

Department of Mechanical and Aerospace Engineering

Assessment of Wind Resources Modelling Tools for Wind Energy Generation Systems

Author: Gurudatt Bhardwaj

Supervisor: Dr. Daniel Cóstola

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Abstract

Wind energy is an increasingly key contributor to the transition to low-carbon energy systems in the current energy market. Therefore, modelling and simulation of the wind energy systems has received significant research attention. There are plenty of modelling tools for wind energy assessment like HOMER Pro, energyPRO, EnergyPLAN, WAsP, WindStation. Each tool requires different inputs to perform the simulation. Accordingly, they require different modelling approach to provide the desired output. Also, there are a set of assumptions, each tool makes for the simulation. Due to such variance, the outcomes of the defined inputs vary with respect to the tool. Softwares like HOMER Pro, energyPRO & EnergyPLAN do not require many inputs. They perform simplified modelling based on few inputs & sets of assumptions, taken by the tool. On the contrary of it, softwares like WAsP, WindStation include many aspects during the simulation and attain closest result to the actual scenario.

The objective of this thesis is to assess the accuracy of various wind resources modelling tools for wind energy generation systems by performing simulation on various simplified and detailed modelling tools. Initially a literature review is carried out which includes required inputs & outputs, set of assumptions taken, and modelling techniques behind each tool. In methodology, simulations are performed on each modelling tool (HOMER Pro, energyPRO, WAsP, WindStation) separately without interlacing parameters within each of them. Further, simulations are performed on these simple and detailed modelling tools considering one specific location- Langeland, Denmark, and results with improved precision are achieved by defining inputs and outputs of softwares interdependently.

Key words: renewable energy, simplified modelling tools; detailed modelling tools, HOMER Pro; energyPRO; WAsP; WindStation; wind data; annual energy production; wind turbines; hub height; turbine losses; electricity demand; terrain, turbulence, temperature, iteration, computational fluid dynamics, elevation, wind climate

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List of Abbreviations

RES: Renewable energy sources

NREL: National renewable energy laboratory

CFD: Computational fluid dynamics

O&M: Operations and maintenance

WT: Wind turbine(s)

Meteo Station: Meteorological station

WASP: Wind Atlas Analysis and Application Program

HOMER: Hybrid optimization model for electrical renewable

MWh: Megawatts- hour

MW: Megawatt(s)

GWh: Gigawatts- hour

Kg/m³: Kilograms per cubic meter

m: Meter

m/s: Meters per second

kW: Kilowatts

mm: Millimeters

N/m²: Newtons per square meter

N/m²: Newton second per square meter

WTG: Wind turbine generator

STP: Standard temperature and pressure

GWEC: Global wind energy council

CHP: Combined heat and power

GHG: Greenhouse gas

OWC: Observed wind climate

AEP: Annual energy production

REN: Renewable Energy Policy Network for the 21st Century

a.g.l.: Above ground level

1. Introduction

1.1. Background

Energy crisis has become a global concern for sustainable development as a result of rapid industrialization and economic growth. Coal, oil, and gas are traditional energy resources that are limited on the planet and will certainly be depleted in the future. Global warming, resulted from aggressive consumption of fossil fuels is currently affecting human society, and national governments are endeavouring to tackle the problem by encouraging the installation of renewable energy sources (RESs) to replace fossil fuels. Renewable energy has emerged as a key player in global energy and development strategy, accounting for 62% of new power generation capacity between 2009 and 2018. Onshore wind energy, which has been developed from 13 percent to 24 percent of renewable energy capacity over this period, is the most major non-hydropower renewable technology. Renewable energy capacity, including wind, must expand four times faster than this from now and 2030 to ensure climate protection and sustainable development. A comprehensive assessment of the potential available to reach this goal in a cost-effective and socially acceptable manner is required to achieve such growth. As a result of the worldwide push toward more sustainable energy systems, resource assessments for renewable energy have become an active subject of research. Over the last few decades, researchers have focused a lot of emphasis on this topic, which has resulted in considerable methodological advancements and more accurate resource estimations. Improvements in atmospheric modelling and data availability, land use mapping with open-source data, and knowledge of techno-economic turbine features are all part of this. One additional area where methodological attention has been focused is on how non-technical (e.g., social) constraints for renewable resources like onshore wind are accounted for in such studies [1].

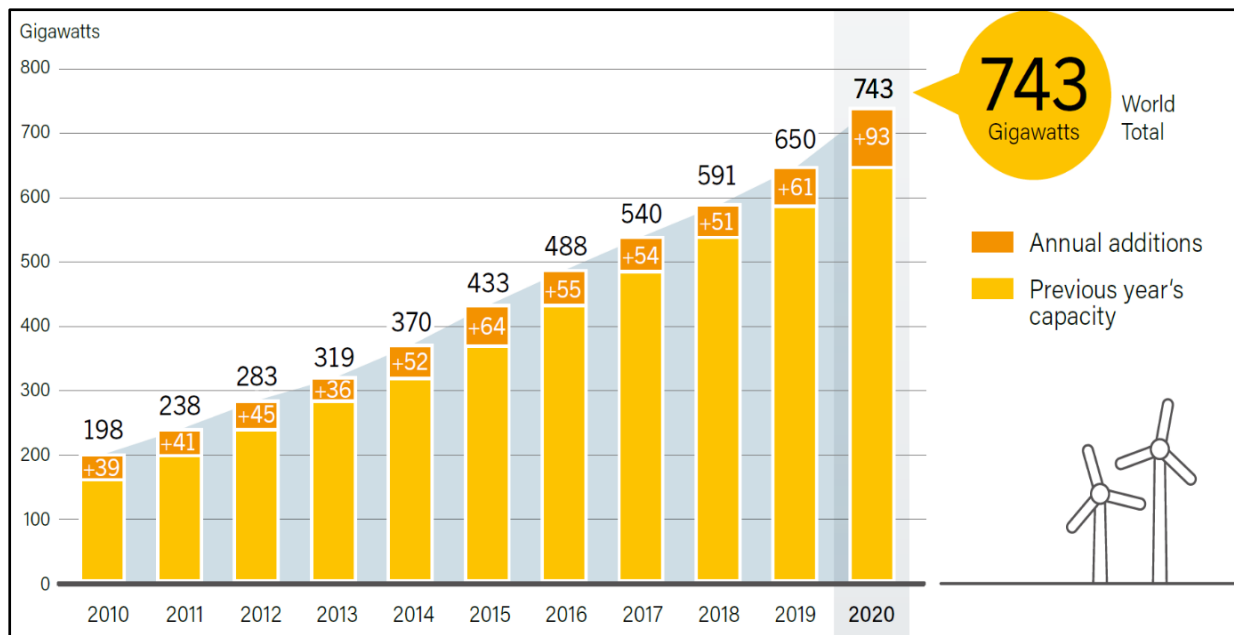


Figure 1: Wind Power Global Capacity and Annual Additions, 2010-2020 (Adapted from REN21 Global status report-2021) [2]

Wind energy has been in practice for several purposes for many years. Many nations are now aware of the scarcity of fossil fuels and the relevance of wind energy. It has resurfaced as a viable source of renewable energy on a global scale. This energy transition could minimize GHG (greenhouse gas) emissions and reduce the usage of carbon fuel reserves while also reducing geopolitical conflicts regarding access to oil and gas sources. Wind energy has been used for thousands of years as a clean, environmentally preferable, and almost inexhaustible source of energy. The extraction of water from wells, the production of flour from grain, and other agricultural applications are among the oldest uses of wind energy. Wind energy is one of the world's fastest growing and most cost-effective sources of electricity. A vast number of wind energy farms are now being built or are scheduled to be erected in various nations throughout the world, either on land (onshore) or at sea (offshore). Wind energy has been widely used for energy production in recent decades all over the world. According to the Global Wind Energy Council (GWEC), the global wind energy had its best year ever in 2020, with a 53 percent year-over-year (YoY) growth rate. The wind industry's extraordinary endurance has been proved by the installation of more than 93 GW of wind power in a difficult year marked by disruptions to both the global supply chain and project execution [3]. With the inclusion of 93 GW of new capacity, the global cumulative installation of wind power capacity now stands at 743 GW. Wind power generation systems are generally composed of onshore and offshore wind farms. To date, the majority of wind power has been extracted by onshore wind farms. In the onshore market, 86.9 GW was installed, up 59 percent from the previous year. The world's largest markets for new onshore additions are China and the United States. In recent years,

offshore wind power has been increasingly appealing due to its constant wind resources, generally lower environmental impacts, less restrictions on wind turbine size, and many other factors. As a result, innovative offshore options such as larger rotor wind turbines, deep sea foundations, and floating platforms have received increased attention. Over the last three decades, the offshore wind energy community has grown significantly. The world's first offshore wind farm (OWF), Vindeby was built in Denmark in 1991. That wind farm has now been decommissioned, and interest in deep-water floating wind farms has grown. Since the installation of the first prototypes of bottom fixed and floating offshore wind farms in the Baltic Sea and Scotland pilot park, Northern and Central European nations (ECs) have a long history of designing, constructing, and deploying offshore wind farms. Europe is home to about 90% of the world's MREs [4].

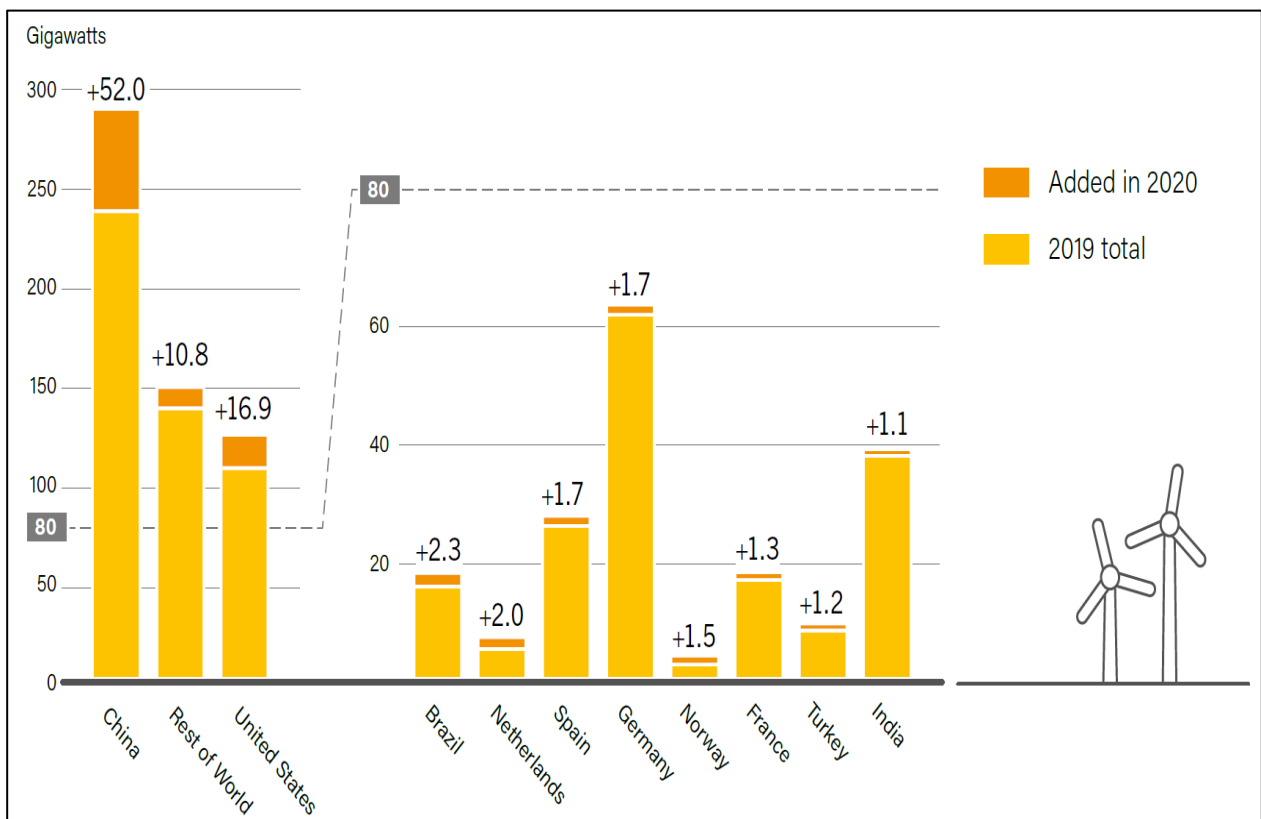


Figure 2: Wind Power Capacity and additions in top 10 Countries in 2020 (Adapted from REN21 Global status report-2021) [2]

Below figure shows the additions in wind energy capacity in top 10 countries. Numbers above bars are gross additions, but bar heights reflect year-end totals. It is clear from the figure that China & United states are the leading countries in wind energy generation with addition of 52 percent and 16.9 percent respectively from 2019 to 2020.

1.2. Aim

To evaluate and perform wind resources modelling for a wind energy generation system, on a variety of tools, analyse their resemblance & disparity with each-other & generate precise results by using all tools interdependently.

1.3. Objectives

Following are the objectives of the project:

- To perform wind resources modelling & simulation on simplified modelling tools.
- To perform wind resources simulation on detailed modelling tools, for a site.
- To analyse their outcomes and evaluate the quantified differences, predicted by tools.
- To perform wind resources simulation for a particular location, using all tools interdependently to generate outcomes with better precision.

1.4. Methodology Structure

Section 2 contains the review of the literature that was used for the completion of this study. The review begins with detailed study of each modelling tool and areas where it is widely used. Section 2.1 provides an overview of each modelling tool as well as their as benefits and drawbacks. This section also clarified specific parameters for each tool. Section 2.2 clarifies the specific inputs required for each tool, outputs extracted after the simulation. Each wind resources modelling tool requires a set of assumptions and specific boundaries for simulation. They also use a series pre-established mathematical equations to provide the desired results. Those equations and calculations are elucidated in section 2.3.

Section 3 outlines the methodology of the project, with section 3.1 containing simulations of each tool for different scenarios. The simulations are run on each tool separately, taking into account the assumptions made by the tools. In the section 3.2, simulation has been run by considering the wind farm at the location “Langeland, Denmark”. The simulation tools define inputs and outputs interdependently in an attempt to obtain accurate results.

Section 4 contains the results of simulations on the wind resources modelling tools. Section 4.1 will discuss about the results of simulation on each tool for different scenarios which are done by considering the assumptions taken by the tools. Section 4.2 shows the results of simulations done

by all tools interdependently for the location “Langeland, Denmark”. It displays the results of each tool, which are based on the outcomes of other tools.

Section 5 is the Discussion, which outlines the whole approach used for obtaining more exact results by combining tools. It also compares the results obtained with and without the use of combination of tools with the help of graphs.

2. Literature Review

Section 2 contains the review of the literature that was used for the completion of this study. The review begins with detailed study of each modelling tool and areas where it is widely used. This section also clarifies the specific inputs required for each tool, outputs extracted after the simulation, and sets of assumptions required. Strength and weakness of each tool are briefly explained in this section. Each wind resources modelling tool uses a series pre-established mathematical equations to provide desired results. Those equations and calculations are elucidated here.

2.1. Overview of Wind Resources Modelling Tools:

2.1.1. HOMER Pro

HOMER Pro (Hybrid optimization model for electrical renewable) is an optimization modelling tool which is used to evaluate and perform wind resources modelling for different energy mix, renewable energy resources and other fuel sources. HOMER Pro is developed for National Renewable Energy Laboratory (NREL) USA by Mistaya Engineering, Canada in 1993. Generators, solar PV, wind turbines, hydropower, biomass, storage capacity, and batteries are some of the appliances that might be included in the assessment [5]. It can also calculate the entire cost of installing and operating the system during its lifetime. The tool is helpful since it compares several design options based on their technical and economic merits. There are numerous possibilities for different component sizes, components to be added to the system, and cost functions of components in the system. The optimization and sensitivity analysis algorithms of HOMER Pro helps to assess the system configuration possibilities [6]. For modelling, a variety of fuel prices and wind speeds are also taken into account. Capital, operation, replacement and maintenance, fuel, and interest are all factored into the system cost calculations [7].

There are following advantages of HOMER Pro tool [8]:

- HOMER Pro is easy to use and easily accessible (open source).
- It has the ability to handle data on an hourly basis.
- It provides graphical and tabular results to the user.
- It can consider purchase or sales of electricity from grid as per user demand.
- It takes very less time to simulate.
- Fluctuation in bus voltage is not taken into account.

There are following disadvantages of this tool:

- It considers imperial units only.
- Importing time series data in the form of a daily average is not possible.
- In thermal system, it does not have analytic capability.

Different parameters requested by HOMER Pro software for the specific economic and wind resources modelling calculations are specified below [9]:

Table 1: Parameters used in HOMER Pro Software

S. No.	Parameter	Description
1	Wind turbine hub height	Height of the rotor measured from the ground
2	Wind O&M cost per unit	Operation and maintenance cost per wind turbine unit
3	PV O&M cost per unit	Operation and maintenance cost per PV unit
4	Grid power price	Price that the electric utility charges for energy purchased from the grid
5	Simulation period	Time considered for the study
6	Annual scaled average	Parameter used to scale the whole array of hourly data up or down
7	Pike	Energy top value
8	Rate of inflation	The percentage at which money is devalued along time
9	Discount rate	The rate considered to borrow money

S. No.	Parameter	Description
10	Grid CO ₂	CO ₂ emission factor of the energy generated by the grid

2.1.2. energyPRO

energyPRO is the leading tool in industries for modelling and analysing extensive energy projects that include both electrical and thermal energy (process heat, hot water, and cooling). energyPRO is commonly used for techno-economic analysis of energy projects like district heating cogeneration plants with gas engines, boilers, and thermal storage, industrial cogeneration plants supplying both electricity, steam [10], and hot water to a site, cogeneration plants with absorption chilling (trigeneration), biogas fuelled CHP plants with a biogas store, and biomass cogeneration plants [11]. It may be used to model any form of energy plant due to its flexible and generic framework. Also, it is used to perform detailed technical and financial analyses of existing and future energy projects in a user-friendly interface that gives the user a clear picture of the project [12]. It includes a graphical display of the simulated operation, which provides an overview and in-depth comprehension of dynamics in a complicated energy system. energyPRO generates a detailed financial plan in a format that is widely accepted by international banks and funding agencies. This covers the project's operating outcomes, monthly cash flows, income statements (P&L), balance sheets, and critical investment numbers including net present value, internal rate of return, and payback period. The software allows the user to calculate and generate a report for the proposed project's emissions (CO₂, NO_x, SO₂, and so on). energyPRO allows the daily optimization of the operation to be made against fixed tariffs for electricity or against spot market prices. The optimization is taking into account the limited sizes of thermal and fuel stores [13].

2.1.3. WAsP

WAsP (Wind Atlas Analysis and Application Program) is a numerical model was first developed in 1987 by the Department of Wind Energy at the Technical University of Denmark [17]. It was developed for the analyses presented in the European Wind Atlas. This programme predicts wind farm energy output, wind climates, and wind resources. WAsP is a key tool for wind farm pre-construction and operational analyses. When used appropriately, it allows the user to select a suitable location for new development or capacity expansion. These outputs are based on wind data from meteo stations in the same location or generalised wind conditions generated from mesoscale model results. A complicated terrain flow model, a roughness change model, a

sheltering obstacle model, a wind turbine wake model, and a model for the average atmospheric stability conditions at the site are all part of the programme. This software also includes a Climate Analyst for preparing wind-climatological inputs, a Map Editor for creating and editing topographical inputs, and a Turbine Editor for making wind turbine inputs to WAsP. The European Wind Atlas explains the basics of WAsP and the wind atlas technique. The WAsP simulation software is comprised of four Microsoft loader files, including the WAsP Climate Analyst, WAsP Map Editor, and WAsP programme. The WAsP Turbine Editor is also established as part of the WAsP placement programme [18]. It entails a few physical designs to characterise wind flow near shelter barriers and across various terrains. The documentation is provided in the form of online help files. The WAsP simulation application works on Windows 7, XP, and Vista. WAsP is an application of the so-called wind map methodology, which may be shortly determined as shown in below figure [19].

