Unadjusted Energy Production (MWh)	HOMER Total Energy Production (MWh)	Difference
1,532	1,515	+1.12%

The larger wind farm included 76 VESTAS, 600 kW turbines or a total capacity of roughly 46 MW for the wind farm. The same input data was used for both models, like in the prior example. Comparison of the gross AEP predictions from both models can be seen in **Table 2** below. As can be seen the comparison is good, and only -2.6% difference was observed.

Table 2 – Comparison of the AEP predictions in RETScreen and HOMER. Source: (RETScreen, 2005).

RETScreen Unadjusted Energy Production (GWh)	HOMER Total Energy Production (GWh)	Difference
258.2	265.2	-2.64%

What is though worth discussing is what this tells about the accuracy of RETScreen. HOMER and RETScreen differ in the type of weather data that they require. HOMER requires monthly wind speed values and stochastically estimates hourly values from those, while in this case RETScreen only used annual average wind speed. By keeping all the other input variables the same, it can be stated based on these two examples the two methodologies compare very well.

This does, however, not give any indication about how well the predictions of the model compare to real projects as will be discussed in the following example.

Comparison with monitored data

For the comparison to the monitored data which is the main validation of the RETScreen predictions, data from Kotzebue in Alaska was used like in the first example. Annual operational data from the wind farm has been published which made the comparison possible. This is data from the first couple of years of the wind farm operation, which sometimes are not representative of the AEP because of initial adjustments in the system which is worth to keep in mind.

Monitored annual average wind speeds at the site were used as input values in RETScreen, and losses roughly estimated. The comparison for four different time periods can be seen in **Table 3** below. As can be seen the energy predictions are fairly good in RETScreen except for 1999. It is thought likely that in 1999 the system was underperforming as further discussed in (RETScreen, 2005).

Table 3 – Comparison of RETscreen predictions against monitored data for Kotzebue, AK. Source: (RETScreen, 2005).

Period	Turbines	Average Wind Speed (m/s)	RETScreen Prediction (MWh)	AEP (MWh)	Difference
1998	1-3	4.9	250	270.9	-8%
1999	1-3	5.4	317	208.6	+52%
July 1999-June 2000	4-10	5.1	646	546.9	+18%
1999-2000	1-10	5.4	1,057	≈1,170	-10%

In (RETScreen, 2005), it is said “the comparison of the RETScreen predictions with real data is nevertheless acceptable and this, together with the model-to-model comparison, confirms the adequacy of RETScreen for pre-feasibility studies of wind energy projects" (RETScreen, 2005:WIND.25).

If the year 1999 in the case study above is excluded, the AEP predictions from RETScreen compare rather well with the operational data or somewhere in the range of -10% to +18%. This is though based on only one case study, and the wind farm is very small. In the case, on-site monitored wind speeds values were used in the AEP predictions which are not commonly available at the pre-feasibility stage. It would have been good to have a validation effort were the integrated or web-based weather database would have been used, and those predictions compared to real data from an actual wind farm. Therefore, it is felt that this one case study is not enough to be able to generalize anything about the accuracy in the AEP predictions. No further validation efforts of the model were, however, found in publically available articles.

2.4.2 SAM

The SAM program is relatively new, and the wind energy module was only added in 2010. Since the program was originally designed for solar energy, most of the work and validation of the program has been done in that field, like previously mentioned.

In (NREL, 2013a) and (NREL, n.d.b) a list of case studies and validation efforts as well as any publication related to the SAM model can be found. No direct validation or case study of the wind energy module in SAM can be found there and based on information from Tom Ferguson, software developer for SAM at NREL, no serious validation efforts have been done since funding has not been available. However, at least one case study has been conducted which is not yet publically available (Tom Ferguson, software developer at NREL, e-mail conversation, 2013). In *Ummel* (2013) the calculation engine of SAM was used in a study of *Planning for Large-Scale Solar Power in South Africa* but the weather data was obtained from a different source. However, there are many studies related the solar energy module as well as validation studies that compare the system advisor model to real performance data, those can be found in in *Freeman et. al.* (2013) and *Blair et. al.* (2012). Since no serious validation efforts have been conducted for the wind energy module of SAM, this study would be one of the first to do that.

2.5 Summary

Table 4 summarizes the key information from previous sections for both RETScreen and SAM and compares the main characteristics of each model as discussed in previous sections.

Even though it is not the purpose of this study to compare the models and determine which one can give more accurate and reliable energy output prediction of a given wind farm, it is though thought necessary to highlight the main differences between the programs and how they are developed.

Both models have a similar purpose, which is to facilitate decision making by being an assessment tool for renewable energy projects. RETScreen has been around for over 15 years while the wind energy module in SAM was only added about three years ago. Therefore, SAM has developed more over recent years, and new features are frequently being added to the model while the wind energy module of RETScreen has stayed more or less the same. RETScreen is an Excel Add-on while SAM is run on a platform developed by NREL. Both models have performance/energy models and financial models and the capabilities of performing risk and sensitivity analysis. RETScreen also has emission model.

Table 4 - Summary of the key information about RETScreen and SAM.

	RETScreen	SAM
Purpose of software	Pre-feasibility decisions tool for renewable energy projects.	To facilitate decision making in the renewable energy industry
Software Platform	Spreadsheet program, Excel Add-On	Platform Developed by NREL, Integrated Scripting Language
Software launched	1998, current version is RETScreen 4	Initially 2007, Wind Power module added in 2010
Latest update	2013.8.28	2013.9.20
Performance Model	Yes	Yes
Financial Model	Yes	Yes
Emission Model	Yes	No
Risk and Sensitivity Analysis	Yes	Yes
	Weather Database – Wind Module	
Cover of Weather Data	Global	The United States
Source of Data	NASA and Ground Observations	3TIER, AWS Truepower
Spatial Resolution	Irregular for ground data ≈ 80 x 110 km - NASA	≈ 10 x 10 km West of 100° but much denser for East of 100°
Temporal Resolution	Monthly/Annual Averages	Hourly Data
Number of data-points	6,700 Ground Stations, 64,800 NASA	192,000 for WWDS and 1,326 for EWDS
Type of Data	Ground Measurements over 30 years and Satellite Data over 10/22 years	Modeled Data
Data Available for	Average Year based on 10 - 30 years of data, no standard deviation given.	2004, 2005 and 2006 as well as typical year for 39 locations
	Energy Calculation - Wind Energy Module	
Number of Weather Files to represent Wind farm	One	One
Wind Speed Distribution	Weibull used to represent probability of wind speed over a given range	Hourly Energy Time Steps
Adjustments for Air Density	Adjust based on monthly/annual averages with pressure, temperature	Adjusted hourly with Pressure and Temperature
Turbine Layout	No	Yes
Accounted for Terrain Effects	No	No
Accounted for vegetation	No	No
Wind Flow Calculation?	No	No
Losses Calculations	Percentages for four loss categories	Wake Affects calculated, accounted for other losses using percentages

The weather databases associated with the programs are very different. RETScreen has weather files with global coverage while SAM covers the United States. The ground monitoring data in RETScreen is not adjusted to account for conditions at the site for a given project and one might argue that weather conditions at an airport location, very often located in or close to an urban environment is very different than at a given project site which can be located in remote and rural area. However, using this data might be fine for a first estimate as long as its limitations are known. The NASA database is thought to be more relevant in rural and remote areas, but because of the coarse resolution it might not be accurate enough especially when complex topographical features are at the project site. The SAM weather database is much more comprehensive and has higher spatial resolution and therefore likely to have more accurate weather files for a given location, it is also hourly values compared to monthly and annual averages in RETScreen. The RETScreen data represents an "average year" collected over a long period based on direct measurements and satellite data while the SAM data is modeled data created using micro models and is available for three years, 2004, 2005 and 2006, except for the representative typical weather files for the 39 locations in the US. The modeled data is known to have its limitations especially in complex topography. SAM also includes over 192,000 data points in US alone, while RETScreen includes about 70,000 data points world-wide.

Both models use only one weather file to represent the whole wind farm regardless of its size. No wind flow model is integrated to adjust the wind speed based on the location of turbines, nor are effects of topography and land cover taken into accounts (except for a very rough estimate of e.g. shear coefficient). This is very different than in commercially used WRA micro models, where wind resource map of resolution of e.g. 50 meters is calculated and wind speed, and air density at each turbine location is calculated and energy output calculations based on that. This is one of the known limitations of the models, but how much effect this limitation has on the predicted energy output is one of things to examine in this study. While SAM has hourly meteorological data, RETScreen uses annual (or monthly) wind speed values and Weibull distribution to create an annual wind speed distribution based on user defined shape factor. RETScreen does not take into account any turbine layout while SAM allows that but assumes that the wind farm is located in a flat terrain. RETScreen adjusts the energy output for losses using percentages which is the same in SAM except for the wake losses which can be calculated in SAM using commercially used wake models with the big simplification of assuming a flat terrain.

It can therefore be said that RETScreen makes very rough energy output predictions in a relatively simple way, while SAM takes it one step further and allows for turbine layout considerations and wake losses calculations which is usually not done until at the micro model level. It is thought worth to keep in mind that RETScreen and SAM have very different spatial cover.

3 Methodology

This chapter covers the methodology of the study. It starts off with a discussion about the wind farm data and how the relevant weather data, user defined inputs, and variables were determined. There is a separate section on each model, but since several variables are the same for both models those were combined and discussed in a separate section. Input data was kept as consistent as possible between the two models to give an accurate and fair comparison. *MS. Excel* with the *XLSTAT 2013* add-in was used to analyze the data.

3.1 Wind Farm Data

The operational data that was available for comparison comes from a wind farm located in the western part of the US. It has been in operation for several years and has well over one-hundred VESTAS turbines with a hub height of 67 meters (Wind Farm 1). The wind farm was enlarged after a few years of operation and larger turbines were installed in the new part (Wind Farm 2). In this study, only the data from Wind Farm 1 is used for comparison, mainly because both SAM and RETScreen can only model one type of wind turbine at a time. Running two separate analyses for the two farms would have increased the level of uncertainty in the analysis, e.g. when wake losses would be modeled in SAM for Wind Farm 2 they would have been independent of Wind Farm 1 resulting in inaccurate results. Wind Farm 2 is not located in the prevailing wind direction of Wind Farm 1 and has relatively little impact on Wind Farm 1. Therefore, modeling only Wind Farm 1 is considered appropriate.

The wind farm is in a complex topographical location or hilly/mountainous area. The elevation change inside the farm is around 400 meters and the turbines are located 800 – 1200 m above sea level (a.s.l.). They are mostly located on small mountainous ridgelines, in several rows in an irregular layout, to maximize the energy production based on the prevailing W/SW wind direction. Vegetation at the site is similar to the one seen on **Figure 15** and the climate is dry with largely basalt outcroppings.

Figure 15 – Vegetation similar to the one on the Wind Farm site.

A significant amount of data is monitored and continuously measured inside the farm. All of the turbines have sensors located at hub height which record the vector average wind speed (in m/s) and wind direction (in degrees) every 10 minutes. Additionally, meteorological towers are located within the wind farm and have sensors at the same height as the turbines and measure wind speed and direction every ten minutes. Meteorological data such as temperature is also collected. The following data was obtained from the wind farm and available for analysis and comparison:

- *Electricity production*, *availability* and *wind farm capacity* over five year period from 2007 – 2011 for each month for Wind Farm 1 and Wind Farm 2 separately.
- *Wind speed* and *wind direction* from meteorological tower (MET Tower) sampled every 10 minutes for the year 2011 (data was missing for the first half of January).

The measured energy production data is available for a five year period while RETScreen calculates the energy output for a typical year and SAM for a typical year or from modeled data for 2004, 2005 and 2006. It was, therefore, decided that the best way to compare the operational data to the two models would be to calculate the average of the energy production from the wind farm over a five year period. The average μ was calculated according to:

$$\mu = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad \textbf{(Eq. 3-1)}$$

where x_i is the energy production at a given year (annual or monthly) and n is the number of measurements, in this case five. As well, the standard deviation σ was calculated according to:

$$\sigma = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \mu)^2} \, . \qquad \textbf{(Eq. 3-2)}$$

Lastly, to have a better measure of the variance of the data, i.e. how distributed the data is relative to the average, the coefficient of variation c_v was also used and is defined as:

$$c_v = \frac{\sigma}{\mu} \, . \qquad \textbf{(Eq. 3-3)}$$

No criteria was established to neglect any data values that were thought to be considerably low or high; detailed information about the operation of the wind farm for each month was not accessible to do that. Instead of using the average as an absolute measure for comparison with the models, ± one standard deviation was used as the estimate of a range of the annual energy production for the wind farm. Even though this is not a perfect way, it is thought to be the best one to use based on the data available and sufficient enough for a relatively broad and rough comparison as being conducted here. The electricity production data from the wind farm include several losses that can be expected inside a wind farm such as array losses, availability, airfoil, curtailment, etc. Data for the availability at the wind farm was available. The monthly and annual averages, standard deviation, and coefficient of variation were calculated according to **(Eq. 3-1)**, **(Eq. 3-2)** and **(Eq. 3-3),** respectively. While wake losses can be roughly estimated in SAM, other loss categories had to be determined for the models as discussed in **Section 3.4.2**.

Secondly, the wind speed data for the MET tower was analyzed and monthly and annual average wind speed calculated according to **(Eq. 3-1)**, since the wind speed was only available for one year the standard deviation was not calculated. This was then compared to the weather data from the databases associated with RETScreen and SAM.

The following notation will be used in the paper: $\bar{E}$ is used to represents average energy production (monthly or annual) and $\bar{\lambda}$ for the average availability. The subscript WF will be used to denote when data from the wind farm is being used e.g. $\overline{E_{WF}}$ is the measured average energy production for the wind farm. A similar notation will be used to represent results from SAM and RETScreen (RET), therefore $\overline{E_{SAM}}$ and $\overline{E_{RET}}$ are used to denote predicted average energy production for SAM and RETScreen, respectively.

All input variables and climate data used in both RETScreen and SAM were selected to represent the wind farm as best as possible. In the case when assumptions and approximations had to be made, they are listed and potential effects on the results discussed.

3.2 RETScreen

The version of RETScreen used in this study is RETScreen 4 with newest updates dated 2013.8.28.

3.2.1 Weather Data Determination

To determine the weather data representative of the wind farm site RETScreen Plus was used. The closest ground data site is roughly 20 km away at a nearby airport location. All the required data for the energy calculations in RETScreen, i.e. temperature, pressure and wind speed is, however, from the NASA database but is integrated in the software like discussed in **Section 2.2.1**. Therefore, the ground data is the same as in the NASA database for that cell. It was, therefore, decided to use the NASA database. The relevant weather files can be seen on **Figure 16**. The wind farm location is on the boundary of two weather cells labeled as CELL 1 and CELL 2 in the figure. If based on the coordinates of the turbines, 90% of them are in CELL 1 while 10% are in CELL 2. Both CELL 1 and CELL 2 are used in the study even though CELL 1 is thought to be the most representative of the site. In **Table 5** below, a summary of the weather data used in RETScreen is listed.

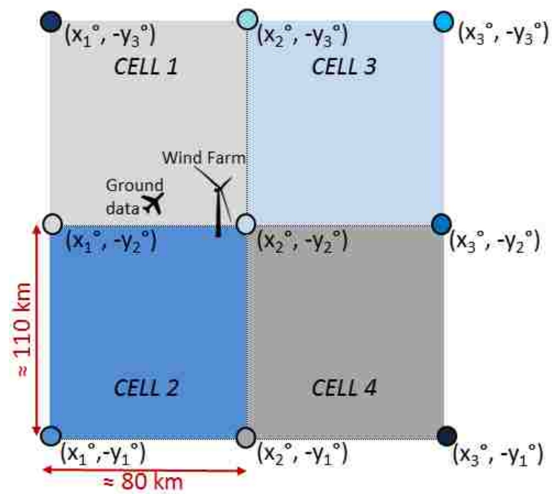


Figure 16 – Location of weather files from the NASA database relevant to the wind farm.

Table 5 - Summary of the weather data used in RETScreen.

Dataset	Period and comparison	Comments
NASA Web Database	Typical year. Compared to wind farm average.	Two locations, CELL 1 (*C1*) and CELL 2 (*C2*) analyzed.

3.2.2 Shape Coefficient of the Weibull Distribution

In RETScreen, the shape coefficient k of the Weibull distribution is commonly on the range from 1 – 3 and if no information is available about k at a given site, 2 should be used as the default value (RETScreen, 2013d). Similar, it is stated in *Jain* (2011) that empirically it has been found that many locations fit a Weibull distribution and k is approximately 2 for most wind profiles. In *Brower* (2012), it is stated that commonly observed k range is 1.6 – 2.4.

Since the wind speed data was available from the MET tower, it was decided to use the data and see how well that would fit the Weibull distribution and what k that would give. The XLSTAT[3] add-in was used. Bins with 1 m/s increments and the method of maximum likelihood with convergence interval of 0.00001 were used. The results are shown in **Figure 17**, and as can be seen the calculated k is roughly 1.7.

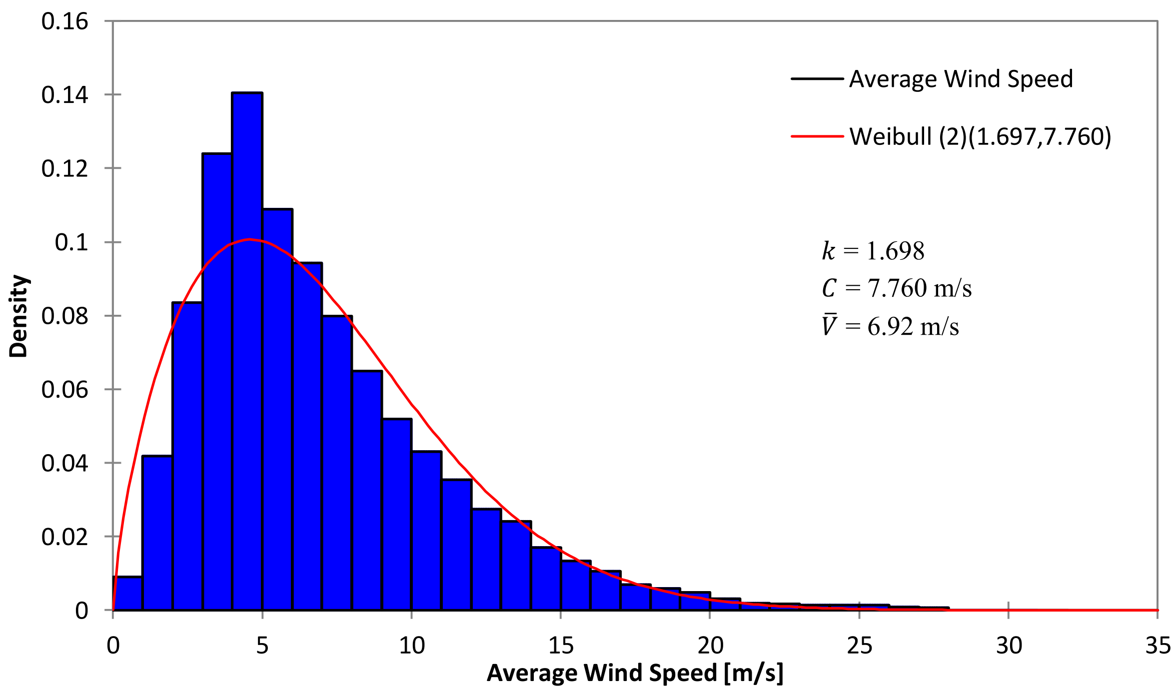


Figure 17 – Weibull fit of the MET Tower data at the wind farm site using *XLSTAT*.

In **Figure 18,** the observations from the MET tower and the Weibull distribution are plotted together as a histogram. The MET data is close to fitting a Weibull distribution, however, theoretically it does not. If statistical tests such as Kolmogorov-Smirnov or Chi-square with very low confidence intervals (e.g. $\alpha = 0.2$) are performed, the hypothesis of the data being Weibull distributed should be rejected. This is the best estimate of k at the site. In the available literature examined for this study, it was not common to see a statistical analysis of

[3] It is a data analysis and statical solution for Microsoft Excel, more infromation can be found on (XLSTAT, n.d.).

the Weibull fit at a given site. It is the industry standard and is known to be a rough estimate that has its limitations. One of the research questions of the study was to look into how the main input variables affect the energy production of the models. Therefore, results for $k = 1\text{–}3$ were recorded in the study, but results for $k = 1.7$ (which is thought to be the best estimate for the site) and $k = 2$ (commonly used value as a first estimate) are analyzed in depth.

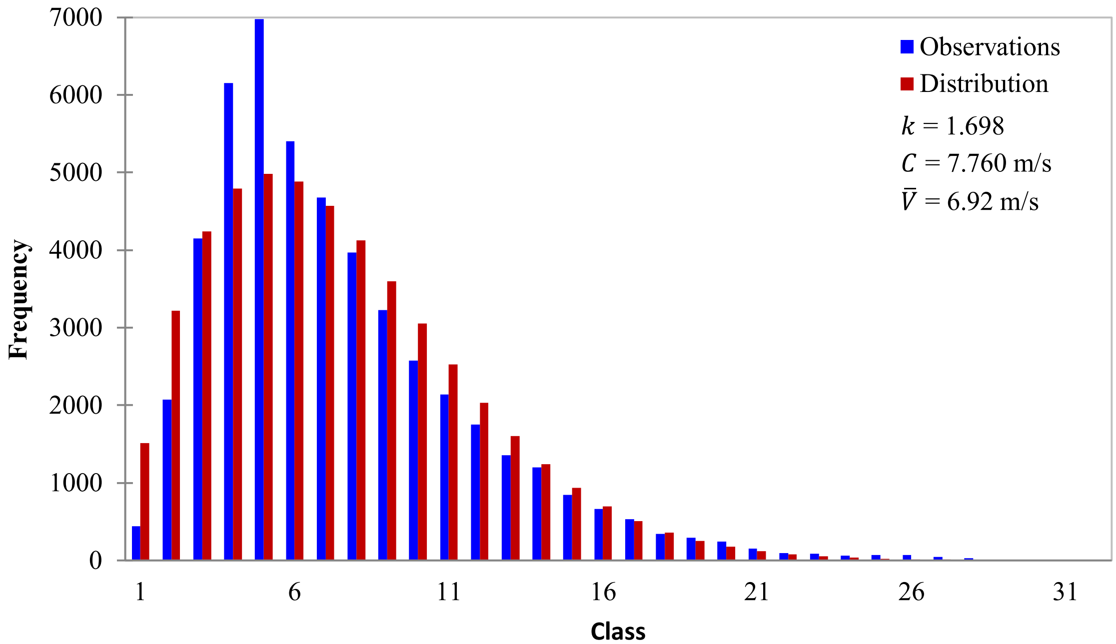


Figure 18 – Observed wind speed frequencies from the MET Tower data and theoretical Weibull distribution using *XLSTAT*.

3.2.3 Wind Shear Coefficient

Average wind shear coefficient $\bar{\alpha}$ over a given period, such as a year, of a given site is usually on the range from 0.10 – 0.40. It is among other factors dependent on the land cover, topography and time of day, short time interval shear can exceed these values. If all other things are constant, the shear usually increases with taller vegetation and obstacles and more complex terrain increases the shear, except in a certain conditions like on exposed ridges and mountain tops, where topographically drive acceleration can lead to a lower shear (Brower, 2012). Like discussed in **Section 3.1,** the topography at the site is complex with few obstacles while no tall vegetation is at the site. In **Table 6,** a list of shear coefficient for similar topographical and vegetation conditions like at the wind farm site is listed from several sources. As can be seen the values vary quite a bit but are in general on the range of 0.15 – 0.25. These are taken from tables from each source that gave a range of topographical and vegetation conditions, the whole tables from each source can be found in **Appendix A**, in **Appendix - Table 1** to **Appendix - Table 5**.

Table 6 - List of shear coefficients for similar topographical and vegetation conditions as at the wind farm site, from several different sources.

Description of terrain and vegetation	α	Source
Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills	0.15	(Jain, 2011)
Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain	0.25	(Jain, 2011)
Complex, ridgeline with low to moderate vegetation	0.15-0.25	(Brower, 2012)
Flat or rolling, with low or moderate vegetation	0.12-0.25	(Brower, 2012)
Hilly, mountainous terrain	0.25	(The Engineering ToolBox, n.d.)
Rough terrain (i.e. With sizeable obstacles)	0.25	(RETScreen, 2005)

Average wind shear coefficient $\bar{\alpha}$ of a given site is commonly calculated from wind speed measurements (v_1 and v_2) at two different measurement heights (h_1 and h_2) of the same anemometer. It can be calculated according to:

$$\bar{\alpha} = \frac{\log\left(\frac{\overline{v_2}}{\overline{v_1}}\right)}{\log\left(\frac{h_2}{h_1}\right)} \qquad \textbf{(Eq. 3-4)}$$

it can vary based on the height intervals used but is most accurate when it fulfills (Brower, 2012):

$$0.5 < \frac{h_2}{h_1} < 2$$

The data from the wind farm in this study did only include wind speed measurements at single height. Calculating α according to **(Eq. 3-3)** was therefore not possible and had to be estimated. Since the wind shear is an engineering approach it should be used with caution. Ideally in commercially used WRA programs, the wind speed measurements used in the wind flow calculations should be at the same height as the hub height of the turbines used. When nothing else is known a common value to start off with and a recommend default value in RETScreen is $\alpha = 0.14$ (RETScreen, 2013d). This will however most likely result in significant error in the energy predictions (Brower, 2012) for most wind farm sites. Wind shear coefficients have been estimated for several sites in the US, calculated annual average values, the two measurements heights and measurement duration can be seen in **Table 7** and **Table 8**. As can be seen they vary a lot and measured values have been found to be 0.11 to 0.35 based on values listed in *Firtin et. al.* (2011) and *Smith et. al.* (2002) and 0.11 – 0.25 based on values listed in *Gipe* (2004). These table values however mostly indicate that the shear coefficient varies significantly based on conditions on site. In *Smith et. al*. (2002) information about topography and vegetation at site is not addressed and therefore these values cannot be used to estimate the wind shear at the wind farm used in this study.

Table 7 - List of shear coefficients for several sites in the US. [1] (Firtin, Guler, & Akdag, 2011) and [2] (Smith, Randall, Malcolm, Kelley, & Smith, 2002).

Location	h_1	h_2	Measurement duration	α	Source
Boulder, CO, USA	10	20	1997-2003	0.11	[1]
Ft. Davis, Texas, USA	25	40	1998-1999	0.11	[2]
Lamar, Colorado, USA	52	113	2001-2002	0.20	[2]
Breckenridge, MN, USA	10	30	1996-2005	0.21	[1]
Big Spring, Texas, USA	40	80	1999-2000	0.21	[2]
Nebraska, USA	40	65	1999-2001	0.22	[2]
Wisconsin, USA	37	123	1999-2001	0.28	[2]
Clarks Grove, MN, USA	10	30	1996-2000	0.28	[1]
Oak Ridge	10	30	2003-2004	0.29	[1]
Iowa, USA	25	50	1999-2001	0.33	[2]
Red Oak, IA, USA	10	33	1995-1997	0.35	[1]

Table 8 - Shear Coefficients for several sites in the US. (Gipe, 2004).

Site	α
Finley, North Dakota	0.25
Block Island, Rhode Island	0.24
Boardman, Oregon	0.23
Huron, South Dakota	0.23
Russel, Kansas	0.20
Clayton, New Mexico	0.19
Minot, North Dakota	0.16
Amarillo, Texas	0.16
San Gorgonio Pass	0.13
Livingston, Montana	0.13
Kingsley Dam, Nebraska	0.13
Bridger Butte, Wyoming	0.11

The wind shear is also very dependent on the time of the day and closely related to the stability of the air. The atmosphere cools during the night, resulting in highly stable conditions and formation of strong turbulence. One of the byproducts of this strong turbulence is noticed within 200 m of the surface as high shear events. On the opposite, during the day the heating of air surface convective air mixing resulting in of low or even negative wind shear (Den Norske Veritas & RISO National Laboratory, 2002). This was can be seen in *Smith et. al.* (2002) where very strong diurnal shear pattern was observed for several sites, at night very positive shear was observed while the opposite and even negative values were observed at the day, this can be seen on **Figure 19**. An annual average is always a very rough estimation.

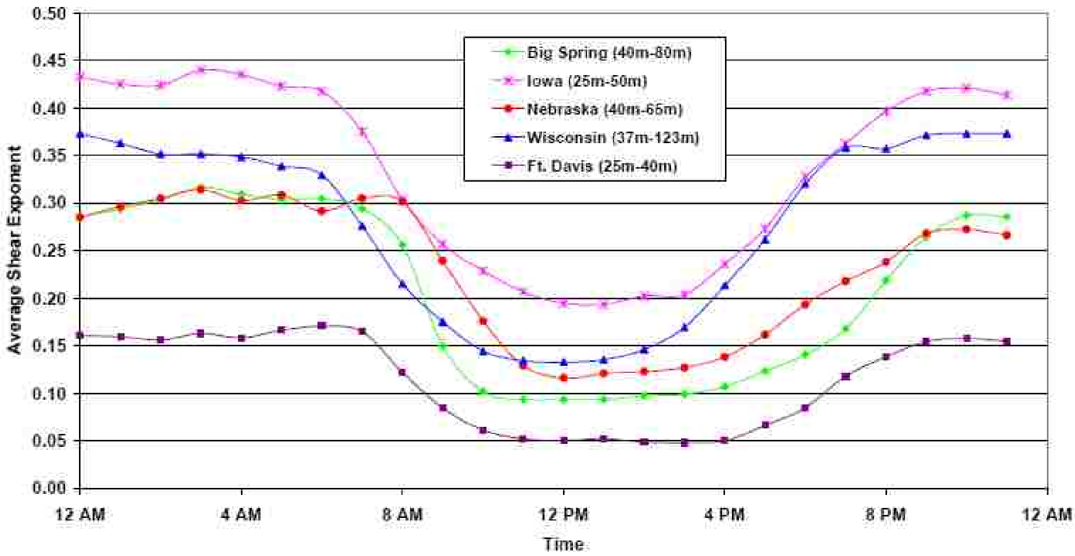


Figure 19 - Shear Coefficients as a function of the hour of the day, for the sites examined in Smith et.al. (2002).

Since hourly wind speed data was available in SAM for different measurement height, it was interesting to see what shear coefficient that would give. In SAM, the wind speed is available at 10, 20, 50, 100 and 200 meters. The wind speed at 200 meters was not used since the turbine hub-height is at 67 meters. The wind shear was calculated according to **(Eq. 3-4)** for the all of the measurements heights (10-20, 20- 50 and 50 – 100 m) and (10-20, 10-50 and 10-100). Then the average of the wind shears was taken, as seen in **Table 9** and **Table 10** below for two weather files at locations, *L1* and *L4* (which will discussed in **Section 3.3.1**).

Table 9 - Shear coefficients based on wind data from SAM for location L1.

	$\alpha_{\text{average (10-20, 20-50, 50-100)}}$	$\alpha_{\text{average (10-20, 10-50, 10-100)}}$
2004_{L1}	0.20	0.23
2005_{L1}	0.19	0.22
2006_{L1}	0.20	0.23
Average$_{L1}$	**0.20**	**0.23**

Table 10 - Shear coefficients based on wind data from SAM for location L4.