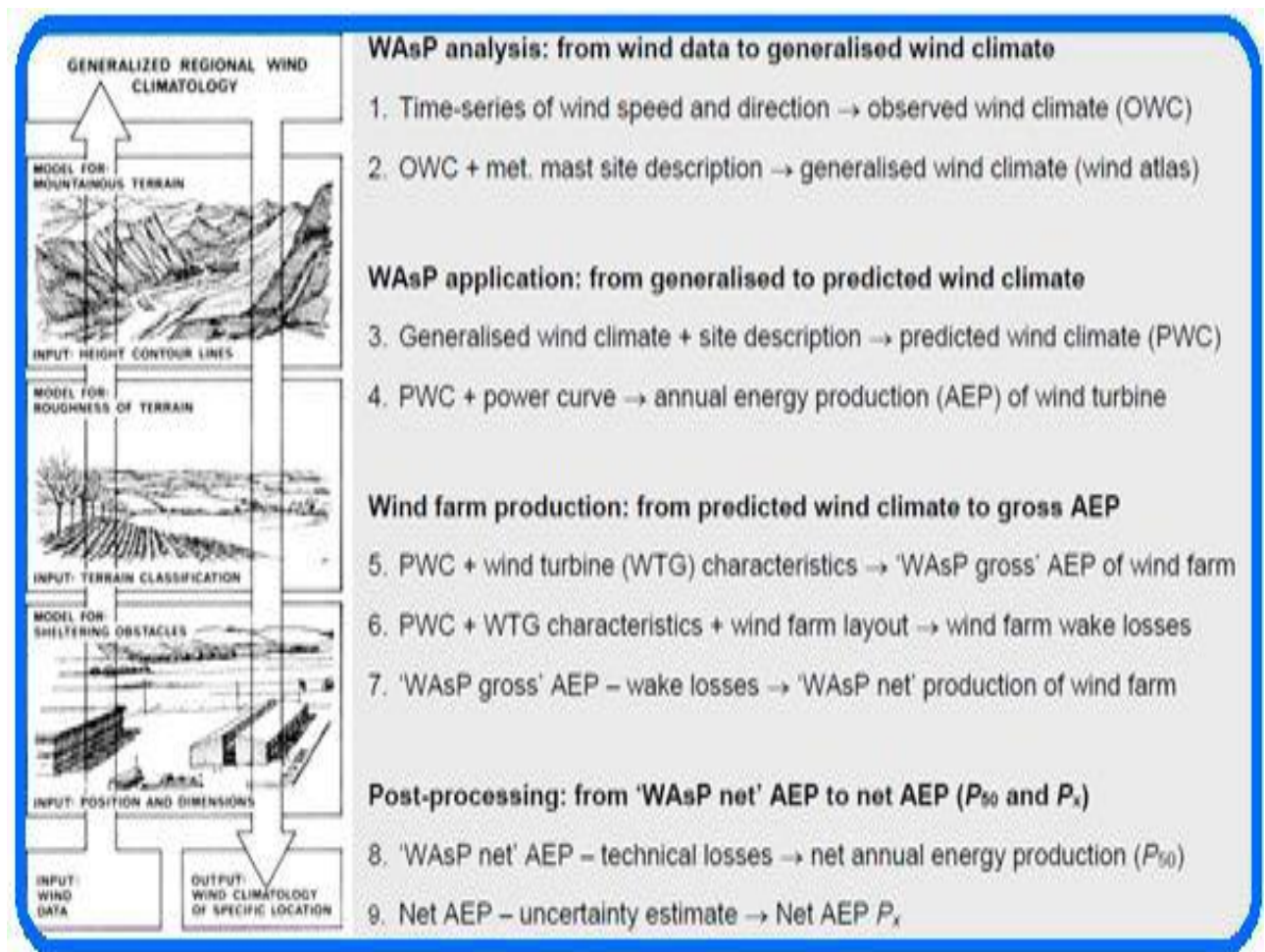


Figure 3: Wind methodology of WAsP

There are following advantages of WAsP tool:

- It has the ability to simulate in complex topographical conditions.
- It is a linear numerical model which is based on the physical principles of flows in the atmospheric boundary layer.
- The program is capable of describing wind flow over different terrains, close to sheltering obstacles and at specific points.
- WAsP models the estimated power loss in wind farms due to the wind speed reduction in wakes from up-wind turbines

There are following limitations of this tool [20]:

- When calculating power density, WAsP utilises an air density of 1.225 kg/m³. If one of the sample power curves is utilised, power production is estimated for this standard air density.
- Any modifications made to the map in the WAsP Map Editor are not automatically applied in WAsP; the map must be saved and reloaded into WAsP for the changes to take effect.
- The wind turbine power production computed by WAsP will only correspond to this air density if the power curve is specified for the actual site air density, or if an existing power curve has been scaled to the site air density (this is only recommended for few turbines). In 'real' projects it is strongly recommended to obtain a site-specific power curve from the manufacturer.

2.1.4. WindStation

WindStation is a wind energy software that does wind resource assessments on complex terrain using computational fluid dynamics (CFD). The terrain description in raster format, as well as wind observations and atmospheric stability, are all input data to WindStation. The non-linear fluid dynamics equations are solved by taking into account of the Coriolis effects. The user can run the simulation with measured wind data or mesoscale data with the help of included nesting mechanism. Flexibility is provided by domain and meshing, which includes features such as automated alignment with free stream direction. In order to assess the feasibility of wind farms, WindStation can be used to generate wind resource assessments in complex terrain. This is accomplished by incorporating terrain and roughness data, as well as measured wind data from a measuring mast or reanalysis data [21]. It can also be used to evaluate the flow around buildings

in cities. WindStation can also be used to do specific analyses of urban climate, including air pollution and dispersion calculations. Multiple projects, including climatology calculations for statistical analysis, can be set up and calculated using batch run features. For visualisation, there are postprocessing tools as well as data export choices. Since WindStation is integrated into Microstation's graphical environment, the user may utilise all of the CAD tools to add text labels and drawings, perform dynamic rotations and zooms, and apply rendering options for additional visualisation work [22].

2.2. Inputs & Outputs for each Modelling Tool

Each wind resources modelling tool considers different sets of parameters & calculations to achieve the desired results. Therefore, they require specific inputs to provide particular outcome. Following table shows the inputs & outputs required for each tool.

Table 2: Inputs & outputs for each wind resources modelling tool

Wind resources modelling tool	Inputs required	Desired outputs
HOMER Pro	wind speed of the location, electric load for the chosen facility, number of wind turbines, type of wind turbine (rated capacity, hub height, lifetime), storage system to store surplus energy, quantity of storage system, efficient of converter, cost for each item (Capital cost, replacement cost, O&M cost).	Number of components (turbines, batteries) and their capacity required to suffice particular demand, cost of energy, Net present cost, operating cost
energyPRO	Hourly wind speed data, Set of energy units with specifications, Electrical demand	Monthly energy output by all energy units and each energy unit (MWh)
WAsP	Hourly wind data (wind speed and wind direction), topography of the area on which the measuring station is located, area roughness information, co-ordinates	Mean wind speed at turbine site, Annual energy production by wind turbine facility, wake effect (wake

	of wind turbine facility on site, hub height, and obstacle information about the surrounding environment around the wind measurement station [23]	loss) in wind turbine wind farm performance by the impact of turbines on each-other
WindStation	terrain data of site (including elevation & roughness), wind turbine data, temperature, direction & turbulence for the entire site	wind data (wind speed, direction, turbulence intensity, temperature) at different heights

2.3. Modelling techniques behind Wind Resources Modelling Tool

2.3.1. HOMER Pro

HOMER Pro provides an option to choose the location & the resources data (Solar, Temperature, Wind) is taken from NASA Surface Meteorology. A three-step technique is used by HOMER Pro to determine the wind turbine's power output at each time step. First, HOMER Pro determines the wind speed at the wind turbine's hub height. The wind turbine's output power is then calculated at that wind speed and standard air density. Finally, HOMER Pro compensates for the real air density by adjusting the power output value [24].

Calculating Hub Height wind speed: Considering the inputs of the user in the Wind Resource page and the wind shear entry, HOMER Pro calculates the wind speed at the hub height of the wind turbine in each time step. If you use the logarithmic law, HOMER Pro estimates the wind speed at the hub height using the following equation:

$$U_{hub} = U_{anem} * \frac{\ln\left(\frac{Z_{hub}}{Z_0}\right)}{\ln\left(\frac{Z_{anem}}{Z_0}\right)} \quad (1)$$

where:

U_{hub} = the wind speed at the hub height of the wind turbine [m/s]

U_{anem} = the wind speed at anemometer height [m/s]

Z_{hub} = the hub height of the wind turbine [m]

Z_{anem} = the anemometer height [m]

Z_0 = the surface roughness length [m]

After determining the hub height wind speed, HOMER Pro analyses the wind turbine's power curve to calculate the expected power output at that wind speed under standard temperature and

pressure conditions. As shown in the below figure, the red dotted line represents the wind speed at hub height, and the blue dotted line represents the wind turbine power output predicted by the power curve at that wind speed.

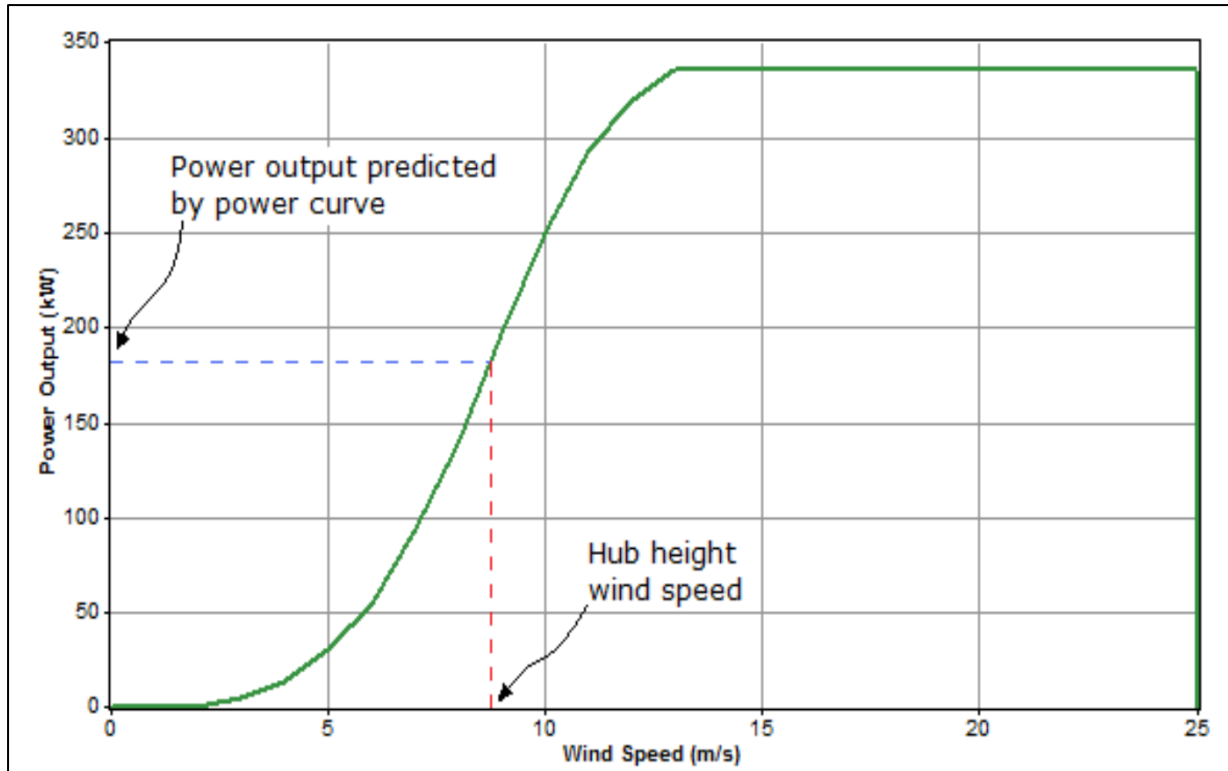


Figure 4: Graph showing power curve of a wind turbine

Power curve typically describes the wind turbine performance under standard temperature and pressure (STP) conditions. HOMER Pro multiplies the power value predicted by the power curve by the air density ratio to adjust to real conditions, as shown in the below equation [24]:

$$P_{WTG} = \left(\frac{\rho}{\rho_0} \right) * P_{WTG,STP} \quad (2)$$

where:

P_{WTG} = the wind turbine power output [kW]

$P_{WTG,STP}$ = the wind turbine power output at standard temperature and pressure [kW]

ρ = the actual air density [kg/m^3]

ρ_0 = the air density at standard temperature and pressure ($1.225 \text{ kg}/\text{m}^3$)

2.3.2. energyPRO

In energyPRO, there are five areas containing formula fields. There are a set of standard mathematical functions as well as certain specialised functions available in each of those fields. Those areas are listed below [25]:

- Time series functions
- Demands
- Energy Units
- Economy (Revenues and operational expenditures)
- Economy (Taxation)
- Economy (Define annual key figures)

energyPRO tool uses a variety of formulas and techniques for solar energy, wind energy, heat pump and others too. In this section, methodologies associated with wind energy are addressed below.

Wind speed at hub height

In energyPRO, the wind farm model covers three possible scenarios.

Case 1. Annual production calculated when power curve is used directly

Case 2. Annual production calculated when power curve is scaled to another level

Case 3. Fixed annual production calculated (wind speed is scaled)

Calculated annual production:

In this case, the productions from the wind farm are evaluated using the wind speed parameters and the power curve of the wind farm. There are options to scale the power curve and hence the production as an advanced setting.

Fixed annual production:

This option distributes a desired annual production, given all wind speeds specified via “Wind speed specification” are scaled by the modification factor, which ensures that the annual production, power curve, and wind speeds are all in harmony. Iterations are used to discover this parameter.

Calculated wind speed at hub height in cases 1 and 2 =

$$WS_c(t) = WS_m(t) * \left(\frac{H_h}{H_m}\right)^\alpha \quad (3)$$

Calculated wind speed at hub height in case 3 =

$$WS_c(t) = WS_m(t) * \left(\frac{H_h}{H_m}\right)^\alpha * m_f \quad (4)$$

Where $WS_c(t)$ = Calculated wind speed (in m/s) at time t

$WS_m(t)$ = Measured wind speed (in m/s) at time t

H_h = Hub height (in m)

H_m = Height of measurements (m)

α = Hellmann coefficient

m_f = Wind speed modification factor

Calculation of production at time t

Following are the formulas for calculation of production at time t:

- For case 1: $P(t) = PC(WS_c(t))$ (5)

- For case 2: $P(t) = PC(WS_c(t)) * P_{max} / P_{maxPC}$ (6)

- For case 3: $P(t) = PC(WS_c(t))$ (7)

Where $PC(WS_c(t))$ = the power from the power curve based on the calculated wind speed at hub height and linear interpolation on power curve.

Calculation of modification factor

Modification is found through iteration processes.

$$P_{\text{annualCalc}} = \sum_{t=0}^{t=H_{\text{Year}}} PC(WS_c(t)) * \Delta T \quad (8)$$

Where the formula for $WS_c(t)$ will be 'Calculated wind speed at hub height in case 3'.

Now take value of $m_f = 1, 2, 3, 4, \dots$

In each iteration, annual production is calculated and it is compared with the desired value.

If $P_{\text{annual Calc}} > P_{\text{annual Desired}}$ then decrease m_f

If $P_{\text{annual Calc}} < P_{\text{annual Desired}}$ then increase m_f

This process is repeated

Until $P_{annual\ Calc} = P_{annual\ Desired}$

Then the value of m_f is calculated.

Following parameters are used to define the wind speed at hub height of wind turbines, which is used for converting the wind speed in measure height to wind speed at hub height [25].

- A time series holding the wind speed
- The measure height of the time series
- The hub height of the turbines
- The Hellmann exponent

2.3.3. WAsP

WAsP simulates the expected power loss in wind farms due to wake speed reduction in wakes from up-wind turbines [20]. This is a key aspect for wind farm evaluation. A number of wind turbines are deployed in a windy environment. They provide a unique opportunity to increase the overall installed capacity to the desired level. A turbine placed in a low wind speed region will create very little power, while installing a turbine near another turbine can reduce production at one of the locations significantly due to wake effects. While doing so, it becomes necessary to arrange the turbines in such a manner that at each location, the operation of the turbines has the least interference from other turbines and by itself will not cause strong interference to other turbines in the vicinity. There will be a shift in the wind environment in the near vicinity when a turbine is erected in a small region. There are two major effects discovered. The first is that the wind speed in front of the rotor will decrease. The other is that the rotor action introduces an extra turbulence in the wind field. Both these effects will result in reduction of wind power produced by the machines in the "wake" of machines in the front.

The drop in power generation for a specific turbine in a given array owing to other turbine's interference in the flow field varies depending on its placement in relation to other turbines and the flow field. It will be appropriate to consider park efficiency as a single figure if the whole wind farm is under one ownership. However, if multiple people or businesses own their own turbines, the net generation that each turbine finally produces could become a contentious issue. As a result, it may be necessary to limit array losses in a given wind farm site to a minimal. This factor becomes considerably more important in complex terrain, where land availability is a major constraint [26].

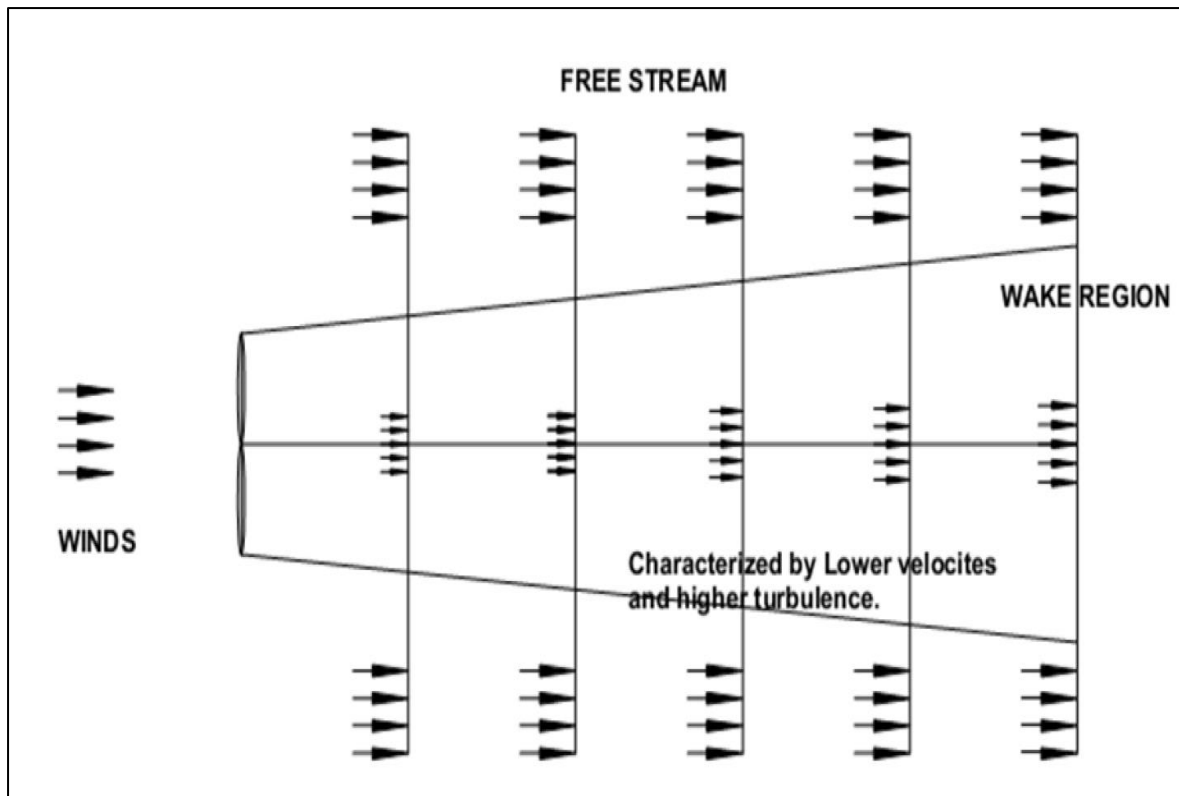


Figure 5: Wake behind wind turbine rotor

Increased turbulence will also affect the fatigue spectrum that the wind turbine is susceptible to. This will have a particularly negative impact on the rotor blades. When performing micro-siting exercises, this factor should also be taken into account. The important fact to notice is that there will be no immediate effects on energy generation, except that there will be a slight decrease in generation due to increased turbulence. Increased turbulence has an impact on the service life of a given turbine. The cumulative damage that occurs on various components due to stress cycling determines the fatigue life of essential components such as blades. The fatigue damage caused by this effect should be evaluated quantitatively and taken into account. The optimization of land use is another factor to consider. Closely packed wind farms have larger array losses, according to studies, especially in low to moderate wind regimes. Micro siting of wind turbines is the study of reducing array impacts through appropriate geometric machine structure. In practise, there are not any straight formulas to follow. The term array efficiency is defined as follows:

$$\text{Array efficiency} = \frac{E_{farm}}{E_{free}} * 100 \quad (9)$$

Where E_{farm} = Output from the turbine in the wind farm.