	$\overline{\alpha}$ (10-20, 20-50, 50-100)	$\overline{\alpha}$ (10-20, 10-50, 10-100)
2004_{L4}	0.16	0.21
2005_{L4}	0.16	0.20
2006_{L4}	0.16	0.20
Average$_{L4}$	**0.16**	**0.20**

As can be seen from the tables, the wind shear is on the range of 0.20 – 0.23 for location *L1*, and 0.16 – 0.20 for location *L4*. Lastly, annual wind speed average measurement at two heights from a nearby wind farm located in a little less complex topography were used to calculate that wind shear coefficient according to **(Eq. 3-4)** which gave $\alpha = 0.19$. Therefore, all of the calculated values are similar to what typical values based on topography and vegetation in **Table 6** gave.

Based on the table values above as well as the calculated values it was decided to use $\boldsymbol{\alpha = 0.20 - 0.25}$ for the study. It was decided to estimate the wind shear rather on the higher side and on a range rather than as one single value. It is thought to be very likely that the wind shear for the wind farm site is on this range or lower.

3.3 SAM

The version of SAM that was used in this study was SAM 2013.9.20. As the name indicates, it was launched on the 20th of September 2013. Originally the Beta version, released in early July was used, but once the newest version was available, the calculations were updated.

3.3.1 Weather Data Determination

The location of the wind farm is in the west part of the US, west of 100° latitude. The relevant weather database for that location and the one used in the study is the Western Wind Dataset (WWDS), which is discussed in **Section 2.3.1** earlier. To find the weather file that best represents the wind farm the coordinates of the turbines and MET towers were used, as well as coordinates of the weather files in the database, and located on a map using Google™ earth. This is plotted on **Figure 20** below. As can be seen, the wind farm is located on the boundary of two weather cells and there are four weather files that are located closest to the wind farm, notated *L1 – L4*. *L1* and *L4* are however the closest ones and are therefore thought to be the most representative of the wind farm.

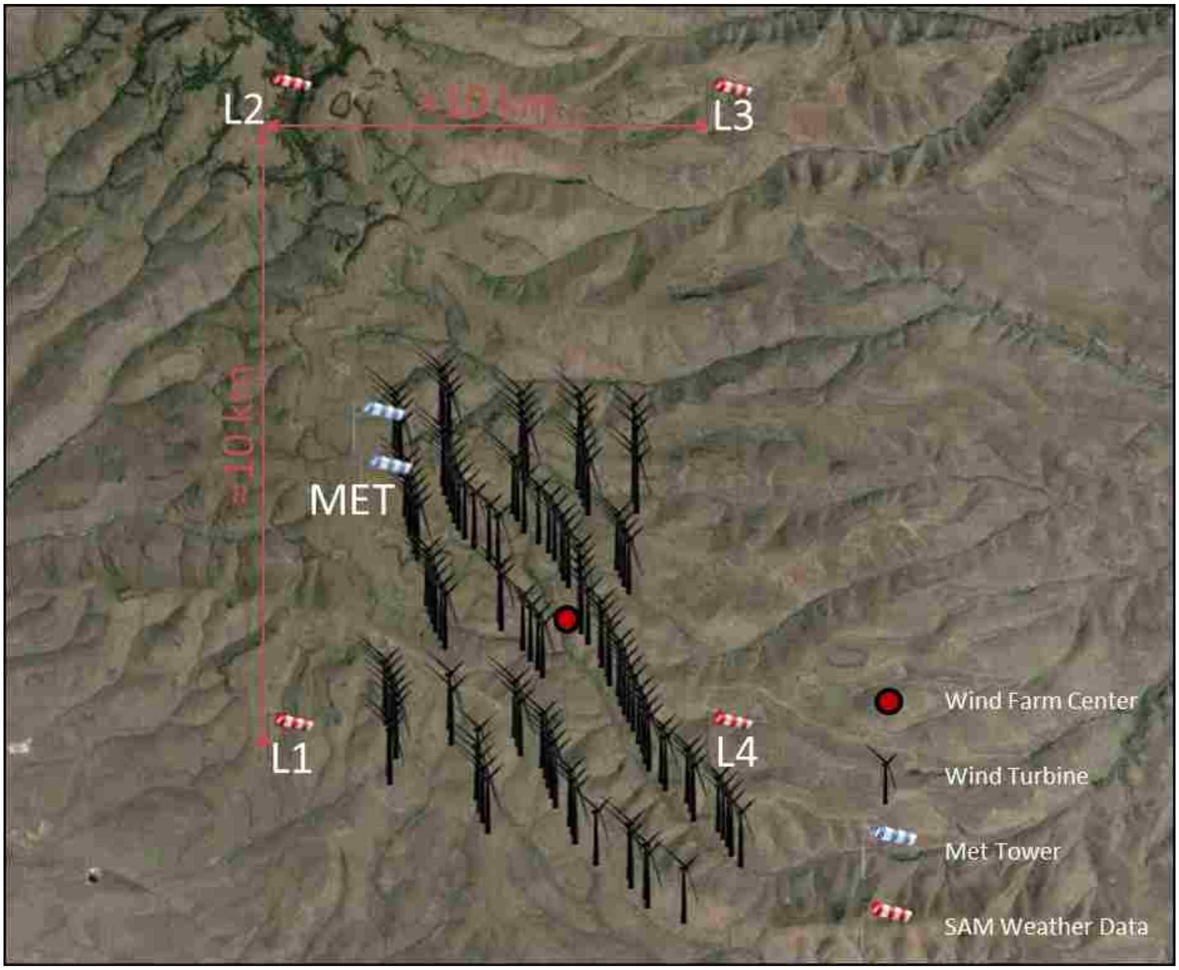


Figure 20 – SAM weather file location and the wind farm layout.

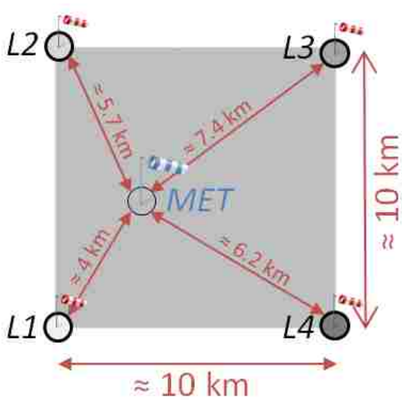


Figure 21 – The relevant weather files in SAM and the MET location.

Initially, the coordinates of the MET tower, located on the upper boundaries of the wind farm were used to find the representative weather file, which gave the weather file for location *L1* since it is the closes to the MET tower as seen on **Figure 21**. However *L4* is just as good to represent the wind farm as seen on

Figure 20 and **Figure 22**, therefore it was decided to use both *L1* and *L4* and do separate analysis for each location. All necessary data for the energy calculations in SAM is available since the weather file is coming from the WWDS. The weather data used in the calculations is wind speed, wind direction and temperature at 50 and 100 meters, as well as atmospheric pressure. Since weather data is available on either side of the turbine height and less the 35 m away from the hub height, the shear coefficient is not used in the calculations but instead linear interpolation.

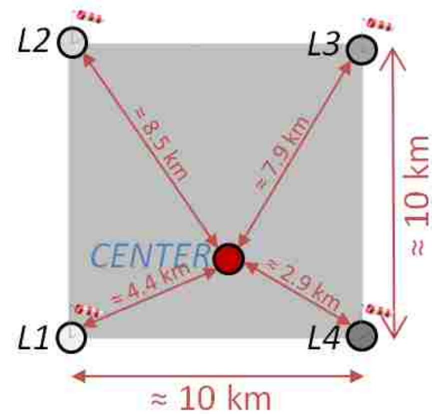


Figure 22 – The relevant weather files in SAM and the Wind farm center location.

Typical weather file was not available for similar topographical conditions as at the wind farm site and therefore not used in the study. A summary of the weather data used in for SAM can be seen in **Table 11**.

Table 11 – Summary of weather data used in SAM.

Dataset	Period and comparison	Comments
WWDS	Average of 2004, 2005 and 2006 $\mu \pm \sigma$ compared to average of wind farm	Two locations, *L1* and *L4* analyzed.

3.3.2 Turbine Layout

The turbine layout of the wind farm was defined in X and Y coordinates on a CSV format to use in SAM. The coordinates of the turbines were taken from Google™ earth and converted into the UTM system using WGS84 projection. This was then prepared in Excel on CSV format and uploaded to SAM.

3.3.3 Wake Loss Calculations

As discussed in **Section 2.3.2** there are three wake models available in SAM, *Simple Wake Model* (the Pat Quinlan model), the *Eddy-Viscosity Model* and the *Park Model (WAsP)*. The first model is very simple, it is the first wake model that was integrated in SAM and is not commonly used in commercially used wind design software, while the latter two both are. Both the Simple Wake Model and the Eddy-Viscosity Model are a function of turbulence intensity (TI) which is defined as:

$$TI = \frac{\sigma}{v_{avg}} \quad \textbf{(Eq. 3-5)}$$

where $v_{average}$ is the average wind speed and σ is the standard deviation of the wind speed. Most often this is based on 10 minutes observations at site. TI is simple a measure of the stability of the air. As a rule of thumb, a value of 0.1 or less is considered low turbulence, the range 0.1 < TI < 0.25 is considered moderate, and 0.25 or larger is higher turbulence (Jain, 2011). For smooth terrain and little vegetation, a typical value might be around 0.1 while for areas with air mixing caused by thermal effects the value might be 0.5 (System Advisor Model Version 2013.9.20, 2013). As no data was available about the TI at the site it was decided to use the Park Model which is not a function of TI, instead of the other two. This was mostly done to decrease the number of variables in the analysis that needed to be determined. The Park Model however requires a decay factor l. This is an empirical factor that varies from 0.04 to 0.075, the lower value are experienced at sites which produce longer-lived wakes while higher produce wakes that decay faster (Brower, 2012). In SAM, l is not user defined and the default value was used. SAM does not account for any topography and assumes that the wake farm is located on a flat surface, which is a clear limitation.

3.4 Common Inputs for Both Models

Several input variables were common for both programs, when that was the case they were selected the same to allow for as a good comparison between the models as possible. These included the definition of the turbine characteristics and the wind farm losses.

3.4.1 Turbine Characteristics

One of the most important input variables to define is the turbine characteristics. This is done by identifying the turbine power curve. Both RETScreen and SAM have integrated product databases that have information for many well established manufactures in the industry. Both models included power curve for the same turbine type as are on site, VESTAS V80 – 1.8 MW.

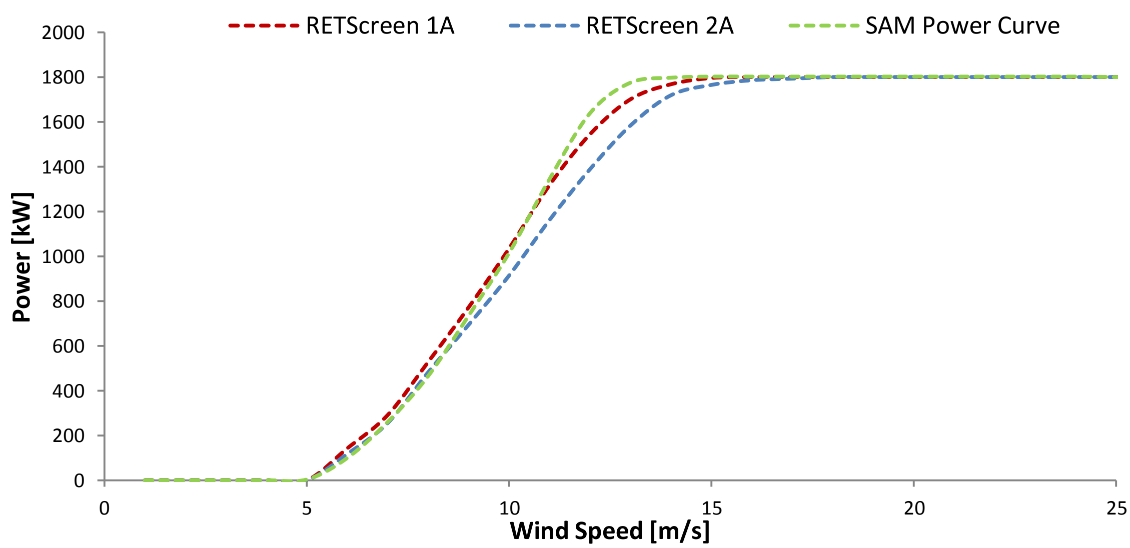


Figure 23 – The power curves from RETScreen and SAM for VESTAS V80-1.8MW 1A/2A.

In RETScreen, two different types, 1A and 2A are available. Since it was not possible to get more detailed information about the turbine at the wind farm site it was decided to run analysis for both types. As can be seen on **Figure 23** there is a minor difference in the power curve for 1A and 2A where the latter mentioned has a slight lower power curve. It can also be seen that the power curve for 1A and the power curve from SAM coincide much better.

Therefore, it was decided to use the 2A turbine as the primary one for comparison but also do the same analysis using the 1A turbine, which is though mostly listed in appendix. Ideally exact information of which turbine type is used at the site would have been available. The power curve should be the same for the two different models since it should be based on manufacturers' data, but there is a noticeable minor difference between the models.

3.4.2 Wind Farm Losses

Several different operational losses can be expected in a wind farm. There has been a tendency to underestimate losses in energy production estimation in preconstruction studies, "In North America, the overestimation [of AEP] averaged around 10% for project built up to 2008 (Brower, 2012, p. 245)". The following is a description of the most common loss categories and typical range of values for each can be found in **Table 12**. They are listed as a percentage of the gross energy production based on values from real projects and obtained from three sources; *Jain* (2011), *Brower* (2012) and *RETScreen* (2013d). The values coming from the RETScreen Software are mostly from relatively old sources (e.g. from 1994) and might not be as relevant today. In the SAM help manual, neither information nor guidelines are given about the ranges of the losses. Each project is different and therefore the losses can vary based on conditions at each site, however these values should give a range of what might be expected. In *Jain* (2011), it is said that in preliminary wind resource assessment, it is common to use a loss estimate of 10% as a placeholder. In this study however, a more accurate estimation was attempted.

Wake Effects/Array Losses

The wake effects or array losses are the losses effected by the reduced wind speed that occurs downstream of a wind turbine and varies based on the layout of the wind farm (Jain, 2011).

Commonly wind turbines have a minimum of 6 rotor diameter spacing in the prevailing wind direction to minimize these losses (Brower, 2012). This is a very important topic in wind resource assessment and most commonly the largest loss category. Several wake models in WRA programs can be used to calculate wake losses as discussed in **Section 2.3.2**. In the study, this was calculated in SAM using the Park Wake model and the same percentage used in RETScreen to keep the comparison between the models as accurate as possible. As seen on **Table 12** this usually ranges from 3 - 15%.

Downtime/Availability

This is the loss of the energy due to the plant not being available even though the wind resource is. This can be because some of the turbines are out or even the whole wind farm. This includes unscheduled or scheduled maintenance as well as the grid not being available (Jain, 2011). As seen in **Table 12** this usually ranges from 2 - 10%. Information about the availability of the wind farm in this study was available and used.

Electrical Losses

The difference in the electricity produced at the turbine generator and what is delivered to the electrical grid is due to electrical losses. This can be experienced in any electrical component of the system e.g. transformers, collection system and internal power consumption (Brower, 2012). These losses are however typically low or on the range of 2-4% as seen on **Table 12**. It was not known if the data that was given for this study is the energy production at generators or the electricity delivered to the grid. It was however decided to account for these losses in the study as will be discussed later.

Turbine Performance Losses

This is the decrease in the production based on aerodynamic, mechanical and electrical performance of the turbine as well as high wind hysteresis. The first two mentioned can be lumped together and called power curve losses, which are due to "soiling of blades, deterioration in performance of the gearbox and other mechanical components and the generator (Jain, 2011, p. 161)". Secondly, when the wind speed exceeds the cutoff speed, the wind turbine will shut down and will not restart until the wind speed drops a certain amount below the cut-off speed (Jain, 2011). For VESTAS V90 the cut out speed is 25 m/s and the turbine will not restart until the speed drops below 20 m/s (NREL, 2012b). There is also evidence that turbines do not always reach their advertised power curves (Brower, 2012). The site used in the study experiences high wind speeds, this was accounted for as discussed later.

Environmental Losses

This loss category is rather broad and includes losses as accumulation of ice on wind turbine blades, blade soiling and degradation, extreme weather conditions, seasonal activity such as migratory birds etc. lightning strikes and change in roughness because of growth (Brower, 2012 and Jain, 2011). The site used in the study experiences some losses due to ice on blades and some extreme weather conditions; this was accounted for and is discussed later.

Curtailments

The energy production of a wind farm may be curtailed due to grid constraints to help manage the transmission grid or manufacturer requirements. This can vary a lot based on the grid operator and therefore varies between projects. As the wind penetration on the grid increases plant-level curtailments are becoming more common and can well exceed the high range in **Table 12** (Jain, 2011). It is known that curtailments at the wind farm used in this study are very low and therefore neglected in the study.

Table 12 – Typical values for several loss categories based on three different sources.

Source	(Brower, 2012)			(Jain, 2011)			(RETScreen, 2013d)[4]		
Loss Category	***Low***	***Typical***	***High***	***Low***	***Mean***	***High***	***Low***	***Mean***	***High***
Wake Affects[%]	3	6.7	15	5	10	15	0	10	20
Availability[%]	2	6	10	2	3.5	5	2	4.5	7
Electrical[%]*	2	2.1	3	2	3	4	-	-	-
Turbine Performance[1][%]	0	2.5	5	1.5	3.3	5	1	5.5	10
Environmental[2][%]	1	2.6	6	1	2	3	2	4	6
Curtailment[%]*	0	0	5	1	2	3	-	-	-
Total Losses [%]	**7.8**	**18.5**	**37**	**11.9**	**21.3**	**30.7**	**4.9**	**21.0**	**37.1**

[1] It is called airfoil losses in RETScreen, based on the description it is thought to be comparable.
[2] Environmental losses are called miscellaneous losses in RETScreen, based on description it is thought comparable.
*Curtailment and Electrical losses are not discussed in RETScreen.

The first two loss categories listed in **Table 12** are accounted for by using the Park wake model in SAM as well as availability data from the wind farm. Curtailment assumed to be negligible while electrical losses, turbine performance and environmental losses had to be estimated. The quantification is rather subjective since no information is available except the fact that the site experiences extreme weather, some losses due to ice and so forth. It was decided to use the values from **Table 12**. If the average is taken from *Jain* (2011) and *Brower* (2012) for each loss category and the losses then chained together according to **(Eq. 2-16)**, they are found to be 3.7% on the low side, 7.5% for a typical and 12.5% as a upper bound. Therefore, it was decided to run a couple of different loss scenarios that give the energy prediction over a range of losses rather than one single value. Four different scenarios were analyzed as listed below:

[4] Values from RETScreen are based on old sources which might not be as relevant today, they are however listed

- **Scenario 1 (*S1*):** Gross Energy Production, all losses neglected.
- **Scenario 2 (*S2*):** Accounting for wake losses calculated in SAM (kept the same percentage in RETScreen) and availability based on operational data.
- **Scenario 3 (*S3*):** Accounting for wake losses and availability as in *S2* but adding additional 5% losses to account for low-typical losses due to environmental, turbine performance and electrical factors.
- **Scenario 4 (*S4*):** Accounting for wake losses and availability as in *S2* but adding additional 10% losses to account for typical-high losses due to environmental, turbine performance and electrical factors.

The four loss scenarios are summed up in **Table 13** below.

Table 13 – The Four Loss Scenarios of the study, S1 – S4.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wakes and PA	×	✓	✓	✓
Additional 5%	×	×	✓	-
Additional 10%	×	×	×	✓

To make the comparison between the two models as accurate as possible it was decided to use the wake losses calculated by SAM in RETScreen as a percentage number.

3.4.3 Comparison with Wind Farm Data

For SAM, both monthly and annual energy production was compared to the wind farm data. Since SAM has data available for three years 2004, 2005 and 2006 for the WWDS it was decided to take the average of these three according to **(Eq. 3-1)** as well as calculating the standard deviation and coefficient of variation according to **(Eq. 3-2)** and **(Eq. 3-3)**. Then $\overline{E_{SAM}} \pm \sigma$ was compared to $\overline{E_{WF}} \pm \sigma$. As well the average wind speed, $\overline{v_{SAM}} \pm \sigma$ from the weather files in SAM for 2004, 2005 and 2006 was compared to the wind speed at the MET tower, v_{MET}. The difference d between the measured values from the wind farm and predicted values by SAM for both energy production and wind speed was calculated according to:

$$d = \frac{Model - Wind\ Farm}{Wind\ Farm} \cdot 100 \qquad \textbf{(Eq. 3-6)}$$

Positive number indicates overestimation by the model, while negative one implies underestimation by the model compared to the actual wind farm values.

For RETScreen, only annual energy was calculated according to Method 3, (i.e. using monthly averages of wind speed, pressure and temperature) as so many input variables were kept on a range, and therefore several values were recorded. The difference was calculated as for SAM according to **(Eq. 3-6)**.

3.5 Summary of Input Data for both Models

Table 14 summarizes the input data for both RETScreen and SAM. The selection of the input data was kept the same for the models when possible, to assure inaccurate and fair comparison between the two models.

Table 14 - Summary of input data for RETScreen and SAM.

Variable	RETScreen	SAM	Comments
Weather Data	NASA web data for two different Cells, *C1* and *C2*.	WWDS for two closes locations, *L1* and *L4*.	
Shape Coefficient k	Recorded for $k = 1 - 3$ but $k = 1.7$ (based on Weibull fit for MET data) and $k = 2$ (default value) analyzed comprehensively.	Does not apply	
Wind Shear Coefficient	Recorded for the range $\alpha = 0.20 - 0.25$.	Does not apply	
Turbine Layout	Does not apply.	Coordinates from Google Earth converted to UTM system with WGS-84 projection.	
Wake Losses	Set the same percentage as in SAM.	Park Model.	Park Model doesn't account for any topography.
Turbine Characteristics	VESTAS V80 – 1.8MW 1A/2A (1A primarily).	VESTAS V80 – 1.8 MW	There was slight difference on the power curves in SAM and RETScreen, 1A similar to SAM power curve and therefore used.
Wind Farm Losses	Four Scenario; **S1:** Gross Energy Production **S2:** Wakes and Availability **S3:** Additional 5% on top of S2. **S4:** Additional 10% on top of S2.	Same as RETScreen.	Availability based on wind farm data, wakes calculated but other losses assumed.

3.6 Limitations

The wind speed from the MET tower is from 2011 while RETScreen has wind speed for typical year and SAM for 2004, 2005 and 2006. The wind speed can vary a lot between the same months of different years. Therefore a direct comparison between the MET wind speed and the ones from the models is not feasible. However, the annual average wind speed should give an idea about how good the weather data in the models is compared to on-site data.

The operational data for the wind farm is available for the period 2007 – 2011 while it can be calculated in SAM for 2004, 2005 and 2006. Ideally they should cover the same time period.

That was however not available, by averaging the data over the period and using $\pm\sigma$ as a measure of uncertainty and comparing it like that over a range is thought to give a fairly good indication of "typical" AEP at site. Since RETScreen has data for a typical year, comparing that to an average over a 5 year period is very relevant.

That exact information about the subtype of the turbine of site was not available increase the uncertainty in the study, however be recording the values for both turbine types that is minimized.

Several input variables had to be estimated very broadly based on relatively limited data such as the shear coefficient and wind farm losses. This was however estimated based on available references as possible and by using these values over a range rather than single values it decreases the uncertainty in the study.

4 Results

The following chapter contains the results of the study, mostly in the form of graphs and tables. Additional numerical data is listed in Appendix as necessary.

4.1 Wind Farm Data

The first sets of results are from the analyzed data for the wind farm. This includes the wind speed for the MET tower in 2011, availability and average energy production over the five year period, 2007-2011.

4.1.1 Wind Speed

Figure 24 shows the monthly and annual average wind speed at the MET Tower for the year 2011. Since the data was only available for one year, the standard deviation was not calculated. The wind speed varies between months, with the highest wind speed in April, at 8.4 m/s, and the lowest in September and November at 5.9 m/s. The annual average wind speed is 6.9 m/s.

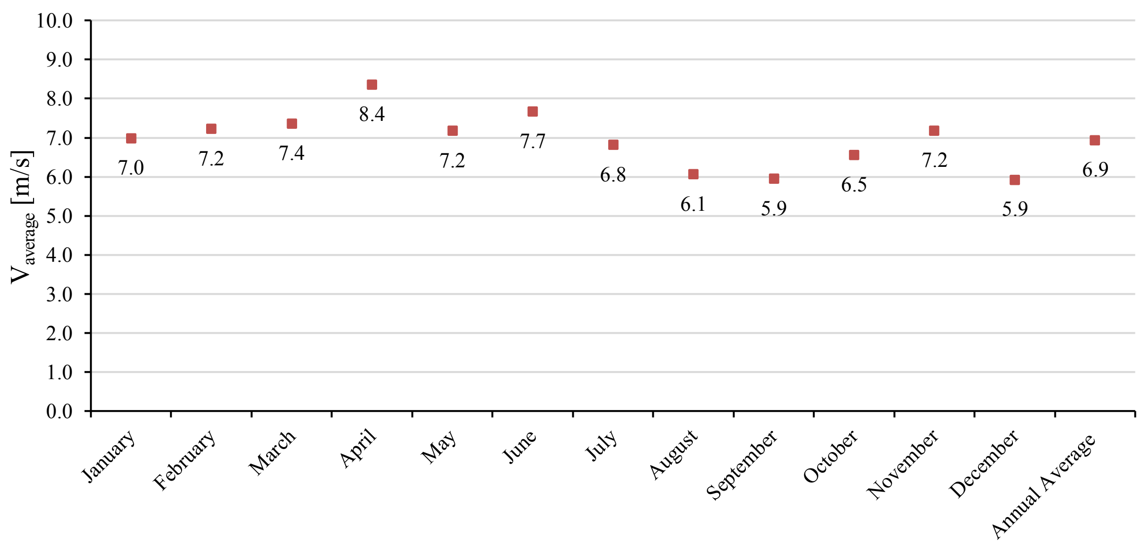


Figure 24 – Average monthly and annual wind speeds from the MET Tower for the year 2011.

4.1.2 Availability

The average monthly and annual availability of the wind farm from 2007 – 2011 ± one standard deviation can be seen on **Figure 25**. Since the values are all in the range of 95% - 100%, the y-axis was defined from 95 – 100%.

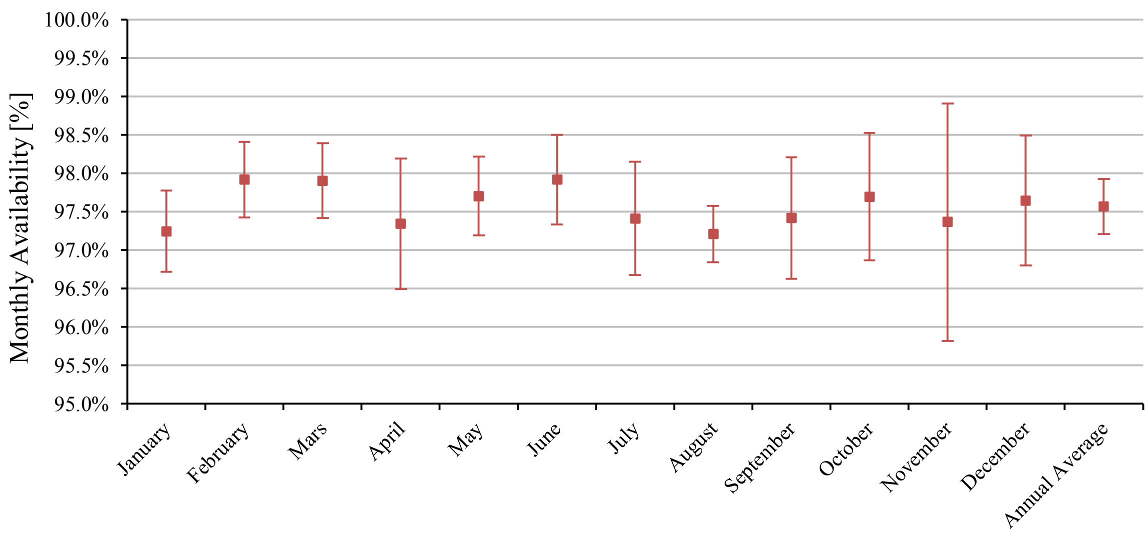


Figure 25 – Average monthly availability 2007 – 2011, ± one standard deviation with y-axis from 95 – 100%.

The annual average availability of the wind farm over the five year period is:

$$\bar{\lambda}_{WF} \pm \sigma = \mathbf{97.6} \ \pm \mathbf{0.4}\ \% \qquad \textbf{(Eq. 4-1)}$$

Therefore, the losses due to availability of the wind farm are only 2.4±0.4%.

4.1.3 Energy production

Figure 26, shows $\overline{E_{WF}} \pm \sigma$ for the MEP. In **Table 15** the monthly and annual production of the wind farm from 2007 – 2011 as well as $\bar{E}_{WF}, \sigma_{WF}$ and C_v are listed.

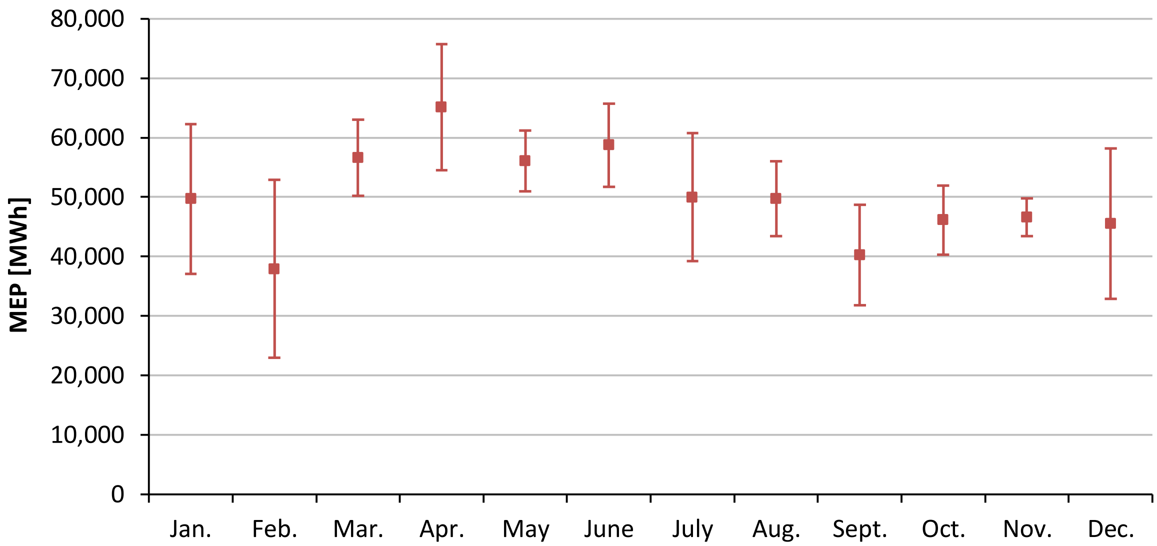


Figure 26 – Average monthly production 2007 – 2011 ± one standard deviation.

Table 15 – Monthly production 2007 – 2011 for the wind farm as well as, monthly average, standard deviation and coefficient of variation.