E_{free} = Turbine output without influence of other turbines.

The following parameters influence array efficiency:

- Mean wind speeds and predominant wind directions in relation to available land area.
- Turbulence intensity (TI) and turbine design in relation to TI
- Shape, orographic, roughness features and orientation of the land that is made available for wind farming.
- The number of turbines to be installed or the Megawatt capacity.
- Anticipated average wind farm output in MWh per year
- Legislative restrictions on the use of neighbouring lands.

It will be necessary to perform an optimization with these inputs.

WAsP uses the Park model to predict wake effects and their impact on power production. The Park model is a computationally efficient model that makes several estimating simplifications. The software assumes an initial velocity loss behind the turbine rotor, which is calculated using the thrust coefficient curve of the turbine and an empirically established wake-decay constant. It makes the computation easier by neglecting some characteristics in the near-flow environment around a turbine rotor and assuming that the wakes expand linearly with distance. According to the Park model, the flow follows the terrain. When there are multiple wakes, the upstream turbines' wake cross sections are superimposed. The free stream wind speed minus wake effects is used to calculate the expected wind speed at a downwind turbine [26].

The wind speed deficit due to wake effects is then calculated downwind by using:

$$\delta V_{01} = U_0(1 - \sqrt{1 - C_t}) \left(\frac{D_0}{D_0 + 2kX_{01}} \right)^2 \frac{A_{overlap}}{A_1^{(R)}} \quad (10)$$

Where

U_0 = the undisturbed wind speed at the up-wind turbine

D_0 = rotor diameter

k = wake coefficient

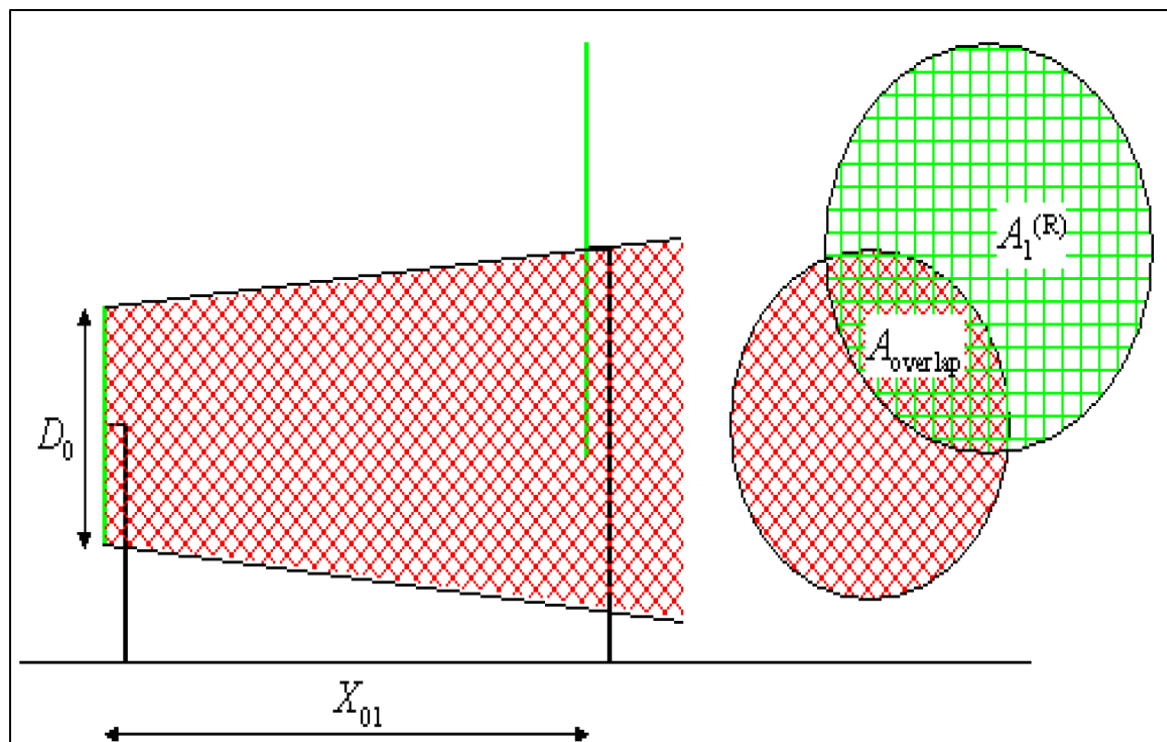


Figure 6: Illustration of how WASP calculates wind turbine output at turbine downwind

The precision of WASP software can be unreliable if a site has complex, rocky terrain or very complex air conditions [27]. The orography and site ruggedness index (ΔRIX) of the overall grid layout are analysed by WASP. The associated performance indicator (RIX) might help to identify problematic areas in a project. ΔRIX is defined as the fractional extent of surrounding terrain that is steeper than a critical slope and falls within the operating envelope of the WASP flow model. ΔRIX is defined as the difference in fractions (percentage) between the predicted and reference locations is defined as ΔRIX .

There is a formula to express the relationship between ΔRIX and estimation error of wind speeds:

$$U_m = U_p / \exp(\alpha \Delta\text{RIX}) \quad (11)$$

Where

U_m = Estimation error in wind speeds

U_p = project wind speed at hub height

α = constant

WAsP uses the linear atmospheric model to extrapolate wind climate data within a region by considering orography and roughness. This model uses linear components of Navier-Stokes equations to solve for wind speed at different locations [17].

The terrain analysis member during WAsP simulation comes in two types: IBZ or CFD. The IBZ terrain analysis corresponds to the classic WAsP models: the roughness change model based on internal boundary layer theory and the linearised BZ flow model. These models have been the basis of WAsP since it was first launched in 1987. The CFD terrain analysis corresponds to the EllipSys CFD option. This member will help you set up the CFD calculations by arranging the calculation tiles to cover all sites and by making a request for the CFD cluster [28].

WAsP uses vector maps to obtain information about the landscape's elevation (orography) and land cover (roughness) parameters. Maps are the children of a terrain analysis component that determine which models are utilised to analyse the flow. TA's and maps can exist in many places within the workspace hierarchy, but each project will normally have its own map. For the meteo stations and the prediction locations, different maps are often used. In WAsP, bitmap image files that can be used as map underlays are known as spatial images. They can be placed anywhere in the hierarchy, as well as many types can be linked to the same vector map. Meteo stations and (less commonly) turbine sites can have sheltering obstacles in their surroundings. An obstacle group is a description of some sheltering obstacles which can be associated with one or more sites. The calculation of a wind farm power curve, i.e. the production of a particular wind farm as a function of wind speed and direction at the reference site, is assisted by reference sites. Because they calculate a predicted wind climate for a particular location, reference sites are similar to turbine sites [29].

Seven variables can be used to define the state of the atmosphere: pressure, temperature, density, moisture, and two horizontal velocity components, all functions which are time and position dependent. Seven equations are generally used to describe these seven variables: the equation of state, the first law of thermodynamics, three components of Newton's second law, and the mass and substance continuity equations. Integrating the appropriate equations with special initial and boundary conditions provides mathematical models of the atmosphere. The models solve these equations by numerically forward marching in time, using the time rates of change of the variables, replacing the derivative with a ratio of finite differences, and computing the changes of the variables over a given time interval as many times as necessary

to obtain an estimate of acceptable accuracy. There are motions in the atmosphere with scales ranging from 1 mm to many kilometres [30].

It should be noted that when planning the layout of wind farms, a number of problems will arise. In most cases, the layouts are determined in terms of row and column spacing. The micro-siting of wind turbines has been found to pose a number of scientific and administrative challenges. The debate as to whether simplified thumb rules can be formulated such that authorities responsible for granting permissions for wind farming can employ without having to go back to the subject experts cannot be easily settled. To make the most use of the land and resources, some basic rules can still be devised. Land in windy areas sells at a premium [31].

The following is a general cost breakdown for a wind farm project:

- cost of WT hardware: 75 %
- foundation: 7 %
- land 2 %
- electrical infrastructure 10 %
- Miscellaneous 6 %

However, if one considers the land utilization point of view, it would become quite apparent that a given tract of land could accommodate much more installed power both on a per hectare basis and on a yield per hectare basis. [32]

Level terrain sites: Under identical conditions, a rigorous analysis was carried out to establish the extent of array losses and related concerns. The findings of this investigation show that [28]:

- Array spacing can be a little tight in high wind conditions. As a result, the units can be near to one another.
- Under moderate wind conditions, the normally employed 5D X 7D or 4D X 8D may be still acceptable keeping in view multiple ownerships.
- When measured in terms of land use efficiency, the generation loss as a result of tighter spacing is slightly lower than originally anticipated.
- Inter-column distances should not be less than 3D and inter row less than 5 D.

Level terrain sites: High winds are a feature of many complicated terrain settings, and the wind field is also found to be heterogeneous: that is, the same hill may have huge variations in wind over small areas. Aside from that, the actual space available for erecting wind turbines will be restricted. Due to local defects, it becomes necessary to shift locations (sudden depressions, extended cracks on the rocky hill tops etc.) Many of the hilltops would be too narrow to handle the machine and installation equipment, so they could have to be flattened [33]. In many circumstances, only one row of machines will be possible to accommodate. As a result, when micro-siting on difficult terrain, extreme caution is required. Each location must be assessed on an individual basis in this instance. In the event of difficult terrain settings, it has been discovered that winds will impact the rotor blades at an angle due to terrain inclination. This angle should not be more than 5° to 10° .

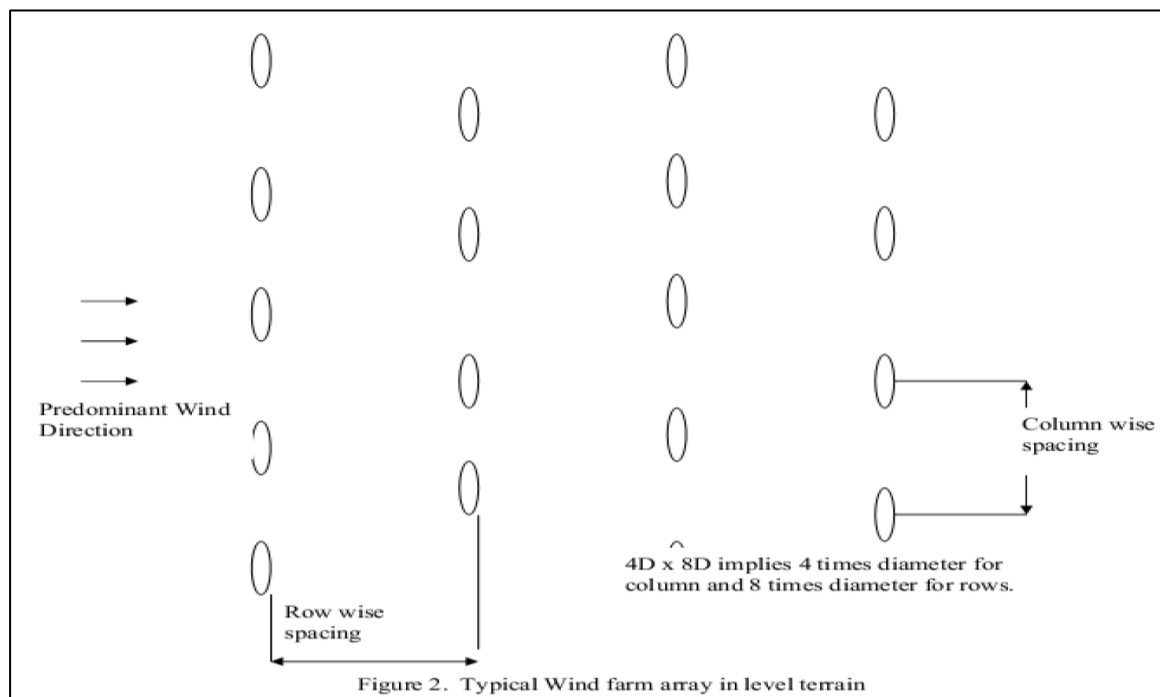


Figure 7: Typical wind farm array in level terrain [28]

2.3.4. WindStation

WindStation uses a control volume approach in a terrain-following mesh to solve the momentum (Navier-Stokes) equations, continuity, energy, and turbulence equations. The SIMPLEC algorithm is used in conjunction with a collocated grid arrangement to create the underlying approach. For faster convergence, the pressure correction equation is solved using a multigrid approach. WindStation is a software package that combines a recent version of turbine wake modelling with a numerical simulation of turbulent flow over complex

topography. The numerical wind fields are calculated using given nonlinear fluid dynamics equation solutions in conjunction with turbulence models [34].

The nonlinear fluid dynamics equations, specifically the Navier-Stokes equations, the continuity equation, and the energy equation, are used to assist the numerical calculation. The Navier-Stokes equation is a function of a pressure term and a diffusion viscous term that represents the conservation of momentum for a fluid flow. The WindStation steady state formula for Navier-Stokes equation is [22]:

$$\begin{aligned} \frac{\partial}{\partial x_j}(\rho u_i u_j) = & -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\Gamma \left(2 \frac{\partial u_j}{\partial x_j} - \frac{2}{3} \text{div} \vec{V} \right) \right] + \frac{\partial}{\partial x_j} \left[\Gamma \left(2 \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \\ & + \left(\rho g \beta (T - T_{ref}) \right)_{i=3} + S_{ci} + S_{ui} \end{aligned} \quad (12)$$

Where

ρ = the fluid density [kg/m³]

x_i = generic Cartesian coordinate [m]

p = pressure [N/m²]

$\Gamma = \mu_{eff} = \mu + \mu_t$ the time diffusion coefficient for momentum i.e. effective viscosity [N s/m²]

The Coriolis effect occurs when a mass moving in a rotating system is subjected to a force (the Coriolis force) that acts perpendicular to the direction of motion and the axis of rotation. The effect deflects moving objects to the right in the northern hemisphere and to the left in the southern hemisphere, and it is significant in the generation of cyclonic weather systems. The Coriolis effect is also included by adding an additional term to the u ($i=1$; west-east direction) and v ($i=2$; south-north direction) equations.

These equations are:

$$S_{c1} = -f_c \rho v \quad (13)$$

$$S_{c2} = f_c \rho u \quad (14)$$

$$S_{c3} = 0 \quad (15)$$

f_c = Coriolis term (given by: $f_c = 2\Omega \sin \lambda$)

λ = local altitude

Ω = Earth's rotation rate

S_{ui} = accounts for the presence of porous obstacles such as trees or bushes and it is computed with forest model.

The continuity equation is used to show the mass conservation:

$$\partial(\rho u_j)/\partial x_i = 0 \quad (16)$$

The energy equation is written for potential temperature as the dependent variable:

$$\frac{\partial}{\partial x}(\rho c_p u T) + \frac{\partial}{\partial x}(\rho c_p w T) = \frac{\partial}{\partial x}(\Gamma \partial T / \partial x) + \frac{\partial}{\partial z}(\Gamma \partial T / \partial z) \quad (17)$$

The diffusion coefficient is (for the case of a fluid domain):

$$\Gamma = \left(\frac{\mu}{P_r} + \frac{\mu}{\sigma_T} \right) c_p \quad (18)$$

P_r (0.71) and σ_T = the laminar and the turbulent Prandtl numbers, respectively. The value of the turbulent Prandtl number is determined on the basis of turbulence model used.

WindStation has four turbulence models implemented, all of which are distinct versions of the k- ϵ turbulence model. Using the transport equations, these turbulence models calculate the turbulent viscosity.

Following are the models:

- Standard k- ϵ model
- RNG k- ϵ model
- Realizable k- ϵ model
- Limited- length k- ϵ model

The turbulent viscosity is defined by the standard model as follows:

$$\mu_t = C_\mu \frac{\rho k^2}{\epsilon} \quad (19)$$

Where

k = turbulence kinetic energy, which is a measure of flow turbulence velocity T_l (m^2/s^2)

ϵ = Dissipation rate of turbulence kinetic energy

Relation between turbulence kinetic energy (k) and flow turbulence intensity (T_l):

$$k = \frac{3}{2} (T_1 V)^2 \quad (20)$$

V = Velocity magnitude (m/s)

The dissipation rate of turbulence kinetic energy, ε [m²/s³] is related to the dissipation length scale L_d as follows:

$$\varepsilon = C_\mu \left(\frac{3}{4}\right) \frac{k^{\frac{3}{2}}}{L_d} \quad (21)$$

In WindStation, the vertical spacing is determined by the altitude (above sea level) of the domain top (Z_{top}), the vertical distance between the first calculation point and the ground (First node), and the number of calculation levels (levels). The maximum vertical spacing is determined by the height of the last control volume. The difference between Z_{top} and Height above terrain is given by:

$$\text{Height above terrain} = Z_{top} - \text{Altitude} \quad (22)$$

The Height distribution factor determines the percentage difference between the cell at the ground and the cell at the upper edge:

$$\text{Height distribution factor} = \frac{\text{First node}}{\text{Maximum vertical spacing}} \quad (23)$$

3. Methodology

3.1. Simulation on each tool separately

This section will have simulation on each tool for different scenarios. The simulation is run on each tool individually by considering assumptions taken by the tools.

3.1.1. WindStation

The input data for WindStation consists of the terrain data of the site, the meteo mast data, and the wind turbine data. The location for this simulation is taken as 'Udaipur, India'. The terrain data was composed by the elevation and roughness files. The initialization of the wind fields in WindStation is accomplished by assigning average wind speed, turbulence, and temperature values for the entire domain. In this case, these figures are based on meteo mast data. The below table shows the data taken for this simulation for Udaipur location. This data is taken from external source.

Table 3: Data for defining meteo station.

Height (m)	Wind speed (m/s)	Direction (^o)	Temperature (^o C)	Turbine Intensity	X- Coordinate	Y- Coordinate
50	7	20	26	12	191247.6	350389.9

The meteo station generated in Udaipur is depicted in the figure below. The green colour in the figure depicts trees or any forest region, while the yellow colour denotes the terrain without any obstructions. The water-filled area is characterized by the sky-blue colour.

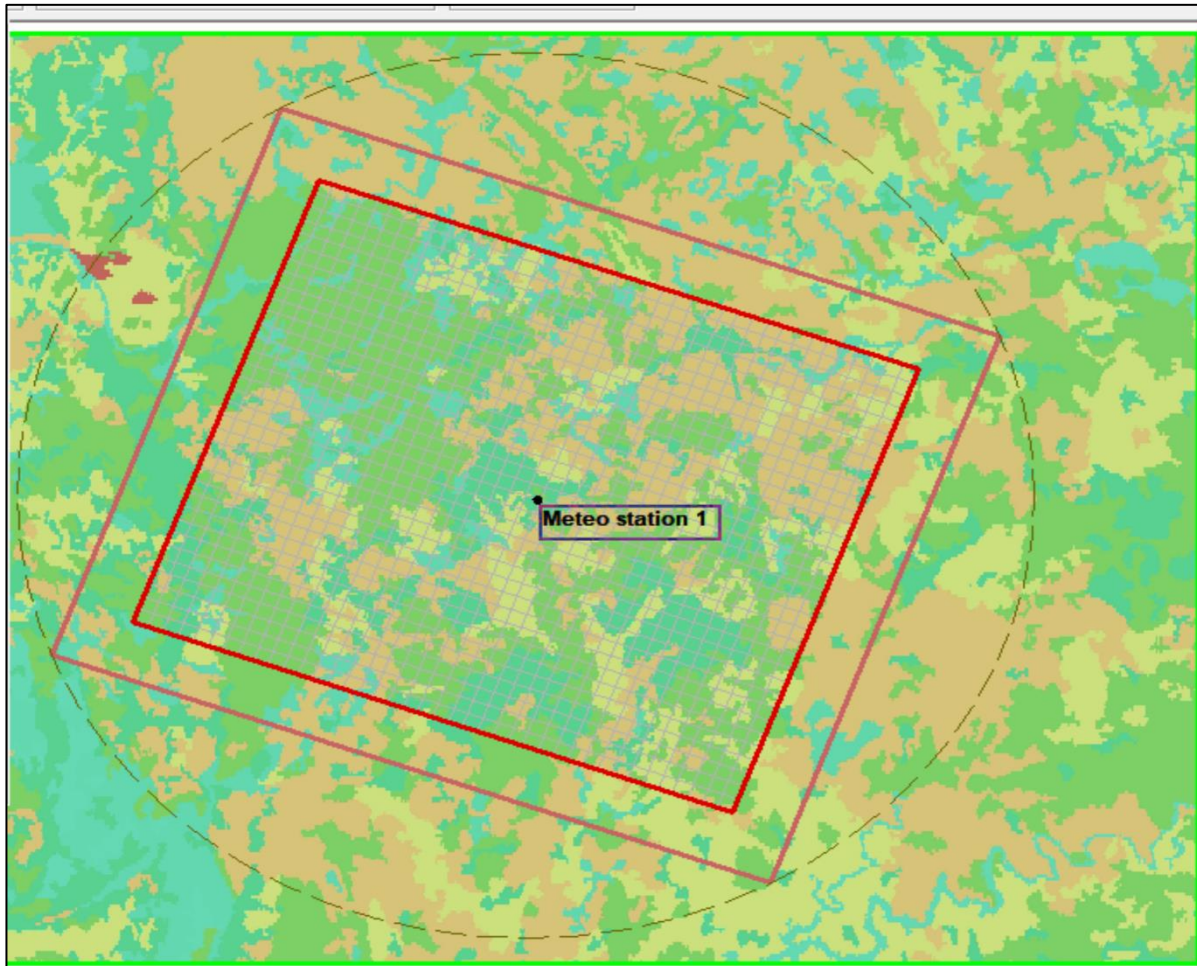
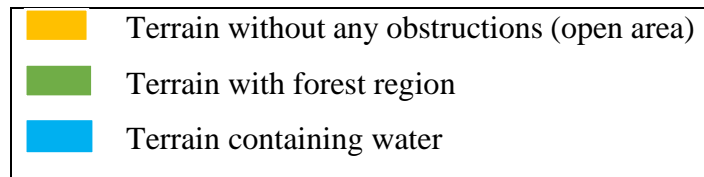


Figure 8: Defined Mateo station by entering input values (X - Y parameters of location, height, wind speed, direction, temperature, turbine intensity) in WindStation.