	2011 [MWh]	2010 [MWh]	2009 [MWh]	2008 [MWh]	2007 [MWh]	$\bar{E}_{WF}$ [MWh]	σ_{WF} [MWh]	C_v
January	59,853	26,377	58,027	57,896	46,268	**49,684**	**12,612**	**25%**
February	47,954	15,046	30,698	58,982	36,811	**37,898**	**14,973**	**40%**
Mars	51,723	46,583	63,934	59,883	61,008	**56,626**	**6,452**	**11%**
April	75,048	75,169	57,766	69,554	48,059	**65,119**	**10,624**	**16%**
May	55,317	53,161	60,833	62,610	48,639	**56,112**	**5,093**	**9%**
June	68,251	49,428	52,017	63,021	60,992	**58,742**	**7,011**	**12%**
July	57,032	43,286	35,067	66,150	48,299	**49,967**	**10,782**	**22%**
August	44,416	52,841	40,758	58,144	52,559	**49,744**	**6,280**	**13%**
September	39,571	42,987	30,661	33,447	54,682	**40,270**	**8,420**	**21%**
October	51,882	35,680	45,117	46,831	51,187	**46,139**	**5,820**	**13%**
November	45,587	45,267	49,505	50,834	41,988	**46,636**	**3,176**	**7%**
December	38,941	45,993	25,790	54,746	62,360	**45,566**	**12,661**	**28%**
Annual	**635,575**	**531,818**	**550,173**	**682,097**	**612,851**	602,503	55,265	9%

The annual average production of the wind farm over the five year period is:

$$\bar{E}_{WF} \pm \sigma = \mathbf{603} \pm \mathbf{55}\ \boldsymbol{GWh} \quad \textbf{(Eq. 4-2)}$$

C_v is high for some of the months, e.g. January, February and December or 25%, 40% and 28% respectively, the C_v is much lower for the annual average or 9%. Some values in the operational data are thought to be suspicious such as February in 2010, when the MEP was only 15,046 MWh. No criteria were established to neglect specific values.

4.2 RETScreen

In this section, the results for analyses involved using the two relevant weather locations for RETScreen; *C1* and *C2* are listed. Wind speed and energy output predictions were compared to the operation data, since several input variables were kept on a range only the AEP was calculated.

4.2.1 Wind Speed

The average wind speed of *C1* and *C2* was compared to the wind speed from the MET in 2011. Since the wind data from the database is at 10 m height the wind speed at hub height was calculated using the power law according to **(Eq. 2-10)**. The wind speed is therefore a function of the shear coefficient α on the range of 0.20 – 0.25.

CELL 1 (C1)

In **Table 16,** the wind speeds from weather cell *C1*, as a function of the shear coefficient, are listed at a turbine hub height of 67 m. The wind speed at 10 m measurement height is low or only 3.2 m/s which results in 4.7 m/s at hub height for $\alpha = 0.20$ and 5.2 m/s for $\alpha = 0.25$.

Table 16 - Wind Speed [m/s] as a function of the shear coefficient at 67 m hub height and database values at 10 m measurement height for *C1*.

Height [m] *Month/α*	10	67 0.20	67 0.21	67 0.22	67 0.23	67 0.24	67 0.25	67 $\overline{v}_{2011,MET}$ [m/s]
January	3.51	5.13	5.23	5.33	5.44	5.54	5.65	6.98
February	3.33	4.87	4.97	5.06	5.16	5.26	5.36	7.21
March	3.19	4.67	4.76	4.85	4.94	5.04	5.13	7.35
April	3.10	4.53	4.62	4.71	4.80	4.89	4.99	8.35
May	2.86	4.18	4.26	4.35	4.43	4.51	4.60	7.16
June	3.01	4.40	4.49	4.57	4.66	4.75	4.84	7.66
July	3.02	4.42	4.50	4.59	4.68	4.77	4.86	6.80
August	3.07	4.49	4.58	4.67	4.75	4.85	4.94	6.06
September	3.24	4.74	4.83	4.92	5.02	5.11	5.21	5.94
October	3.22	4.71	4.80	4.89	4.99	5.08	5.18	6.55
November	3.59	5.25	5.35	5.46	5.56	5.67	5.78	7.18
December	3.38	4.94	5.04	5.14	5.23	5.34	5.44	5.92
Annual	**3.21**	**4.70**	**4.79**	**4.88**	**4.97**	**5.07**	**5.16**	**6.93**

Figure 27 shows the difference d between the monthly MET tower wind speed and the RETScreen values for $\alpha = 0.20$ and $\alpha = 0.25$ respectively, calculated according to **(Eq. 3-6)**. All of the months are lower in RETScreen, and underestimated in the range of 16% - 46% for $\alpha = 0.20$ and 8% - 40% for $\alpha = 0.25$. In **Figure 28**, the difference for the annual average wind speed as a function of $\alpha = 0.20 - 0.25$ is plotted. As for the monthly values, the wind speeds from RETScreen are much lower than at the MET tower, and the annual average wind speed is 32% lower for $\alpha = 0.20$ and 25% lower for $\alpha = 0.25$.

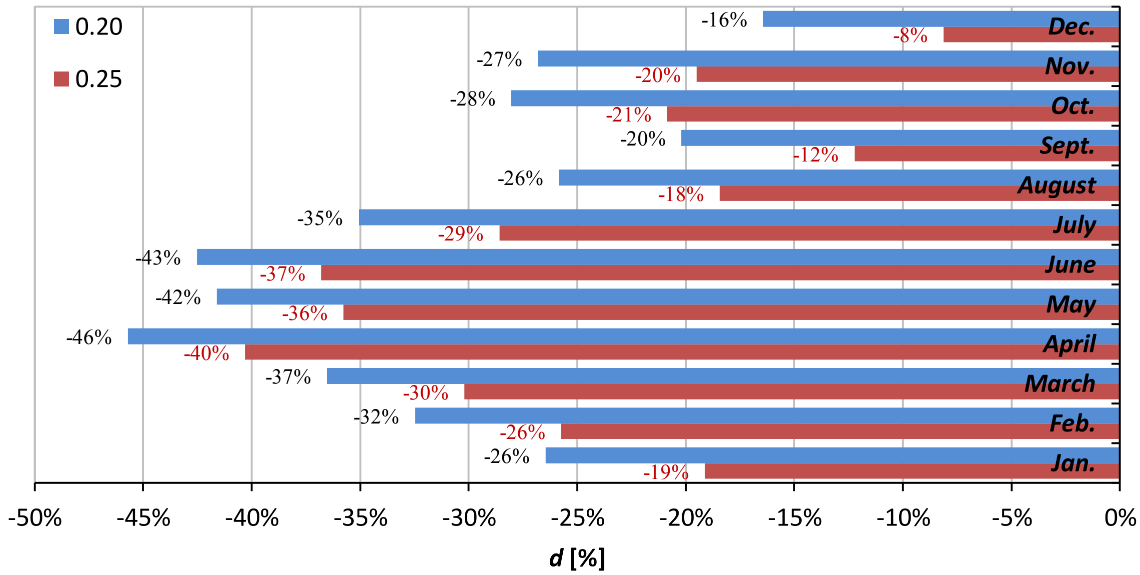


Figure 27 – The difference *d*, between monthly wind speed in RETScreen (C1) and the MET tower data, for shear coefficients of $\alpha = 0.20$ and $\alpha = 0.25$.

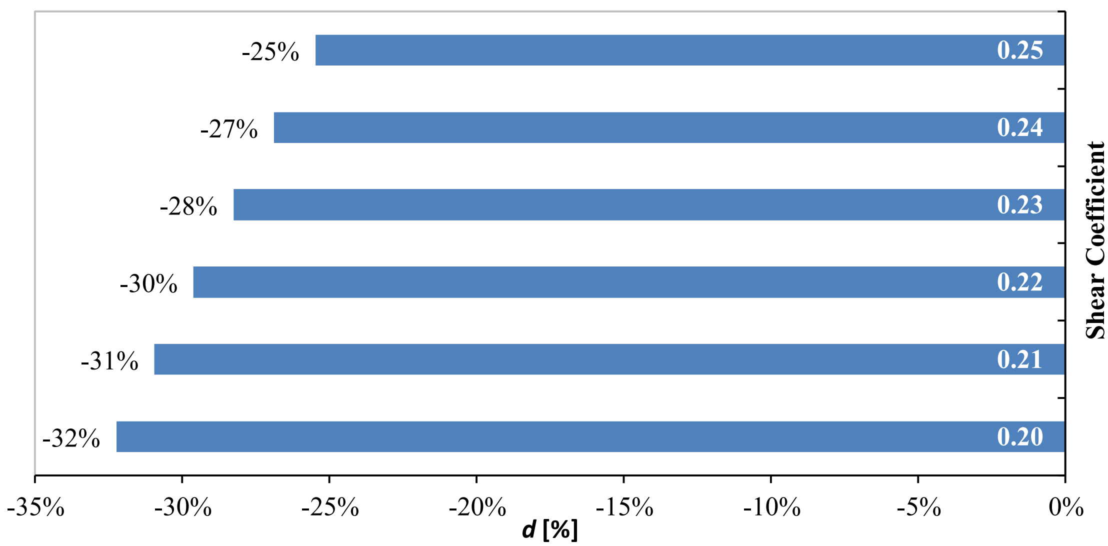


Figure 28 – The difference *d*, between the annual average wind speed in RETScreen (C1) and the MET tower data in 2011, for shear coefficient of 0.20 - 0.25.

CELL 2 (C2)

In **Table 17**, wind speeds for weather cell *C2* as a function of the shear coefficient are listed. The wind speed at 10 m measurement height is low or only 3.6 m/s. This results in 5.3 m/s wind speed at 67 m hub height for $\alpha = 0.20$ and 5.83 m/s wind speed for $\alpha = 0.25$.

Table 17 - Wind Speed [m/s] as a function of the shear coefficient at 67 m hub height and database values at 10 m measurement height for C2.

Height [m] / *Month/α*	10	67 0.20	67 0.21	67 0.22	67 0.23	67 0.24	67 0.25	67 $\overline{v}_{2011,MET}$ [m/s]
January	4.10	6.00	6.11	6.23	6.35	6.47	6.60	6.98
February	3.90	5.71	5.81	5.93	6.04	6.16	6.27	7.21
March	3.60	5.27	5.37	5.47	5.58	5.68	5.79	7.35
April	3.50	5.12	5.22	5.32	5.42	5.52	5.63	8.35
May	3.20	4.68	4.77	4.86	4.96	5.05	5.15	7.16
June	3.30	4.83	4.92	5.01	5.11	5.21	5.31	7.66
July	3.30	4.83	4.92	5.01	5.11	5.21	5.31	6.80
August	3.40	4.97	5.07	5.17	5.27	5.37	5.47	6.06
September	3.50	5.12	5.22	5.32	5.42	5.52	5.63	5.94
October	3.60	5.27	5.37	5.47	5.58	5.68	5.79	6.55
November	4.20	6.14	6.26	6.38	6.50	6.63	6.76	7.18
December	3.90	5.71	5.81	5.93	6.04	6.16	6.27	5.92
Annual	**3.63**	5.30	5.40	5.51	5.61	5.72	5.83	**6.93**

Figure 29 shows the difference between the monthly MET tower wind speed and the RETScreen values for *C2* for $\alpha = 0.20$ and $\alpha = 0.25$ respectively. December is the only month in which it is higher in RETScreen, and the difference is on the range of 4% - 39% for $\alpha = 0.20$ and -6% $-$ +33% for $\alpha = 0.25$. **Figure 30** shows the difference for the annual average wind speed as a function of $\alpha = 0.20 - 0.25$. The wind speeds from RETScreen are a lot lower than at the MET tower, annual average wind speed is 23% lower for $\alpha = 0.20$ and 16% lower for $\alpha = 0.25$.

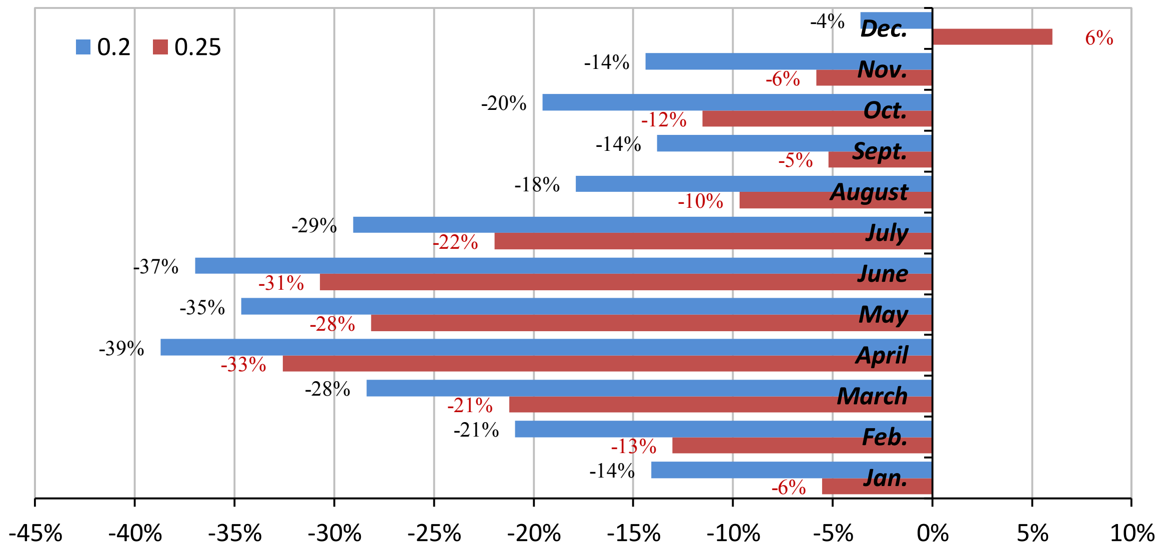


Figure 29 – The difference between monthly wind speed in RETScreen (C2) and the MET tower data in 2011 for shear coefficient of 0.20 and 0.25.

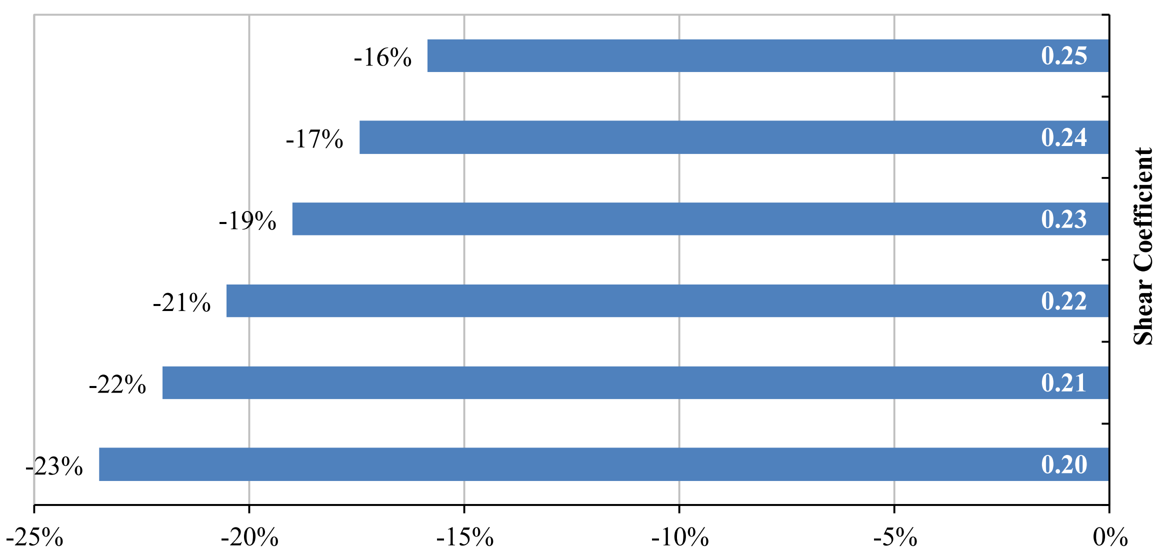


Figure 30 – The difference between the annual average wind speed in RETScreen (C2) and the MET tower data in 2011, for shear coefficient of 0.20 - 0.25.

Comparison of C1 and C2

Table 18 shows a comparison between the two weather cells used, *C1* and *C2*. The wind speed in *C2* is roughly 0.4 m/s higher (12%) than in *C1*. For $\alpha = 0.25$, the wind speed at hub height is roughly 5.16 m/s at *C1* compared to 5.83 m/s at *C2*, both wind speeds are low compared to the MET tower data or 25% and 16% lower respectively.

Table 18 - Comparison of the weather cells in RETScreen, C1 and C2 and difference from the MET tower data.

Height [m]	α	CELL 1 [m/s]	Difference	CELL 2 [m/s]	Difference
10		3.21		3.63	
67	0.20	4.70	-32%	5.30	-23%
67	0.21	4.79	-31%	5.40	-22%
67	0.22	4.88	-30%	5.51	-21%
67	0.23	4.97	-28%	5.61	-19%
67	0.24	5.07	-27%	5.72	-17%
67	0.25	5.16	-25%	5.83	-16%

4.2.2 Predicted Energy Production

The predicted energy production for the two weather datasets *C1* and *C2* using RETScreen was compared with the average operational data from the wind farm over the five year period. Only an annual comparison was performed, but for two wind turbine types VESTAS V80 1.8MW 1A and 2A. Results for turbine type 1A are listed here while the results for 2A are listed in **Appendix B**.

Weather File C1

In **Table 19** below, the AEP as a function of $\alpha = 0.20 - 0.25$ and $k = 1.7$ and $k = 2.0$ for all loss scenarios *S1* – *S4* are listed. In **Table 20**, the difference d between the RETScreen predictions and the wind farm average AEP can be seen. The AEP for $\alpha = 0.25$ is 361,240 MWh and 335,377 MWh for $k = 1.7$ and $k = 2.0$ respectively. This is substantially lower than the average calculated AEP for the wind farm which is 602,503 MWh. This leads to a roughly 40% and 44% underestimation for $k = 1.7$ and $k = 2.0$ respectively neglecting losses while it is 52% and 55% for loss scenario *S4*, i.e. accounting for all losses. In **Table 21**, the difference d range can be seen for $k = 1.7$ based on $\pm\sigma$ of the wind farm. The underestimation is in the range of [-34%; -45%] for α = 0.25 and [-48%; -56%] for α = 0.20 in both cases assuming no losses. If *S4* is examined, the difference is in the range of [-47%; -

56%] for α = 0.25 and [-58%; -65%] for α = 0.20. Therefore, RETScreen is underestimating the AEP substantially. In **Appendix B**, detailed tables (**Appendix - Table 6** to **Appendix - Table 9**) list the AEP as a function of the shear coefficient in the range of 0.20 – 0.25 and for $k = 1 - 3$ for each of the four loss scenarios.

Table 19 –RET Screen's AEP predictions for k=1.7 and k=2.0. Weather file C1 and turbine type 1A used.

	k = 1.7				k = 2.0			
α	*S1 [MWh]*	*S2 [MWh]*	*S3 [MWh]*	*S4[MWh]*	*S1[MWh]*	*S2[MWh]*	*S3[MWh]*	*S4[MWh]*
0.20	287,103	255,834	243,042	230,251	258,368	230,229	218,717	207,206
0.21	300,141	267,452	254,079	240,707	271,742	242,146	230,039	217,931
0.22	315,842	281,443	267,371	253,299	287,923	256,565	243,736	230,908
0.23	330,465	294,473	279,750	265,026	303,067	270,059	256,556	243,053
0.24	345,692	308,042	292,640	277,238	319,020	284,275	270,061	255,847
0.25	361,240	321,897	305,802	289,707	335,377	298,850	283,908	268,965

Table 20 – The difference *d* between the RETScreen predictions and the wind farm data for C1 and 1A for k=1.7 and k=2.0.

	k = 1.7				k = 2.0			
α	*S1 [%]*	*S2 [%]*	*S3 [%]*	*S4 [%]*	*S1 [%]*	*S2 [%]*	*S3 [%]*	*S4 [%]*
0.20	-52.3	-57.5	-59.7	-61.8	-57.1	-61.8	-63.7	-65.6
0.21	-50.2	-55.6	-57.8	-60.0	-54.9	-59.8	-61.8	-63.8
0.22	-47.6	-53.3	-55.6	-58.0	-52.2	-52.7	-59.5	-61.7
0.23	-45.2	-51.1	-53.6	-56.0	-49.7	-55.2	-57.4	-59.7
0.24	-42.6	-48.9	-51.4	-54.0	-47.1	-52.8	-55.2	-57.5
0.25	-40.0	-46.6	-49.2	-51.9	-44.3	-50.4	-52.9	-55.4

Table 21 – The range of the difference *d* between RETScreen's predictions and wind farm data based on ±σ for the wind farm data. This is for k = 1.7 and 1A turbine in weather cell C1.

	S1	S2	S3	S4
α	**[Min; Max] [%]**	**[Min; Max] [%]**	**[Min; Max] [%]**	**[Min; Max] [%]**
0.20	[-48; -56]	[-53; -61]	[-56; -63]	[-58; -65]
0.21	[-45; -54]	[-51; -59]	[-54; -61]	[-56; -63]
0.22	[-42; -52]	[-49; -57]	[-51; -59]	[-54; -61]
0.23	[-40; -50]	[-46; -55]	[-49; -57]	[-52; -60]
0.24	[-37; -47]	[-44; -53]	[-47; -56]	[-49; -58]
0.25	[-34; -45]	[-41; -51]	[-44; -54]	[-47; -56]

To examine the input variables and what affect they have on AEP predictions in RETScreen, a few plots were made. **Figure 31** examines the impacts of the shear coefficient, as expected as the shear coefficient increases so does the AEP and the difference d between the AEP predictions in RETScreen and the wind farm average decreases. The difference between $\alpha = 0.25$ and $\alpha = 0.20$ is roughly 60,000 MWh for loss scenario *S4*. **Figure 32** shows the AEP for *S4* and $\alpha = 0.25$, as a function of $k = 1 - 3$. The maximum AEP is gained at $k = 1.1$ or 319,742 MWh (orange point) while AEP is 289,707 MWh and 268,695 MWh at $k = 1.7$ and $k = 2.0$ (red and green points) respectively. **Figure 33** shows the difference between the AEP predictions in RETScreen and the wind farm average as a function of k, as k increases the difference does as well in harmony with **Figure 32**.

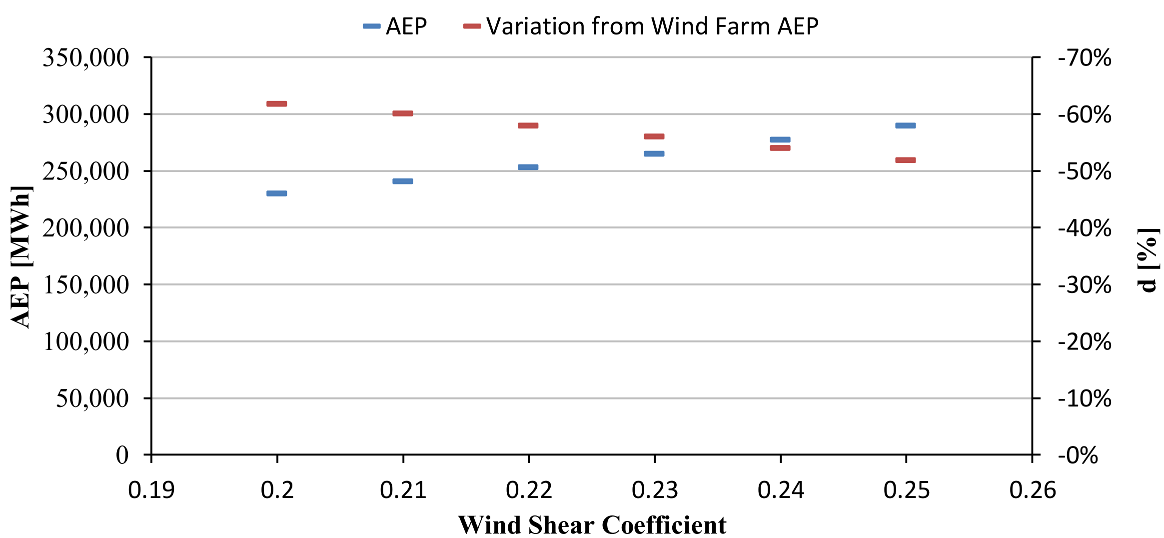


Figure 31 – AEP [left axis] for k=1.7 and S4 and *d* the difference from wind farm AEP [right axis] as a function of wind shear coefficient from 0.20 – 0.25.

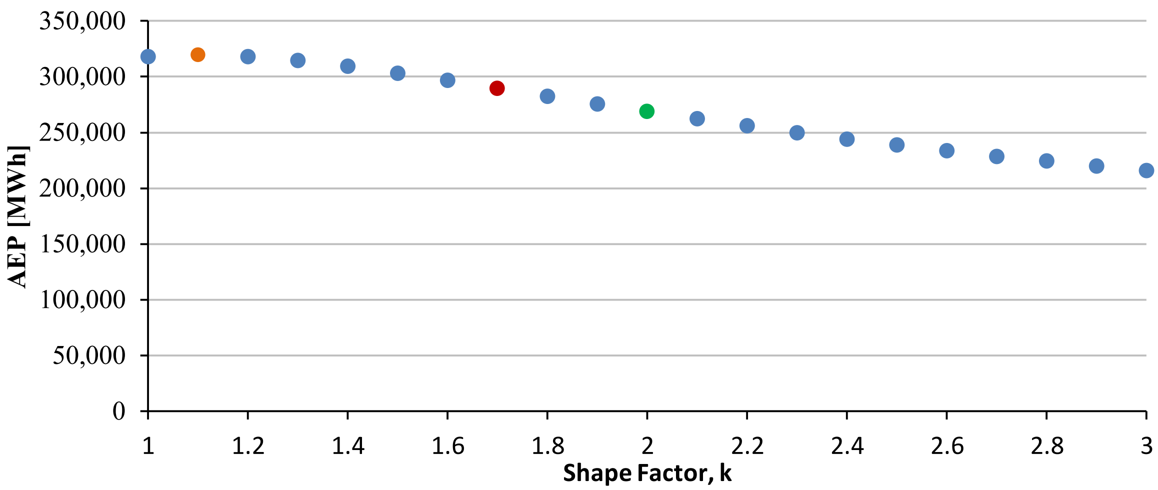


Figure 32 – AEP as a function of the shape factor k with α= 0.25 for loss scenario S4 i.e. assuming all losses.

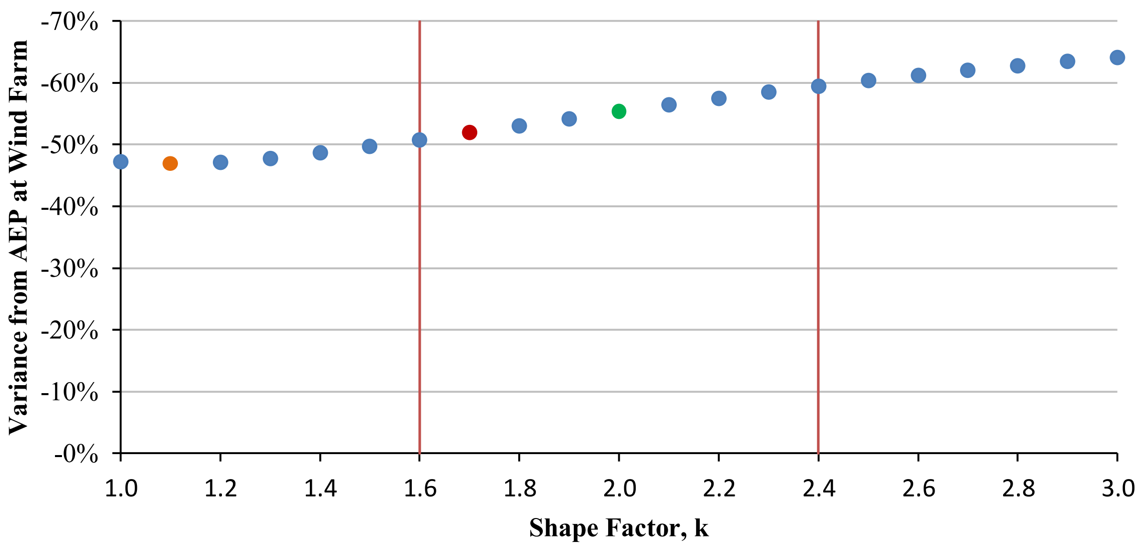


Figure 33 – The difference *d* between the AEP predictions in RETScreen and the wind farm operational data as a function of the shape factor k with α = 0.25 for loss scenario S4 i.e. assuming all losses. The red lines indicate the range where k is commonly found.

Table 22 shows the percentage point difference between AEP predictions compared to the wind farm average for turbine type 1A and 2A. Using turbine type 2A would increase the difference by roughly 4 - 6 percentage points. The turbine type is of course important but would not lead to a huge difference. In **Appendix B**, the AEP for all loss scenarios using turbine type 2A can be seen in **Appendix - Table 10** to **Appendix - Table 13**.

Table 22 - Percentage points difference between turbine type 1A and 2A for all loss scenarios.

α	*S1 [%]*	*S2 [%]*	*S3 [%]*	*S4 [%]*
0.20	4.8	4.2	4.0	3.8
0.21	4.8	4.2	4.0	3.8
0.22	5.1	4.6	4.4	4.1
0.23	5.3	4.7	4.5	4.3
0.24	5.5	4.9	4.7	4.4
0.25	5.7	5.1	4.8	4.6

Weather File C2

In **Table 23**, below the AEP as a function of $\alpha = 0.20 - 0.25$ and $k = 1.7$ and $k = 2.0$ can be seen for all loss scenarios *S1 – S4*. In **Table 24**, the difference *d* between the RETScreen predictions and the wind farm operational data average can be seen. The AEP for $\alpha = 0.25$ is 472,571 MWh and 455,342 MWh for $k = 1.7$ and $k = 2.0$, respectively. This leads to a roughly 22% and 24% underestimation for $k = 1.7$ and $k = 2.0$ respectively when ignoring losses, while it is 37% and 39% for loss scenario *S4*, i.e. accounting for all losses. In **Table 25**, the difference can be seen for $k = 1.7$ for expected range of *d* based on $\pm\sigma$ of the wind farm. The underestimation is in the range of 14% - 28% for $\alpha = 0.25$ and 29% - 41% for $\alpha = 0.20$ in both cases assuming no losses. If *S4* is examined the difference is in the range of 31% - 42% for $\alpha = 0.25$ and 43% - 53% for $\alpha = 0.20$. Like for C1, RETScreen is underestimating the AEP substantially. In **Appendix B**, detailed tables (**Appendix - Table 14** to **Appendix - Table 17**) list the AEP as a function of the shear coefficient on the range of $0.20 - 0.25$ and for $k = 1 - 3$ for each of the four loss scenarios.

Table 23 –RET Screen's AEP predictions for k=1.7 and k=2.0. Weather file *C2* and turbine type 1A used.

	k = 1.7				k = 2.0			
α	*S1 [MWh]*	*S2 [MWh]*	*S3 [MWh]*	*S4[MWh]*	*S1[MWh]*	*S2[MWh]*	*S3[MWh]*	*S4[MWh]*
0.20	386,962	344,817	327,576	310,335	362,672	323,173	307,014	290,855
0.21	403,355	359,425	341,454	323,482	380,208	338,799	321,859	304,919
0.22	420,111	374,356	355,638	336,920	398,183	354,816	337,075	319,334
0.23	437,280	389,655	370,172	350,689	416,792	371,398	352,828	334,259
0.24	454,738	405,212	384,951	364,690	435,842	388,374	368,955	349,536
0.25	472,571	421,102	400,047	378,992	455,342	405,750	385,462	365,175

Table 24 – The difference *d* between the RETScreen predictions and the weather file C2 using 1A for k=1.7 and k=2.0.

	k = 1.7				k = 2.0			
α	*S1 [%]*	*S2 [%]*	*S3 [%]*	*S4 [%]*	*S1 [%]*	*S2 [%]*	*S3 [%]*	*S4 [%]*
0.20	-35.8	-42.8	-45.6	-48.5	-39.8	-46.4	-49.0	-51.7
0.21	-33.1	-40.3	-43.3	-46.3	-36.9	-43.8	-46.6	-49.4
0.22	-30.3	-37.9	-41.0	-44.1	-33.9	-38.2	-44.1	-47.0
0.23	-27.4	-35.3	-38.6	-41.8	-30.8	-38.4	-41.4	-44.5
0.24	-24.5	-32.7	-36.1	-39.5	-27.7	-35.5	-38.8	-42.0
0.25	-21.6	-30.1	-33.6	-37.1	-24.4	-32.7	-36.0	-39.4

Table 25 – The range of the difference *d* between RETScreen's predictions and wind farm data based on ±σ for the wind farm data. This is for k = 1.7 and 1A turbine in weather cell C2.