A constant horizontal spacing and a variable vertical spacing define the mesh in WindStation. A mesh refinement analysis was performed by reducing the horizontal spacing from 1000 m to 599.7 m in order to choose a value for the horizontal spacing. Because the landscape is quite smooth and the measurements are very simple, it was expected that mesh refinement would have little impact on the results. The vertical spacing in WindStation is determined by calculating domain top's (Z_{top}) altitude (above sea level), the vertical distance between the first calculation point and the ground (First node), and the number of calculation levels (Levels). The height of the last control volume is the maximum vertical spacing.

Figure 9: Wind calculation domain (defining horizontal & vertical spacing)

After pressing the start button, the iterative calculation procedure starts and the dialog box displays the evolution of the equations as a function of the iteration number. A horizontal red line represents the convergence criterion value. Residuals should decrease as the iterations proceed, though some oscillations as shown in the figure, are quite normal. The calculation is run by taking Coriolis effects into account. Based on the input data, the calculating procedure begins by computing the 1D incident profiles. During this initial stage, no residual is presented and the message 'Computing incident profiles' is displayed. The calculation time for 1D profiles depends solely on the number of vertical levels and processor speed. Typically, values should be between 20 seconds and 2 minutes. The iteration time for this run is 1 minute 11 seconds.

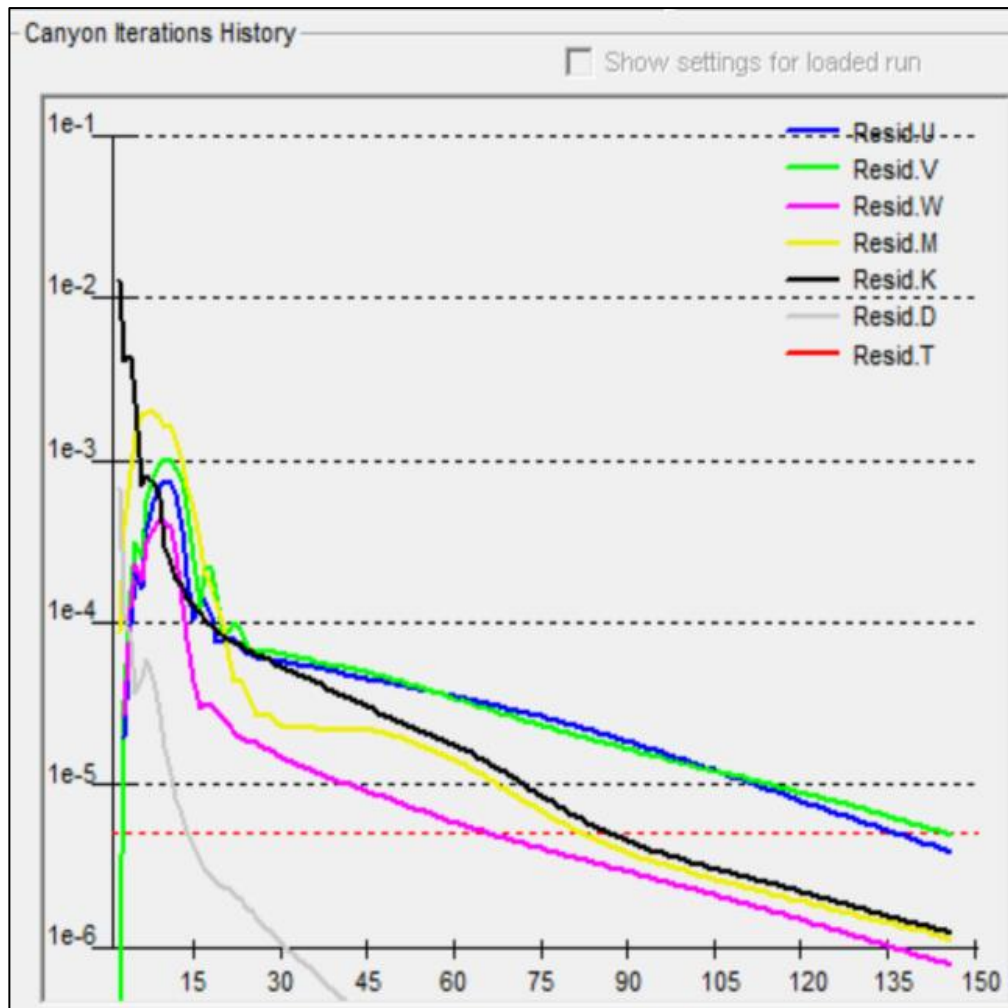


Figure 10: Dialog box for run control through Canyon iterations

3.1.2. WAsP

The input data for WAsP consists of the location of site, terrain data of the site. The location of this simulation is taken as "Santa Luzia Dam". Projects are always children of the workspace root. The following picture shows the spatial view of the site. The mouse pointer hovered carefully over a rose sector to reveal the actual values used to create the rose. The disparities between the observed wind climate and the self-prediction are shown in the red and green sector segments. There is a graph for each sector, as well as a graph for all sectors (omni-directional) and it can be chosen by clicking on a sector in the rose. To choose all sectors, click anywhere outside the circled area on the rose. When a sector is selected, the graph is changed to reflect that sector's statistics.

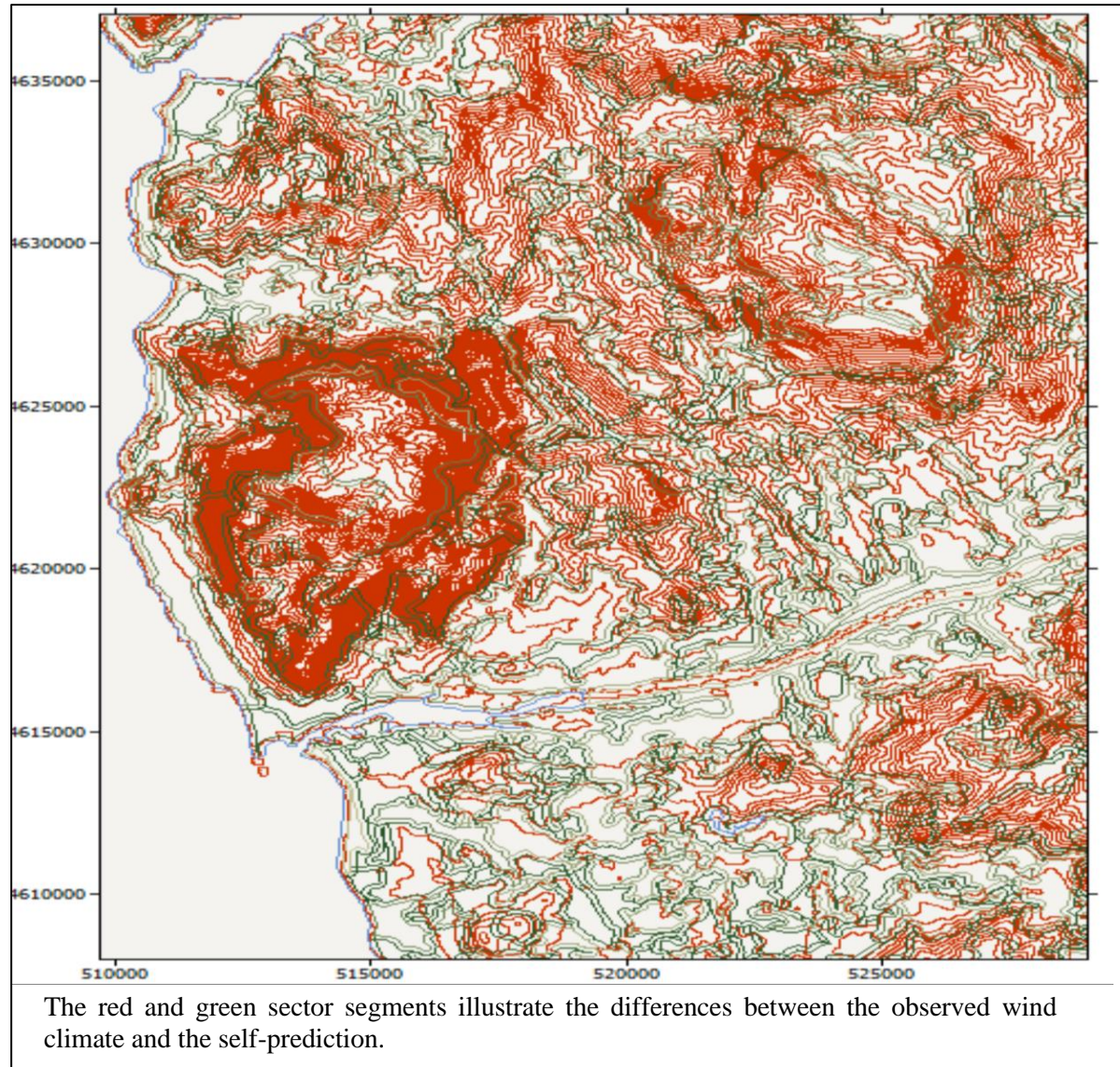


Figure 11: Spatial view of the site

To calculate a generalised wind climate (wind atlas data set), a meteo station (meteo station or meteo mast for short) is used. It denotes a data collection site on an associated map. A meteo station has no data other than its location on a map and user-specified corrections. It is associated to a wind climate that's been recorded at the station. It can be associated to a list of barriers in the station's close surroundings as well as a description of the area's geography. The zone has set to 29 and datum to WGS 1984.

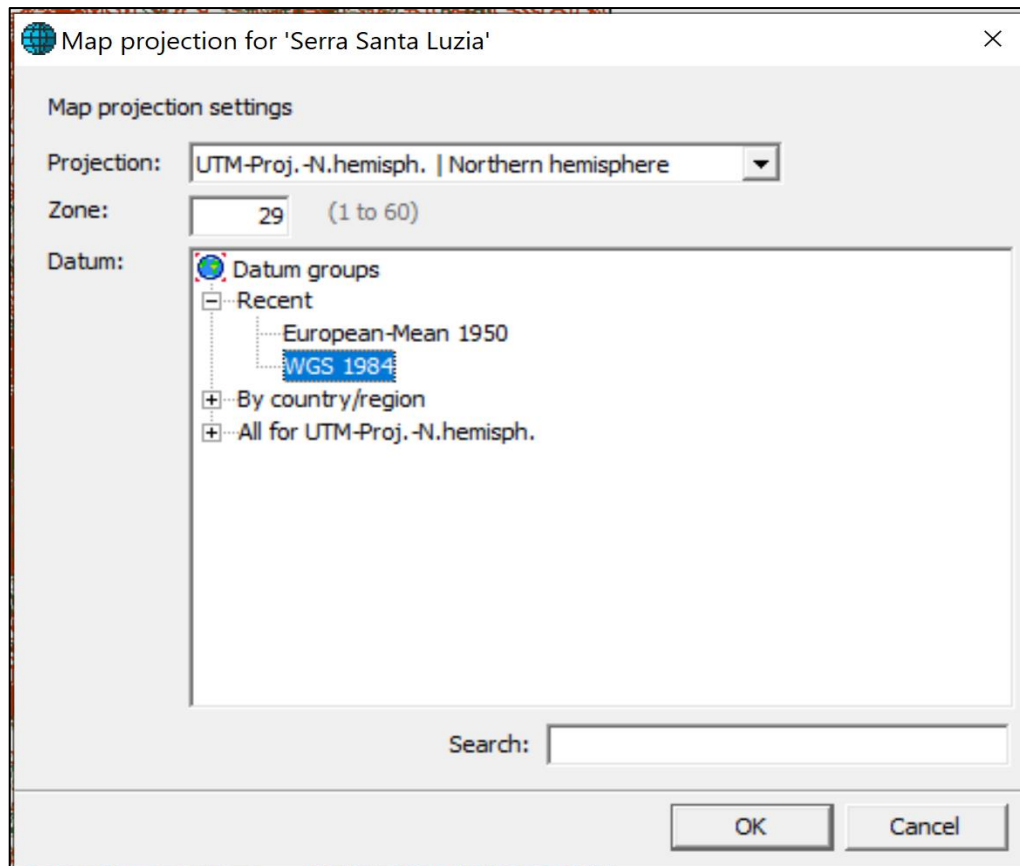


Figure 12: Map projection of the site

Once X & Y coordinates of the wind turbine facility has been chosen, wind speeds of the particular area are extracted & linked to the scenario. The whole direction (360°) is divided in 12 sections, each having difference of 30° . Below table shows the mean wind speed (m/s), frequency (%), power density (W/m^2) and speed discrepancy.

Table 4: Observed wind climate of the site

Number	Angle ($^{\circ}$)	Frequency (%)	Weibull-A (m/s)	Weibull-k	Mean speed (m/s)	Power density (W/m^2)
1	0	5.3	5.5	1.92	4.85	139
2	30	3.3	5.3	2.15	4.74	116
3	60	4.7	5.7	2.59	5.10	125
4	90	8.6	6.7	2.26	5.96	221
5	120	10.3	7.5	2.41	6.66	293
6	150	7.1	6.8	2.40	6.07	223
7	180	6.9	7.0	2.26	6.23	253

8	210	9.8	7.2	2.36	6.42	267
9	240	12.1	7.7	2.36	6.86	325
10	270	13.3	8.0	2.26	7.11	375
11	300	11.5	7.3	2.18	6.47	292
12	330	7.1	6.0	1.97	5.34	181
					6.24	261

The figure clearly shows that wind is more predominant in west direction. If turbines are installed, facing west direction then more energy can be extracted from wind. An observed wind climate (or OWC for short) is a summary of the wind data obtained at a meteo station. It is generally based on the inputs without considering roughness and height. It consists of a wind rose (wind direction frequency distribution) and numerous wind speed frequency distributions, one for each sector. The observed wind climate shows the average mean wind speed as 6.24 m/s and power density as 261 W/m².

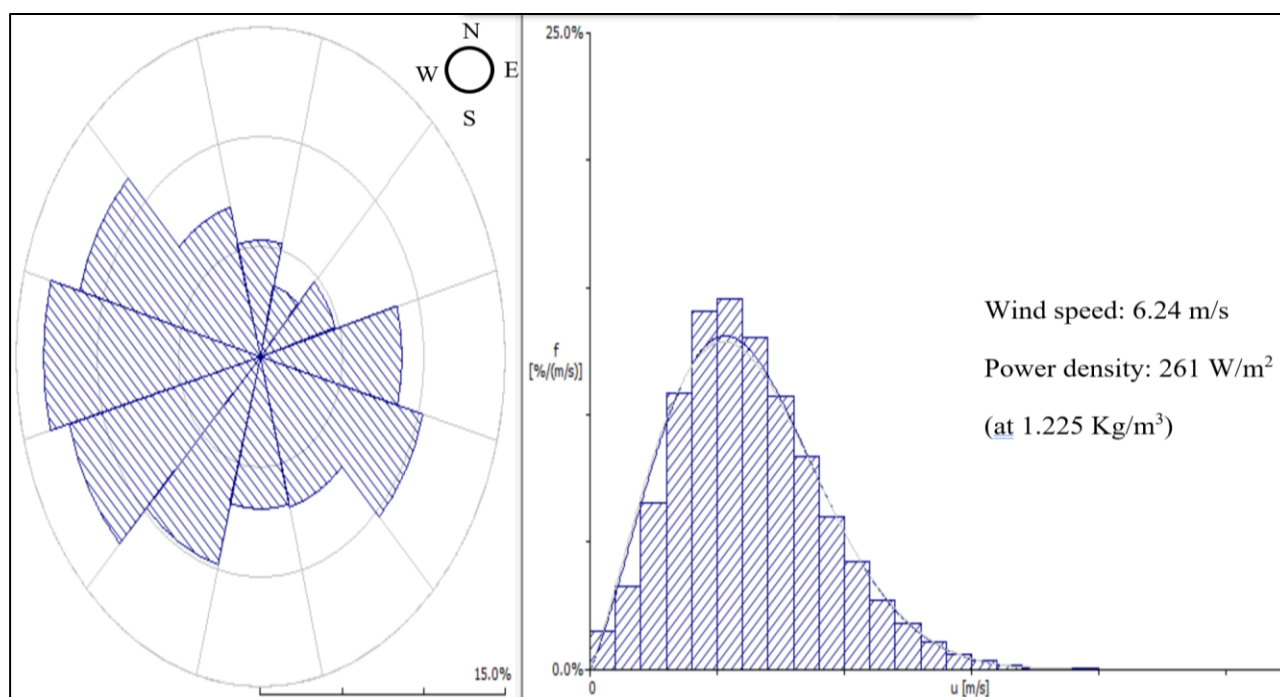


Figure 13: Observed wind climate of the site

Generalised wind climate (Wind atlas data sets) are the hierarchy's most key members. A WAsP generalised wind climate is a set of data that describes a site-independent characterization of a given area's wind climate. The WAsP models are dedicated to analysing wind data gathered from meteo stations in order to generate generalised wind climates and

applying the GWC to estimate wind climate (and power production) at turbine sites. The GWC considers the height and roughness level to generate wind data.

Table 5: Generalised wind data at different heights and roughness level

	R-Class 1 (0.000 m)	R-Class 2 (0.030 m)	R-Class 3 (0.100 m)	R-Class 4 (0.400 m)	R-Class 5 (1.500 m)
Height 1 (10 m a.g.l.)	*U = 6.60 m/s	4.77 m/s	4.17 m/s	3.30 m/s	2.21 m/s
Height 2 (25 m a.g.l.)	7.24 m/s	5.72 m/s	5.16 m/s	4.36 m/s	3.35 m/s
Height 3 (50 m a.g.l.)	7.79 m/s	6.64 m/s	6.07 m/s	5.28 m/s	4.32 m/s
Height 4 (100 m a.g.l.)	8.47 m/s	7.89 m/s	7.26 m/s	6.42 m/s	5.45 m/s
Height 5 (200 m a.g.l.)	9.33 m/s	9.69 m/s	8.91 m/s	7.94 m/s	6.8 m/s

*U = Wind speed

A turbine facility has been erected at the hilltop. The hub height for the turbine is taken as 60 m. Now the turbine can be spotted in spatial view at the given coordinates. The chosen turbine has the rated power capacity of 2 MW.

Below diagram shows the power curve of the chosen wind turbines. It says that maximum power of 1.972 MW can be generated from each turbine, when rated wind speed is 14.4 m/s. The cut-in and cut-off wind speeds are 2.3 m/s and 25 m/s respectively.