	S1	S2	S3	S4
α	[Min; Max] [%]	[Min; Max] [%]	[Min; Max] [%]	[Min; Max] [%]
0.20	[-29; -41]	[-37; -48]	[-40; -50]	[-43; -53]
0.21	[-26; -39]	[-34; -45]	[-38; -48]	[-41; -51]
0.22	[-23; -36]	[-32; -43]	[-35; -45]	[-38; -49]
0.23	[-20; -34]	[-29; -41]	[-32; -44]	[-36; -47]
0.24	[-17; -31]	[-26; -38]	[-30; -41]	[-33; -45]
0.25	[-14; -28]	[-23; -36]	[-27; -39]	[-31; -42]

Figure 34 shows AEP and d as a function of α. The difference between $\alpha = 0.25$ and $\alpha = 0.20$ is roughly 70,000 MWh for loss scenario *S4*. **Figure 35** shows the AEP for *S4* as a function of $k = 1 - 3$ and for $\alpha = 0.25$. The maximum AEP is gained at $k = 1.1$ or 319,742 MWh (orange point) while the AEP is 378,992 MWh and 365,175 MWh at $k = 1.7$ and $k = 2.0$ respectively (red and green point). **Figure 36** shows the difference *d*, between

the AEP predictions in RETScreen and the wind farm average as a function of k, as k increases the difference does as well in harmony with **Figure 35**.

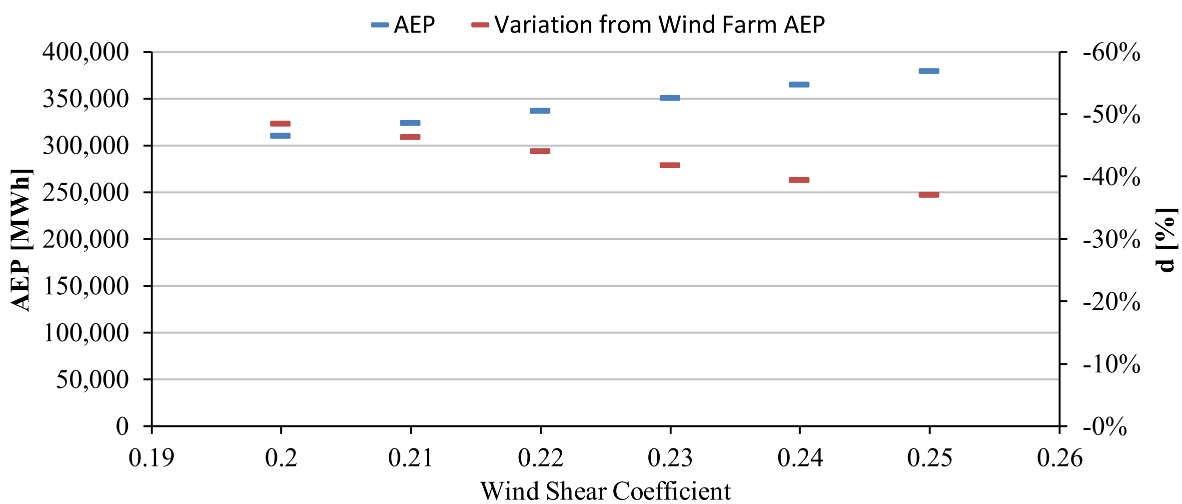


Figure 34 – AEP [left axis] and difference *d* from wind farm AEP [right axis] as a function of wind shear coefficient from 0.20 – 0.25 for *S4*.

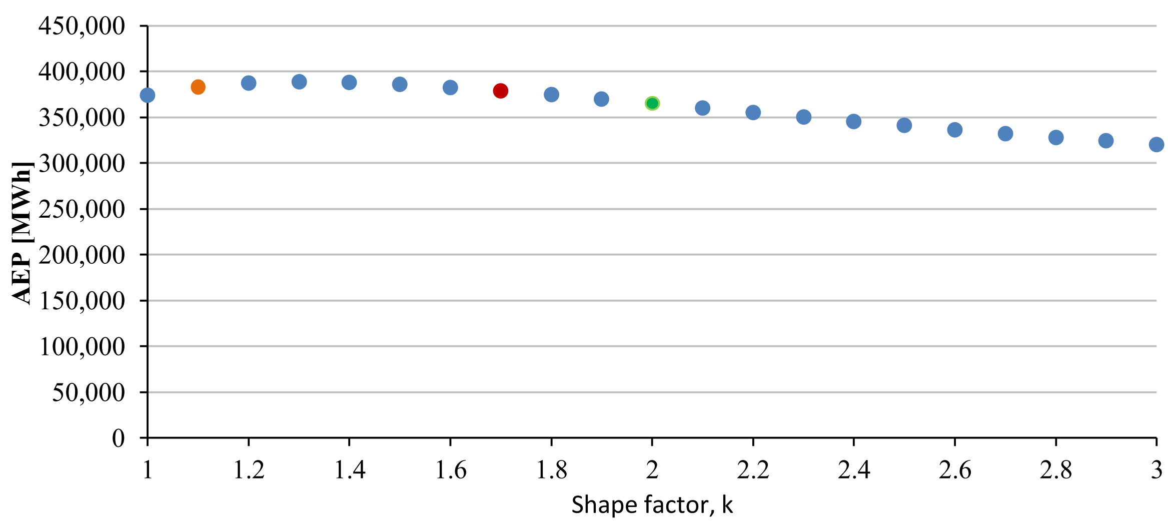


Figure 35 – AEP as a function of the shape factor k with α= 0.25 for loss scenario *S4*.

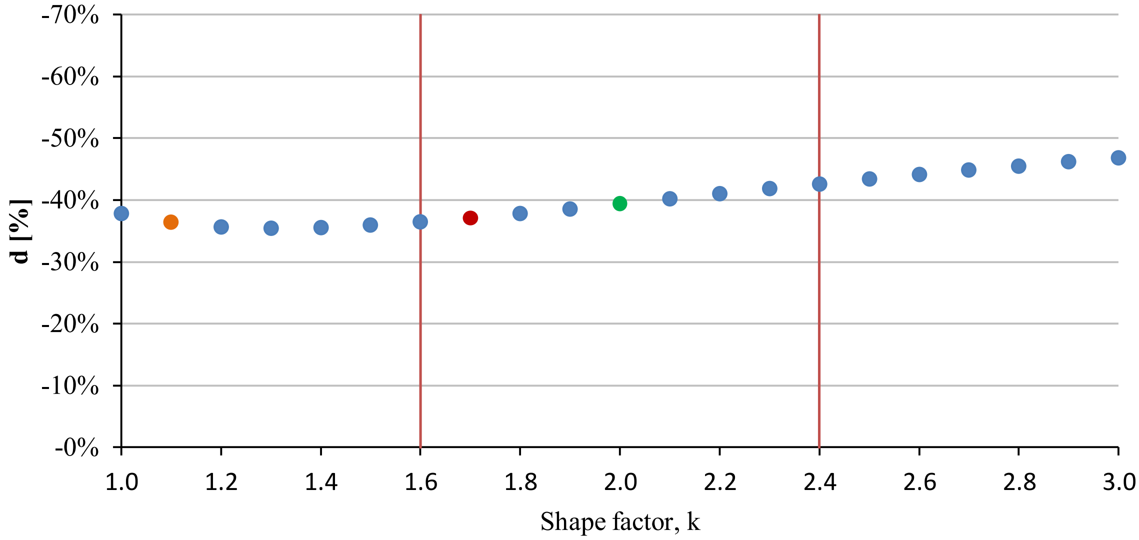


Figure 36 – Difference *d* between the AEP predictions and the wind farm operational data as a function of the shape factor k with α = 0.25 for S4. The red lines indicate the range where k is commonly found.

At last the turbine type 1A versus 2A was examined. **Table 26,** shows the percentage point difference between AEP predictions compared to the wind farm average for turbine type 1A and 2A. Using turbine type 2A would increase the difference by roughly 5 - 7 percentage points. Therefore, while the turbine type is important, it would not lead to a huge difference. In **Appendix B**, the AEP for all loss scenarios using turbine type 2A for $k = 1 - 3$ and $\alpha = 0.20 - 0.25$ is listed (**Appendix - Table 18** to **Appendix - Table 21**).

Table 26 - Percentage points difference between turbine type 1A and 2A for all loss scenarios.

α	S1 [%]	S2 [%]	S3 [%]	S4 [%]
0.20	5.9	5.3	5.0	4.8
0.21	6.1	5.4	5.2	4.9
0.22	6.3	5.6	5.3	5.0
0.23	6.4	5.7	5.4	5.2
0.24	6.6	5.9	5.6	5.3
0.25	6.7	6.0	5.7	5.4

Comparison between C1 and C2

As discussed in the methodology, *C1* is thought to be more representative of the wind farm if the turbine coordinates are used. In **Table 27,** the comparison of the results from the two weather cells can be seen and the difference *d* from the wind farm data in **Table 28**.

The AEP predictions are higher for *C2* which is not a surprise since the wind speed for that cell was higher. If the difference from the wind farm data is examined for $\alpha = 0.25$, it is found to be in the range of [-34%; -45%] for *C1* and [-14%; -28%] for *C2* assuming no losses while it is in the range of [-47%; -56%] and [-31%; -42%] for *C1* and *C2* respectively accounting for losses. Therefore, even if the maximum values are assumed and *C2* used the AEP predictions are still in the range of [-31%; -42%] underestimation.

Table 27 - Comparison of the AEP predictions for the two different weather cells, C1 and C2.

	k = 1.7 – CELL 1				k = 1.7 – CELL 2			
α	*S1 [MWh]*	*S2 [MWh]*	*S3 [MWh]*	*S4[MWh]*	*S1[MWh]*	*S2[MWh]*	*S3[MWh]*	*S4[MWh]*
0.20	287,103	255,834	243,042	230,251	386,962	344,817	327,576	310,335
0.21	300,141	267,452	254,079	240,707	403,355	359,425	341,454	323,482
0.22	315,842	281,443	267,371	253,299	420,111	374,356	355,638	336,920
0.23	330,465	294,473	279,750	265,026	437,280	389,655	370,172	350,689
0.24	345,692	308,042	292,640	277,238	454,738	405,212	384,951	364,690
0.25	361,240	321,897	305,802	289,707	472,571	421,102	400,047	378,992

Table 28 - Comparison of the difference *d* of RETScreen predictions and wind farm data for the two weather files, C1 and C2 and k=1.7.

	CELL 1				CELL 2			
	S1	S2	S3	S4	S1	S2	S3	S4
α	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
0.20	[-48; -56]	[-53; -61]	[-56; -63]	[-58; -65]	[-29; -41]	[-37; -48]	[-40; -50]	[-43; -53]
0.21	[-45; -54]	[-51; -59]	[-54; -61]	[-56; -63]	[-26; -39]	[-34; -45]	[-38; -48]	[-41; -51]
0.22	[-42; -52]	[-49; -57]	[-51; -59]	[-54; -61]	[-23; -36]	[-32; -43]	[-35; -45]	[-38; -49]
0.23	[-40; -50]	[-46; -55]	[-49; -57]	[-52; -60]	[-20; -34]	[-29; -41]	[-32; -44]	[-36; -47]
0.24	[-37; -47]	[-44; -53]	[-47; -56]	[-49; -58]	[-17; -31]	[-26; -38]	[-30; -41]	[-33; -45]
0.25	[-34; -45]	[-41; -51]	[-44; -54]	[-47; -56]	[-14; -28]	[-23; -36]	[-27; -39]	[-31; -42]

4.3 SAM

In this section the results for analyses using the two weather locations in SAM; *L1* and *L4* are listed. Wind speed and energy output predictions were compared to the operation data, both AEP and MEP.

4.3.1 Wind Speed

The average wind speed at *L1* and *L4* was compared with the wind speed from the MET in 2011. The average wind speed is calculated based on the modeled data for the years 2004, 2005 and 2006.

Location 1 (L1)

Figure 37 shows the monthly average wind speed in SAM over the three year period at *L1* compared to the MET tower data. **Figure 38**, shows the difference *d* between the average wind speeds in SAM and at the MET tower in percentages.

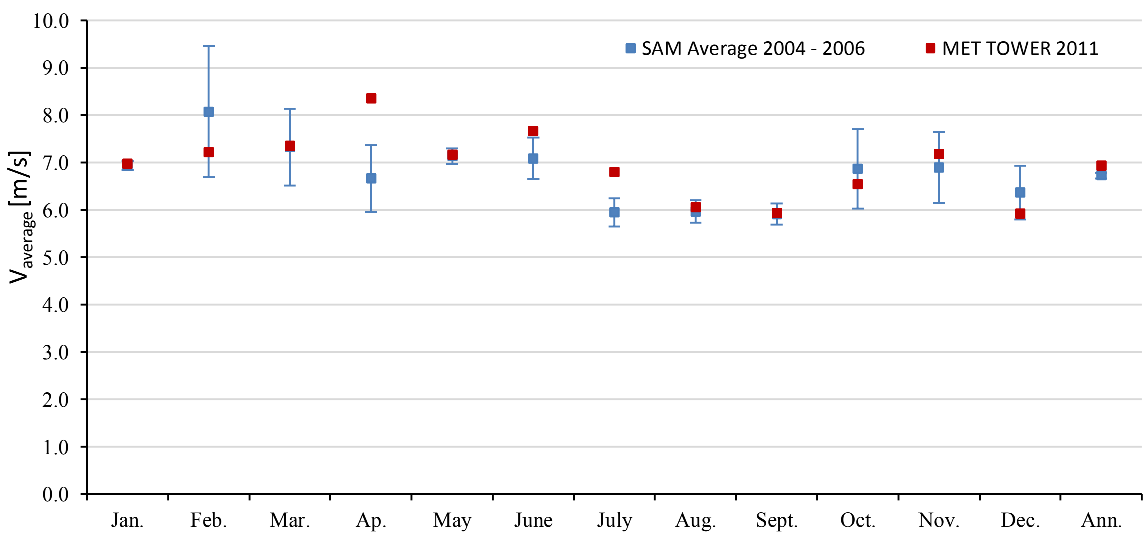


Figure 37 – Average wind speeds in SAM at location L1 over the three year period $\pm\sigma$, compared to the MET tower wind speeds in 2011.

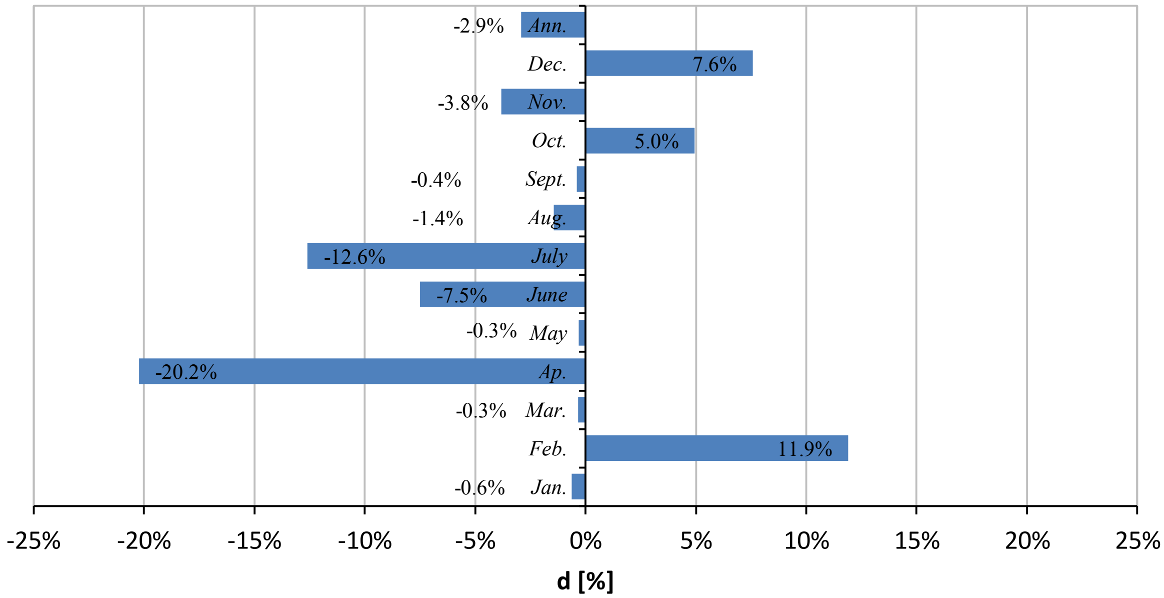


Figure 38 – Difference *d* between the SAM and MET wind speeds.

Table 29, shows monthly wind speed from SAM at *L1* for individual year (2004, 2005, 2006) as well as $\boldsymbol{\bar{v}_{2004-2006}}$, $\boldsymbol{\sigma_{2004-2006}}$ and $\boldsymbol{C_v}$. In **Table 30**, the difference *d* between the MET data and the wind speeds from SAM for individual years as well as the average over the three year period is listed. The average wind speed from SAM at *L1* over the three year period is:

$$\bar{v}_{SAM,2004-2006} \pm \sigma = \mathbf{6.73} \pm \mathbf{0.06}\, \boldsymbol{m/s}. \qquad \textbf{(Eq. 4-3)}$$

This is roughly 3% lower compared to the MET tower average. The average winds speeds are relatively similar over the three individual years with values of 6.69 m/s, 6.69 m/s and 6.81 m/s for 2004, 2005 and 2006 respectively. Hence, the coefficient of variation of the average is low or only about 1%.

Table 29 – Monthly wind speeds from SAM at L1 for 2004, 2005, 2006 as well the three year average, standard deviation and coefficient of variation.

Month	$\overline{v}_{2004}$ [m/s]	$\overline{v}_{2005}$ [m/s]	$\overline{v}_{2006}$ [m/s]	$\overline{v}_{2004-2006}$ [m/s]	$\sigma_{2004-2006}$ [m/s]	C_v [%]	$\overline{v}_{2011,MET}$ [m/s]
January	6.81	7.01	7.00	**6.94**	**0.09**	**1.3**	6.98
February	6.49	7.86	9.86	**8.07**	**1.39**	**17.2**	7.21
March	8.45	6.96	6.58	**7.33**	**0.81**	**11.0**	7.35
April	6.43	7.62	5.94	**6.66**	**0.70**	**10.6**	8.35
May	6.95	7.34	7.14	**7.14**	**0.16**	**2.3**	7.16
June	7.65	7.04	6.58	**7.09**	**0.44**	**6.2**	7.66
July	6.26	6.03	5.55	**5.95**	**0.30**	**5.0**	6.80
August	6.21	5.65	6.04	**5.97**	**0.24**	**3.9**	6.06
September	6.19	5.66	5.90	**5.92**	**0.22**	**3.7**	5.94
October	7.08	5.76	7.77	**6.87**	**0.84**	**12.2**	6.55
November	6.05	6.77	7.88	**6.90**	**0.75**	**10.9**	7.18
December	6.11	7.15	5.84	**6.37**	**0.56**	**8.9**	5.92
Annual	**6.69**	**6.69**	**6.81**	6.73	0.06	0.9	6.93

Table 30 – Difference *d* between SAM and the MET tower wind speeds.

Month	d_{2004} [%]	d_{2005} [%]	d_{2006} [%]	$d_{2004-2006}$ [%]
January	-2.5	+0.4	+0.2	-0.6
February	-10.0	+9.0	+36.7	+11.9
March	+14.9	-5.4	-10.5	-0.3
April	-23.0	-8.8	-28.9	-20.2
May	-3.0	+2.5	-0.4	-0.3
June	-0.1	-8.2	-14.2	-7.5
July	-7.9	-11.3	-18.5	-12.6
August	+2.6	-6.7	-0.2	-1.4
September	+4.2	-4.7	-0.7	-0.4
October	+8.2	-12.1	+18.7	+5.0
November	-15.7	-5.6	+9.8	-3.8
December	+3.2	+20.8	-1.3	+7.6
Annual	**-3.5**	**-3.5**	**-1.7**	**-2.9**

Location 4 (L4)

Figure 39 shows the monthly average wind speed in SAM over the three year period at *L4* compared to the MET tower. **Figure 40** shows the difference between the average wind speeds in SAM and at the MET tower in percentages.

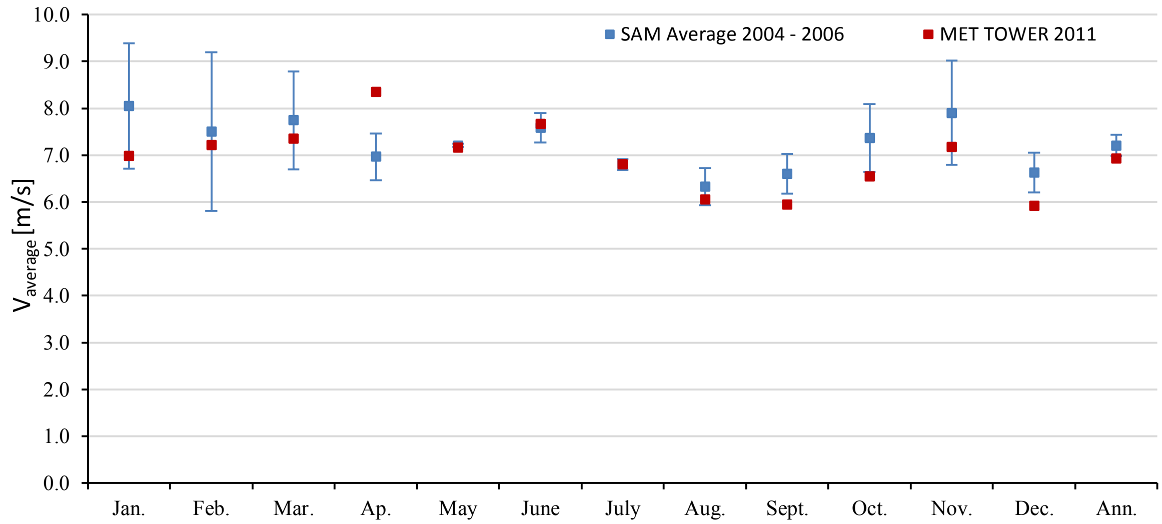


Figure 39 – Average wind speed in SAM at location L4 over the three year period $\pm\sigma$, compared to the MET tower wind speed in 2011.

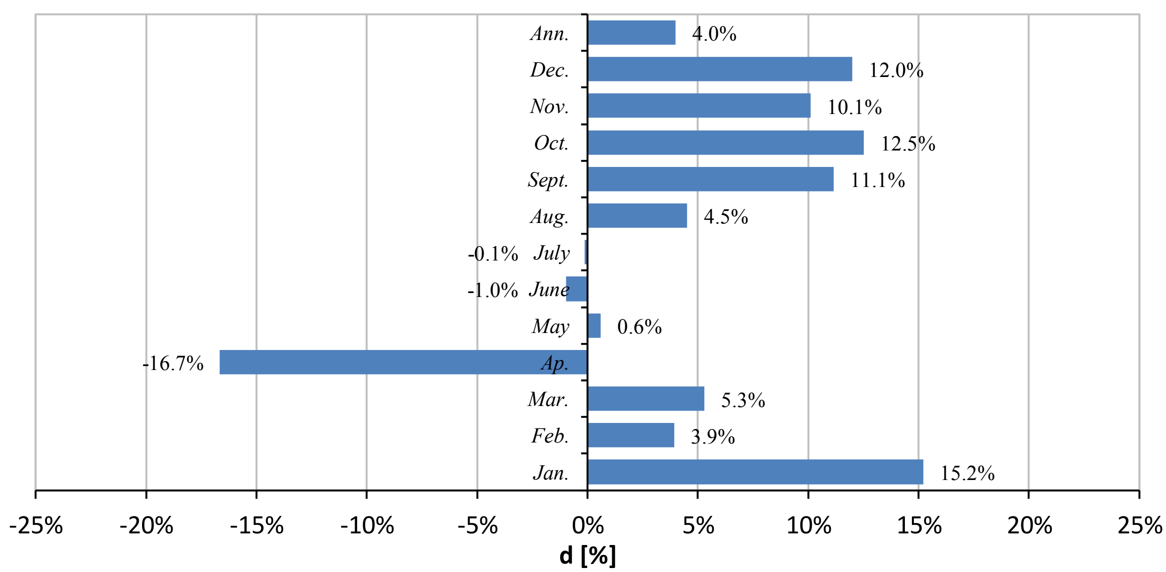


Figure 40 – Difference *d* between the SAM and MET average wind speeds.

Table 31, shows monthly wind speed from SAM at *L4* for individual years (2004, 2005, 2006) as well as $\bar{\boldsymbol{v}}_{\mathbf{2004-2006}}$, $\boldsymbol{\sigma}_{\mathbf{2004-2006}}$ and $\boldsymbol{C_v}$. In **Table 32**, the difference *d* between the MET and SAM for individual years as well as the average over the three year period is listed. The average wind speed from SAM at *L4* over the three year period is:

$$\bar{v}_{SAM,2004-2006} \pm \sigma = \mathbf{7.21} \ \pm \mathbf{0.22} \ \boldsymbol{m/s}. \qquad \textbf{(Eq. 4-4)}$$

This is roughly 4% higher than the MET tower average. The average winds speeds are relatively similar for 2004 and 2005 or 7.06 m/s and 7.04 m/s respectively while the wind speed in 2006 is slightly higher or 7.52 m/s. Therefore, the coefficient of variation of the average is slightly higher than for location 1 or about 3%.

Table 31 – Monthly wind speeds from SAM at L4 for 2004, 2005, 2006 as well the three year average, standard deviation and coefficient of variation.

Month	$\overline{v}_{2004}$ [m/s]	$\overline{v}_{2005}$ [m/s]	$\overline{v}_{2006}$ [m/s]	$\overline{v}_{2004-2006}$ [m/s]	$\sigma_{2004-2006}$ [m/s]	C_v [%]	$\overline{v}_{2011,MET}$ [m/s]
January	7.27	6.93	9.93	**8.05**	**1.34**	**16.6%**	6.98
February	5.68	7.05	9.76	**7.50**	**1.69**	**22.6%**	7.21
March	9.08	7.61	6.54	**7.74**	**1.04**	**13.4%**	7.35
April	6.83	7.63	6.43	**6.96**	**0.50**	**7.2%**	8.35
May	7.24	7.17	7.21	**7.21**	**0.03**	**0.4%**	7.16
June	7.65	7.93	7.18	**7.59**	**0.31**	**4.1%**	7.66
July	6.88	6.87	6.63	**6.80**	**0.12**	**1.7%**	6.80
August	6.69	5.77	6.52	**6.33**	**0.40**	**6.3%**	6.06
September	7.16	6.51	6.13	**6.60**	**0.43**	**6.5%**	5.94
October	7.29	6.52	8.28	**7.37**	**0.72**	**9.8%**	6.55
November	6.58	7.83	9.30	**7.90**	**1.11**	**14.1%**	7.18
December	6.43	7.21	6.25	**6.63**	**0.42**	**6.3%**	5.92
Annual	**7.06**	**7.04**	**7.52**	7.21	0.22	3.1%	**6.93**

Table 32 – Deviation in SAM from the MET tower data, average compared to average.

Month	d_{2004} [%]	d_{2005} [%]	d_{2006} [%]	$d_{2004-2006}$ [%]
January	+4.2	-0.7	+42.2	+15.2
February	-21.3	-2.2	+35.3	+3.9
March	+23.4	+3.6	-11.1	+5.3
April	-18.3	-8.6	-23.0	-16.7
May	+1.1	+0.1	+0.6	+0.6
June	-0.1	+3.5	-6.3	-1.0
July	+1.1	+1.0	-2.5	-0.1
August	+10.5	-4.7	+7.7	+4.5
September	+20.6	+9.7	+3.2	+11.1
October	+11.4	-0.4	+26.6	+12.5
November	-8.3	+9.1	+29.6	+10.1
December	+8.6	+21.8	+5.6	+12.0
Annual	**+1.8**	**+1.6**	**+8.5**	**+4.0**

Comparison of L1 and L4

In **Table 33**, a comparison of the annual average wind speed at *L1* and *L4* is listed. Monthly comparison as well as the difference[5] in percentages can be found on **Figure 41** and **Figure 42** respectively. The average wind speed at *L1* is lower than at *L4* or 6.73±0.06 m/s compared to 7.21±0.22 m/s, both are comparable with the MET tower wind speed.

Table 33 – Comparison of the wind speeds at L1 and L4.

Month	$\overline{v}_{2004}$ [m/s]	$\overline{v}_{2005}$ [m/s]	$\overline{v}_{2006}$ [m/s]	$\overline{v}_{2004-2006}$ [m/s]	$\sigma_{2004-2006}$ [m/s]	C_v [%]	$\overline{v}_{2011,MET}$ [m/s]
L1	6.69	6.69	6.81	6.73	0.06	0.9	6.93
L4	7.06	7.04	7.52	7.21	0.22	3.1%	6.93

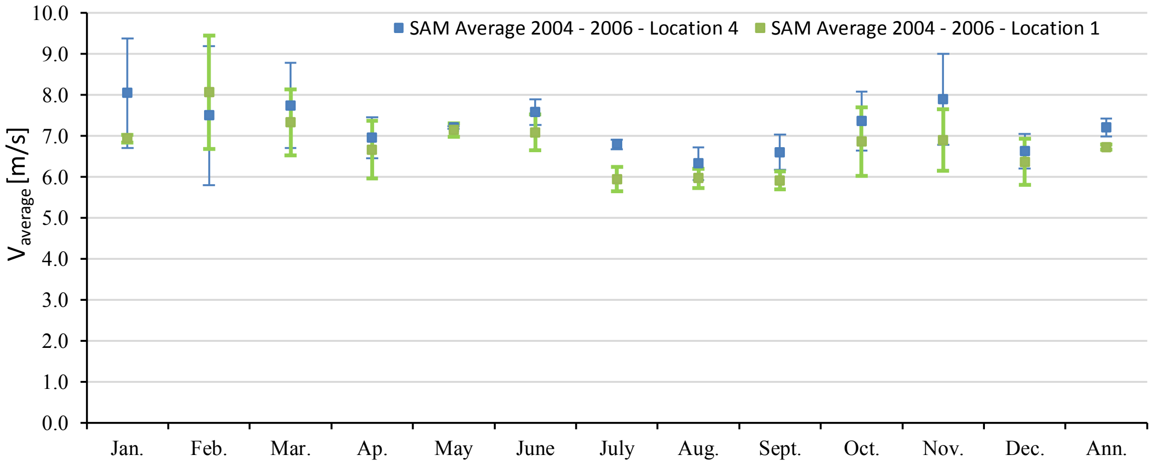


Figure 41 – Average wind speed in SAM for 2004-2006 at L1 compared to the L4.