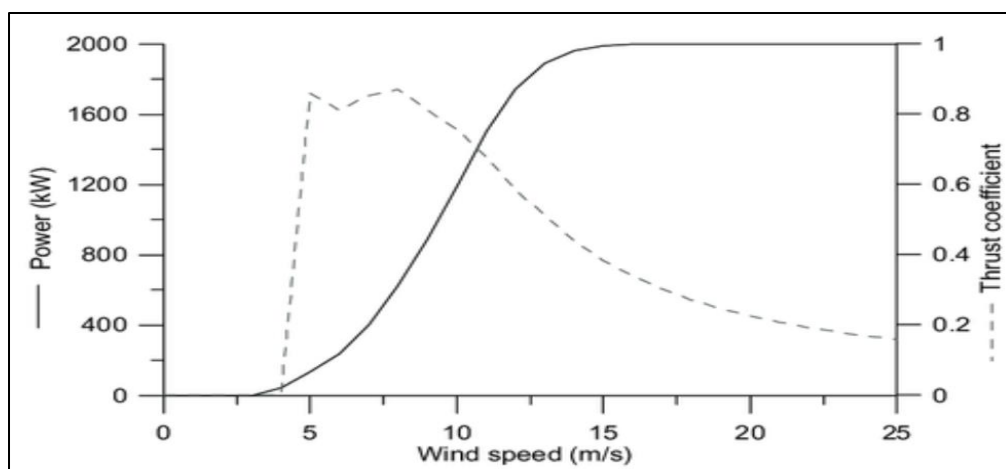


Figure 14: Power curve of wind turbine facility.

The number of turbines, chosen for this simulation are 4, having same specifications, as indicated in table below.

Table 6: Specifications of chosen wind turbines

Rotor diameter (m)	Rated power (MW)	Control system (inferred)	Hub height
76	2	Pitch	60

After selecting “Calculate the AEP, predicted wind climate, site effects and delta-RIX for turbine site Turbine site 001” by right clicking on turbine site option, the calculation is performed. It shows the calculated hub height above sea level as well as the calculated site-specific mean air density as shown in the below diagram.

The screenshot shows the 'Instrument location' section of the HOMER Pro software. It displays the following calculated values:

Parameter	Value	Unit
Hub height a.g.l.	60	m
X co-ordinate	514862.6	m
Y co-ordinate	4622806.0	m
Elevation a.s.l.	458.4	m
Hub altitude a.s.l.	518.4	m
Mean air density	1.162	kg/m ³

Figure 15: Calculated site-specific results

3.1.3. HOMER Pro

The first input HOMER Pro requires, is the “Location of the site”. It can be typed manually or chosen by hovering at the map. For this simulation, “Langeland, Denmark” location has been chosen. All the resources for the locations are pre-installed in the software [35]. The data is taken from NASA Prediction of Worldwide energy resource (POWER) database.

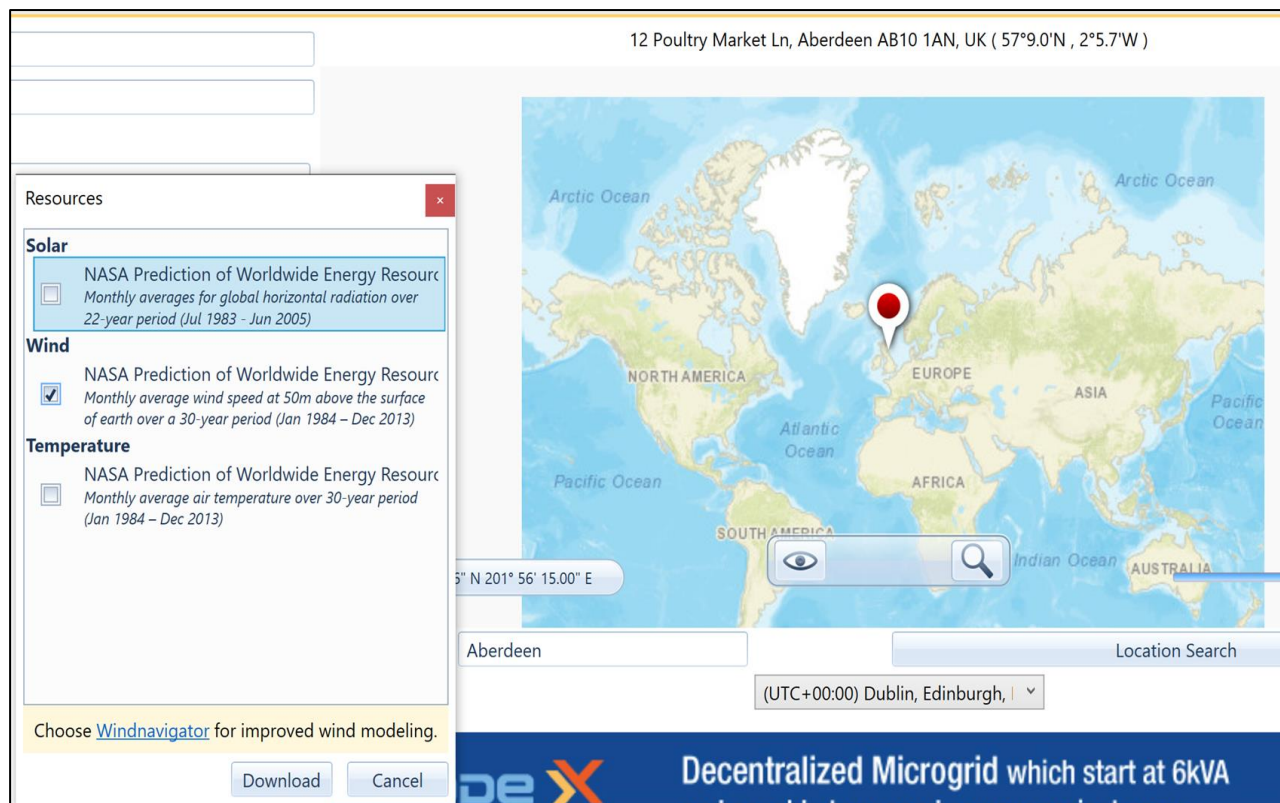


Figure 16: Illustration of how to download resources for any chosen location in HOMER Pro

Wind speed variation across the year can be visualised. If required, wind speeds can be changed manually depending on a particular site for wind turbine installation. For this simulation, wind speeds are obtained from NASA Prediction of Worldwide energy resource (POWER) database, as suggested by software. The table below shows the average wind speeds for each month.

Table 7: Wind data based on NASA database in Homer PRO

Month	Wind speed (m/s)
January	4.070
February	4.220
March	4.300
April	4.630
May	5.360
June	5.580
July	5.260
August	5.060
September	4.990

October	5.010
November	5.150
December	4.630
	4.85

The below figure shows the graph of variation in wind speed for the whole year.

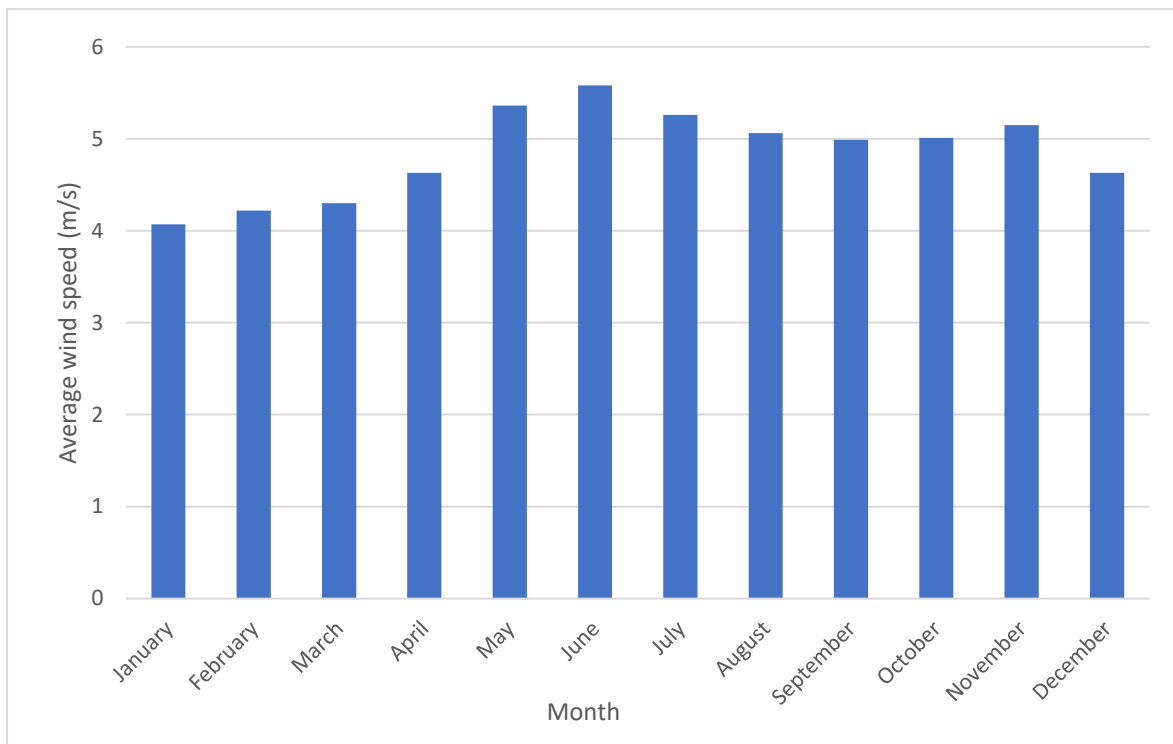


Figure 17: Wind speed variation on a monthly basis

Electric load has been chosen for the simulation on an hourly basis. The required electric load is around 11.26 kWh/day. The below figure shows 3 graphs. Graphs 1, 2 and 3 show the daily, monthly and yearly profile of electric load, respectively.

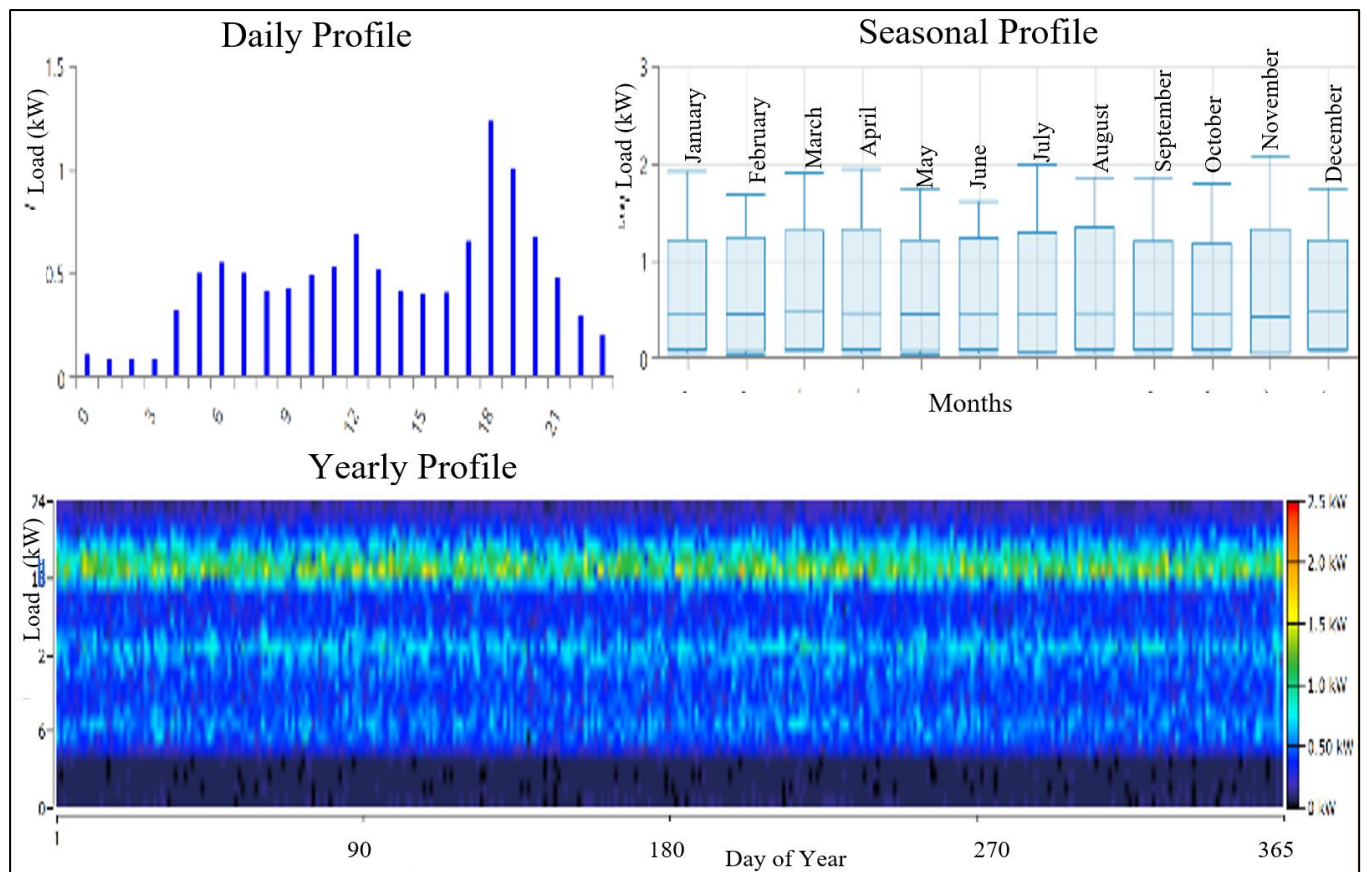



Figure 18: Electric load in HOMER Pro

A wind turbine facility has to be chosen to suffice the above demand [36]. Enercon E-126 wind turbine has been taken for this simulation, having the rated capacity of 7.5MW with hub height of 135 m. Cost is also added in the section. Capital cost and replacement cost is taken as \$30,000. However, operation & maintenance cost is taken as \$400.

Add/Remove Enercon E-126 [7.5MW]

WIND TURBINE  Name: Enercon E-126 [7.5MW] Abbreviation: E-126 Remove
Copy To Library

Properties

Name: Enercon E-126 [7.5MW]
 Abbreviation: E-126
 Rated Capacity (kW): 7580.00
 Manufacturer: Enercon
[Product Brochure](#)
 Notes:

Costs

Quantity	Capital (\$)	Replacement (\$)
1	\$30,000.00	\$30,000.00
Click here to add new item		
Multiplier:	{..}	{..}


Site Specific Input

Lifetime (years): 20.00 {..} Hub Height (m): 135.00 {..} Consider ambient temperature effects?

Figure 19: An illustration of how to choose wind turbine facility in HOMER Pro

In case of excess generation of electricity, a storage system is required. 1 kWh Li- Ion battery is taken to store the surplus energy for this simulation. All the specifications of the battery are illustrated in the figure below.

Add/Remove Generic 1kWh Li-Ion

STORAGE  Name: Generic 1kWh Li-Ion

Properties

Idealized Battery Model

Nominal Voltage (V): 6
 Nominal Capacity (kWh): 1
 Nominal Capacity (Ah): 167
 Roundtrip efficiency (%): 90
 Maximum Charge Current (A): 167
 Maximum Discharge Current (A): 500




Figure 20: Inclusion of a storage battery in HOMER Pro

A converter is also added to convert AC power generated from wind turbines to DC power, required for the storage.

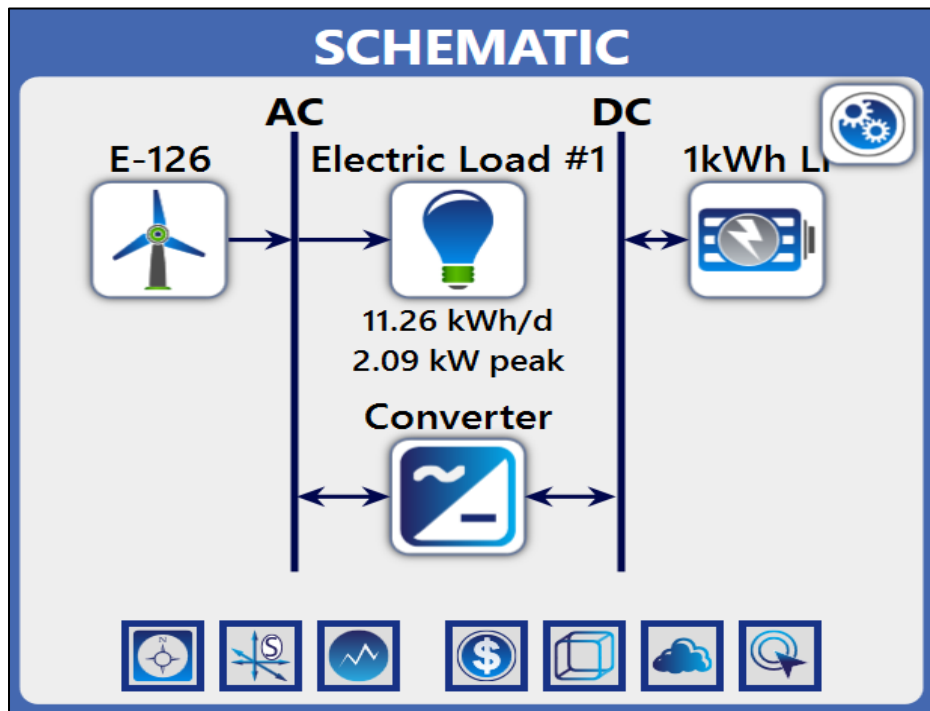


Figure 21: Schematic of whole wind energy system in HOMER Pro

3.1.4. energyPRO

In energyPRO, the wind farm is a specialised energy unit with general energy unit characteristics like "non-availability periods," "operation dependent on other units," and the "restricted to period" option. To calculate wind farm electric production, the wind farm uses an external time series containing measured wind speed and a wind farm power curve.

The hourly wind speed of the site, specified for the scenario, is the primary input for energyPRO. The site 'Langeland' was chosen for this simulation. The hourly wind speed data is obtained by using the 'google earth' software to obtain latitude and longitude, and then uploading this information to the 'renewable ninja' website, which contains wind data from all around the world. The below figure shows graph of wind speed data (in m/s) for the whole year [37]. The graph clearly shows that wind speed is stronger in the first and last month, and moderate in the middle.

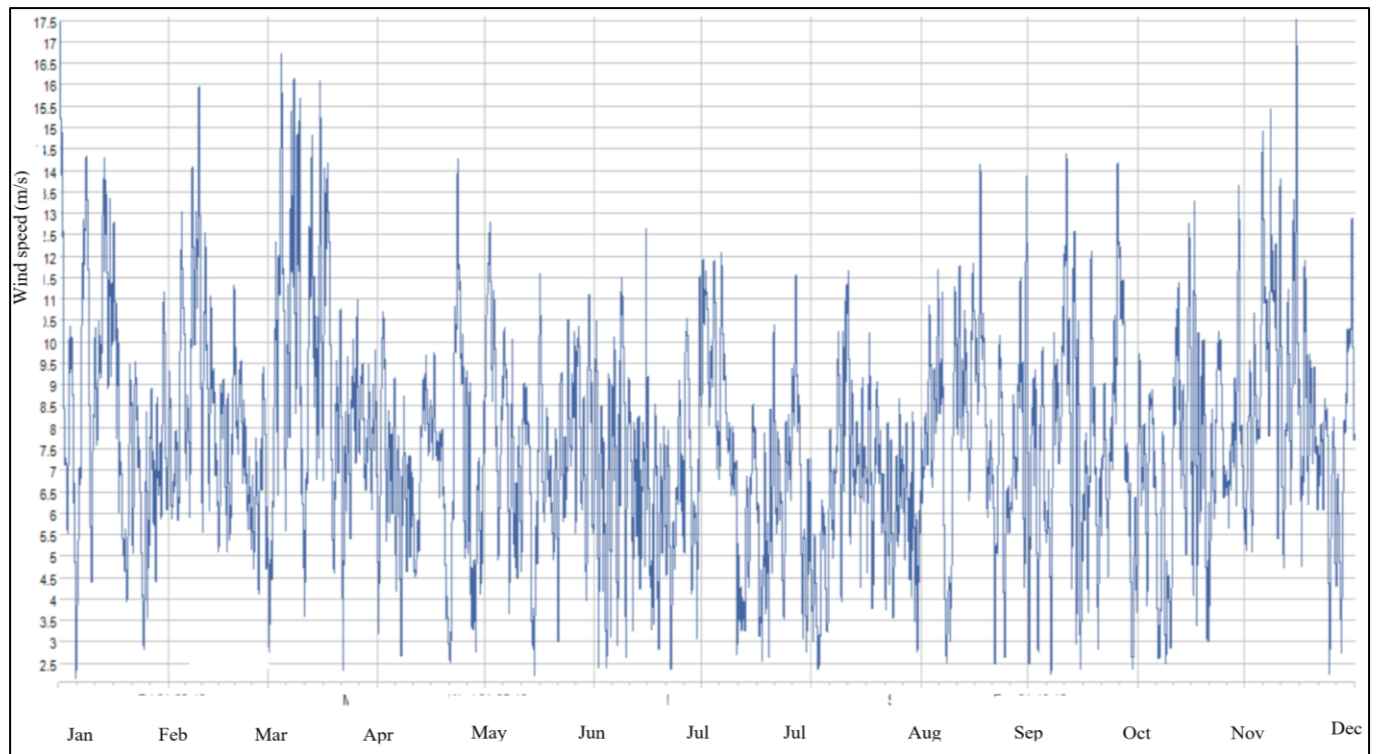


Figure 22: Graph of wind speed data for the facility

The turbine facility consists of four turbines each having rated capacity of 2 MW. Two turbines have a hub height of 60 metres, while the other two have a hub height of 90 metres. 'Vestas' is the manufacturer of the turbines used in this simulation.

A data set of values containing the wind speed and the associated power production from the turbines makes up the power curve. The power output is assumed to be linear between two data elements in the calculation. A data table is used to define the power curve, which is then displayed on a graph. The power curve, in the below figure shows that cut-in and cut-out wind speeds are 2 m/s and 27 m/s respectively. The wind speed for this location is in between the cut-in and cut-out wind speed range. Hence, the turbines are suitable for this facility.

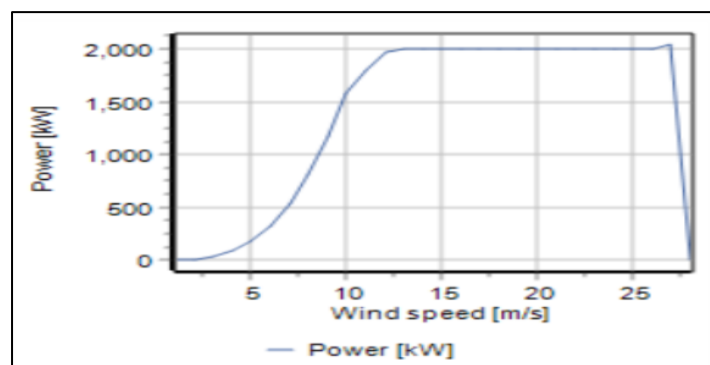


Figure 23: Power curve of chosen wind turbine

An electricity demand of 3.5 MW is taken for this scenario. Below figure shows the schematic after adding four wind turbines with the specified specifications and new electricity demand.

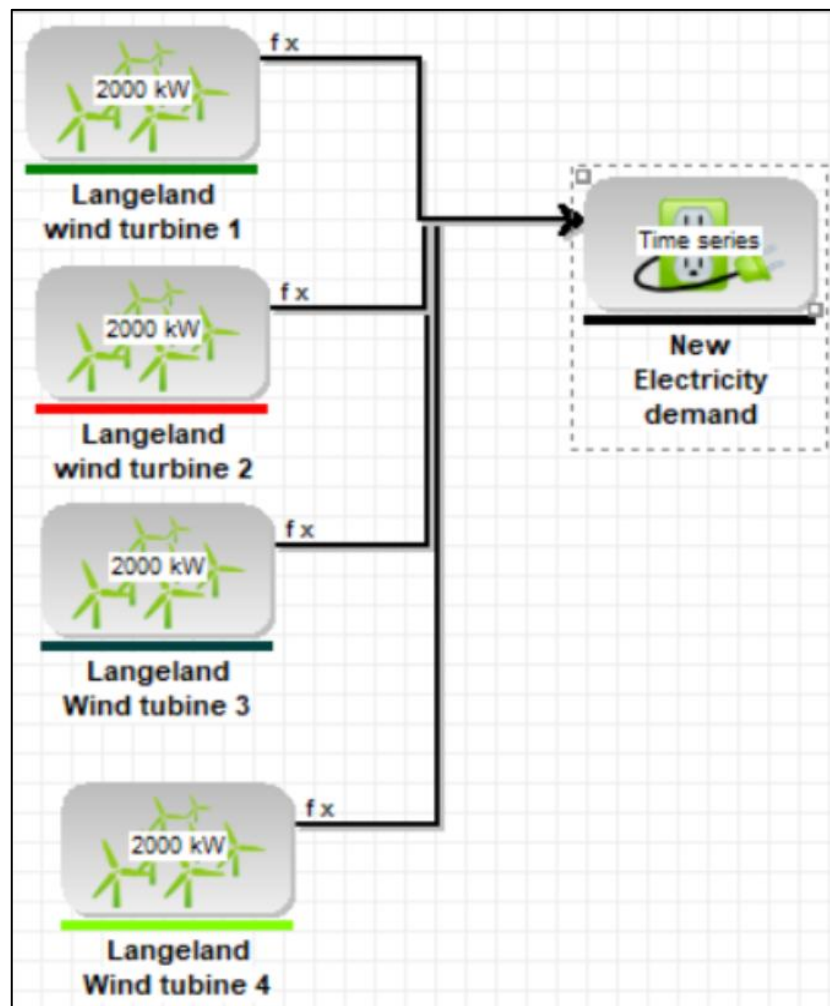


Figure 24: Schematic of overview of wind turbines and new electricity demand

3.2. Simulation using all tools interdependently for the location ‘Langeland’

As section 3.1 consists of simulation on each tool. Different assumptions are being taken by each tool. For a particular location, HOMER Pro considers same wind speed for a number of wind turbines regardless of their terrain, roughness, topography and elevation. It also does not consider wake effect. If the same scenario is run in WAsP software before, it will provide mean wind speed and wake effect as an output. Wake loss can be minimized by providing sufficient distance and elevation to the turbines. This result can be used as an input for HOMER Pro. By incorporating these losses and wind speed in HOMER Pro, more precise result can be obtained. Further, WindStation can provide wind data (wind speed, turbulence

intensity, direction, and temperature) at different heights. These outputs can help to decide the hub height and direction of wind turbines to extract the maximum energy from the wind. If these softwares are used altogether, it is possible to achieve more accurate results.

In the section 3.2, simulation has been run by considering the wind farm at the location “Langeland, Denmark”. It is an effort to produce accurate results by defining inputs and outputs interdependently by the simulation tools.

3.2.1. WindStation

First, WindStation tool is used for the simulation. A terrain is generated by considering the elevation & roughness of the Langeland. Yellow colour in the below figure shows more hilly area. Meteo station is defined towards more hilly area since it has high wind compared to rest.

The mesh is uniform in the horizontal plane, with a constant spacing that is a multiple of the grid resolution from the input DTM file. More mesh size means more precise results. For this simulation mesh size is taken as 200 m. Vertical levels are calculated by interpolating between the ground boundary and the domain top, using a variable expansion factor. Choices are available for the number of calculation levels, the vertical distance between the first calculation point and the ground (first node) and the altitude (above sea level) of the calculation domain top (Z_{top}). A layer of equally spaced nodes near the ground is generated, with the specified number of levels, which is 7 for this case.

Height of the first control volume is also displayed (first CV), which is 3 m in this scenario. This value is twice the distance between the first node to the ground. The maximum vertical spacing between levels is 96.1 m.

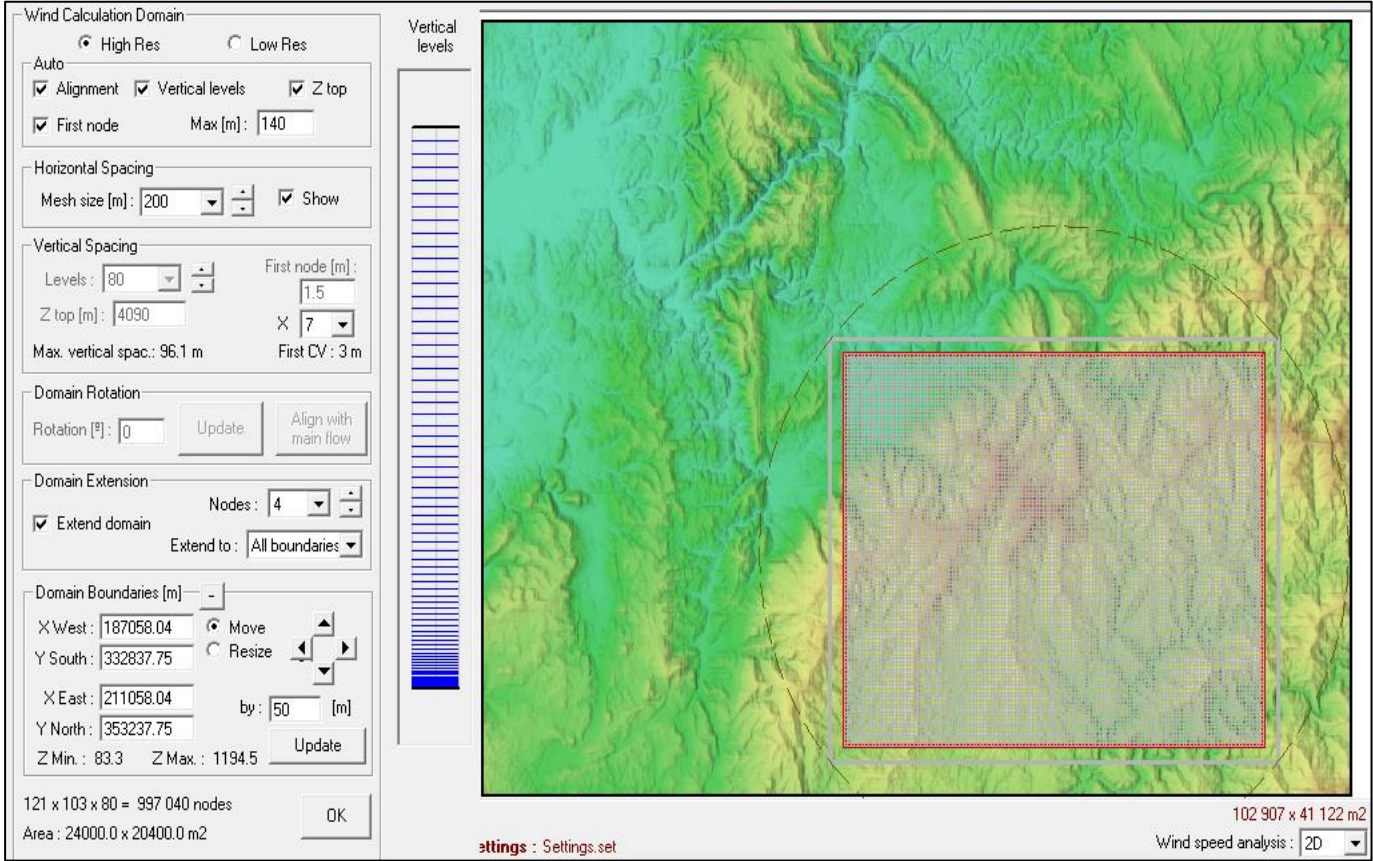
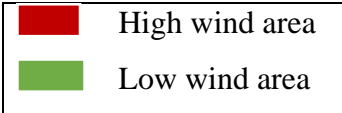


Figure 25: Defined Mateo station by entering input values (X-Y parameters of location) and mesh size

Meteo stations is made to provide input data to wind model. By using google earth, accurate data were taken for the Langeland location.

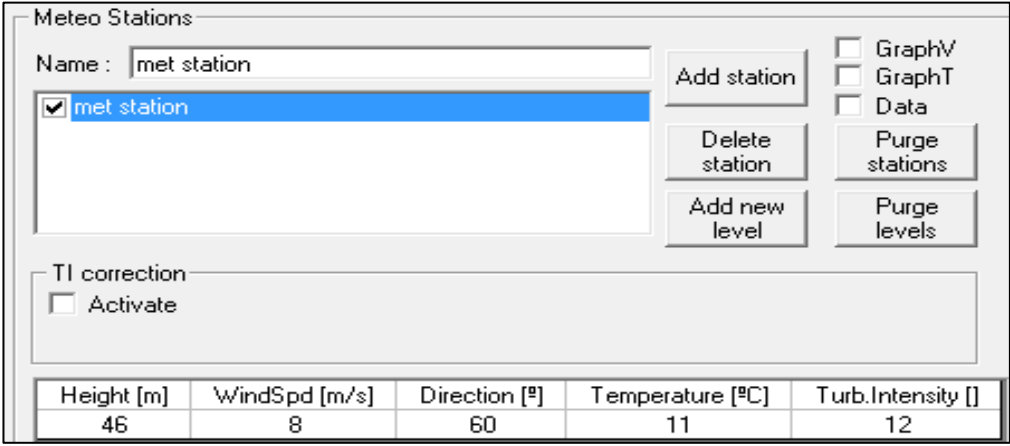


Figure 26: Input data for defined Mateo station

After defining all inputs, the calculation is launched by running the simulation. Coriolis effects are taken into consideration in the calculation. The calculating technique starts by computing the 1D incident profiles based on the input data. The iteration time for this simulation is 1 minute 51 minutes.

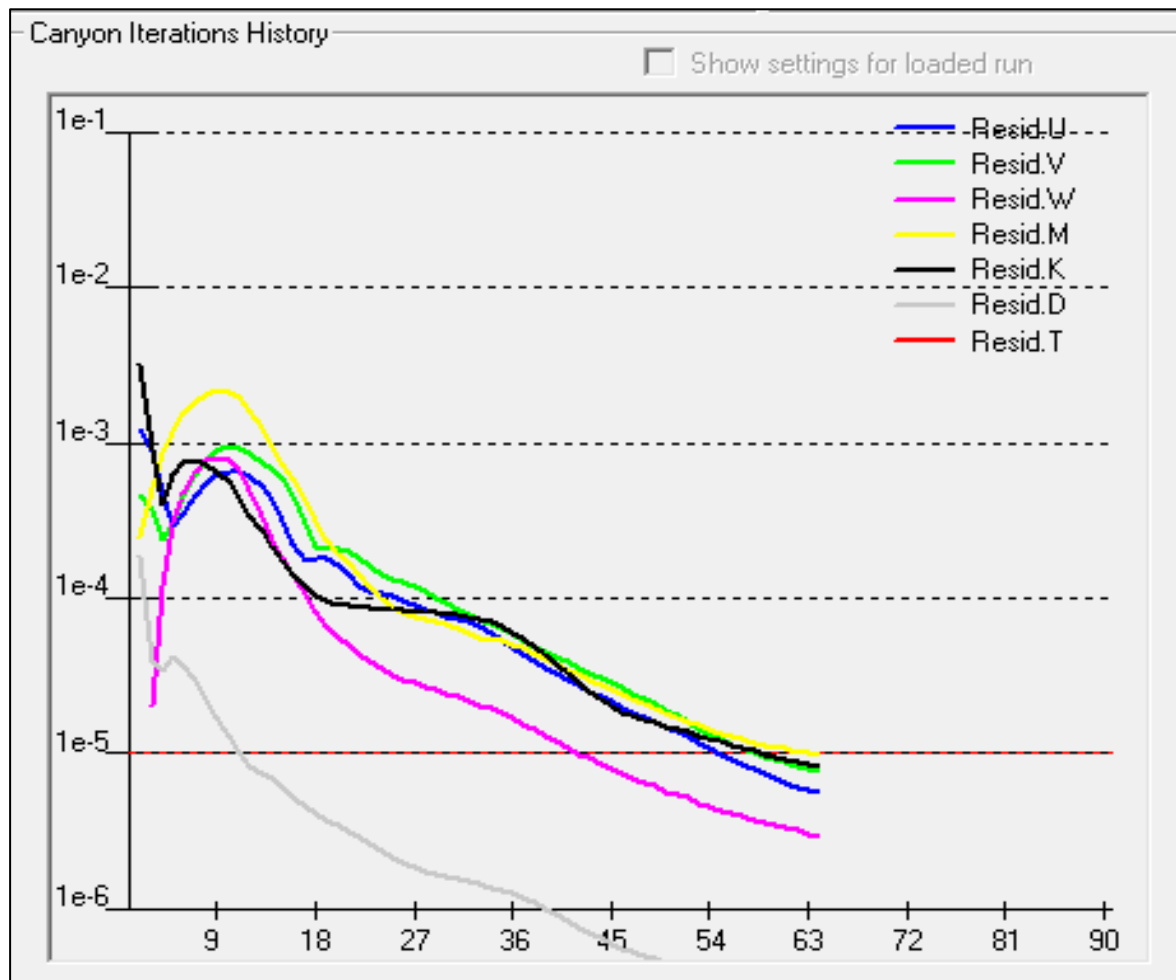


Figure 27: Dialog box for run control through canyon iterations

In the context of WindStation, the term 'horizontal plane' refers to a surface at a constant height from ground. Vectors are located at computational mesh nodes. Interpolation in the vertical levels for the specific height provides the local wind speed and direction. The length of each vector is proportional to the local wind speed. The default proportionality factor may be adjusted by a multiplier (Scale factor). To declutter the vector field, the reduction factor allows for the display of every n th of the available information in both x and y directions. When the mesh is very fine, this may be advantageous (high resolution). The line width (Width) for the vector representation can be chosen, as well as their Color, which can be either 'Constant' or 'Variable,' depending on the velocity magnitude in the latest case.

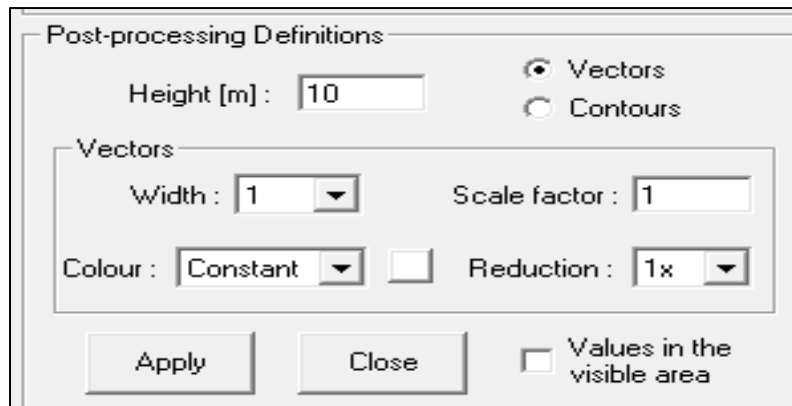


Figure 28: Dialog box for run control through canyon iterations

The below figure shows the project summary which includes calculation domain, boundary conditions and numerical models. Calculation domain tells about mesh size, vertical levels, first node and number of nodes. Boundary conditions define the problem physics. Top boundary is closed for this scenario. An open boundary is more realistic but may lead to numerical instability for non-neutral atmosphere. The domain top boundary should ideally be situated far enough from the ground so that conditions at the top boundary have no significant impact on the solution. Lateral boundaries are conditionally closed. Choice for 'closed lateral boundary' is only effective in the calculation procedure if the free stream direction is the same as the lateral boundaries direction. Otherwise, an open condition is considered.

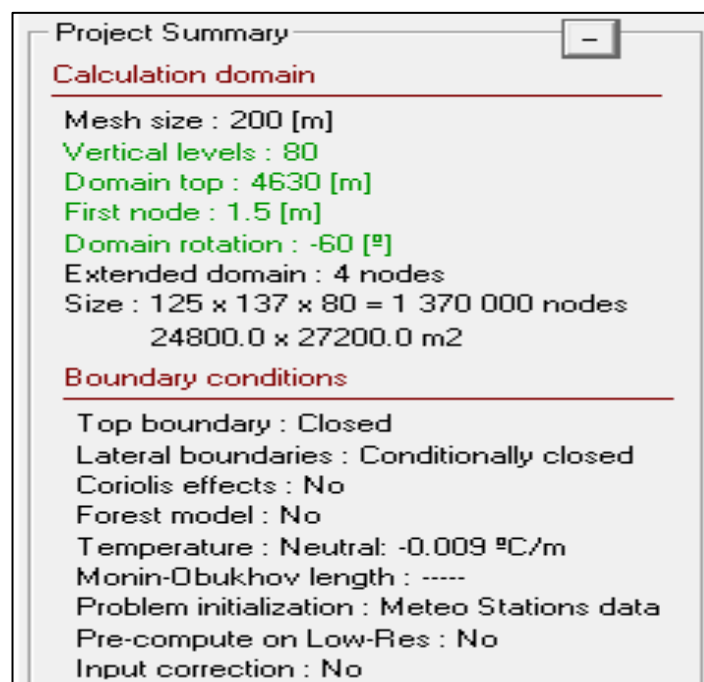


Figure 29: Project summary

3.2.2. WAsP

The following image depicts the site's spatial layout. The red colour lines represent locations that are an uphill or downhill gradient, making the terrain more complex. There might be high winds in certain regions and low winds in others [38].