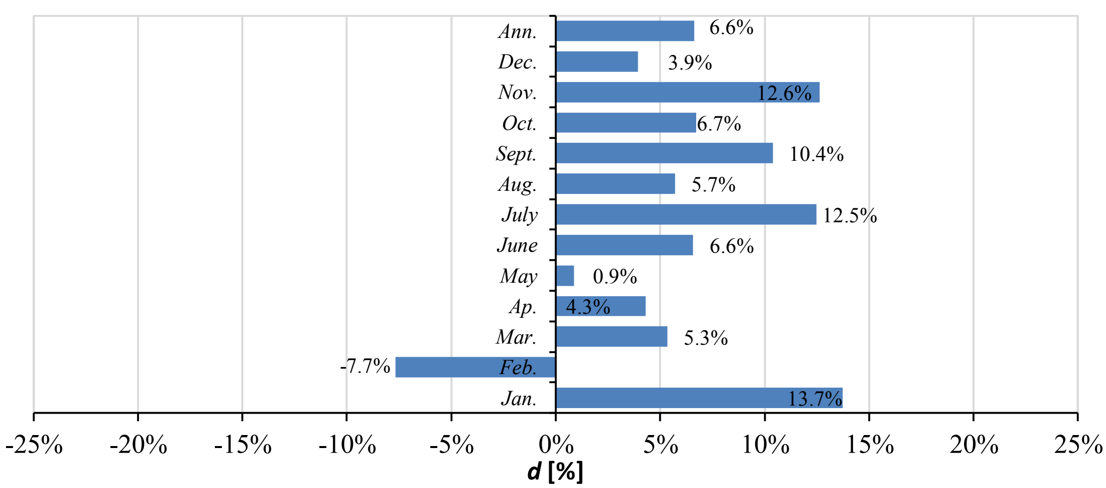


Figure 42 – Difference *d* between the average wind speeds at location L4 and L1.

[5] The difference is calculated according to d = (SAM_{L4} - SAM_{L1})/SAM_{L4}.

4.3.2 Predicted Energy Production

The predicted energy production at the two locations (*L1*) and (*L4*) from SAM over the three year period was compared with the average operational data from the wind farm over the five year period. Both monthly and annual comparison was performed.

Location 1 (L1)

The energy production for individually years, 2004, 2005 and 2006 as well as the average over the three year period, $\bar{E}_{2004-2006}$, $\sigma_{2004-2006}$ and C_v can be seen in **Table 34**. This is the gross energy output i.e. before any losses are accounted for. In **Table 35**, the energy production when wake losses have been accounted for is shown for individual years, and the three year average.

Table 34 - Summary of results from SAM for L1, loss scenario S1 i.e. assuming no losses.

Month	E_{2004} [MWh]	E_{2005} [MWh]	E_{2006} [MWh]	$\bar{E}_{2004-2006}$ [MWh]	$\sigma_{2004-2006}$ [MWh]	C_v [%]
January	55,532	53,134	50,257	52,974	2,157	4.1
February	45,084	65,535	82,880	64,500	15,447	23.9
March	75,564	52,574	51,640	59,926	11,065	18.5
April	42,348	58,846	37,226	46,140	9,225	20.0
May	49,709	52,510	55,074	52,431	2,191	4.20
June	57,754	54,430	48,411	53,532	3,867	7.20
July	45,141	40,164	31,661	38,989	5,565	14.3
August	44,218	34,371	44,078	40,889	4,609	11.3
September	44,728	32,875	39,904	39,169	4,867	12.4
October	55,788	38,374	66,943	53,702	11,756	21.9
November	43,085	50,973	65,585	53,214	9,321	17.5
December	44,591	57,091	40,566	47,416	7,036	14.8
Annual	**603,545**	**590,877**	**614,224**	**602,882**	**9,543**	**1.6**

As seen in **Table 34**, the gross average AEP over the five year period is:

$$\bar{E}_{2004-2006} \pm \sigma = \mathbf{602,882} \pm \mathbf{9,543} \; \boldsymbol{MWh}. \qquad \textbf{(Eq. 4-5)}$$

The annual energy of each individual year is relatively similar over the three year period or 603,545 MWh, 590,877 MWh and 614,224 MWh for 2004, 2005 and 2006 respectively. Therefore, the coefficient of variation is relatively low or 1.6%. The wake losses as seen in

Table 35 are found to be 8.5%, 8.5% and 9.1% for 2004, 2005 and 2006. This results in an average wake loss of 8.7% over the three years average.

Table 35 – AEP predictions and wake losses of individual years as well as for the three years average for location L1.

	E_{2004} [MWh]	WL [%]	E_{2005} [MWh]	WL [%]	E_{2006} [MWh]	WL [%]	$\bar{E}_{2004-2006}$ [MWh]	$\sigma_{2004-2006}$ [MWh]	C_v [%]	WL [%]
Jan.	52,249	5.9	49,706	6.5	45,110	10.2	49,022	2,955	6.0	7.5
Feb.	40,959	9.2	62,280	5.0	79,110	4.5	60,783	15,611	25.7	5.8
March	70,405	6.8	49,386	6.1	46,031	10.9	55,274	10,787	19.5	7.8
April	38,941	8.0	53,357	9.3	32,873	11.7	41,723	8,591	20.6	9.6
May	43,868	11.7	47,967	8.7	49,504	10.1	47,113	2,379	5.0	10.1
June	53,569	7.2	48,809	10.3	44,369	8.3	48,915	3,757	7.7	8.6
July	40,683	9.9	35,884	10.7	28,069	11.3	34,878	5,198	14.9	10.5
August	39,353	11.0	30,841	10.3	40,178	8.8	36,791	4,220	11.5	10.0
Sept.	40,260	10.0	28,917	12.0	35,808	10.3	34,995	4,666	13.3	10.7
Oct.	51,249	8.1	34,124	11.1	61,395	8.3	48,923	11,254	23.0	8.9
Nov.	39,746	7.7	46,468	8.8	59,222	9.7	48,479	8,077	16.7	8.9
Dec.	41,123	7.8	52,624	7.8	36,502	10.0	43,417	6,779	15.6	8.4
Annual	**552,405**	**8.5**	**540,361**	**8.5**	**558,170**	**9.1**	**550,312**	**7,419**	**1.3**	**8.7**

In **Table 36**, the net average MEP and AEP for the 2004-2006 period can be seen for *S1*-*S4* and **Table 37** shows the deviation from the wind farm.

Table 36 – Average MEP and AEP predictions in SAM for 2004-2006 for L1 for all loss scenarios.

	S1 - No Losses		*S2 - Wakes and PA*		*S3 - Additional 5%*		*S4 - Additional 10%*	
Month	$\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	$\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	$\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	$\bar{E}_{2004-2006}$ [MWh]	σ [MWh]
Jan.	52,974	2,157	47,671	2,873	45,287	2,730	42,904	2,586
Feb.	64,500	15,447	59,519	15,286	56,543	14,522	53,567	13,757
March	59,926	11,065	54,115	10,561	51,410	10,033	48,704	9,505
April	46,140	9,225	40,614	8,363	38,584	7,945	36,553	7,526
May	52,431	2,191	46,030	2,324	43,729	2,208	41,427	2,092
June	53,532	3,867	47,895	3,678	45,500	3,494	43,106	3,310
July	38,989	5,565	33,976	5,064	32,277	4,811	30,578	4,557
August	40,889	4,609	35,764	4,103	33,976	3,898	32,188	3,692
Sept.	39,169	4,867	34,091	4,546	32,387	4,319	30,682	4,091
Oct.	53,702	11,756	47,795	10,995	45,406	10,445	43,016	9,896
Nov.	53,214	9,321	47,202	7,864	44,842	7,471	42,482	7,078
Dec.	47,416	7,036	42,395	6,619	40,275	6,288	38,155	5,957
Annual	**602,882**	**9,543**	**537,105**	**7,242**	**510,249**	**6,879**	**483,394**	**6,517**

In **Appendix B**, the net energy production for each individual year for all loss scenarios can be found in **Appendix – Table 23** to **Appendix - Table 27**.

Table 37 – The difference *d* between the wind farm and the SAM data for the four loss scenarios.

Month	*S1* $d_{2004-2006,S1}$ [%]	*S2* $d_{2004-2006,S2}$ [%]	*S3* $d_{2004-2006,S3}$ [%]	*S4* $d_{2004-2006,S4}$ [%]
Jan.	+6.6	-4.1	-8.8	-13.6
Feb.	+70.2	+57.0	+49.2	+41.3
March	+5.8	-4.4	-9.2	-25.0
April	-29.1	-37.6	-40.7	-43.9
May	-6.6	-18.0	-22.1	-26.2
June	-8.9	-18.5	-22.5	-26.6
July	-22.0	-32.0	-35.4	-38.8
August	-17.8	-28.1	-31.7	-35.3
Sept.	-2.7	-15.3	-19.6	-23.8
Oct.	+16.4	+3.6	-1.6	-6.8
Nov.	+14.1	+1.2	-3.8	-8.9
Dec.	+4.1	-7.0	-11.6	-16.3
Annual	**+0.1**	**-10.9**	**-15.3**	**-19.8**

Figure 43 to **Figure 46** show the SAM 2004 – 2006 monthly average production compared with the wind farm data and the difference *d* between the two for loss scenario *S1* and loss scenario *S4*.

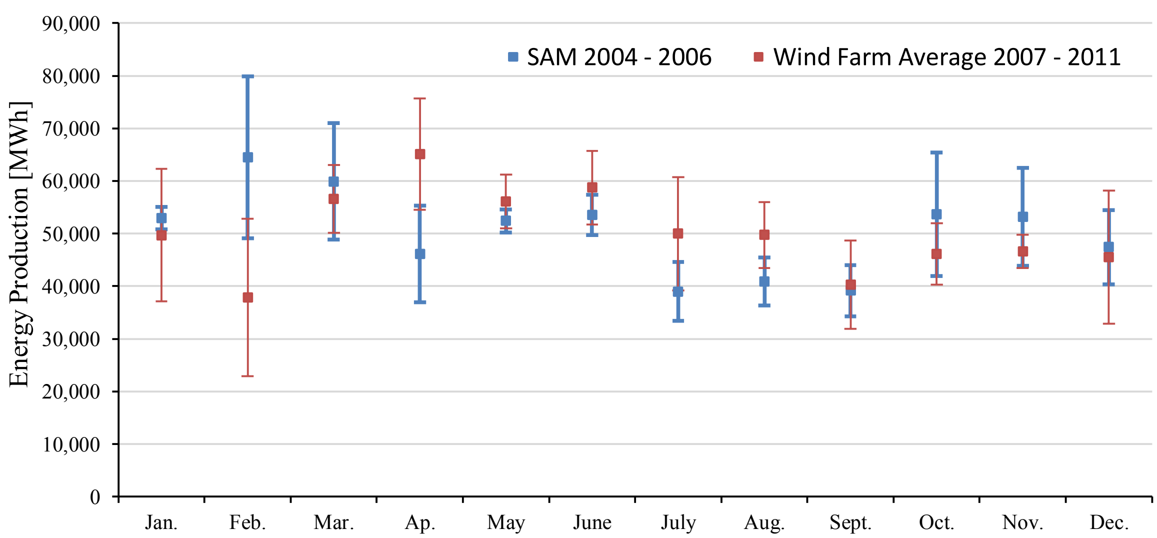


Figure 43 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S1 ignoring losses.

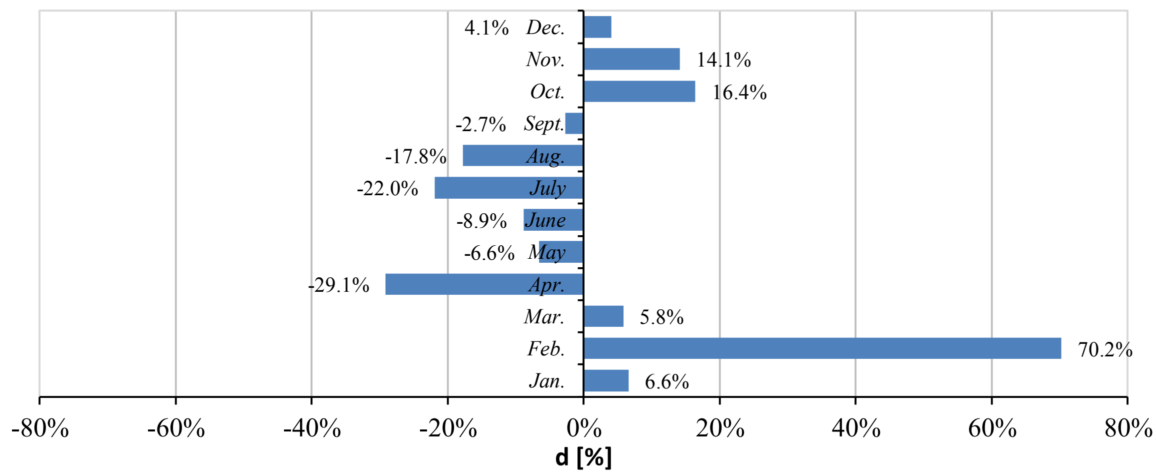


Figure 44 – Difference between the average MEP for SAM and the operational data from the wind farm for S1, i.e. assuming no losses.

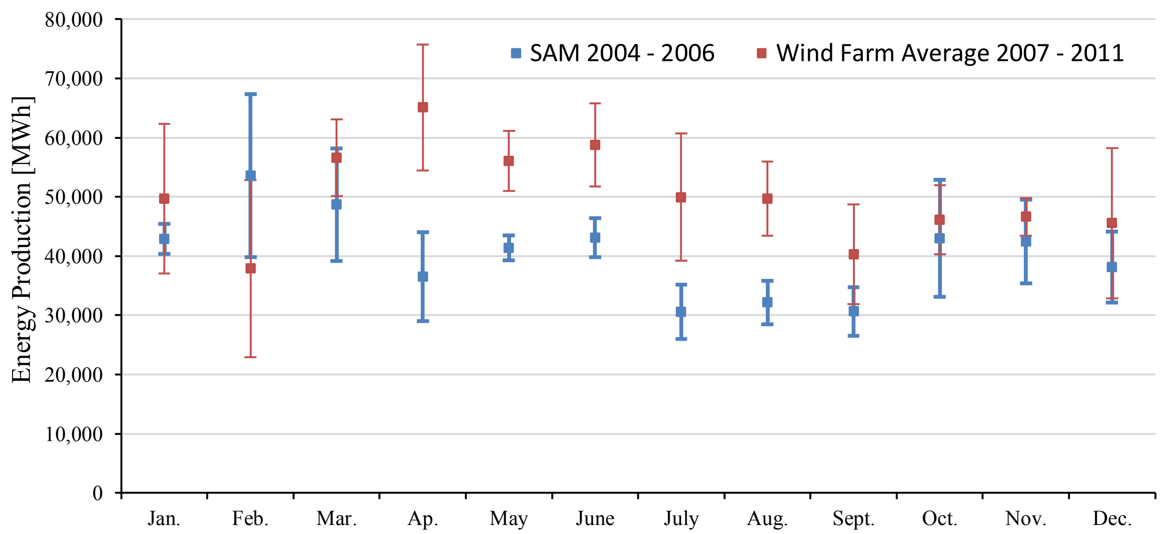


Figure 45 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S4 i.e. assuming all losses [Wakes, PA and 10% additional].

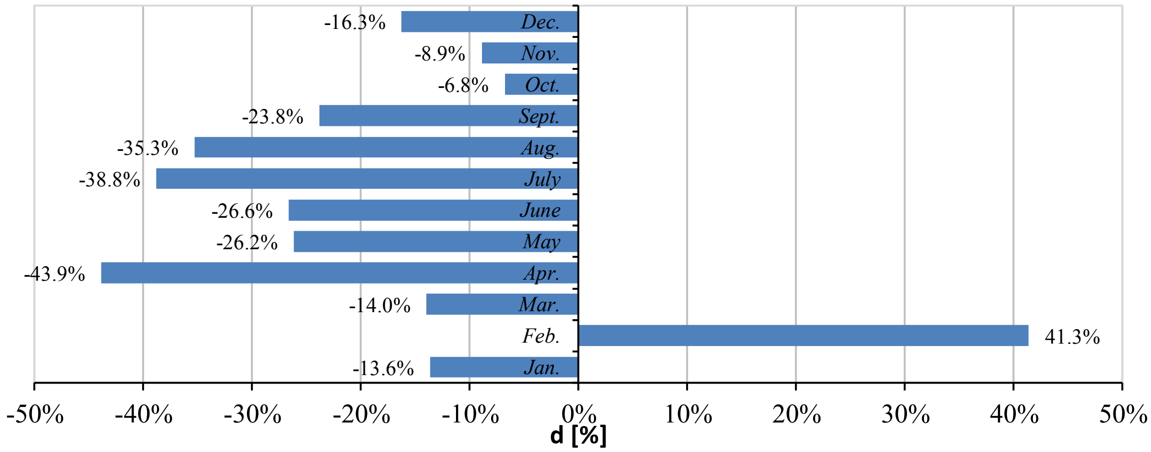


Figure 46 – The difference *d* between the average MEP for SAM and the operational data from the wind farm for S4, i.e. assuming all losses [Wakes, PA and 10% additional].

There is a difference between individual months, for *S1,* February is quite large at -70.2%, it must however be noted that the wind farm values for February in 2010 were suspiciously low. For 6 months the difference is less than 10%. When however all losses are assumed, the difference increases and seven months are 25-45% off while only 2 are inside the 10% difference. This is only the direct comparison of the averages. If $\pm\sigma$ is used as a measure of the uncertainty as plotted on the figures above, it can be seen that for *S1* all the months overlap. While looking at *S4*, five months do not overlap. **Figure 47** shows the AEP ± one standard deviation for the wind farm and SAM for all scenarios *S1* – *S4*.

Table 38 summarizes the AEP for each loss scenario, the range of the AEP based on $\pm\sigma$ and the correlative deviation range as well as total losses for each loss scenario.

Figure 47 – AEP from SAM for all losses scenarios for 2004-2006 at location 1 compared with AEP from the wind farm.

Table 38 - Summary of the AEP predictions from SAM for L1 and S1-S4 and comparison with the wind farm data.

	Wind Farm 2007 - 2011	$SAM_{2004-2006}$ S1	$SAM_{2004-2006}$ S2	$SAM_{2004-2006}$ S3	$SAM_{2004-2006}$ S4
AEP [GWh]	603±55	603±10	537±7	510±7	483±7
AEP Range [GWh]	[547, 658]	[593, 612]	[530, 544]	[503, 517]	[477, 490]
Deviation from average [%]		+0.1	-10.9	-15.3	-19.8
Deviation Range [%]		[+12; -10]	[-1; -19]	[-6; -23]	[-10, -28]
Wake Losses [%]			8.7%	8.7%	8.7%
Availability Losses [%]			2.4%	2.4%	2.4%
Additional Losses [%]				5%	10%
Total Losses [%]			**10.9**	**15.4**	**19.8**

If the average for loss scenario *S1* and the wind farm data is compared, there is only +0.1% difference and if the AEP range is used, the deviation is +12% to -10%. In other words, the AEP in SAM is in the range of 12% overestimation to roughly 10% underestimation, this is without accounting for any losses. The total losses for the three other scenarios *S2*, *S3* and *S4* are 10.9%, 15.4% and 19.8%. The average for *S2* compared to the wind farm data is -10.9% with a range of [-1; -19%], for *S3*, it is -15.3% when comparing averages with the range of [-6; -23%] and lastly for *S4*, the difference is -19.8% with the range of [-10; -28%].

Location 4 (L4)

The energy production for individual years, 2004, 2005 and 2006 and the average over the three year period, $\bar{E}_{2004-2006}, \sigma_{2004-2006}$ and C_v, can be seen in **Table 39**. This is the gross energy output, before accounting for any losses. In **Table 40,** the energy production when wake losses have been accounted for is shown for individual years and the three year average.

Table 39 - Summary of results from SAM for L4, loss scenario S1 i.e. assuming no losses.

Month	E_{2004} [MWh]	E_{2005} [MWh]	E_{2006} [MWh]	$\bar{E}_{2004-2006}$ [MWh]	$\sigma_{2004-2006}$ [MWh]	C_v [%]
January	54,967	50,363	96,448	67,259	20,725	30.8
February	35,493	54,594	82,992	57,693	19,515	33.8
March	81,385	61,670	49,416	64,157	13,169	20.5
April	50,333	60,782	49,915	53,677	5,027	9.4
May	56,078	48,836	63,718	56,211	6,076	10.8
June	59,410	65,638	51,638	58,896	5,727	9.7
July	52,815	51,863	48,022	50,900	2,072	4.1
August	48,432	35,775	48,763	44,324	6,046	13.6
September	55,507	45,627	42,349	47,828	5,592	11.7
October	58,908	50,658	76,000	61,856	10,554	17.1
November	51,572	63,255	83,621	66,150	13,243	20.0
December	50,944	63,465	47,257	53,889	6,937	12.9
Annual	**655,845**	**652,526**	**740,139**	**682,837**	**40,542**	**5.9**

Table 40 – AEP and wake losses of individual years as well as for the three years average for location L4.

	E_{2004} [MWh]	WL [%]	E_{2005} [MWh]	WL [%]	E_{2006} [MWh]	WL [%]	$\bar{E}_{2004-2006}$ [MWh]	$\sigma_{2004-2006}$ [MWh]	C_v [%]	WL [%]
Jan.	51,394	6.5	46,888	6.9	91,150	5.5	63,144	19,888	31.5	6.1
Feb.	32,026	9.8	48,668	10.9	78,029	6.0	52,908	19,018	35.9	8.3
March	76,471	6.0	56,718	8.0	44,332	10.3	59,174	13,235	22.4	7.8
April	45,498	9.6	54,923	9.6	45,150	9.5	48,523	4,527	9.3	9.6
May	50,208	10.5	44,403	9.1	59,483	6.6	51,365	6,211	12.1	8.6
June	54,865	7.7	60,825	7.3	48,417	6.2	54,702	5,067	9.3	7.1
July	46,843	11.3	46,021	11.3	44,447	7.4	45,770	994	2.2	10.1
August	44,575	8.0	31,609	11.6	42,770	12.3	39,651	5,734	14.5	10.5
Sept.	51,483	7.2	39,758	12.9	37,952	10.4	43,064	5,998	13.9	10.0
Oct.	53,941	8.4	47,496	6.2	69,133	9.0	56,857	9,071	16.0	8.1
Nov.	46,054	10.7	59,653	5.7	78,482	6.1	61,396	13,296	21.7	7.2
Dec.	47,129	7.5	59,432	6.4	42,433	10.2	49,664	7,168	14.4	7.8
Annual	**600,487**	**8.4**	**596,394**	**8.6**	**681,776**	**7.9**	**626,219**	**39,320**	**6.3**	**8.3**

As seen in **Table 39**, the gross average AEP over the three year period is:

$$\bar{E}_{2004-2006} \pm \sigma = \mathbf{682,837 \pm 40,542} \qquad \textbf{(Eq. 4-6)}$$

The annual energy of each individual year is relatively similar for 2004 and 2005 or 655,845 MWh and 652,394 MWh, respectively. For the year 2006, the energy production is substantially higher or 740,139 MWh or roughly 13% higher than the two prior mentioned years. This leads to a higher standard deviation and consequently higher coefficient of variation or 6.3%. The wake losses, as seen in **Table 40**, are found to be 8.4%, 8.6% and 7.9% for 2004, 2005 and 2006. This results in an average wake loss of 8.3% over the three years average. In **Table 41**, the net average MEP and AEP for the 2004-2006 period can be seen for all four loss scenarios *S1*-*S4* and in **Table 42**, the difference d from the wind farm.

Table 41 – Average MEP and AEP from SAM for 2004-2006 for L1 for all loss scenarios.

Month	*S1 - No Losses* $\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	*S2 - Wakes and PA* $\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	*S3 - Additional 5%* $\bar{E}_{2004-2006}$ [MWh]	σ [MWh]	*S4 - Additional 10%* $\bar{E}_{2004-2006}$ [MWh]	σ [MWh]
Jan.	67,259	20,725	61,404	19,340	58,334	18,373	55,264	17,406
Feb.	57,693	19,515	51,807	18,623	49,217	17,692	46,627	16,761
March	64,157	13,169	57,933	12,958	55,037	12,310	52,140	11,662
April	53,677	5,027	47,233	4,407	44,872	4,187	42,510	3,966
May	56,211	6,076	50,184	6,068	47,675	5,764	45,166	5,461
June	58,896	5,727	53,561	4,961	50,883	4,713	48,205	4,465
July	50,900	2,072	44,586	969	42,356	920	40,127	872
August	44,324	6,046	38,545	5,574	36,618	5,295	34,690	5,017
Sept.	47,828	5,592	41,952	5,843	39,855	5,551	37,757	5,259
Oct.	61,856	10,554	55,547	8,862	52,770	8,419	49,992	7,976
Nov.	66,150	13,243	59,779	12,946	56,790	12,298	53,801	11,651
Dec.	53,889	6,937	48,495	6,999	46,071	6,649	43,646	6,299
Annual	**682,837**	**40,542**	**611,028**	**38,362**	**580,476**	**36,444**	**549,925**	**34,526**

Table 42 – The difference *d* between the wind farm and the SAM data for the four losses scenarios, average compared to average.

Month	*S1* $d_{2004-2006,S1}$ [%]	*S2* $d_{2004-2006,S2}$ [%]	*S3* $d_{2004-2006,S3}$ [%]	*S4* $d_{2004-2006,S4}$ [%]
Jan.	+35.4	+23.6	+17.4	+11.2
Feb.	+52.2	+36.7	+29.9	+23.0
March	+13.3	+2.3	-2.8	-7.9
April	-17.6	-27.5	-31.1	-34.7
May	+0.2	-10.6	-15.0	-19.5
June	+0.3	-8.8	-13.4	-17.9
July	+1.9	-10.8	-15.2	-19.7
August	-10.9	-22.5	-26.4	-30.3
Sept.	+18.8	+4.2	-1.0	-6.2
Oct.	+34.1	+20.4	+14.4	+8.4
Nov.	+41.8	+28.2	+21.8	+15.4
Dec.	+18.3	+6.4	+1.1	-4.2
Annual	**+13.3**	**+1.4**	**-3.7**	**-8.7**

In **Appendix B**, the net energy production for each individual year for all loss scenarios can be found in **Appendix - Table 28** to **Appendix - Table 33**. **Figure 48** to **Figure 51** show the SAM 2004 – 2006 monthly average production compared with the wind farm data and the difference between the two for loss scenario 1 (assuming no losses) and loss scenario 4 (PA, wakes and 10% additional losses).

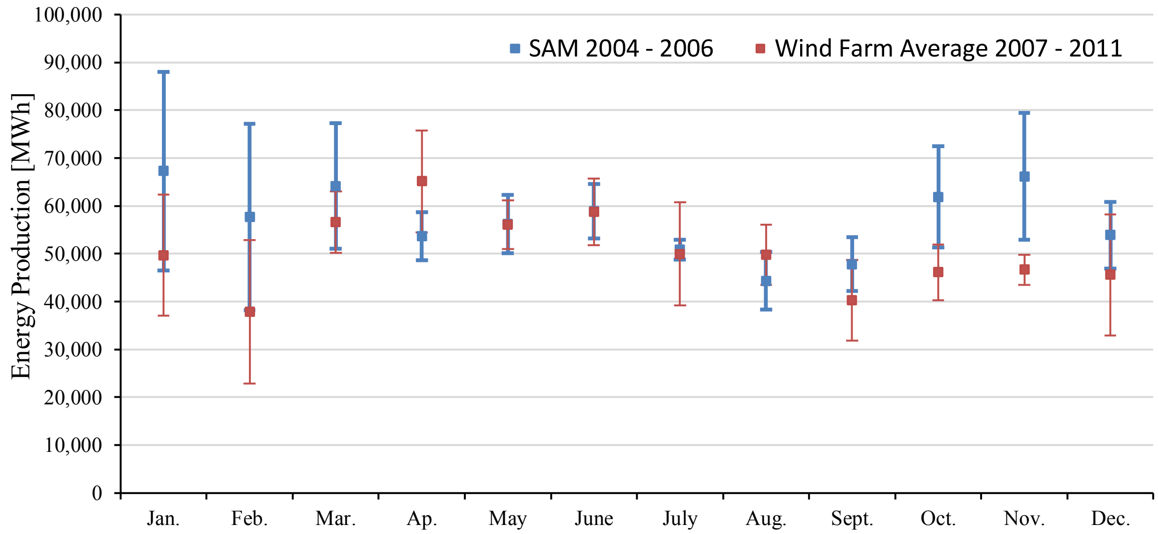


Figure 48 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S1, i.e. assuming no losses.

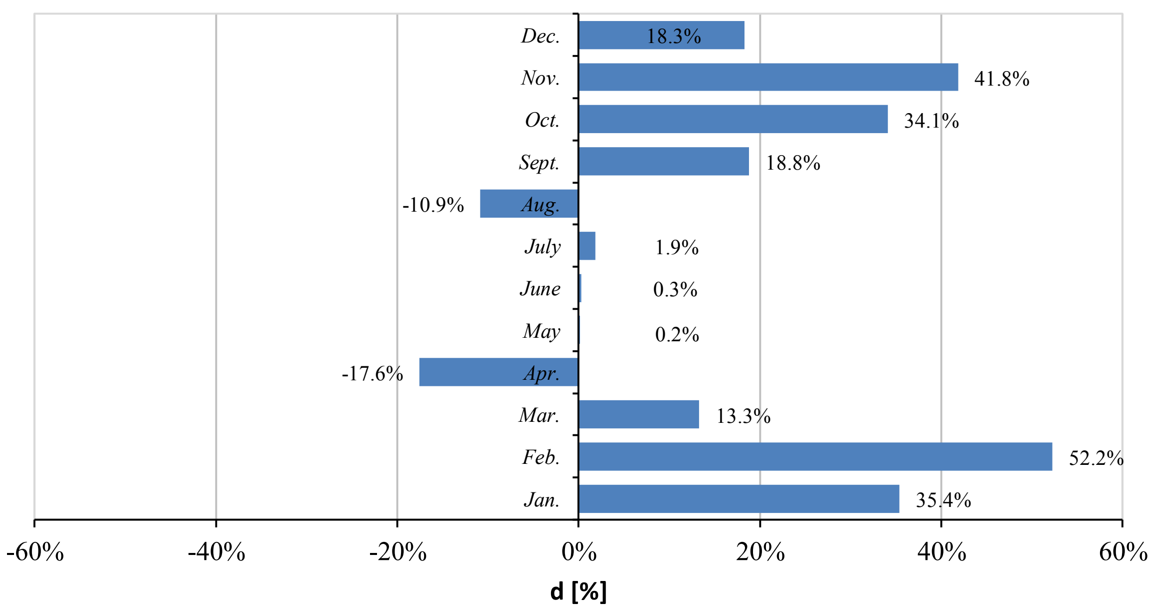


Figure 49 – Difference *d* between the average MEP for SAM and the operational data from the wind farm for S1, i.e. assuming no losses.