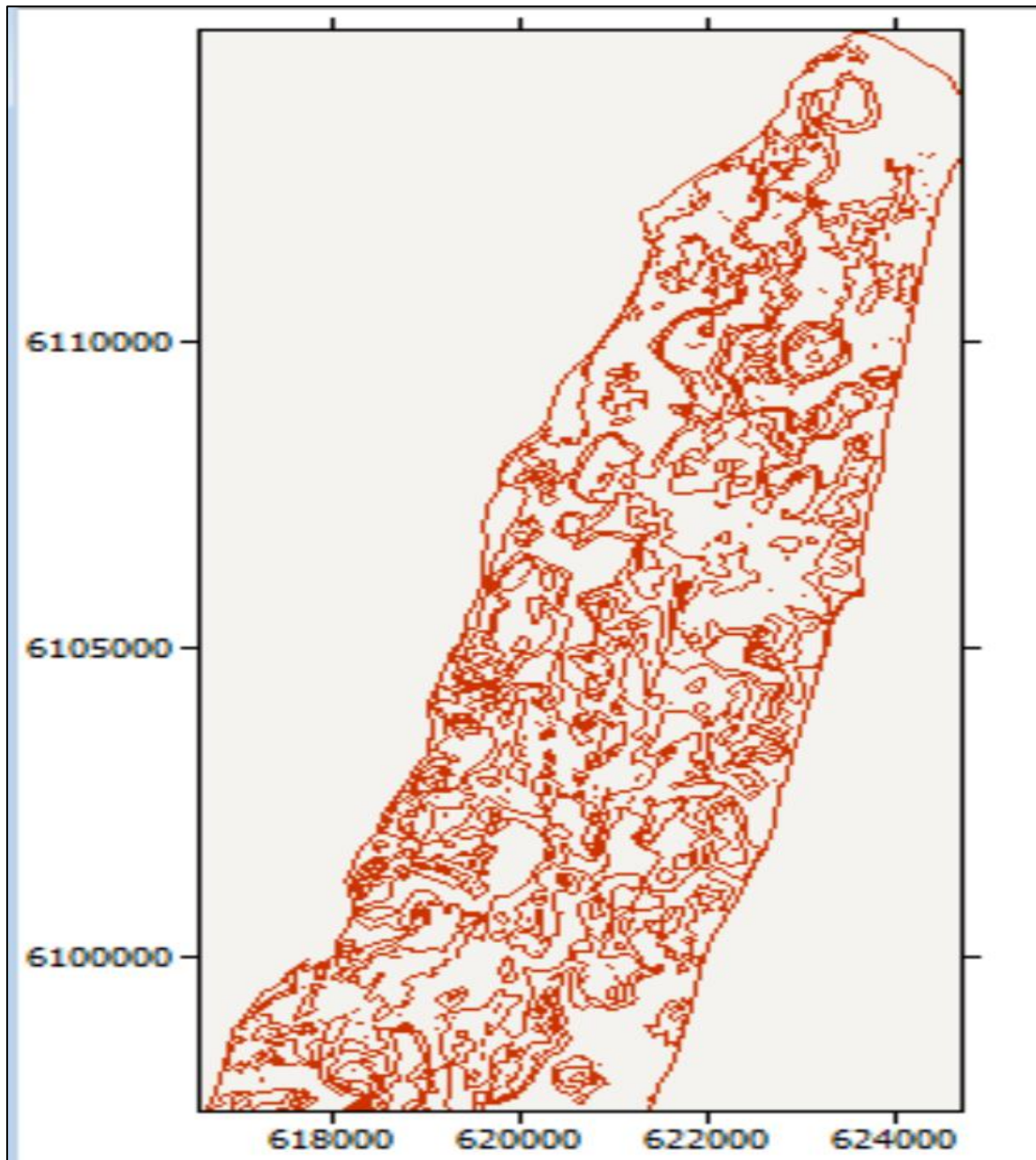


Figure 30: Spatial view of Langeland site

With the help of 'Google Earth Pro' software, co-ordinates of Langeland location are determined, and other parameters like latitude, longitude are taken when looking at the meteo station, which supplied accurate information about the site.

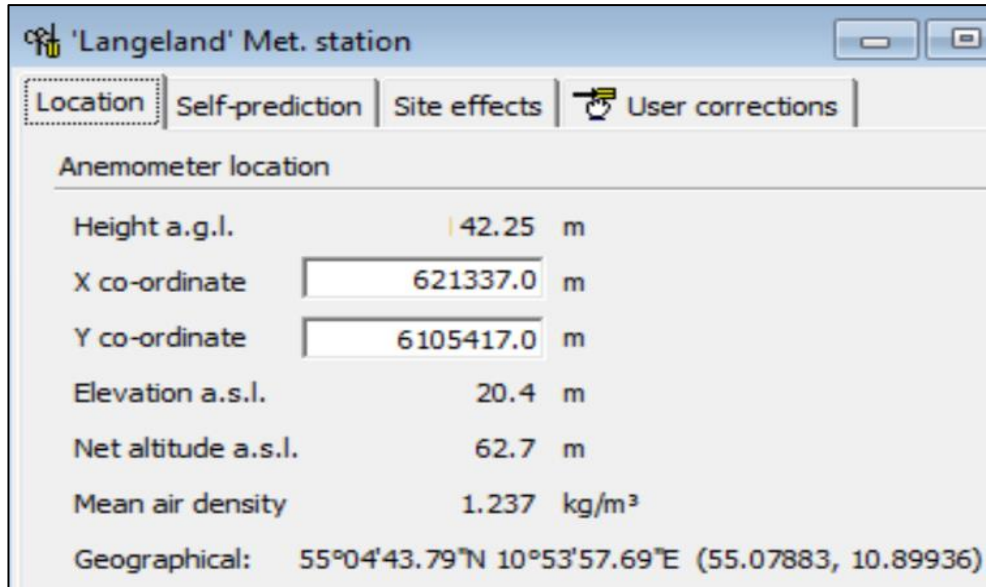


Figure 31: Defined Meteo station at Langeland.

The 'observed wind climate' section shows the wind speed, power density and other wind parameters from various directions. With a 30° angle difference, 12 sectors are taken to show the wind variation in all directions.

Table 8: Observed wind climate of the site

Number	Angle ($^{\circ}$)	Frequency (%)	Weibull-A (m/s)	Weibull-k	Mean speed (m/s)	Power density (W/m 2)
1	0	7.1	7.3	1.91	6.49	335
2	30	3.2	6.1	2.36	5.38	157
3	60	4.8	7.1	2.92	6.36	225
4	90	5.8	9.4	3.17	8.38	491
5	120	10.6	9.3	2.88	8.33	508
6	150	8.2	8.2	2.58	7.26	361
7	180	5.5	7.7	2.33	6.82	323
8	210	8.2	8.9	2.48	7.93	484
9	240	11.4	10.0	2.63	8.90	656
10	270	13.7	10.3	2.35	9.15	775
11	300	12.8	9.5	1.97	8.43	709
12	330	8.8	7.4	1.61	6.61	435
					7.85	519

Below picture shows observed wind climate that wind speed is predominant at angles 270° and 300° which are 9.15 m/s and 8.43 m/s respectively [39].

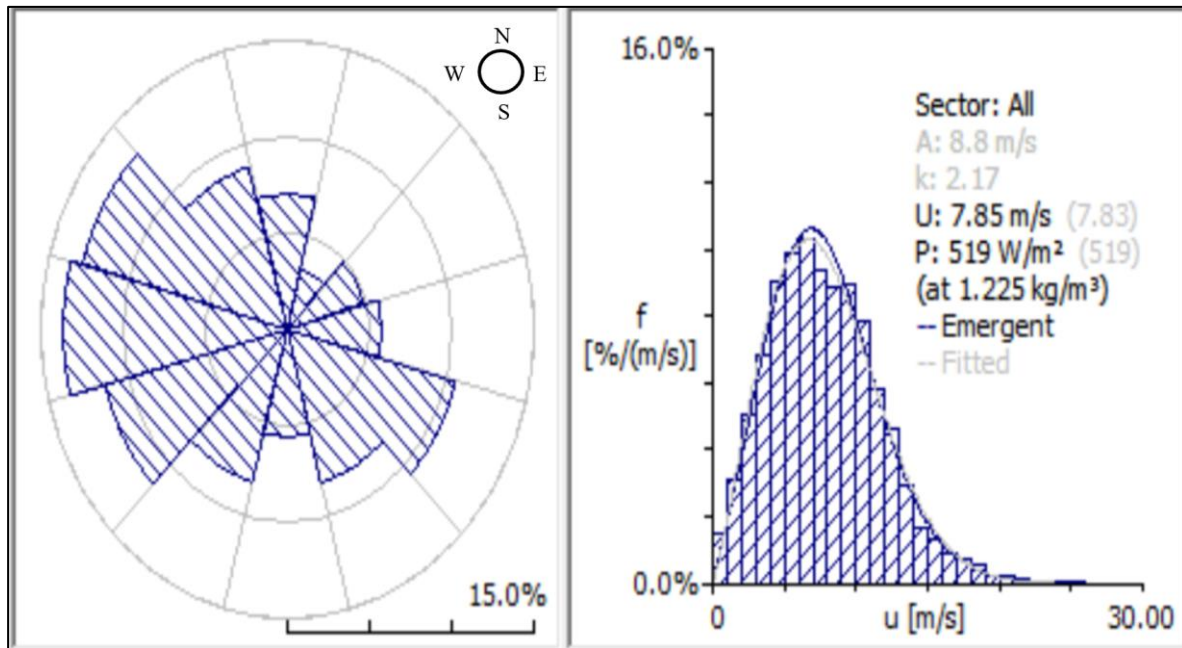


Figure 32: Observed wind climate for Langeland site

A wind climate is generated in WASP tool by taking the wind measurements at a specific meteo station in Langeland. Below figure shows the generalised wind climate of the location. Wind speed is depicted at various heights by taking into account different roughness levels [40]. It is clear from the diagram that wind is predominant from west direction. Therefore, installing turbines, facing west direction will extract most of the wind energy and generate maximum power.

Table 9: Generalised wind data at different heights and roughness level

	R-Class 1 (0.000 m)	R-Class 2 (0.030 m)	R-Class 3 (0.100 m)	R-Class 4 (0.400 m)	R-Class 5 (1.500 m)
Height 1 (10 m a.g.l.)	*U = 7.42 m/s	5.35 m/s	4.68 m/s	3.69 m/s	2.47 m/s
Height 2 (25 m a.g.l.)	8.12 m/s	6.38 m/s	5.75 m/s	4.85 m/s	3.73 m/s
Height 3	8.72 m/s	7.34 m/s	6.71 m/s	5.84 m/s	4.77 m/s

(50 m a.g.l.)					
Height 4 (100 m a.g.l.)	9.44 m/s	8.61 m/s	7.93 m/s	7.02 m/s	5.96 m/s
Height 5 (200 m a.g.l.)	10.33 m/s	10.41 m/s	9.58 m/s	8.56 m/s	7.43 m/s

*U = Wind speed

A wind farm is made, consisting of 4 turbines, 2 turbines having 90 m hub height and other 2 having 60 m hub height (hub height was decided form the WindStation simulation which predicted maximum wind at this height). Since the wind is majorly coming from west direction. It is made sure that there should not be any obstruction to any turbine towards west direction. The geography of Langeland is shown in the image below. The exact location of wind turbines can be clearly displayed in the Google Earth software by using same zone, latitude, longitude and other parameters. The dark lines in the figure indicate that the ground is not flat, and it is complex terrain.



Figure 33: Topography of Langeland

$$\begin{aligned} \text{Difference in wind} \\ \text{energy during WAsP} \\ \text{simulation} \end{aligned} = \frac{\pm(V_2 - V_1)}{V_1} * 100 \quad (24)$$

Where V_1 = Wind speed given as an input in WAsP

V_2 = Output wind speed generated after WAsP simulation

3.2.3. HOMER Pro

The outputs of WindStation and WAsP assist HOMER Pro in producing more accurate findings. First, the ‘Langeland, Denmark’ location is chosen in the tool and the software extracts all the pre-installed data from NASA's Prediction of Worldwide Energy Resource (POWER) database which automatically sets the monthly wind speeds for this location. As per the database, average wind speed for Langeland location is 4.86 m/s (referred from section 3.1.3 and 4.1.3). Following table shows the inputs, given for this simulation

Table 10: Inputs for HOMER Pro

Equipment	Capacity	Quantity
Vestas turbine (60 m hub height)	2 MW	2
Vestas turbine (90 m hub height)	2 MW	2
Li-Ion battery	1 kWh	1
Converter	1.58 kW	1

The elevation and roughness are not taken into account. These figures are based on the assumption that the turbine facility has flat terrain. However, based on the simulation results in WAsP, the average wind speed for that area increases, approximately by 3.3 % after installing wind turbines such that they extract maximum wind. Thus, the new wind speeds can be calculated by increasing the wind speeds mentioned in NASA database by 3.3 %. energyPRO.

The wind data, derived for ‘Langeland’ location from previous simulations (WAsP, WindStation) is used here. For this simulation, wind speeds are manually entered instead of using NASA database.

$$\begin{aligned} \text{Actual wind speed based on WASP results} = & \\ \text{Wind speed from HOMER Pro} * (1 + \text{Percentage increase in wind speed}) & \end{aligned} \quad (25)$$

3.2.4. EnergyPRO

The simulation results on WindStation and WASP aids energyPRO in delivering more accurate results by providing inputs like wind speed data and turbine losses etc. The simulation for the Langeland location is already done in section 3.1.4 using four wind turbines. Two turbines have hub heights of 90 metres, while the other two have hub heights of 60 metres. All of the turbines have the same rated capacity of 2 MW. For the earlier simulation, wind data was gathered from an external source. In this section, wind data will be substituted by that generated by the simulation on the WASP and WindStation tools.

The average mean wind speed for Langeland location is 7.6 m/s, according to the external source. It does not consider the elevation and roughness. These values are derived by assuming the flat terrain. However, according to the modelling results in WASP, after erecting wind turbines that can extract maximum wind, the average wind speed for that area rises by about 3.3 percent. As a result, the new wind speeds may be determined by 3.3 percent increase in the wind speeds considered before.

$$\begin{aligned} \text{The new average wind speed} = & \\ = \text{initial wind speed} * (1 + \text{percentage difference in wind speed}) & \end{aligned} \quad (26)$$

4. Results

4.1. Results of simulation, performed on each tool separately

This section will discuss about the results of simulation on each tool for different scenarios. The simulation is run on each tool individually by considering the assumptions taken by the tools.

4.1.1. WindStation

To visualize the outcomes of the simulation, velocity vectors and colour contours can be displayed for the selected variable at a constant height from the ground in horizontal plane. The contour shown below is for a height of 50 metres above the ground. The high wind zone is indicated by the red colour in this colour contour. The colour green denotes the presence of

forests, implying that there will be less wind. Areas containing water is indicated by the colour blue.

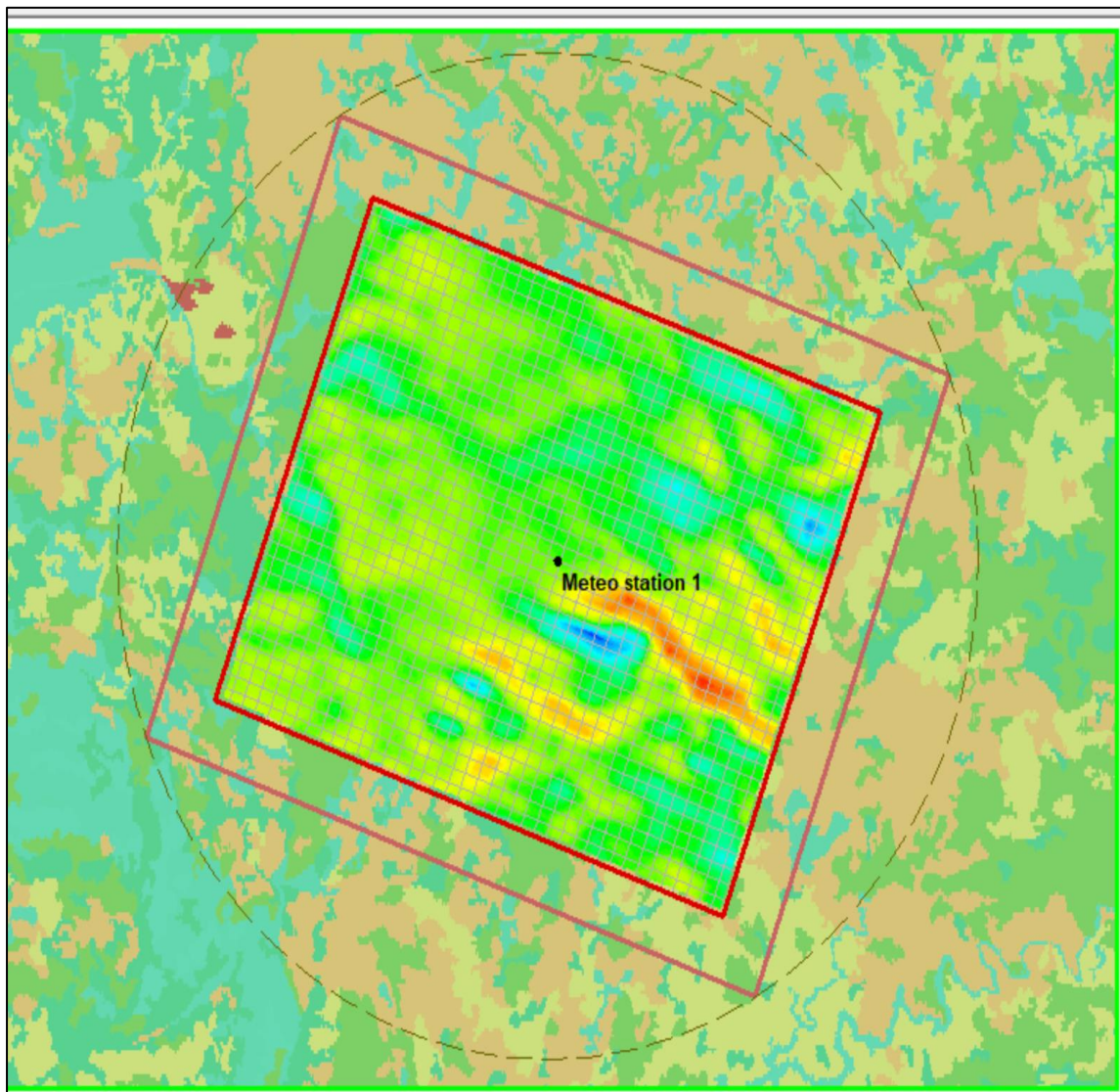
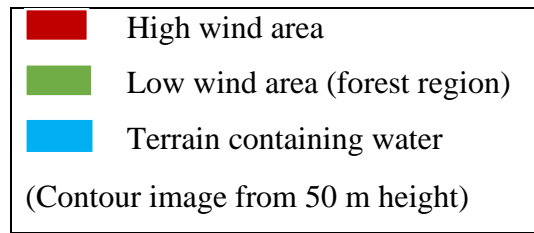


Figure 34: Colour contour on horizontal plane

The above contour also gives the x coordinates of the minimum and maximum wind speed at a specified y coordinate. This will assist in the placement of wind turbines. The below table shows the minimum and maximum wind speed and their coordinates.

Table 11: Generated maximum and minimum wind speeds

	Wind speed (m)	X- Coordinate	Y- Coordinate
Minimum value	0.51	193516.4	348410.9
Maximum value	16.72	198913.7	348410.9

For the visualization in the vertical plane, any two locations on the map can be chosen. Further, velocity vectors & colour contours can be easily displayed by setting number of samples. Point 1 (x = 184088.53 m, y = 355606.42 m) is the start point and point 2 (x = 194908.07 m, y = 357356.05 m) is the end point of a sampling line. Sampling take place at vertical plane by these x and y coordinates. When the cursor is hovered at the below diagram, it tells x & y coordinates, altitude, height and wind speed at that point.

WindStation results can be extracted by exporting Microsoft excel file from “Single run” option in the software. The result shows wind data (wind speed, direction, turbulence intensity, temperature) at different heights. It can help to decide the hub height of wind turbines to utilize maximum energy from wind.