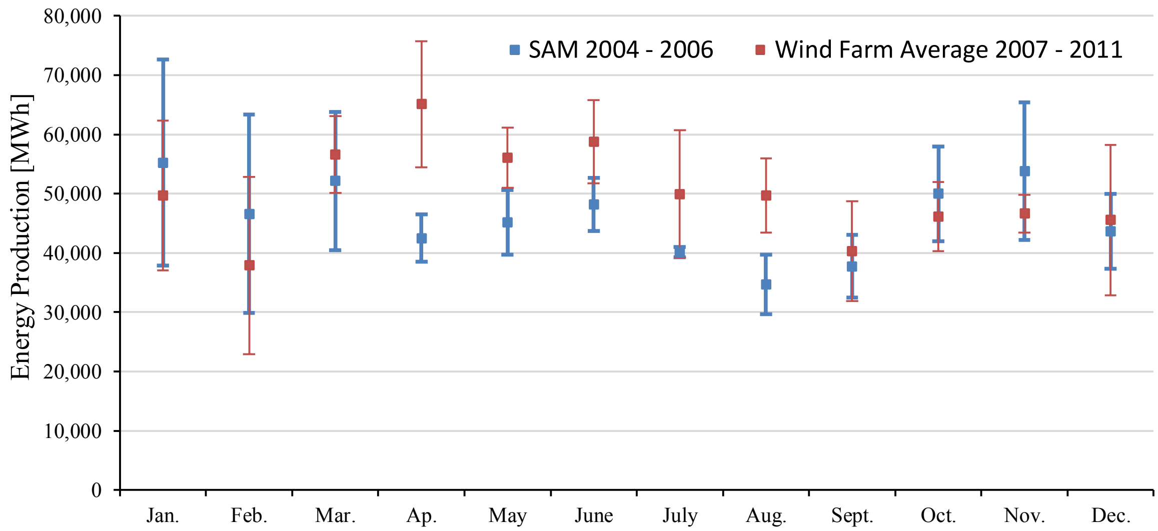


Figure 50 – MEP in SAM for 2004 - 2006 compared to the wind farm production 2007 – 2011 for S4 i.e. assuming all losses [Wakes, PA and 10% additional].

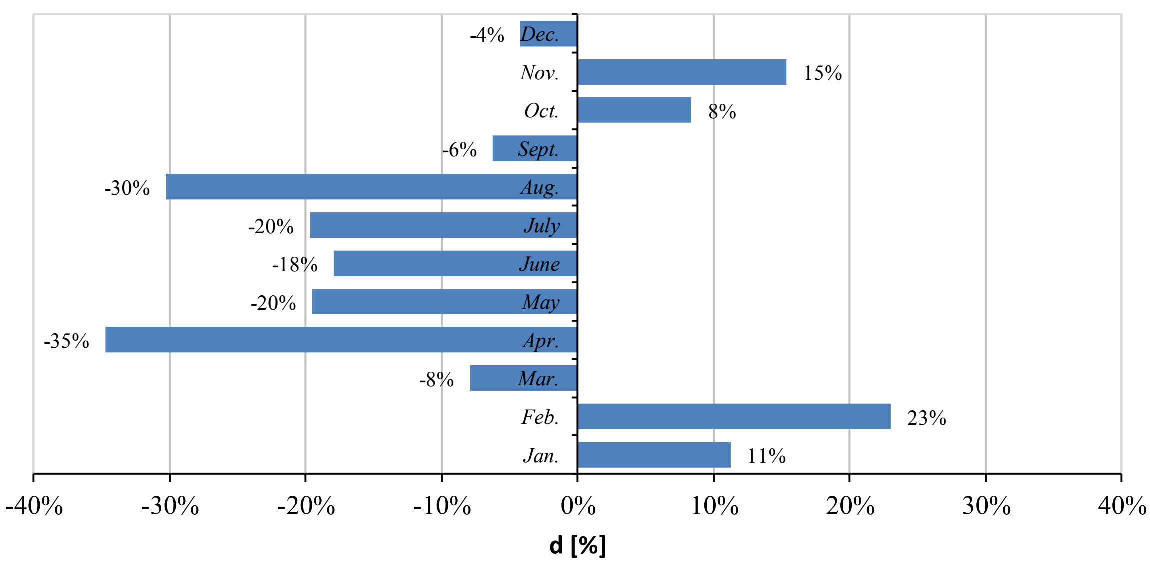


Figure 51 – Difference between the average MEP for SAM and the operational data from the wind farm for S4, i.e. assuming all losses [Wakes, PA and 10% additional].

As for location *L1*, there is a difference between individual months. For *S1*, the difference for February is -52.2%, but as previously mentioned, the wind farm values for February in 2010 were suspiciously low. Most of the autumn and winter months (Sept – April) have a large difference, while for May, June and July there is less than a 2% difference. This though is only the direct comparison of the averages. If $\pm\sigma$ is used as a measure of the uncertainty, as plotted in the figures above, it can be seen that for *S1*, all the months except for one overlap. For *S4*, two of the months do not overlap.

Figure 52 shows the annual energy production ± one standard deviation for the wind farm and SAM, for all loss scenarios *S1 – S4*. **Table 43** summarizes the AEP for each loss scenario, the range of the AEP based on $\pm\sigma$ and the correlative deviation range as well as total losses.

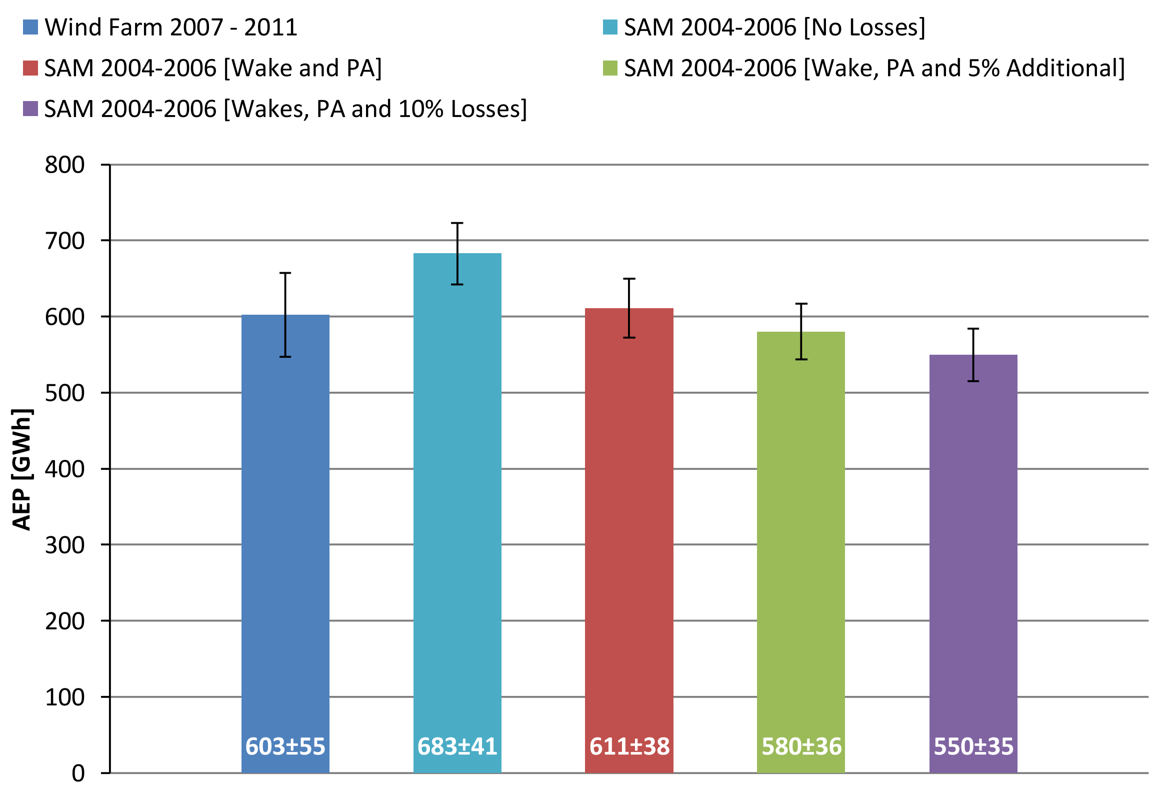


Figure 52 – AEP from SAM for all losses scenarios for 2004-2006 at location 4 compared with AEP from the wind farm.

Table 43 - Summary of the AEP predictions from SAM for L1 and S1-S4 and comparison with SAM.

	Wind Farm 2007 - 2011	$SAM_{2004-2006}$ S1	$SAM_{2004-2006}$ S2	$SAM_{2004-2006}$ S3	$SAM_{2004-2006}$ S4
AEP [GWh]	603±55	683±41	611±38	580±36	550±35
AEP Range [GWh]	[547; 658]	[642; 723]	[573; 649]	[544; 617]	[515; 550]
Deviation from average [%]		**+13.3%**	**+1.4%**	**-3.7%**	**-8.7%**
Deviation Range [%]		[+32%; -2%]	[+19%; -13%]	[+13%; -17%]	[+7%; -22%]
Wake Losses [%]			8.3%	8.3%	8.3%
Availability Losses [%]			2.4%	2.4%	2.4%
Additional Losses [%]				5%	10%
Total Losses [%]			**10.5%**	**15.0%**	**19.4%**

If the average for loss scenario *S1* and the wind farm data is compared, there is a +13.3% difference. From this, it can be seen that SAM is over predicting the AEP. If the AEP range is used, the difference is [+32%; -2%] ignoring losses. The total losses for the three other scenarios *S2*, *S3* and *S4* are 10.5%, 15.0% and 19.4%. The average for *S2* compared to the wind farm data is +1.4% with a range of [+19; -13%], for *S3*, it is -3.7% when comparing averages with the range of [+13; -17%] and lastly for *S4*, the difference is -8.7% with the range of [+7;-22%].

Comparison of L1 and L4

Table 44 shows a comparison of the AEP for SAM for *L1* and *L4* and all the loss scenarios. Wake losses for *L1* are roughly 8.7% while for *L4*, they are 8.3%. The total losses for *S4* at *L4* and *L1* are 19.4% and 19.8%, respectively. If this is compared to the typical values discussed in **Chapter 3**, it is found that this is on a range for typical total losses for a wind farm, which is convincing. Therefore, *S4* represents a very good estimate of AEP, including typical losses that might be expected inside a wind farm while *S2* is on the lower end. If the average AEP at the wind farm is compared with average AEP for *L1* and *L4* for *S4*, it is found that at *L1* it is 19.8% underestimated and at *L4*, 8.7% underestimated. While *L1* is in the range of [-10;-28], *L4* ranges from [+7%; -22%].

Table 44 - Comparison of SAM 2004 – 2006 average for both L1 and L4 and comparison with the wind farm data.

	Wind Farm 2007 - 2011	SAM2004 -2006 S1	SAM2004 -2006 S2	SAM2004 -2006 S3	SAM2004 -2006 S4	Wind Farm 2007 - 2011	SAM2004 -2006 S1	SAM2004 -2006 S2	SAM2004 -2006 S3
		L1	*L4*	*L1*	*L4*	*L1*	*L4*	*L1*	*L4*
AEP [GWh]	603±55	603±10	683±41	537±7	611±38	510±7	580±36	483±7	550±35
AEP Range [GWh]	[547; 658]	[593, 612]	[642; 723]	[530, 544]	[573; 649]	[503, 517]	[544; 617]	[477, 490]	[515; 550]
Deviation from average [%]		+0.10%	+13.3%	-10.9%	+1.4%	-15.3%	-3.7%	-19.8%	-8.7%
Deviation Range [%]		[+12; -10]	[+32%; -2%]	[-1; -19]	[+19%; -13%]	[-6; -23]	[+13%; -17%]	[-10, -28]	[+7%; -22%]
Wake Losses [%]				8.7%	8.3%	8.7%	8.3%	8.7%	8.3%
Availability Losses [%]				2.4%	2.4%	2.4%	2.4%	2.4%	2.4%
Additional Losses [%]						5%	5%	10%	10%
Total Losses [%]				**10.9%**	**10.5%**	**15.4%**	**15.0%**	**19.8%**	**19.4%**

5 Discussion

In this chapter the results listed in **Chapter 4** are discussed and analyzed.

5.1 RETScreen

5.1.1 Wind Speed

The wind speed data obtained from the NASA database and used in RETScreen for the AEP predictions is very low compared to the annual average MET tower wind speed from 2011. For the closest weather cell *C1,* the annual average wind speed is only 4.7 m/s for $\alpha = 0.20$ and 5.2 m/s for $\alpha = 0.25$ compared to 6.9 m/s at the MET tower, in all cases at 67 m hub height. Therefore, this is a 25% to 32% underestimation compared to the wind speed at the site. For *C2*, the wind speeds are higher or 5.3 m/s for $\alpha = 0.20$ and 5.83 m/s for $\alpha = 0.25$ which is a 16% to 23% underestimation. The wind speeds from the NASA database are, therefore, substantially lower than what might be expected at the wind farm site, which impacts the AEP predictions greatly.

The coarse 80 km x 110 km resolution is not enough, and if the discussion about the NASA dataset from **Chapter 2** is reviewed, these low wind speeds should not be surprising. There, it is stated that the coarse resolution "may be insufficient to catch local peculiarities of the climate; natural or human (urban affect) microclimates are not taken into account, and the SSE data alone is not appropriate where there are large topographic features within a cell of the grid" (RETScreen, 2005, p. INTRO.44). Furthermore, it has been found that for wind speed the SSE values are:

> …usually lower than measurements in mountain regions where localized accelerated flow may occur at passes, ridge lines or mountain peaks. One-degree resolution wind data is not an accurate predictor of local condition in regions with significant topography variation or complex water/land boundaries (NASA, 2013, p. 38).

Since the wind farm is located in a complex topographical landscape, the NASA weather database is not accurate enough and might not be appropriate to represent the site used in this study. However, what one might argue is what data should then be used? Since no ground station data was available, this was the only database associated with RETScreen that could be used. Many good wind resource sites, and indeed where many wind farms have already been built in the US, are in rather rural areas in complex topographical conditions. It is a clear limitation that no data is available that is thought to be able to represent those sites.

As discussed in **Chapter 2**, wind resource maps can be used in RETScreen since the model only requires annual average wind speed. Wind resource maps of the whole United States are publically available from NREL. These maps were created by AWS Truepower in 2.5 km spatial resolution and show annual average wind speed at 80 m height in 0.5 m/s increments. Detailed maps are available for each state and can be found at (NREL, n.d.), and (NREL, 2013g), as well as on an interactive map at (NREL, n.d.d).

If a NREL wind resource map for the wind farm location is used, the wind speed is in the range of 7.0-7.5 m/s at 80 meters in height. Using the same shear coefficient range as before leads to 6.70-7.17 m/s and 6.75-7.24 m/s for $\alpha = 0.20$ and $\alpha = 0.25$ respectively. The relationship with the shear coefficient is reversed since using the power law from the higher height to a lower one and a higher shear coefficient will lead to a lower wind speed at hub height. If the difference from the MET tower is examined, it is found that for $\alpha = 0.20$, the wind speed is in the range of [−2.5%; +4.5%], and [−3.4%; +3.5%] for $\alpha = 0.25$. This is a lot closer to average wind speed at the site than the NASA Web database gives. In **Table 45**, a summary is listed of wind speeds used in RETScreen and comparison with the MET data at the wind farm site.

Table 45 - Comparison of the wind speeds used in RETScreen and the MET Data.

Data height [m]	α	NASA Database [m/s]				NREL Wind Map [m/s]				MET data [m/s]
		CELL 1	d	CELL 2	d	Low	d	High	d	
10/80		3.21		3.63		7.0		7.5		
67	0.20	4.70	-32%	5.30	-23%	6.76	-2.5%	7.24	+4.5%	6.93
67	0.25	5.16	-25%	5.83	-16%	6.70	-3.4%	7.17	+3.5%	6.93

5.1.2 Energy Predictions

The AEP predictions in RETScreen were low compared to the average AEP of the wind farm, as a result of the low wind speeds obtained from the database. Several input variables had to be determined, as discussed below, which affected the AEP predictions greatly. Using the upper limits[6] of the ranges selected for those variables, (i.e. they are all selected in favor of RETScreen) the energy predictions are still in the range of [−34%, −45%] underestimation when ignoring losses, and [−47%; −56%] assuming all losses. Using a lower shear coefficient, defined in the range of α=0.20-0.25, or k= 2.0, results in even higher underestimation. It can conservatively be said that the underestimation of the AEP is at least in this range and might even be higher. The second weather data set C2 is less relevant for the wind farm based on the fact that only 10% of the turbines are inside the cell based on the coordinates. It had, however, 0.4 m/s higher wind speed at measurement height. For the same conditions as for C1 above, the AEP predictions are underestimated in the range of [−14%; −28%] neglecting losses, and in the range of [−31%; −42%] when accounting for all losses. Even by using C2, the underestimation is still severe. This also shows the impact that only a 0.4 m/s increase in the wind speed has on the AEP predictions.

[6] This is by using weather data from *C1*, $k = 1.7$ as the shape factor, $\alpha = 0.25$ for the shear coefficient, VESTAS 1.8 MW 1A and comparing with $\bar{E}_{WF} \pm \sigma = \mathbf{603} \pm \mathbf{55}\ \boldsymbol{GWh}$.

If the wind speed is obtained from the NREL wind resource map and the input variables kept the same as for *C1* and *C2*, the estimated AEP and d, the difference from the wind farm data, can be seen in **Table 46** and **Table 47** below; the estimated range of d is also listed in **Table 48**.

Table 46 - AEP [MWh] for 7.0 – 7.5 m/s wind speed at 80 meters, for α = 0.20, α = 0.25, and k = 1.7; 2.0 for all loss scenarios S1-S4.

	Upper boundary - 7.5 m/s at 80 m				*Lower Boundary - 7.0 m/s at 80 m*			
α	*0.20*		*0.25*		*0.20*		*0.25*	
k	*1.7*	*2*	*1.7*	*2*	*1.7*	*2*	*1.7*	*2*
S1	686,191	693,711	677,195	683,452	614,453	612,679	605,128	602,235
S2	611,457	618,158	603,440	609,016	547,532	545,951	539,222	536,644
S3	580,884	587,250	573,268	578,565	520,155	518,653	512,261	509,812
S4	550,311	556,342	543,096	548,114	492,779	491,356	485,300	482,980

Table 47 – The difference *d* between the wind farm average AEP compared to RETScreen AEP predictions.

	Upper boundary - 7.5 m/s at 80 m				*Lower Boundary - 7.0 m/s at 80 m*			
α	*0.20*		*0.25*		*0.20*		*0.25*	
k	*1.7*	*2*	*1.7*	*2*	*1.7*	*2*	*1.7*	*2*
S1	+13.9%	+15.1%	+12.4%	+13.4%	+2.0%	+1.7%	+0.4%	+0.0%
S2	+1.5%	+2.6%	+0.2%	+1.1%	-9.1%	-9.4%	-10.5%	-10.9%
S3	-3.6%	-2.5%	-4.9%	-4.0%	-13.7%	-13.9%	-15.0%	-15.4%
S4	-8.7%	-7.7%	-9.9%	-9.0%	-18.2%	-18.4%	-19.5%	-19.8%

Table 48 - The range of *d* for the AEP predictions using NREL's wind resource map.

	d [%]			
α	*0.20*		*0.25*	
k	*1.7*	*2*	*1.7*	*2*
S1	[+25, -7]	[+27, -7]	[+24, -8]	[+25, -8]
S2	[+12, -17]	[+13, -17]	[+10, -18]	[+11, -18]
S3	[+6, -21]	[+7, -21]	[+5, -22]	[+6, -22]
S4	[+1, -25]	[+2, -25]	[-1, -26]	[0, -27]

The difference d in the AEP prediction, compared to the average wind farm AEP, is in the range of [+12.4%, 0%] ignoring losses (*S1*) and [−9.9%; −19.8%] when accounted accounting for all losses (*S4*). If compared to $\bar{E}_{WF} \pm \sigma$, the difference is in the range of [+24%, −8%] for *S1* and [−1%, −26%] for *S4*. Using the NREL wind resource map leads to a much better estimation of the AEP at the wind farm site than using the NASA database. It is still important to know the limitations of using a wind resource map. As seen in **Table 43**, the AEP is 548,114 MWh and 482,980 MWh, for the upper and lower boundaries of the wind speed estimates (assuming k=1.7 and α=0.25), or roughly 65,000 MWh difference. Therefore, the AEP will always be predicted over a large range and is, therefore, always a very rough estimate.

Lastly, the MET tower data can be used in RETScreen to estimate the AEP. In this case, the AEP is not a function of α and only a function of k. For the same conditions as stated above, the predicted AEP compared to the wind farm is +0.2% for *S1* and −19.6% for *S4*, as listed in **Table 49.** In this case, the AEP predictions are compared to the AEP in 2011, but not the five-year average and the results, therefore, are not given in a range. Using the MET tower data gives a relatively good estimate of the AEP at the site. If onsite data would be available such as from a MET tower in this study, it is unlikely that RETScreen would be used for AEP predictions. This comparison was primarily performed to estimate the expected error of the assumption of using only one weather file to represent the whole wind farm. It must, though, be mentioned that, both for the NREL data and the MET data, wind turbine type 1A was used. Since it could not be confirmed if the turbines at the site are 1A or 2A there is an uncertainty associated with that. Using 2A wind turbines will result in lower AEP and, therefore, these results are in favor of RETScreen.

Table 49 - RETScreen's AEP predictions using the MET tower data and the difference from the operational data in 2011.

	AEP [MWh]		*d [%]*	
K	*1.7*	*2.0*	*1.7*	*2.0*
S1	636,811	638,498	+0.2	+0.5
S2	567,455	568,958	-10.7	-10.5
S3	539,082	540,510	-15.2	-15.0
S4	510,709	512,062	-19.6	-19.4

Using the NASA weather database associated with RETScreen will lead to substantial underestimation of the AEP at the site in this case study. The low wind speeds result in high underestimation in AEP predictions. If looking at the theory behind the dataset and its resolution this is not surprising. Therefore, it is not recommended if a site in complex topographical settings is being modeled. Using RETScreen to do any further assessment (e.g. of financial viability of the project) will always be invalid, as the energy predictions are so inaccurate. Wind resource maps can be used in RETScreen in complex topographical locations, but should be known to be a very rough estimation and predict AEP over a large range; pressure and temperature data would need to be obtained from the NASA database as well. Using both the wind map and the MET tower data established some confidence that using only one weather file to represent a whole wind farm can be relevant. As observed here, this can be expected to be at least in the range of up to 30% off. However, based on only one case in this study, it is not possible to generalize about the accuracy of the program and further studies would need to be conducted.

5.1.3 Determination of Input Variables

In RETScreen, the user defines the shape factor k, shear coefficient α, and the turbine type in the energy model. Proper selection of each plays a major role in the AEP predictions; these should be selected as accurately as possible. Ideally, the turbine type that the user wants to use is known or if a validation of the models is being conducted like in this study, the turbine type of the project must be known. If not, the uncertainty of the assessment is increased greatly.

The shear coefficient was selected in a range from $\alpha = 0.20 - 0.25$ and as expected, larger shear leads to higher AEP predictions. The difference in using the upper and lower boundary of α resulted in roughly a 60,000 MWh difference for *S4* using *C1*. When compared to the wind farm data, the difference was 11 percentage points (i.e. using $\alpha = 0.20$ compared to $\alpha = 0.25$ increased the underestimation of AEP predictions by 11 percentage points). The shape coefficient k of the Weibull distribution was also defined in a range and AEP recorded for $k = 1 - 3$. The detailed results are listed in **Appendix B** while results for $k = 1.7$ and $k = 2.0$ were analyzed comprehensively. The value $k = 2.0$ is often used as a default value if no information about the distribution is available, and in *Browner* (2012), it is said that commonly found k are in the range from 1.6 to 2.4, as previously discussed. If that is used as a guideline and loss scenario *S4* (assuming all losses) where the weather cell *C1* was used, the difference in using $k = 1.6$ and $k = 2.4$ resulted in roughly a 40,000 MWh difference, where $k = 1.6$ gave the higher predicted AEP. If this is compared to the wind farm data, the difference is roughly 6 percentage points (i.e. using $k = 2.4$ compared to $k = 1.6$ increases the underestimation of AEP in RETScreen compared to the wind farm data by 6 percentage points).

In a pre-feasibility assessment, like the one done with RETScreen, accurate knowledge about α and k at a given site is uncommon. It is recommended that those be defined as ranges rather than as single values based on how much impact the determination of this has on the predicted AEP. The user cannot do this directly in RETScreen, which is a limitation. In the sensitivity and risk analysis, the user can estimate the financial impacts if the AEP is changed by a certain percentage. It would be very helpful if the user could estimate the effects of changes in the input variables in the energy module or be able to define the input variables as ranges. It is at least necessary that the user recognizes the impacts that the selection of both k and α have on the predicted AEP and the uncertainty associated with that.

5.2 SAM

5.2.1 Wind Speed

Since the spatial resolution is a lot denser in SAM than RETScreen it was expected that the weather data would be more representative for the wind farm. The 10 km x 10 km resolution is, nonetheless, still coarse if compared to commercially used micro-models and it is important to keep in mind that this is modeled data.

Two weather files (*L1* and *L4*), at locations closest to the existing wind farm, were selected as representative of the wind farm site. For location *L1*, annual average wind speed is $6.73 \pm 0.06\ m/s$ but $7.21 \pm 0.22\ m/s$ for *L4*. The annual average wind speed at both locations is very similar between 2004 and 2005. In both cases, 2006 is higher and substantially for *L4*. The difference from the MET tower annual average is −2.9% for *L1* and +4% for *L4* (i.e. the annual average wind speed at *L1* is 2.9% lower than at the MET tower while being 4.0% higher at *L4*). If the monthly average wind speeds are compared they are different; for some months the differences are substantial and do not overlap inside ± one standard deviation. This is not a surprise, as there can be substantial variance in the monthly average wind speeds at a given site between years. It is also necessary to understand that this comparison is more to give an idea of whether the weather data is relevant since the wind speeds from the database are averages from 2004, 2005, and 2006 while the MET tower data is from 2011 and, therefore, not directly comparable. The wind speed can also vary a lot based on measurement location, especially in complex terrain. In this case, the difference between the MET tower location and the location of *L1* and *L4* was 4 km and 6 km respectively so only that can explain a difference. Also, even though the annual average wind speeds are identical, the wind speed distribution over the year is what really matters. The comparison, however, gives a rough idea about how relevant the data obtained from the weather databases is. For this case, both locations *L1* and *L4* are thought to be fairly representative for the wind farm.

5.2.2 Energy Predictions

The AEP predictions from SAM are more accurate for the wind farm than from RETScreen. For *L1*, the predicted AEP over the three year period is very similar or 603,545 MWh, 590,877 MWh, and 614,224 MWh for 2004, 2005, and 2006 respectively. Therefore, the coefficient of variation is relatively low or 1.6%. For *L4*, the AEP is similar for 2004 and 2005 or 655,845 MWh and 652,394 MWh. For the year 2006, the energy production is substantially higher or 740,139 MWh, roughly 13% higher than the two prior mentioned years. This leads to a higher standard deviation and coefficient of variation or 6.3%; therefore, the AEP for *L4* is predicted over a larger range. For *L4*, the difference compared to the average wind farm AEP is +13.3% and in the range of [+32%, −2%] when neglecting losses. When accounting for all losses the difference is in the range of [+7%, −22%]. For *L1*, the difference is −8.7% and the range is [−1%, −19%] neglecting losses, and −19.8% and in the range of [−10%, −28%] when assuming all losses. If the MEP for separate months is examined the comparison is not as good, and is quite frankly all over the place. Even when ± one standard deviation is used many months do not overlap in the uncertainty range. When the comparison data from the wind farm is examined, some months have very high coefficient of variation or over 25% and (e.g. February) the MEP was suspiciously low. Comparison of MEP was, therefore, not thought relevant.

Based on this case study SAM gives relatively good results for AEP prediction for the wind farm site. It must, though, be noted that both the predicted AEP and the comparison data were defined over a rather wide range and the AEP of the wind farm is estimated to lie somewhere in the range of [547 GWh, 658 GWh] and for *L4* and *S4* the range is [515 GWh, 550 GWh]. Therefore, the variance of both is high resulting in uncertainty of the AEP comparison. This is because of the difference in the period of the data being examined. If the same period would be compared, this could be estimated a lot more accurately and the uncertainty associated eliminated. This comparison, however, gives an indication of the AEP predictions in SAM being quite accurate and using only one weather file to represent the whole wind farm is appropriate for rough AEP estimations. However, based on only one case study, it is not possible to generalize about the accuracy of the program and further studies would need to be conducted.

5.2.3 Determination of Input Variables

Input variables in SAM were few. The user defines the turbine type and the wind farm layout, both in a relatively simple way. No shape factor or shear coefficient was required based on the weather data used. The purpose of this study was to see how well the program's predictions compared to measured operational data of a given wind farm. Therefore, the coordinates and the layout of the wind farm were known. The representative weather data was selected subjectively by the author based on **Figure 20**, and as both *L1* and *L4* were thought representative as discussed in **Section 3.3.1**, AEP predictions were conducted for both locations. This was solely based on rough estimation of the distance of the weather file locations to the wind farm. The wind farm is located in a square 10 km x 10 km cell with a weather file at each corner point and four weather locations could, therefore, have been used in this study. A summary of the weather files showing the annual average wind speed and the predicted AEP (without accounting for losses) is listed in **Table 50**.

Table 50 – Comparison of the four weather locations in SAM.

	Elevation of site [m]	Wind Speed [m/s] $\overline{v}_{2004-2006} \pm \sigma$	AEP [GWh] $\overline{E}_{2004-2006} \pm \sigma$	d [%]
Location 1 (L1)	897	6.73±0.06	603±10	+0.1
Location 2 (L2)	1083	6.55±0.10	548±17	-9.1
Location 3 (L3)	745	6.05±0.26	510±44	-15.4
Location 4 (L4)	750	7.21±0.22	683±41	+13.3
MET Tower[1]	1066	6.93	-	-
Wind Farm[2]	800 - 1200	-	603±55	0

L3 has the lowest wind speed and consequently the lowest AEP, followed by *L2* and *L1*, while *L4* has by far the highest AEP. If the averages are compared the difference between the highest and lowest AEP is as high as 173 GWh and if the uncertainty range is used it can be as high as 258 GWh. Therefore, the selection of an appropriate weather file is really important.

In pre-feasibility assessment when the exact location of the wind farm might not be known, how should the weather file be determined? No recommendations are given for this in the help manuals for the program and the weather file closest to the coordinates the user requires will be used in the AEP predictions. What coordinates should be used to represent the wind farm site? Is using only the closest weather file, always the most accurate way? If roughly the middle of the wind farm (based on the height and width, see **Figure 22**) had been used in this study, weather file *L4* would have been selected and used in the AEP predictions. However, as seen on **Figure 20**, several wind turbines in the farm are much closer to the *L1* weather file location. Potentially, should some average of the two be used? One way could be to use inverse distance weighting (**IDW**). The unknown value $u(x)$ (in this case at the middle of the wind farm) is calculated based on known values $u(x_i)$ for $i = 0,1,\ldots,N$ (in this case, at the corner points of the square cell where the wind farm is located) and weighted inversely based on the distance (x, x_i) according to:

$$u(x) = \sum_{i=0}^{N} \frac{w_i(x) \cdot u_i}{\sum_{J=0}^{N} w_j(x)} \qquad \textbf{(Eq. 5-1)}$$

$$where, w_i(x) = \frac{1}{d(x, x_i)^p} \qquad \textbf{(Eq. 5-2)}$$

p is the power parameter (positive real number) used in the weighting. If this method would have been used in this study for $p = 2$ (the distance squared in the weighting) and x_i defined in the middle of the wind farm then the AEP would have been 639 GWh, ignoring losses. Required information for the calculations can be found in **Table 51** below.

Table 51 – IDW information.

	Distance [km]	AEP [GWh]	d^2	$1/d^2$	Fraction [%]
Location 1	4.4	603	19.1	0.052	26.3
Location 2	8.5	548	72.8	0.014	6.9
Location 3	7.9	510	62.2	0.016	8.1
Location 4	2.9	683	8.6	0.116	58.6
				0.198	100

Since *L4* is the closest to the middle of the wind farm, its AEP weights the highest (59%) followed by *L1* (26%), while the predicted AEP at *L2* and *L3* only account for 7% and 8% in the average. This gives relatively good results here. Those are, however, simple speculation and general recommendation about selection of the weather file cannot be based on this simple example. It is, however, recommended that the user examines more than one weather file when the AEP predictions are performed. Google Earth™ can be helpful in locating the weather files and the relevant location of the wind farm.

The user can define the layout of the wind farm and roughly calculate the wake losses according to simplified wake models. In pre-feasibility studies, the detailed layout of the wind farm very likely is unknown, as that is done at the micro-model stage. The user can, however, predict the AEP for a single turbine and then multiply by the number of turbines in the wind farm and account for the wake losses as a percentage value using a spreadsheet program such as MS Excel; this might be more feasible in pre-feasibility studies.

6 Summary and Conclusion

In this study, the wind energy modules of the renewable energy assessment programs RETScreen and System Advisor Model (SAM) were examined, and their predictions compared to measured operational data. Both of these programs have been used in teaching *energy infrastructure* at the University of Washington. It was of interest to see how well they perform, since validation and similar research have been limited to date.

RETScreen, an Excel add-in developed by CanmetENERGY research center in Vareenes, Canada, has been around for over 15 years while the wind energy module in SAM, which is developed by NREL (National Renewable Energy Laboratory), is relatively new. It launched in 2010. The programs have integrated and associated web-based weather databases and, therefore, a preliminary assessment can be performed in the absence of onsite wind speed measurements. Lack of weather data is often a barrier for such an analysis. Both make rough AEP (Annual Energy Production) predictions, as only one weather file is used to represent a wind farm. The spatial and temporal resolution of the weather data is very different, and while RETScreen has global coverage, SAM only covers the United States. Both models were examined comprehensively in the study and the theoretical background behind them carefully studied. In **Table 4**, in **Section 2.5**, a summary of the main characteristics and the difference between the two models are listed.

Operational data from a wind farm in the United States, which included electricity production and availability for a five-year period as well as wind speed measurements from an onsite meteorological (MET) tower, were compared to the weather databases and AEP predictions of the models. Predictions were made with, and without, accounting for losses but availability, wake-, turbine-, environmental- and other miscellaneous losses were estimated, and four different loss scenarios were examined, *S1–S4*. The wind farm is located in a complex topographical location, which increased the complexity of the comparison. The production data was available for a five-year period, 2007–2011 while the MET tower data was for a single year, 2011. The average AEP of the wind farm was used for comparison and one standard deviation in predicted AEP and wind speed based on variation in the input parameter values was used as a measure of uncertainty. AEP predictions were performed from modeled weather data for the years 2004–2006 in SAM while the AEP predictions by RETScreen were for a typical year. The main conclusions listed for each program are the following:

RETScreen

- The weather database associated with RETScreen has too coarse a spatial resolution to be accurate for a given site located in a complex topographical area. Low wind speeds obtained from the database (i.e. 25% to 32% lower than MET data from an on-site weather station), lead to an underestimation of the AEP in the range of [−34%; −45%], assuming no losses and [−47%; −56%], when accounting for losses. In both cases, using input variables in favor of RETScreen (shape factor $k = 1.7$ and shear coefficient $\alpha = 0.25$).
- Using a wind resource map from NREL (National Renewable Energy Laboratory) gives a better estimate of the wind speed at the site, in the range of [−3.4%; +4.5%] difference compared to the MET data. Consequently, the AEP was predicted more accurately in the range of [25%; −8%], assuming no losses and [1%; −27%], when accounting for losses.

- For sites in complex terrain, it is recommended that NREL wind resource maps are used rather than the associated weather databases. However, this estimate should be considered to be very rough as the maps are given in increments of 0.5 m/s and the AEP is, therefore, predicted over a large range.
- It is recommended that the shape factor k and shear coefficient α are defined as ranges rather than single values based on how much impact the determination of those has on the predicted AEP.

SAM

- Two weather files (i.e., *L1* and *L4*), at locations closest to the existing wind farm, were selected as representatives of the wind farm, and the AEP predictions were performed for both. The annual average wind speed was 6.73 ± 0.06 m/s and 7.21 ± 0.22 m/s respectively, compared to 6.93 m/s wind speed at the MET tower. If averages are compared, the wind speed is 2.9% lower for *L1* than the MET tower but 4.0% higher for *L4*.
- For *L4* (the closer to the wind farm), the predicted average AEP is +13.3% compared to the average wind farm AEP and the range is [+32%; −2%] ignoring losses. When accounting for losses, the difference range is [+7%; −22%] and +8.7% when averages are compared (i.e. the average AEP in SAM has an 8.7% underestimation compared to the wind farm data).
- For *L1*, the difference in the predicted average AEP compared to the average wind farm AEP is +0.1% and the range is [−1%; −19%] ignoring losses. When accounting for losses the range is [−10%; −28%] and direct comparison of the average is −19.8%.

Therefore, the average AEP in SAM is underestimated by 19.8% compared to the wind farm data.

- Based on this case study, the AEP predictions in SAM are quite good or in the range of roughly [10% to −30%] compared to the wind farm data. Using only one weather file to represent a whole wind farm is appropriate for rough AEP estimation. However, based on only one case in this study, it is not possible to generalize about the accuracy of the program and further studies would need to be conducted.

Both models have limitations. The spatial resolution of the associated weather databases in RETScreen is too coarse and, therefore, not representative for the wind farm, and additional data was required from the wind resource map. Input variables had also to be determined based on very broad table values, as onsite data was not available, by selecting those in ranges, the uncertainty associated with those was limited. For SAM, the study falls short in the sense that the operational data and the SAM predictions do not cover the same period, resulting in uncertainty of the AEP comparison. It is recommended that additional research is conducted to eliminate the uncertainty. Since 3TIER is currently modeling data for the whole United States for the period 2007–2011, this comparison will be achievable if the data will be made publically available or even integrated in SAM. This would exclude the uncertainty associated with different periods between the predicted and operational data in this study, and give better estimation on how much uncertainty can be expected with using only one weather file to represent a whole wind farm, which is a clear limitation compared to commercially used micro-models. Another topic of interest would be to compare the models to operational data from a site in a flat terrain, as nothing can be assumed about their accuracy in this setting based on this study.

In this study, only the wind energy modules of the programs were examined. For SAM, the solar energy module seems to be powerful. It is the most used and the reason that the software was created in the first place. It also would be interesting to compare the solar energy modules, as has been done for the wind energy modules in this study. The usage of these programs in the industry was not examined in this study and that would need to be done to answer questions such as: *Are the models being used in real projects or mostly in educational and research purposes*? Even though the wind energy module in SAM can be used in pre-feasibility studies it might be used for other purposes. Validation of the performance model is, however, always important and very relevant, especially since no validation has been performed on the model to date. The validation of RETScreen, which is listed in the program's textbook, is on a very small scale or for a wind farm with only 10 turbines. This is not comprehensive enough to estimate the capabilities of the program; also, the validation was done for a site in flat terrain. Since the program was originally launched over 15 years ago, it is not felt that major updates have been done to the methodology used in the AEP predictions, while several other solutions have become available for use in pre-feasibility assessment of wind energy projects. This includes the wind site assessment dashboard from AWS Truepower found at (AWS Truepower, 2013) in 2 km and 200 m spatial resolution and similar solutions from 3TIER in 4 km – 90 m resolution as found at (3TIER, n.d.); both of those are, however, available for purchase while RETScreen and SAM are free.

It is felt like the purpose of the study was reached. A reference guide about the wind energy module in both RETScreen and SAM was created. Comprehensive discussion about the theoretical background of the module, how required input variables should be determined, and what needs to be considered when those are selected, are discussed. By comparing the models to real operational data, an indication about the usage, limitations, and capabilities has also been established. It is, therefore, hoped that this can be used in the University of Washington class on *energy infrastructure*. The programs can suit as educational tools, at least in introduction courses on energy infrastructure to establish the base knowledge and the theory behind such assessment. Also, since weather data can be hard to obtain using the integrated weather data is convenient. It is, however, important that students are enlightened about the capabilities and limitations that these programs have, as well as the difference between those and commercially used WRA micro-models. A major wind energy project will always need micro-modeling to select the turbine layout and maximize the energy output, while pre-feasibility tools can serve in early stages of the project phase.

7 Bibliography

3TIER. (2010, March). *Development of Regional Wind Resource and Wind Plant Output dataset - Final Subcontract Report 15. October 2007 - 15. March 2009.* Retrieved September 1, 2013, from National Renewable Energy Laboratory (NREL): http://www.nrel.gov/docs/fy10osti/47676.pdf

3TIER. (2012, August 21). *3TIER Selected by NREL to Update National Wind* . Retrieved September 20, 2013, from 3TIER: http://www.3tier.com/static/ttcms/us/documents/press-releases/NREL-Selects-3TIER-US-Integration-Dataset.pdf

3TIER. (n.d.). *Wind Energy Project Feasibility - Prospecting & Resource Assessment*. Retrieved November 15, 2013, from 3TIER: http://www.3tier.com/en/products/wind/project-feasibility/

AWS Truepower. (2010, April). *OpenWind Theoretical Basis and Validation.* Retrieved October 2, 2013, from OpenWind: http://www.awsopenwind.org/downloads/documentation/OpenWindTheoryAndValidation.pdf

AWS Truepower. (2013). *AWS Trupower Dashoards.* Retrieved December 1, 2013, from AWS Truepower: https://dashboards.awstruepower.com/

Banuelos-Ruedas, F., & Camacho, C. Á. (n.d.). *Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region.* Retrieved November 4, 2013, from Intech : Open Science - Open Minds: http://cdn.intechopen.com/pdfs/17121/InTech-Methodologies_used_in_the_extrapolation_of_wind_speed_data_at_different_heights_and_its_impact_in_the_wind_energy_resource_assessment_in_a_region.pdf

Blair, N. d. (2012). *Case Studies Comparing System Advisor Model (SAM) Results to Real Performance Data*. Retrieved September 1, 2013, from System Advisor Model - Case Studies and Validation. : http://www.nrel.gov/docs/fy12osti/54676.pdf

Brower, M. (2010). *Development of Eastern Regional Wind Resource and Wind Plant Output Datasets - March 3, 2008 - March 31, 2010.* Retrieved November 4, 2013, from NREL - Transmission Grid Integartion: http://www.nrel.gov/docs/fy10osti/46764.pdf

Brower, M. (2012). *Wind Resource Assessment - A Practical Guide to Developing a Wind Project.* Hoboken, New Jersey, USA.: A John Wiley & Sons, Inc. Publication.

Den Norske Veritas , & RISO National Laboratory. (2002). *Guidelines for Design of Wind Turbines - 2nd edition.* Retrieved November 1, 2013, from Middle East Technical University - Aerospace Engineering: http://www.ae.metu.edu.tr/~ae361/10/windturbine.pdf

EnerNex Corporation. (2011, February). *Eastern Wind Integration and Transmission Study - Executive Summary and Project Overview.* Retrieved November 4, 2013, from NREL - Transmission Grid Integration: http://www.nrel.gov/docs/fy11osti/47086.pdf

ESRI. (n.d.). *Meauring in Arc-Seconds*. Retrieved September 20, 2013, from ESRI - Understanding our World: http://www.esri.com/news/arcuser/0400/wdside.html

Firtin, E., Guler, Ö., & Akdag, S. A. (2011, 11). Investigation of wind shear coefficients and their effect on electrical generation. *Applied Energy*, pp. 4097-4105.

Freeman, J. W. (2013). *System Advisor Model: Flat Plate Photovoltaic Performance Modeling Validation Report.* Retrieved November 15, 2013, from System Advisory Model - Validation and Case studies: http://www.nrel.gov/docs/fy14osti/60204.pdf

Gilman, P. (2013). *Support Forum*. Retrieved November 1, 2013, from NREL - System Advisor Model (SAM): https://sam.nrel.gov/forums/support-forum

Gipe, P. (2004). *Wind Power - Renewable Energy for Home, Farm, and business. .* White River Junction, Vermont: Chelsea Green Publishing Company.

HOMER Energy. (n.d.). *About HOMER Energy*. Retrieved November 15, 2013, from http://homerenergy.com/about.html

Jain, P. (2011). *Wind Energy Engineering.* United States of America: The McGraw-Hill Companies, Inc.

NASA. (2008, March 26). *Surface meteorology and Solar Energy* . Retrieved November 1, 2013, from NASA - The Atmospheric Science Data Center : https://eosweb.larc.nasa.gov/sse/RETScreen/

NASA. (2013, January 10). *Surface meterology and Solar Energy (SSE) Release 6.0 - Methodology Version 3.1.1.* Retrieved September 20, 2013, from Surface meterology and Solar Energy - A renewable energy resource web site (release 6.0).: https://eosweb.larc.nasa.gov/sse/documents/SSE6Methodology.pdf

National Atlas. (2013, January 14). *How precise can we be with latitude and longitude?* . Retrieved November 1, 2013, from National Atlas.gov - Where We Are : http://nationalatlas.gov/articles/mapping/a_latlong.html

NREL. (2012a, October 31). *About the Wind Integration Datasets*. Retrieved September 1, 2013, from NREL - Transmission Grid Integration: http://www.nrel.gov/electricity/transmission/about_datasets.html

NREL. (2012b, October 24). *Western Wind Dataset*. Retrieved September 1, 2013, from Transmission Grid Integration: http://www.nrel.gov/electricity/transmission/western_wind_methodology.html

NREL. (2013a). *Case Studies and Validation*. Retrieved November 15, 2013, from NREL - System Advisor Model: https://sam.nrel.gov/content/case-studies

NREL. (2013b, May 23). *Eastern Renewable Generation Integration Study.* Retrieved November 4, 2013, from Nrel - Transmission Grid Integration: http://www.nrel.gov/electricity/transmission/eastern_renewable.html

NREL. (2013c, March 7). *Eastern Wind Dataset*. Retrieved September 1, 2013, from NREL - Transmission Grid Integation: http://www.nrel.gov/electricity/transmission/eastern_wind_methodology.html#site

NREL. (2013d, March 2013). *Obtaining the Eastern Wind Dataset*. Retrieved September 1, 2013, from NREL - Transmission Grid Integration: http://www.nrel.gov/electricity/transmission/eastern_wind_dataset.html

NREL. (2013e, January 14). *System Advisor Model (SAM) - Help System - Version 2013.1.15.* Retrieved November 4, 2013, from https://sam.nrel.gov/sites/sam.nrel.gov/files/content/documents/pdf/sam-help.pdf

NREL. (2013f, September 24). *Western Wind and Solar Integration Study*. Retrieved November 4, 2013, from NREL - Transmission Grid Integration: http://www.nrel.gov/electricity/transmission/western_wind.html

NREL. (2013g, September 3). *Wind Maps.* Retrieved November 1, 2013, from National Renewable Energy Laboratory - Dynamic Maps, GIS Data, & Analysis Tools: http://www.nrel.gov/gis/wind.html

NREL. (n.d.a). *MapSearch.* Retrieved Novemeber 10, 2013, from National Renewable Energy Laboratory: http://www.nrel.gov/gis/mapsearch/

NREL. (n.d.b). *SAM in Publications*. Retrieved November 15, 2013, from NREL - System Advisor Model: https://sam.nrel.gov/content/sam-publications

NREL. (n.d.c). *Western Wind Resource Dataset Interface*. Retrieved September 1, 2013, from NREL: http://wind.nrel.gov/Web_nrel/

NREL. (n.d.d). *Wind Prospector*. Retrieved November 10, 2013, from National Renewable Energy Labarotory: http://maps.nrel.gov/windprospector

Quinlan, P. J. (1996). *Time Series Modeling of Hybrid Wind Photovotaic Diesel Power Systems.* Retrieved September 5, 2013, from NREL - System Advisor Model (SAM) - Performance Models: http://sel.me.wisc.edu/publications/theses/quinlan_updated_96.zip

RETScreen. (2004, June). *RETScreen International: Results and Impacts 1996-2012.* Retrieved November 4, 2013, from RETScreen International - Empowering Cleaner Energy Decisions.: http://www.retscreen.net/fichier.php/623/Rapport_Impact.pdf

RETScreen. (2005, September). *Clean Energy Project Analysis - RETScreen Engineering & Cases Textbook - Third Edition.* Retrieved November 3, 2013, from RETScreen International: http://www.retscreen.net/ang/12.php

RETScreen. (2012a, June 13). *RETScreen Plus*. Retrieved November 1, 2013, from RETScreen International - Empowering Cleaner Energy Decisions: http://www.retscreen.net/ang/performance_analysis.php

RETScreen. (2012b, June 19). *Software and Data*. Retrieved November 1, 2013, from RETScreen International - Empowering Cleaner Energy Decisions: http://www.retscreen.net/ang/software_and_data.php

RETScreen. (2013a, October 3). *Climate Data*. Retrieved November 4, 2013, from RETScreen International - Empowering Cleaner Energy Decisions: http://www.retscreen.net/ang/d_data_w.php

RETscreen. (2013b, June 14). *Databases*. Retrieved November 1, 2013, from RETScreen International - Empowering Cleaner Energy Decisions: http://www.retscreen.net/ang/databases.php

RETScreen. (2013c, June 14). *RETScreen 4*. Retrieved November 1, 2013, from RETScreen International - Empowering Cleaner Energy Decisions: http://www.retscreen.net/ang/version4.php

RETScreen. (2013d). *RETScreen 4 - Computer Program.* Canada: CanmetENERGY.

RETScreen. (2013e). *RETSCreen Plus - Computer Program.* Canada: CanmetENERGY.

RETScreen. (2013f, September 26). *What is RETScreen?* Retrieved November 4, 2013, from RETScreen International - Empowering Cleaner Energy Decisions.: http://www.retscreen.net/ang/what_is_retscreen.php

Smith, K., Randall, G., Malcolm, D., Kelley, N., & Smith, B. (2002, May). *Evaluation of Wind Shear Patterns at Midwest Wind Energy Facilities.* Retrieved September 10, 2013, from National Renewable Laboratory: http://www.nrel.gov/docs/fy02osti/32492.pdf

Suarez, M. J., Bloom, S., Silva, A., & Dee, D. (2005, April). *Documentation and Validation of the Goddard Earth Observing System (GEOS) Data Assimilation System - Version 4.* Retrieved Novemeber 4, 2013, from NASA Technical Reports Server (NTRS) - Providing Access to NASA's Technology, Reserach and Science: http://ntrs.nasa.gov/search.jsp?R=20050175690

Super Teacher Worksheet. (n.d.). *Latitude and Longitude*. Retrieved November 1, 2013, from Super Teachers Worksheet: http://www.superteacherworksheets.com/graphics1920x1080/1920-us-lat-long-01.jpg

System Advisor Model Version 2013.9.20. (2013). *National Renewable Energy Laboratory. Golden CO.* . Retrieved November 4, 2013, from System Advisory Model: https://sam.nrel.gov/content/downloads.

The Engineering ToolBox. (n.d.). *Wind Shear* . Retrieved October 27, 2013, from The Engineering ToolBox: http://www.engineeringtoolbox.com/wind-shear-d_1215.html

U.S. Department of Energy . (2013, August 6). *Energy Dept. Reports: U.S. Wind Energy Production and Manufacturing Reaches Record Highs*. Retrieved November 15, 2013, from Energy.gov: http://energy.gov/articles/energy-dept-reports-us-wind-energy-production-and-manufacturing-reaches-record-highs

Ummel, K. (2013). *Planning ofr Large-Scale Wind and Solar Power in South Africa: Identifying Cost-Effective deployment Strategies Using Spatiotemporal Modeling - Working Paper 340*. Retrieved October 15, 2013, from Center for Global development: http://www.cgdev.org/publication/planning-large-scale-wind-and-solar-power-south-africa-identifying-cost-effective

Vestas. (2005). *V80-1.8 MW Versatile megawattage*. Retrieved 1 November, 2013, from http://www.pse.com/inyourcommunity/kittitas/Documents/Vestas_turbine_facts.pdf

Weisstein, E. W. (n.d.). *Gamma Function* . Retrieved Novemeber 1, 2013, from MathWorld - A Wolfram Web Resource: http://mathworld.wolfram.com/GammaFunction.html

Wikipedia. (2013, September 3). *Delimiter-separated values*. Retrieved November 4, 2013, from Wikipedia - The Free Encyclopedia: http://en.wikipedia.org/wiki/Delimiter-separated_values

WWEA. (2013, October 17). *2013 - Half-year Report*. Retrieved November 15, 2013, from The World Wind Energy Association: http://www.wwindea.org/webimages/Half-year_report_2013.pdf

XLSTAT. (n.d.). *XLSTAT*. Retrieved September 30, 2013, from XLSTAT - Computer Software: http://www.xlstat.com/en/

Appendix A – Methodology Additions

In **Appendix - Table 1** to **Appendix – Table 5**, detailed information about typical wind shear coefficients α for different terrain types and land cover (vegetation) from several sources can be found**.** A summary table of the shear coefficients that were thought to be relevant to the site in the study can be found in **Table 6** in **Chapter 4**.

Appendix - Table 1 - Wind Shear Exponent for several terrain types. Source: (The Engineering ToolBox, n.d.).

Terrain type	Approximate annual mean α
Open water	0.10
Smooth, level, grass-covered	0.15
Row crops	0.20
Low bushes with a few trees	0.20
Heavy trees	0.25
Several buildings	0.25
Hilly, mountainous terrain	0.25

Appendix - Table 2 - Wind Shear Exponent for several terrain types. Source: (RETScreen, 2013d).

Terrain	Wind Shear α
Smooth Terrain (Sea, sand and snow)	0.10 - 0.13
Rough terrain (i.e. With sizeable obstacles)	0.25
Urban area	0.40
First approximation if nothing else known	0.14

Appendix - Table 3 - Wind Shear Exponent for several terrain types. Source: (Brower, 2012).

Terrain type	Land cover	Approximate range of annual mean α
Flat or rolling	Low to moderate vegetation	0.12-0.25
Flat or rolling	Patchy woods or forest	0.25-0.40
Complex, valley (sheltered)	Varied	0.25-0.60
Complex, valley (gap or thermal flow)	Varied	0.10-0.20
Complex, ridgeline	Low to moderate vegetation	0.15-0.25
Complex, ridgeline	Forest	0.20-0.35
Offshore, temperate	Water	0.10-0.15
Offshore, tropical	Water	0.07-0.10

Appendix - Table 4 – Shear coefficient for different topography and vegetation. Source: (Jain, 2011).

Description	Roughness Class	Roughness Length, m	α
Open Sea	0	0.0001-0.003	0.08
Open terrain with a smooth surface, like concrete runway, mowed grass	0.5	0.0024	0.11
Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills	1	0.03	**0.15**
Agricultural land with some houses and 8-m-tall sheltering heggerows with a distance of approx. 1250 m	1.5	0.055	0.17
Agricultural land with some houses and 8-m-tall sheltering heggerows with a distance of approx. 500 m	2	0.1	0.19
Agricultural land with many houses, shrubs and plants, or 8-m tall sheltering hedgerows with a distance of approx. 250 m.	2.5	0.2	0.21
Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and **very rough and uneven terrain**	3	0.4	**0.25**
Larger cities with tall buildings	3.5	0.8	0.31
Very large cities with tall buildings and skyscrapers	4	1.6	0.39

Appendix - Table 5 - Shear coefficient for different landscape types. Source: (Banuelos-Ruedas & Camacho, n.d.).

Landscape type	α
Lakes, ocean and smooth hard ground	0.10
Grasslands (ground level)	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

Appendix B – Energy Predictions

B.1 RETScreen

The following tables include detailed numerical results for AEP prediction from RETScreen for $k = 1 - 3$ and $\alpha = 0.20 - 0.25$ for both weather locations and all loss scenarios.

CELL1 – 1A

Appendix - Table 6 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S1, i.e. assuming no losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	344,883	354,238	365,369	375,599	385,935	396,374
	1.1	341,825	352,098	364,347	375,632	387,093	398,691
	1.2	335,469	346,493	359,661	371,818	384,226	396,803
	1.3	327,109	338,737	352,652	365,524	378,719	392,116
	1.4	317,616	329,731	344,252	357,708	371,558	385,641
	1.5	307,556	320,060	335,070	349,003	363,399	378,059
	1.6	297,301	310,109	325,508	339,826	354,678	369,822
	1.7	**287,103**	**300,141**	**315,842**	**330,465**	**345,692**	**361,240**
	1.8	277,141	290,344	306,269	321,124	336,655	352,536
	1.9	267,536	280,848	296,929	311,956	327,726	343,874
	2.0	**258,368**	**271,742**	**287,923**	**303,067**	**319,020**	**335,377**
	2.1	249,686	263,082	279,316	294,532	310,620	327,135
	2.2	241,511	254,900	271,148	286,399	302,580	319,210
	2.3	233,849	247,207	263,438	278,695	294,934	311,642
	2.4	226,691	239,999	256,192	271,430	287,699	304,455
	2.5	220,018	233,265	249,401	264,604	280,880	297,658
	2.6	213,807	226,983	243,051	258,206	274,470	291,251
	2.7	208,030	221,131	237,122	252,219	268,459	285,226
	2.8	202,659	215,681	231,591	246,624	262,828	279,570
	2.9	197,664	210,607	226,432	241,397	257,558	274,266
	3	193,017	205,881	211,621	236,516	252,628	269,296
	Max	344,883	354,238	365,369	375,632	387,093	398,691
	Min	193,017	205,881	211,621	236,516	252,628	269,296

Appendix - Table 7 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S2, i.e. accounting for availability and wake losses. Weather CELL1 was used.

Shape Factor	Shear Coefficient 0.20	0.21	0.22	0.23	0.24	0.25
1.0	307,321	315,657	325,576	334,692	343,902	353,204
1.1	304,596	313,750	324,665	334,721	344,934	355,269
1.2	298,932	308,756	320,490	331,323	342,379	353,586
1.3	291,483	301,844	314,244	325,714	337,472	349,410
1.4	283,024	293,819	306,759	318,749	331,091	343,640
1.5	274,059	285,202	298,577	310,992	323,820	336,884
1.6	264,921	276,334	290,056	302,815	316,049	329,544
1.7	**255,834**	**267,452**	**281,443**	**294,473**	**308,042**	**321,897**
1.8	246,957	258,722	272,913	286,150	299,989	314,141
1.9	238,398	250,260	264,590	277,980	292,033	306,422
2.0	**230,229**	**242,146**	**256,565**	**270,059**	**284,275**	**298,850**
2.1	222,492	234,429	248,895	262,454	276,790	291,506
2.2	215,208	227,138	241,617	255,207	269,625	284,444
2.3	208,380	220,283	234,746	248,342	262,812	277,700
2.4	202,002	213,860	228,290	241,868	256,365	271,296
2.5	196,055	207,860	222,238	235,785	250,289	265,239
2.6	190,521	202,262	216,580	230,084	244,577	259,530
2.7	185,373	197,047	211,297	224,749	239,221	254,161
2.8	180,587	192,191	206,368	219,764	234,203	249,121
2.9	176,136	187,669	201,771	215,106	229,507	244,395
3	171,995	183,458	188,573	210,757	225,114	239,966
Max	307,321	315,657	325,576	334,721	344,934	355,269
Min	171,995	183,458	188,573	210,757	225,114	239,966

Appendix - Table 8 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S3, i.e. accounting for availability, wake losses and 5% additional losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	291,955	299,874	309,297	317,957	326,707	335,544
	1.1	289,366	298,063	308,432	317,985	327,687	337,505
	1.2	283,986	293,318	304,465	314,756	325,260	335,907
	1.3	276,909	286,752	298,532	309,428	320,598	331,939
	1.4	268,873	279,128	291,421	302,812	314,536	326,458
	1.5	260,356	270,942	283,648	295,443	307,629	320,040
	1.6	251,675	262,518	275,553	287,674	300,247	313,067
	1.7	**243,042**	**254,079**	**267,371**	**279,750**	**292,640**	**305,802**
	1.8	234,609	245,786	259,267	271,842	284,990	298,434
	1.9	226,478	237,747	251,360	264,081	277,431	291,101
	2.0	**218,717**	**230,039**	**243,736**	**256,556**	**270,061**	**283,908**
	2.1	211,368	222,708	236,450	249,331	262,950	276,931
	2.2	204,447	215,781	229,536	242,446	256,144	270,222
	2.3	197,961	209,269	223,009	235,925	249,672	263,815
	2.4	191,902	203,167	216,875	229,775	243,547	257,731
	2.5	186,253	197,467	211,126	223,996	237,774	251,977
	2.6	180,995	192,149	205,751	218,580	232,348	246,554
	2.7	176,104	187,195	200,732	213,512	227,260	241,453
	2.8	171,558	182,581	196,050	208,776	222,493	236,665
	2.9	167,329	178,286	191,682	204,351	218,032	232,175
	3	163,395	174,285	179,144	200,219	213,858	227,968
Max		291,955	299,874	309,297	317,985	327,687	337,505
Min		163,395	174,285	179,144	200,219	213,858	227,968

Appendix - Table 9 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	276,589	284,092	293,018	301,223	309,512	317,884
	1.1	274,137	282,375	292,199	301,249	310,441	319,742
	1.2	269,039	277,880	288,441	298,190	308,141	318,228
	1.3	262,335	271,660	282,820	293,143	303,725	314,469
	1.4	254,721	264,437	276,083	286,874	297,982	309,276
	1.5	246,654	256,681	268,719	279,893	291,438	303,195
	1.6	238,429	248,701	261,051	272,533	284,444	296,590
	1.7	**230,251**	**240,707**	**253,299**	**265,026**	**277,238**	**289,707**
	1.8	222,261	232,850	245,621	257,535	269,990	282,727
	1.9	214,558	225,234	238,131	250,182	262,829	275,780
	2.0	**207,206**	**217,931**	**230,908**	**243,053**	**255,847**	**268,965**
	2.1	200,243	210,986	224,006	236,209	249,111	262,355
	2.2	193,687	204,424	217,455	229,686	242,663	256,000
	2.3	187,542	198,255	211,272	223,508	236,531	249,930
	2.4	181,801	192,474	205,461	217,681	230,729	244,167
	2.5	176,450	187,074	200,014	212,207	225,260	238,716
	2.6	171,469	182,036	194,922	207,076	220,119	233,577
	2.7	166,836	177,342	190,167	202,274	215,299	228,745
	2.8	162,528	172,972	185,731	197,787	210,783	224,209
	2.9	158,522	168,902	181,594	193,595	206,556	219,956
	3	154,796	165,112	169,716	189,681	202,602	215,970
Max		276,589	284,092	293,018	301,249	310,441	319,742
Min		154,796	165,112	169,716	189,681	202,602	215,970

CELL1 – 2A

Appendix - Table 10 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S1, i.e. assuming no losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	320,801	330,624	340,430	350,276	360,214	370,258
	1.1	316,255	326,986	337,739	348,550	359,527	370,645
	1.2	308,712	320,157	331,667	343,253	355,083	367,087
	1.3	299,456	311,452	323,555	335,753	348,269	360,992
	1.4	289,344	301,759	314,324	327,000	340,066	353,370
	1.5	278,918	291,648	304,568	317,615	331,121	344,893
	1.6	268,523	281,479	294,666	307,995	321,851	335,999
	1.7	**258,380**	**271,488**	**284,868**	**298,404**	**312,533**	**326,981**
	1.8	248,631	261,831	275,340	289,021	303,358	318,038
	1.9	239,366	252,607	266,195	279,968	294,456	309,311
	2.0	**230,634**	**243,877**	**257,502**	**271,323**	**285,916**	**300,896**
	2.1	222,454	235,669	249,298	263,134	277,792	292,857
	2.2	214,823	227,989	241,597	255,422	270,114	285,230
	2.3	207,727	220,828	234,397	248,192	262,893	278,033
	2.4	201,139	214,166	227,682	241,432	256,124	271,267
	2.5	195,028	207,975	221,430	235,127	249,795	264,925
	2.6	189,361	202,224	215,614	229,250	243,885	258,991
	2.7	184,104	196,883	210,204	223,776	238,370	253,444
	2.8	179,223	191,919	205,170	218,676	233,225	248,262
	2.9	174,686	187,301	200,482	213,923	228,424	243,419
	3	170,466	183,000	196,113	209,488	223,941	238,893
	Max	320,801	330,624	340,430	350,276	360,214	370,645
	Min	170,466	183,000	196,113	209,488	223,941	238,893

Appendix - Table 11 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S2, i.e. accounting for availability and wake losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	285,862	294,615	303,353	312,127	320,982	329,932
	1.1	281,811	291,373	300,955	310,589	320,370	330,277
	1.2	275,090	285,288	295,544	305,869	316,410	327,107
	1.3	266,842	277,531	288,316	299,185	310,338	321,676
	1.4	257,831	268,894	280,090	291,386	303,029	314,884
	1.5	248,540	259,884	271,397	283,023	295,058	307,330
	1.6	239,278	250,823	262,573	274,451	286,798	299,405
	1.7	**230,239**	**241,920**	**253,842**	**265,904**	**278,494**	**291,369**
	1.8	221,552	233,314	245,352	257,543	270,319	283,400
	1.9	213,296	225,095	237,203	249,476	262,386	275,623
	2.0	**205,515**	**217,316**	**229,457**	**241,773**	**254,776**	**268,125**
	2.1	198,226	210,002	222,146	234,476	247,537	260,961
	2.2	191,426	203,158	215,284	227,603	240,695	254,165
	2.3	185,103	196,777	208,868	221,161	234,261	247,752
	2.4	179,233	190,841	202,885	215,137	228,229	241,723
	2.5	173,787	185,324	197,314	209,519	222,589	236,071
	2.6	168,737	180,199	192,131	204,282	217,323	230,784
	2.7	164,053	175,440	187,310	199,404	212,409	225,841
	2.8	159,703	171,017	182,825	194,860	207,824	221,223
	2.9	155,661	166,902	178,647	190,624	203,546	216,908
	3	151,900	163,069	174,754	186,672	199,551	212,875
	Max	285,862	294,615	303,353	312,127	320,982	330,277
	Min	151,900	163,069	174,754	186,672	199,551	212,875

Appendix - Table 12 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S3, i.e. accounting for availability, wake losses and 5% additional losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	271,569	279,884	288,185	296,520	304,933	313,436
	1.1	267,720	276,805	285,907	295,059	304,352	313,763
	1.2	261,335	271,024	280,767	290,575	300,590	310,751
	1.3	253,500	263,655	273,900	284,226	294,821	305,592
	1.4	244,939	255,449	266,086	276,816	287,877	299,140
	1.5	236,113	246,890	257,827	268,872	280,305	291,964
	1.6	227,314	238,281	249,445	260,728	272,458	284,434
	1.7	**218,727**	**229,824**	**241,150**	**252,609**	**264,570**	**276,800**
	1.8	210,474	221,649	233,085	244,666	256,803	269,230
	1.9	202,631	213,840	225,343	237,002	249,267	261,842
	2.0	**195,239**	**206,450**	**217,984**	**229,684**	**242,038**	**254,719**
	2.1	188,315	199,502	211,039	222,752	235,160	247,913
	2.2	181,855	193,000	204,520	216,223	228,661	241,457
	2.3	175,848	186,938	198,425	210,103	222,548	235,364
	2.4	170,271	181,299	192,740	204,380	216,818	229,637
	2.5	165,098	176,058	187,448	199,043	211,460	224,268
	2.6	160,300	171,189	182,524	194,068	206,457	219,245
	2.7	155,850	166,668	177,945	189,434	201,788	214,549
	2.8	151,718	162,466	173,683	185,117	197,433	210,162
	2.9	147,878	158,557	169,715	181,093	193,369	206,062
	3	144,305	154,916	166,016	177,339	189,574	202,231
Max		271,569	279,884	288,185	296,520	304,933	313,763
Min		144,305	154,916	166,016	177,339	189,574	202,231

Appendix - Table 13 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL1 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	257,276	265,154	273,018	280,914	288,884	296,939
	1.1	253,630	262,236	270,860	279,530	288,333	297,250
	1.2	247,581	256,759	265,990	275,282	284,769	294,396
	1.3	240,157	249,778	259,484	269,267	279,304	289,508
	1.4	232,048	242,004	252,081	262,247	272,726	283,395
	1.5	223,686	233,896	244,257	254,721	265,552	276,597
	1.6	215,350	225,740	236,316	247,006	258,118	269,464
	1.7	**207,215**	**217,728**	**228,458**	**239,314**	**250,645**	**262,232**
	1.8	199,397	209,983	220,817	231,789	243,287	255,060
	1.9	191,967	202,586	213,483	224,529	236,148	248,061
	2.0	**184,964**	**195,584**	**206,511**	**217,595**	**229,299**	**241,312**
	2.1	178,403	189,002	199,932	211,028	222,783	234,865
	2.2	172,284	182,842	193,756	204,843	216,626	228,749
	2.3	166,593	177,099	187,982	199,045	210,835	222,977
	2.4	161,309	171,757	182,596	193,623	205,406	217,550
	2.5	156,408	166,792	177,582	188,567	200,330	212,464
	2.6	151,864	162,179	172,918	183,854	195,591	207,705
	2.7	147,648	157,896	168,579	179,464	191,168	203,257
	2.8	143,733	153,915	164,542	175,374	187,042	199,101
	2.9	140,095	150,212	160,782	171,562	183,191	195,217
	3	136,710	146,762	157,279	168,005	179,596	191,587
Max		257,276	265,154	273,018	280,914	288,884	297,250
Min		136,710	146,762	157,279	168,005	179,596	191,587

CELL2 – 1A

Appendix - Table 14 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S1, i.e. assuming no losses. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	413,855	424,353	434,991	445,562	456,084	466,760
	1.1	417,976	429,736	441,673	453,601	465,521	477,633
	1.2	417,635	430,492	443,560	456,689	469,858	483,254
	1.3	414,254	428,049	442,089	456,260	470,522	485,044
	1.4	408,886	423,481	438,353	453,427	468,642	484,148
	1.5	402,251	417,535	433,125	448,986	465,038	481,410
	1.6	394,834	410,712	426,925	443,481	460,275	477,417
	1.7	**386,962**	**403,355**	**420,111**	**437,280**	**454,738**	**472,571**
	1.8	378,870	395,706	412,932	430,645	448,696	467,149
	1.9	370,730	387,945	405,576	423,767	442,348	461,355
	2.0	**362,672**	**380,208**	**398,183**	**416,792**	**435,842**	**455,342**
	2.1	354,792	372,596	390,862	409,832	429,295	449,230
	2.2	347,161	365,186	383,693	402,972	422,796	443,111
	2.3	339,825	358,030	376,736	396,277	416,413	437,059
	2.4	332,816	351,165	370,031	389,792	410,197	431,128
	2.5	326,151	344,613	363,608	383,551	404,185	425,360
	2.6	319,837	338,385	357,480	377,573	398,401	419,783
	2.7	313,871	332,485	351,655	371,870	392,862	414,417
	2.8	308,248	326,907	346,134	366,446	387,574	409,275
	2.9	302,954	321,645	340,911	361,300	382,541	404,363
	3	297,976	316,686	335,979	356,427	377,760	399,682
	Max	417,976	430,492	443,560	456,689	470,522	485,044
	Min	297,976	316,686	335,979	356,427	377,760	399,682

Appendix - Table 15 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S2, i.e. accounting for availability and wake losses. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	368,781	378,136	387,615	397,035	406,411	415,924
	1.1	372,453	382,933	393,570	404,198	414,820	425,613
	1.2	372,150	383,606	395,251	406,950	418,685	430,622
	1.3	369,137	381,429	393,940	406,568	419,277	432,217
	1.4	364,353	377,359	390,611	404,043	417,601	431,418
	1.5	358,441	372,060	385,952	400,086	414,390	428,979
	1.6	351,832	365,981	380,428	395,181	410,146	425,421
	1.7	**344,817**	**359,425**	**374,356**	**389,655**	**405,212**	**421,102**
	1.8	337,607	352,609	367,959	383,743	399,828	416,271
	1.9	330,353	345,693	361,404	377,614	394,171	411,108
	2.0	**323,173**	**338,799**	**354,816**	**371,398**	**388,374**	**405,750**
	2.1	316,151	332,016	348,292	365,196	382,540	400,303
	2.2	309,351	325,413	341,904	359,084	376,748	394,851
	2.3	302,814	319,036	335,705	353,118	371,061	389,458
	2.4	296,568	312,919	329,730	347,339	365,522	384,173
	2.5	290,629	307,081	324,007	341,778	360,164	379,033
	2.6	285,003	301,531	318,546	336,451	355,010	374,064
	2.7	279,687	296,273	313,356	331,369	350,075	369,282
	2.8	274,676	291,303	308,436	326,536	345,363	364,700
	2.9	269,959	286,614	303,782	321,950	340,878	360,323
	3	265,523	282,195	299,387	317,608	336,617	356,152
	Max	372,453	383,606	395,251	406,950	419,277	432,217
	Min	265,523	282,195	299,387	317,608	336,617	356,152

Appendix - Table 16 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S3, i.e. accounting for availability, wake losses and 5% additional losses.. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	350,342	359,229	368,234	377,183	386,090	395,128
	1.1	353,831	363,786	373,891	383,988	394,079	404,332
	1.2	353,542	364,426	375,488	386,603	397,751	409,091
	1.3	350,680	362,358	374,243	386,239	398,313	410,606
	1.4	346,136	358,491	371,081	383,841	396,721	409,848
	1.5	340,519	353,457	366,655	380,082	393,670	407,530
	1.6	334,240	347,682	361,406	375,422	389,638	404,150
	1.7	**327,576**	**341,454**	**355,638**	**370,172**	**384,951**	**400,047**
	1.8	320,726	334,978	349,561	364,555	379,836	395,457
	1.9	313,835	328,408	343,334	358,733	374,462	390,553
	2.0	**307,014**	**321,859**	**337,075**	**352,828**	**368,955**	**385,462**
	2.1	300,343	315,415	330,878	346,937	363,413	380,288
	2.2	293,883	309,142	324,809	341,129	357,911	375,108
	2.3	287,673	303,084	318,920	335,462	352,508	369,985
	2.4	281,740	297,273	313,244	329,972	347,246	364,964
	2.5	276,098	291,726	307,806	324,689	342,156	360,082
	2.6	270,753	286,454	302,619	319,628	337,260	355,360
	2.7	265,702	281,460	297,688	314,800	332,571	350,818
	2.8	260,942	276,738	293,014	310,209	328,094	346,465
	2.9	256,461	272,283	288,593	305,853	323,834	342,307
	3	252,247	268,085	284,418	301,727	319,787	338,344
Max		353,831	364,426	375,488	386,603	398,313	410,606
Min		252,247	268,085	284,418	301,727	319,787	338,344

Appendix - Table 17 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 1A and S4, i.e. accounting for availability, wake losses and 10% additional losses.. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	331,903	340,322	348,854	357,331	365,770	374,332
	1.1	335,208	344,639	354,213	363,779	373,338	383,052
	1.2	334,935	345,246	355,726	366,255	376,816	387,560
	1.3	332,223	343,286	354,546	365,911	377,349	388,995
	1.4	327,918	339,623	351,550	363,639	375,841	388,277
	1.5	322,597	334,854	347,357	360,077	372,951	386,081
	1.6	316,649	329,382	342,385	355,663	369,131	382,879
	1.7	**310,335**	**323,482**	**336,920**	**350,689**	**364,690**	**378,992**
	1.8	303,846	317,348	331,163	345,368	359,845	374,644
	1.9	297,318	311,124	325,264	339,852	354,754	369,997
	2.0	**290,855**	**304,919**	**319,334**	**334,259**	**349,536**	**365,175**
	2.1	284,536	298,814	313,463	328,677	344,286	360,273
	2.2	278,416	292,872	307,714	323,175	339,074	355,366
	2.3	272,533	287,133	302,134	317,806	333,955	350,512
	2.4	266,912	281,627	296,757	312,605	328,969	345,756
	2.5	261,566	276,372	291,606	307,600	324,148	341,130
	2.6	256,503	271,378	286,692	302,806	319,509	336,657
	2.7	251,718	266,646	282,020	298,232	315,067	332,354
	2.8	247,208	262,173	277,592	293,882	310,826	328,230
	2.9	242,963	257,953	273,404	289,755	306,790	324,291
	3	238,971	253,976	269,448	285,847	302,956	320,537
Max		335,208	345,246	355,726	366,255	377,349	388,995
Min		238,971	253,976	269,448	285,847	302,956	320,537

CELL2 – 2A

Appendix - Table 18 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S1, i.e. assuming no losses. Weather CELL2 was used.

	Shear Coefficient					
Shape Factor	0.20	0.21	0.22	0.23	0.24	0.25
1.0	387,310	397,451	407,735	417,976	424,187	438,553
1.1	389,387	400,714	412,220	423,748	435,291	447,025
1.2	387,249	399,587	412,139	424,788	437,503	450,446
1.3	382,322	395,504	408,933	422,534	436,258	450,242
1.4	375,656	389,540	403,700	418,106	432,690	447,563
1.5	367,969	382,437	397,209	412,299	427,618	443,255
1.6	359,734	374,689	389,975	405,650	421,605	437,903
1.7	**351,262**	**366,625**	**382,344**	**398,522**	**415,028**	**431,903**
1.8	342,769	358,471	374,552	391,160	408,147	425,524
1.9	334,406	350,386	366,767	383,741	401,144	418,959
2.0	**326,278**	**342,484**	**359,111**	**376,394**	**394,154**	**412,345**
2.1	318,460	334,845	351,670	369,210	387,274	405,787
2.2	310,997	327,523	344,503	362,255	380,577	399,361
2.3	303,915	320,549	337,651	355,574	374,111	393,124
2.4	297,225	313,939	331,133	349,195	367,910	387,113
2.5	290,927	307,698	324,960	343,132	361,993	381,353
2.6	285,010	301,821	319,132	337,389	356,371	375,859
2.7	279,462	296,298	313,642	331,966	351,044	370,637
2.8	274,264	291,114	308,478	326,852	346,009	365,688
2.9	269,396	286,251	303,626	322,038	341,258	361,006
3	264,837	281,690	299,070	317,509	336,780	356,583
Max	389,387	400,714	412,220	424,788	437,503	450,446
Min	264,837	281,690	299,070	317,509	336,780	356,583

Appendix - Table 19 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S2, i.e. accounting for availability and wake losses. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	345,127	354,164	363,328	372,453	377,988	390,789
	1.1	346,978	357,071	367,324	377,597	387,883	398,339
	1.2	345,073	356,067	367,252	378,523	389,854	401,387
	1.3	340,683	352,429	364,395	376,515	388,744	401,205
	1.4	334,743	347,114	359,732	372,569	385,565	398,818
	1.5	327,893	340,785	353,948	367,395	381,045	394,979
	1.6	320,555	333,881	347,502	361,470	375,687	390,210
	1.7	**313,005**	**326,695**	**340,702**	**355,118**	**369,826**	**384,864**
	1.8	305,437	319,429	333,759	348,558	363,695	379,179
	1.9	297,985	312,225	326,822	341,947	357,455	373,329
	2.0	**290,742**	**305,183**	**320,000**	**335,400**	**351,226**	**367,436**
	2.1	283,776	298,376	313,369	328,999	345,095	361,592
	2.2	277,126	291,852	306,982	322,801	339,128	355,866
	2.3	270,815	285,637	300,877	316,848	333,366	350,308
	2.4	264,854	279,747	295,069	311,163	327,840	344,952
	2.5	259,242	274,186	289,568	305,761	322,568	339,819
	2.6	253,969	268,949	284,375	300,643	317,558	334,923
	2.7	249,025	264,028	279,483	295,811	312,811	330,270
	2.8	244,393	259,408	274,881	291,254	308,324	325,860
	2.9	240,056	255,075	270,557	286,964	304,091	321,688
	3	235,993	251,011	266,498	282,928	300,101	317,747
	Max	346,978	357,071	367,324	378,523	389,854	401,387
	Min	235,993	251,011	266,498	282,928	300,101	317,747

Appendix - Table 20 – AEP [MWh] as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S3, i.e. accounting for availability, wake losses and 5% additional losses.. Weather CELL2 was used.

		Shear Coefficient					
		0.20	0.21	0.22	0.23	0.24	0.25
Shape Factor	1.0	327,871	336,456	345,161	353,831	359,089	371,250
	1.1	329,629	339,218	348,958	358,717	368,488	378,422
	1.2	327,819	338,264	348,890	359,597	370,361	381,318
	1.3	323,648	334,807	346,176	357,689	369,307	381,145
	1.4	318,005	329,759	341,746	353,941	366,287	378,877
	1.5	311,498	323,746	336,251	349,025	361,993	375,230
	1.6	304,527	317,187	330,127	343,396	356,903	370,700
	1.7	**297,355**	**310,360**	**323,667**	**337,362**	**351,335**	**365,620**
	1.8	290,165	303,458	317,071	331,130	345,510	360,220
	1.9	283,086	296,614	310,481	324,850	339,582	354,663
	2.0	**276,205**	**289,924**	**304,000**	**318,630**	**333,665**	**349,064**
	2.1	269,587	283,458	297,700	312,549	327,840	343,512
	2.2	263,269	277,259	291,633	306,661	322,171	338,073
	2.3	257,274	271,355	285,833	301,005	316,698	332,793
	2.4	251,611	265,760	280,315	295,605	311,448	327,704
	2.5	246,279	260,477	275,090	290,473	306,439	322,828
	2.6	241,271	255,502	270,156	285,611	301,680	318,177
	2.7	236,574	250,826	265,508	281,020	297,171	313,757
	2.8	232,174	246,438	261,137	276,691	292,908	309,567
	2.9	228,053	242,321	257,030	272,616	288,886	305,604
	3	224,193	238,460	253,173	268,782	285,096	301,859
Max		329,629	339,218	348,958	359,597	370,361	381,318
Min		224,193	238,460	253,173	268,782	285,096	301,859

Appendix - Table 21 – AEP as a function of k=1-3 and α=0.20-0.25 for VESTAS V80 2A and S4, i.e. accounting for availability, wake losses and 10% additional losses. Weather CELL2 was used.

	Shear Coefficient					
Shape Factor	0.20	0.21	0.22	0.23	0.24	0.25
1.0	310,615	318,747	326,995	335,208	340,189	351,710
1.1	312,280	321,364	330,592	339,837	349,094	358,505
1.2	310,566	320,460	330,527	340,671	350,868	361,248
1.3	306,614	317,186	327,956	338,863	349,870	361,085
1.4	301,268	312,403	323,759	335,312	347,008	358,936
1.5	295,103	306,707	318,553	330,655	342,941	355,481
1.6	288,499	300,493	312,752	325,323	338,118	351,189
1.7	**281,705**	**294,026**	**306,632**	**319,606**	**332,844**	**346,377**
1.8	274,894	287,486	300,383	313,702	327,325	341,261
1.9	268,187	281,002	294,140	307,752	321,709	335,996
2.0	**261,668**	**274,665**	**288,000**	**301,860**	**316,103**	**330,692**
2.1	255,398	268,539	282,032	296,099	310,586	325,433
2.2	249,413	262,667	276,284	290,521	305,215	320,279
2.3	243,734	257,074	270,789	285,163	300,029	315,277
2.4	238,368	251,773	265,562	280,047	295,056	310,457
2.5	233,317	246,767	260,611	275,185	290,311	305,837
2.6	228,572	242,054	255,937	270,579	285,802	301,431
2.7	224,123	237,625	251,534	266,230	281,530	297,243
2.8	219,954	233,467	247,393	262,129	277,492	293,274
2.9	216,050	229,567	243,502	258,268	273,682	289,519
3	212,394	225,910	239,848	254,636	270,091	285,972
Max	312,280	321,364	330,592	340,671	350,868	361,248
Min	212,394	225,910	239,848	254,636	270,091	285,972

B.2 SAM

The following tables include detailed numerical results for AEP prediction from SAM and *d* the difference from the wind farm data for *L1* and *L4* for individual years and all loss scenarios *S1* – *S4*.

Appendix - Table 22 : SAM 2004 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	55,532	5.9%	50,809	48,269	45,728
Feb.	45,084	9.2%	40,107	38,102	36,096
March	75,564	6.8%	68,930	65,483	62,037
April	42,348	8.0%	37,905	36,010	34,115
May	49,709	11.7%	42,860	40,717	38,574
June	57,754	7.2%	52,451	49,829	47,206
July	45,141	9.9%	39,630	37,648	35,667
August	44,218	11.0%	38,255	36,342	34,429
Sept.	44,728	10.0%	39,220	37,259	35,298
Oct.	55,788	8.1%	50,068	47,565	45,061
Nov.	43,085	7.7%	38,699	36,765	34,830
Dec.	44,591	7.8%	40,155	38,147	36,140
Annual	603,545	8.5%	538,951	512,004	485,056

Appendix - Table 23 : Deviation for SAM in 2004 – L1.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+11.8%	+2.3%	-2.8%	-8.0%
Feb.	+19.0%	+5.8%	+0.5%	-4.8%
March	+33.4%	+21.7%	+15.6%	+9.6%
April	-35.0%	-41.8%	-44.7%	-47.6%
May	-11.4%	-23.6%	-27.4%	-31.3%
June	-1.7%	-10.7%	-15.2%	-19.6%
July	-9.7%	-20.7%	-24.7%	-28.6%
August	-11.1%	-23.1%	-26.9%	-30.8%
Sept.	+11.1%	-2.6%	-7.5%	-12.3%
Oct.	+20.9%	+8.5%	+3.1%	-2.3%
Nov.	-7.6%	-17.0%	-21.2%	-25.3%
Dec.	-2.1%	-11.9%	-16.3%	-20.7%
Annual	+0.2%	-10.5%	-15.0%	-19.5%

Appendix - Table 24 : SAM 2005 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	53,134	6.5%	48,336	45,919	43,502
Feb.	65,535	5.0%	60,985	57,935	54,886
March	52,574	6.1%	48,351	45,933	43,516
April	58,846	9.3%	51,939	49,342	46,745
May	52,510	8.7%	46,864	44,521	42,178
June	54,430	10.3%	47,790	45,401	43,011
July	40,164	10.7%	34,955	33,207	31,459
August	34,371	10.3%	29,980	28,481	26,982
Sept.	32,875	12.0%	28,170	26,761	25,353
Oct.	38,374	11.1%	33,338	31,671	30,004
Nov.	50,973	8.8%	45,244	42,982	40,720
Dec.	57,091	7.8%	51,386	48,816	46,247
Annual	590,877	8.5%	527,201	500,841	474,481

Appendix - Table 25 : Deviation for SAM in 2005 – L1.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+6.9%	-2.7%	-7.6%	-12.4%
Feb.	+72.9%	+60.9%	+52.9%	+44.8%
March	-7.2%	-14.6%	-18.9%	-23.2%
April	-9.6%	-20.2%	-24.2%	-28.2%
May	-6.4%	-16.5%	-20.7%	-24.8%
June	-7.3%	-18.6%	-22.7%	-26.8%
July	-19.6%	-30.0%	-33.5%	-37.0%
August	-30.9%	-39.7%	-42.7%	-45.8%
Sept.	-18.4%	-30.0%	-33.5%	-37.0%
Oct.	-16.8%	-27.7%	-31.4%	-35.0%
Nov.	+9.3%	-3.0%	-7.8%	-12.7%
Dec.	+25.3%	+12.8%	+7.1%	+1.5%
Annual	-1.9%	-12.5%	-16.9%	-21.2%

Appendix - Table 26 : SAM 2006 for L1 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	50,257	10.2%	43,866	41,673	39,480
Feb.	82,880	4.5%	77,464	73,591	69,718
March	51,640	10.9%	45,066	42,813	40,559
April	37,226	11.7%	31,999	30,399	28,799
May	55,074	10.1%	48,367	45,948	43,530
June	48,411	8.3%	43,443	41,271	39,099
July	31,661	11.3%	27,342	25,975	24,608
August	44,078	8.8%	39,057	37,104	35,151
Sept.	39,904	10.3%	34,884	33,139	31,395
Oct.	66,943	8.3%	59,981	56,982	53,983
Nov.	65,585	9.7%	57,662	54,779	51,896
Dec.	40,566	10.0%	35,643	33,861	32,079
Annual	614,224	9.1%	544,576	517,347	490,118

Appendix - Table 27 : Deviation for SAM in 2006 – L1.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+1.2%	-11.7%	-16.1%	-20.5%
Feb.	+118.7%	+104.4%	+94.2%	+84.0%
March	-8.8%	-20.4%	-24.4%	-28.4%
April	-42.8%	-50.9%	-53.3%	-55.8%
May	-1.9%	-13.8%	-18.1%	-22.4%
June	-17.6%	-26.0%	-29.7%	-33.4%
July	-36.6%	-45.3%	-48.0%	-50.8%
August	-11.4%	-21.5%	-25.4%	-29.3%
Sept.	-0.9%	-13.4%	-17.7%	-22.0%
Oct.	+45.1%	+30.0%	+23.5%	+17.0%
Nov.	+40.6%	+23.6%	+17.5%	+11.3%
Dec.	-11.0%	-21.8%	-25.7%	-29.6%
Annual	+1.9%	-9.6%	-14.1%	-18.7%

Appendix - Table 28 : SAM 2004 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	54,967	6.5%	49,978	47,479	44,980
Feb.	35,493	9.8%	31,360	29,792	28,224
March	81,385	6.0%	74,868	71,125	67,381
April	50,333	9.6%	44,288	42,074	39,859
May	56,078	10.5%	49,054	46,602	44,149
June	59,410	7.7%	53,721	51,035	48,349
July	52,815	11.3%	45,631	43,349	41,068
August	48,432	8.0%	43,331	41,164	38,998
Sept.	55,507	7.2%	50,153	47,646	45,138
Oct.	58,908	8.4%	52,698	50,063	47,428
Nov.	51,572	10.7%	44,841	42,599	40,357
Dec.	50,944	7.5%	46,020	43,719	41,418
Annual	**655,845**	**8.4%**	**585,862**	**556,569**	**527,276**

Appendix - Table 29 : Deviation for SAM in 2004 – L4.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+10.6%	+0.6%	-4.4%	-9.5%
Feb.	-6.3%	-17.3%	-21.4%	-25.5%
March	+43.7%	+32.2%	+25.6%	+19.0%
April	-22.7%	-32.0%	-35.4%	-38.8%
May	-0.1%	-12.6%	-16.9%	-21.3%
June	+1.1%	-8.5%	-13.1%	-17.7%
July	+5.7%	-8.7%	-13.2%	-17.8%
August	-2.6%	-12.9%	-17.2%	-21.6%
Sept.	+37.8%	+24.5%	+18.3%	+12.1%
Oct.	+27.7%	+14.2%	+8.5%	+2.8%
Nov.	+10.6%	-3.8%	-8.7%	-13.5%
Dec.	+11.8%	+1.0%	-4.1%	-9.1%
Annual	**+8.9%**	**-2.8%**	**-7.6%**	**-12.5%**

Appendix - Table 30 : SAM 2005 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	50,363	6.9%	45,596	43,316	41,036
Feb.	54,594	10.9%	47,656	45,273	42,890
March	61,670	8.0%	55,529	52,753	49,976
April	60,782	9.6%	53,463	50,790	48,116
May	48,836	9.1%	43,383	41,213	39,044
June	65,638	7.3%	59,556	56,579	53,601
July	51,863	11.3%	44,830	42,589	40,347
August	35,775	11.6%	30,727	29,191	27,655
Sept.	45,627	12.9%	38,731	36,795	34,858
Oct.	50,658	6.2%	46,402	44,082	41,762
Nov.	63,255	5.7%	58,082	55,178	52,273
Dec.	63,465	6.4%	58,033	55,131	52,229
Annual	**652,526**	**8.6%**	**581,869**	**552,775**	**523,682**

Appendix - Table 31 : Deviation for SAM in 2005 – L4.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+1.4%	-8.2%	-12.8%	-17.4%
Feb.	+44.1%	+25.7%	+19.5%	+13.2%
March	+8.9%	-1.9%	-6.8%	-11.7%
April	-6.7%	-17.9%	-22.0%	-26.1%
May	-13.0%	-22.7%	-26.6%	-30.4%
June	+11.7%	+1.4%	-3.7%	-8.8%
July	+3.8%	-10.3%	-14.8%	-19.3%
August	-28.1%	-38.2%	-41.3%	-44.4%
Sept.	+13.3%	-3.8%	-8.6%	-13.4%
Oct.	+9.8%	+0.6%	-4.5%	-9.5%
Nov.	+35.6%	+24.5%	+18.3%	+12.1%
Dec.	+39.3%	+27.4%	+21.0%	+14.6%
Annual	**+8.3%**	**-3.4%**	**-8.3%**	**-13.1%**

Appendix - Table 32 : SAM 2006 for L4 for all losses scenarios, S1 (no losses), S2 (Wakes and PA), S3 (additional 5%) and 4 (additional 10%).

	S1 [MWh]	Wakes [%]	S2 [MWh]	S3 [MWh]	S4 [MWh]
Jan.	96,448	5.5%	88,638	84,206	79,774
Feb.	82,992	6.0%	76,406	72,586	68,766
March	49,416	10.3%	43,403	41,232	39,062
April	49,915	9.5%	43,949	41,752	39,554
May	63,718	6.6%	58,116	55,210	52,305
June	51,638	6.2%	47,407	45,036	42,666
July	48,022	7.4%	43,296	41,132	38,967
August	48,763	12.3%	41,576	39,497	37,419
Sept.	42,349	10.4%	36,972	35,123	33,275
Oct.	76,000	9.0%	67,541	64,164	60,787
Nov.	83,621	6.1%	76,414	72,594	68,773
Dec.	47,257	10.2%	41,434	39,362	37,290
Annual	**740,139**	**7.9%**	**665,171**	**631,913**	**598,654**

Appendix - Table 33 : Deviation for SAM in 2006 – L4.

	$d_{2004,S1}$ [%]	$d_{2004,S2}$ [%]	$d_{2004,S3}$ [%]	$d_{2004,S4}$ [%]
Jan.	+94.1%	+78.4%	+69.5%	+60.6%
Feb.	+119.0%	+101.6%	+91.5%	+81.4%
March	-12.7%	-23.4%	-27.2%	-31.0%
April	-23.3%	-32.5%	-35.9%	-39.3%
May	+13.6%	+3.6%	-1.6%	-6.8%
June	-12.1%	-19.3%	-23.3%	-27.4%
July	-3.9%	-13.3%	-17.7%	-22.0%
August	-2.0%	-16.4%	-20.6%	-24.8%
Sept.	-+5.2%	-8.2%	-12.8%	-17.4%
Oct.	+64.7%	+46.4%	+39.1%	+31.7%
Nov.	+79.3%	+63.9%	+55.7%	+47.5%
Dec.	+3.7%	-9.1%	-13.6%	-18.2%
Annual	**+22.8%**	**+10.4%**	**+4.9%**	**-0.6%**