Table 12: Extracted result from WindStation

X Coordinate (m)	Y Coordinate (m)	Height (m)	Wind speed (m/s)	Direction ($^{\circ}$)	Turbine Intensity	Temperature ($^{\circ}$ C)
186550.50	357226.40	0.50	0.00	22.50	0.00	18.43
186550.50	357226.40	1.10	1.10	22.50	0.90	18.59
186550.50	357226.40	2.31	2.76	22.51	0.55	18.63
186550.50	357226.40	3.64	3.49	22.55	0.44	18.61
186550.50	357226.40	5.11	4.29	22.57	0.37	18.60
186550.50	357226.40	6.72	4.88	22.58	0.33	18.59
186550.50	357226.40	8.49	5.38	22.59	0.30	18.57
186550.50	357226.40	10.44	5.83	22.59	0.27	18.55
186550.50	357226.40	12.58	6.23	22.59	0.26	18.53
186550.50	357226.40	14.94	6.60	22.58	0.24	18.51
186550.50	357226.40	17.53	6.95	22.58	0.23	18.49
186550.50	357226.40	20.38	7.28	22.56	0.22	18.46

186550.50	357226.40	23.52	7.59	22.55	0.21	18.44
186550.50	357226.40	26.97	7.90	22.53	0.20	18.40
186550.50	357226.40	30.77	8.20	22.50	0.20	18.37
186550.50	357226.40	34.95	8.49	22.47	0.19	18.33
186550.50	357226.40	39.54	8.78	22.44	0.18	18.29
186550.50	357226.40	44.60	9.11	22.41	0.18	18.25
186550.50	357226.40	50.16	9.34	22.37	0.17	18.20
186550.50	357226.40	56.28	9.83	22.33	0.17	18.14

The average wind speed, taken as an input for this simulation is 7 m/s. If a turbine is erected at the location with hub height of 50 m. The rotor will have wind speed of around 9.27 m (taken from above table). The information can then be used to help determine the location for a wind turbine and the hub height to receive more wind. Below calculation shows that there is 32.4 % difference in wind speed between the particular location at which turbine is installed and meteo station. Therefore,

$$\text{Difference in wind speed} = \left[\frac{V_{tur} - V_{meteo}}{V_{meteo}} \right] * 100 \quad (27)$$

Where:

V_{tur} = Wind speed at the particular location where turbine has to be erected

V_{meteo} = Wind speed of the meteo station (used as an input)

$$\text{Difference in wind} = \frac{9.27 - 7}{7} * 100 = 32.4 \% \quad (28)$$

4.1.2. WAsP

The WAsP tool provides the average mean wind speed at different angles. It helps to decide the direction of wind turbines to extract maximum energy from wind. From the methodology, it was clear that there is high wind from the west direction [41]. Therefore, keeping the turbine's direction towards west will generate more power. The observed climate in table 4 and figure 13 shows that mean wind speed at turbine site is 6.49 m/s and the power density is 261 W/m².

To set up a wind farm, 4 wind turbines are being added near to the previous turbine facility, having the same specifications (power is 2 MW and hub height is 60 m). The predicted power

production of the wind farm is 16.271 GWh. Here, total wake loss is 0.20 %. The wake effect is very small here on the facility because the wind farm consists of one row of turbines at right angles to the prevailing wind direction. Also, the distance between 2 turbines is kept sufficient to avoid the wake loss. Therefore, there is no reduction in wind speed due to wake effect.

Table 13: Statistics of annual energy generation & proportional wake loss

	Total	Mean	Minimum	Maximum
Total gross AEP (GWh)	16.304	4.076	3.093	4.933
Total net AEP (GWh)	16.271	4.068	3.086	4.927
Proportional wake loss (%)	0.20	-	0.12	0.36
Capacity factor (%)	23.2	-	17.6	28.1
Mean speed (m/s)	-	6.49	5.87	7.05
Mean speed (wake-reduced) (m/s)	-	6.49	5.86	7.05
Air density (kg/m ³)	-	1.188	1.184	1.197
Power density (W/m ²)	-	281	197	355
RIX (%)	-	-	1.5	5.0

The exact placement of wind turbines in the facility as well as their elevation and hub height are depicted in the below figure. Reduced wind speed is often reported as a result of wake losses. The difference between gross annual energy production (GEP) and Net annual energy production (AEP) is not significant due to negligible wake effect.

Table 14: exact location of each turbine site, the elevation, the hub height, the gross and net power production and the wake loss

Turbine Site	X-location (m)	Y-location (m)	Elevation (m)	Speed (m/s)	Height (m)	Gross (GWh)	Net AEP (GWh)	Loss (%)
Turbine site 001	513028.2	4620972.0	246.0	6.73	60.0	4.458	4452	0.13
Turbine site 002	514163.8	4619356.0	262.8	7.05	60.0	3.820	4927	0.12
Turbine site 003	516347.5	4621234.0	266.5	6.31	60.0	4.933	3806	0.36

Turbine site 004	518968.0	4621408.0	157.5	5.86	60.0	3.093	3086	0.24
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4.1.3. HOMER Pro

After selecting wind turbine specifications and required parameters for Langeland location, the scenario is simulated in HOMER Pro. In the ‘optimized results’ tab, there are 3 sections- architecture, cost & component section. It tells about different combinations which are best suited for the scenario. For this simulation, the best configuration is one, which is shown in below image. In ‘Overall’ tab, plenty of other combinations can be found.

The result of this tool displays the number of components (turbines, batteries) required to suffice the particular demand. It also tells about cost of energy which is \$0.0567 for this case. The results can be viewed in tabular or graphical form. It also performs the cost analysis of each component.

Table 15: Results in HOMER Pro

Equipment	Capacity	Quantity
Turbine (E-126)	7.5 MW	1
Li-ion battery	1 kWh	5
Converter	1.58 kW	1

4.1.4. energyPRO

The electricity generation graph shown below is obtained after simulating four turbines with the provided specifications. The graph shows the electricity generated by each turbine for the whole year, distinguished by 4 different colour coding. The graph in dark green and red colour is for the turbines having hub height of 90 m and rated capacity of 2 MW. However, Blue colour and light green colour shows the electricity generation by turbines having hub height of 60 m and rated capacity of 2 MW. The yellow colour line specifies the electricity consumption, which is 3.5 MW.

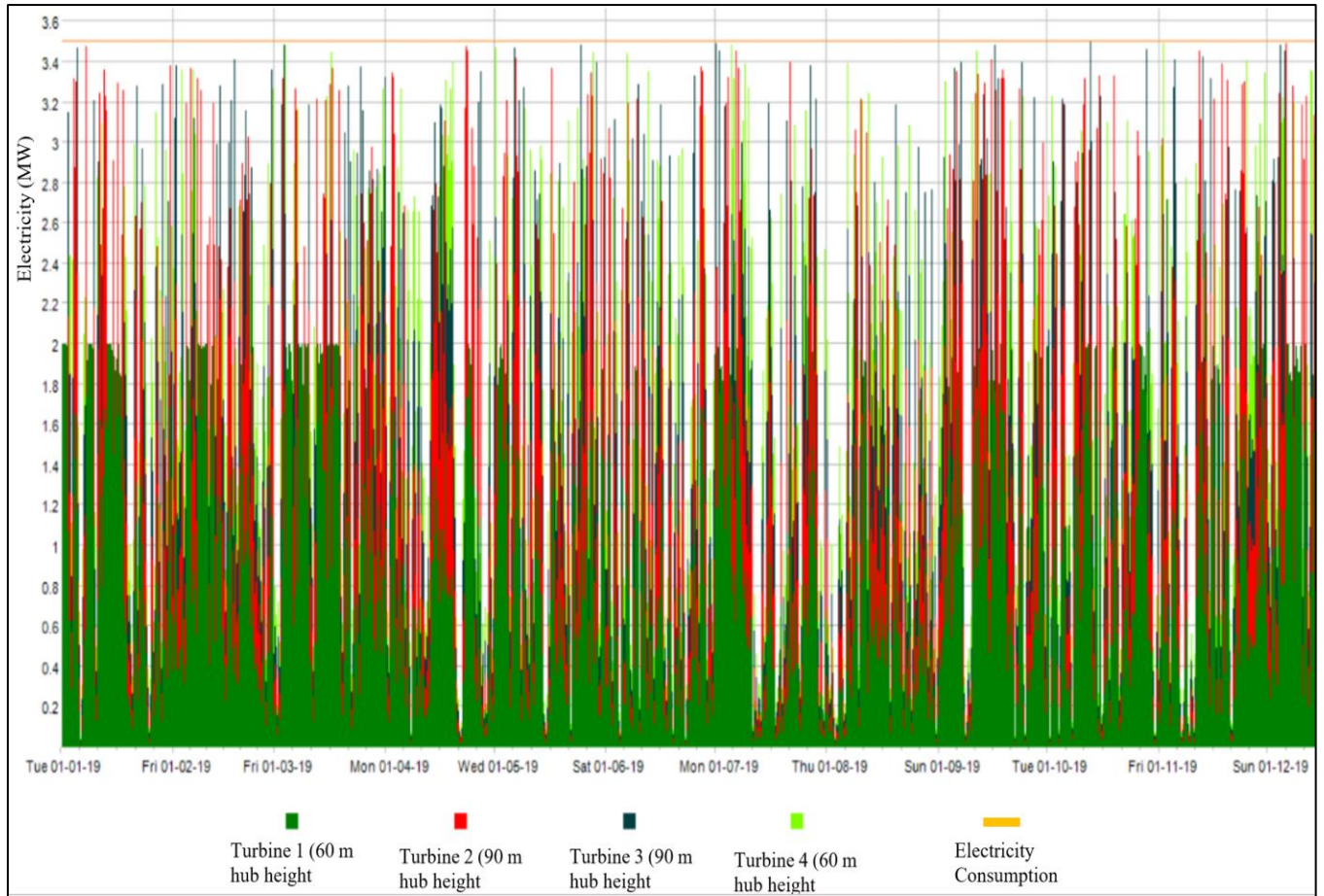


Figure 35: Graph of electricity production by the energy units (MW)

Following table shows the results of energyPRO software for the specified scenario. The electricity demand is 30.7 GWh and the total electricity produced by all the energy units is 29.6 GWh. It is clear from the figures that four turbines will not be enough to meet the demand. To balance demand supply, either the number of turbines must be increased, or demand has to be reduced.

Table 16: Results of energyPRO

Month	Energy demand (MWh)	Energy produced by energy units (MWh)	Energy produced by turbine 1	Energy produced by turbine 2	Energy produced by turbine 3	Energy produced by turbine 4
January	2601.6	3,005.7	763.1	763.1	739.7	739.7
February	2349.9	2,553.8	651.4	651.4	625.5	625.5
March	2601.6	3,423.0	869.2	869.2	842.4	842.4

April	2524.7	1,961.2	502.3	502.3	478.4	478.4
May	2601.6	2,487.7	636.1	636.1	607.7	607.7
June	2524.7	1,810.6	464.0	464.0	441.3	441.3
July	2601.6	2,138.9	546.8	546.8	522.6	522.6
August	2601.6	1,592.2	408.7	408.7	387.4	387.4
September	2524.7	2,771.0	707.6	707.6	677.9	677.9
October	2601.6	2,488.9	634.7	634.7	609.8	609.8
November	2524.7	2,220.8	568.3	568.3	542.1	542.1
December	2601.6	3,125.0	795.8	795.8	766.8	766.8
Total	30,660	29,578.9	7,548.1	7,548.1	7,241.4	7,241.4

4.2. Results of simulation, performed using all tools interdependently for the location ‘Langeland’

As section 3.1 consists of simulation on each tool. Different assumptions are being taken by each tool. For a particular location, HOMER Pro considers same wind speed for a number of wind turbines regardless of their terrain, roughness, topography and elevation. It also does not consider wake effect. If the same scenario is run in WAsP software before, it will provide mean wind speed and wake effect as an output. Wake loss can be minimized by providing sufficient distance and elevation to the turbines. This result can be used as an input for Homer PRO. By incorporating these losses and wind speed in HOMER Pro, more precise result can be obtained. Further, WindStation can provide wind data (wind speed, turbulence intensity, direction, and temperature) at different heights. These outputs can help to decide the hub height and direction of wind turbines to extract the maximum energy from the wind. If these softwares are used altogether, it is possible to achieve more accurate results.

In the section 3.2, simulation has been run by installing wind farm at the location “Langeland, Denmark”. It is an effort to produce more accurate results by defining inputs and outputs interdependently by the simulation tools. Section 4.2 displays the results of each tool, which are based on the outcomes of other tools

4.2.1. WindStation

Once the simulation has been carried out for meteo station. The scenario could be seen from horizontal and vertical planes as shown in the section 4.1.3. The horizontal plane can be visualized at a 60 m height. For the visualization in the vertical plane, any two locations on the map can be chosen. Further, velocity vectors & colour contours can be easily displayed by setting number of samples. One point is the starting point and other is the end point of a sampling line. Sampling take place at vertical plane by these x and y coordinates. When the curser is hovered at the below diagram, it tells x & y coordinates, altitude, height and wind speed at that specific point. These values can be clearly seen in the below table, extracted from the result section. For this simulation x coordinate is taken as 201251.10 m and y coordinate is 340373.50 m.

Table 17: Extracted result from WindStation

X Coordinate (m)	Y Coordinate (m)	Height (m)	Wind speed (m/s)	Direction ($^{\circ}$)	Turbine Intensity
201251.10	340373.50	0.20	0.00	65.36	0.00
201251.10	340373.50	1.10	1.13	65.36	0.48
201251.10	340373.50	2.31	1.78	64.82	0.37
201251.10	340373.50	3.64	2.18	64.28	0.32
201251.10	340373.50	5.11	2.49	63.88	0.29
201251.10	340373.50	6.72	2.75	63.53	0.27
201251.10	340373.50	8.49	2.98	63.22	0.25
201251.10	340373.50	10.44	3.19	62.93	0.24
201251.10	340373.50	12.58	3.39	62.65	0.22
201251.10	340373.50	14.94	3.58	62.37	0.21
201251.10	340373.50	17.53	3.76	62.11	0.20
201251.10	340373.50	20.38	3.94	61.84	0.19
201251.10	340373.50	23.52	4.11	61.58	0.18
201251.10	340373.50	26.97	4.27	61.32	0.18
201251.10	340373.50	30.77	4.43	61.06	0.17
201251.10	340373.50	34.95	4.58	60.82	0.16

201251.10	340373.50	39.54	4.73	60.59	0.16
201251.10	340373.50	44.60	4.87	60.38	0.15
201251.10	340373.50	50.16	5.01	60.17	0.15
201251.10	340373.50	56.28	5.14	59.98	0.14
201251.10	340373.50	60.09	7.39	59.81	0.14
201251.10	340373.50	70.40	5.39	59.65	0.14
201251.10	340373.50	78.54	5.51	59.50	0.13
201251.10	340373.50	89.91	7.52	59.37	0.13
201251.10	340373.50	97.35	5.75	59.25	0.13
201251.10	340373.50	108.18	5.87	59.15	0.13
201251.10	340373.50	120.10	5.98	59.07	0.12
201251.10	340373.50	133.21	6.10	59.00	0.12
201251.10	340373.50	147.63	6.23	58.94	0.12
201251.10	340373.50	163.49	6.35	58.90	0.12
201251.10	340373.50	180.94	6.48	58.87	0.11
201251.10	340373.50	200.14	6.61	58.86	0.11
201251.10	340373.50	221.25	6.75	58.87	0.11
201251.10	340373.50	244.48	6.88	58.88	0.11

It shows that wind speed varies with vertical and horizontal movement. If a turbine of 90 m hub height is installed at this location. The estimated wind speed at the particular height is 7.52 m/s. Below calculation shows that there is 6 % difference in wind speed between the meteo station and particular location at which turbine is installed. Therefore,

$$\begin{aligned} \text{Difference in wind} &= \\ &= \left[\frac{V_{meteo} - V_{tur}}{V_{meteo}} \right] * 100 \end{aligned} \quad (29)$$

Where:

V_{tur} = Wind speed at the particular location where turbine has to be erected

V_{meteo} = Wind speed of the meteo station (used as an input)

$$\text{Difference in wind} = \frac{8-7.52}{8} * 100 = 6 \% \quad (30)$$

4.2.2. WAsP

It was evident from the methodology that there is a strong wind coming from the west direction. As a result, keeping the turbine directed in west direction will produce more electricity. The observed climate in table 8 exhibits a mean wind speed of 7.85 m/s and a power density of 519 W/m² at the turbine site.

The predicted power production of the wind farm is 26.488 GWh and wake effect is 2.57 %. The wake effect is very small here because the wind farm has sufficient distance to each other. However, wake loss can be reduced from this value by varying hub height and distance between them. Approximately, 1.56 % of mean wind speed has been reduced due to wake effect.

Table 18: Statistics of annual energy generation & proportional wake loss

Variable	Total	Mean	Minimum	Maximum
Total gross AEP (GWh)	27.186	6.796	6.009	7.547
Total net AEP (GWh)	26.488	6.622	5.768	7.382
Proportional wake loss (%)	2.57	-	2.09	4.01
Capacity factor (%)	38.8	-	32.9	42.1
Mean speed (m/s)	-	8.11	7.60	8.59
Mean speed (wake-reduced) (m/s)	-	8.00	7.45	8.50
Air density (kg/m ³)	-	1.234	1.231	1.236
Power density (W/m ²)	-	542	455	627
RIX (%)	-	-	0.0	0.0

The exact placement of wind turbines in the facility as well as their elevation and hub height are depicted in the below table. Reduced wind speed is often reported as a result of wake losses. The difference between gross annual energy production (GEP) and Net annual energy production (AEP) is not significant due to negligible wake effect [42].

Following table shows the wind parameters for each turbine generated after performing the simulation. In three turbines, the wake effect is minimal. However, in one turbine wake loss is quite high, which is 4.01. It can be minimised by putting the turbine further away from the others. Increasing the hub height is another approach to reduce the wake loss with this turbine.

Table 19: Site observation (Co-ordinates of each turbine site, the elevation, the hub height, the gross and net power production and the wake loss)

Site description	X-location (m)	Y-location (m)	Elevation (m)	Height (m)	U* (m/s)	U(w)** (m)	Gross (GWh)	Net AEP (GWh)	Loss (%)
Turbine site 001	521337.0	105213.0	20.4	90.0	8.59	8.50	7.547	7.382	2.19
Turbine site 002	521462.0	105571.0	9.8	60.0	7.60	7.45	6.009	5.768	4.01
Turbine site 003	521637.0	105723.0	14.8	90.0	8.47	8.38	7.374	7.214	2.17
Turbine site 004	521937.0	105892.0	15.7	60.0	7.76	7.69	6.256	6.125	2.09

U* Wind speed before considering wake effect

U(w)** Wind speed after considering wake effect

$$\begin{aligned} \text{Difference in wind} \\ \text{energy during WAsP} \\ \text{simulation} \end{aligned} = \frac{\pm(V_2 - V_1)}{V_1} * 100 \tag{31}$$

Where:

V_1 = Wind speed given as an input in WAsP = 7.85 m/s

V_2 = Output wind speed generated after WAsP simulation = 8.11 m/s

$$\begin{aligned} \text{Difference in wind speed} \\ \text{during WAsP simulation} \end{aligned} = \frac{\pm(8.11 - 7.85)}{7.85} * 100 = 3.3 \%$$

This increase in wind speed is due sufficient distance among turbines, particular hub height and facing of turbines where wind is predominant.

4.2.3. HOMER Pro

$$\begin{aligned} \text{Actual wind speed based on WAsP results} \\ = \text{Wind speed from HOMER Pro} * (1 + \text{Percentage increase in wind speed}) \end{aligned} \tag{32}$$

$$= 4.86 * (1 + 0.033) = 5.02 \text{ m/s}$$

As a result, the new wind speeds have been estimated by increasing monthly speed, saved in HOMER Pro by 61%.

Table 20: Wind data extracted from HOMER Pro and Wind data derived based on simulations on WAsP

Month	Wind speed data from HOMER Pro (m/s)	Actual wind speed data derived for the specific meteo station based on the results of WAsP (m/s)
January	4.07	4.20
February	4.22	4.36
March	4.3	4.44
April	4.63	4.78
May	5.36	5.54
June	5.58	5.76
July	5.26	5.43
August	5.06	5.23
September	4.99	5.15
October	5.01	5.18
November	5.15	5.32
December	4.63	4.78
Average wind speed	4.86	5.02

The annual energy production provided by wind turbines has been estimated by WAsP. As a result, the monthly energy load has been given in HOMER Pro accordingly. The average monthly electric load is taken as 6,796 KW.

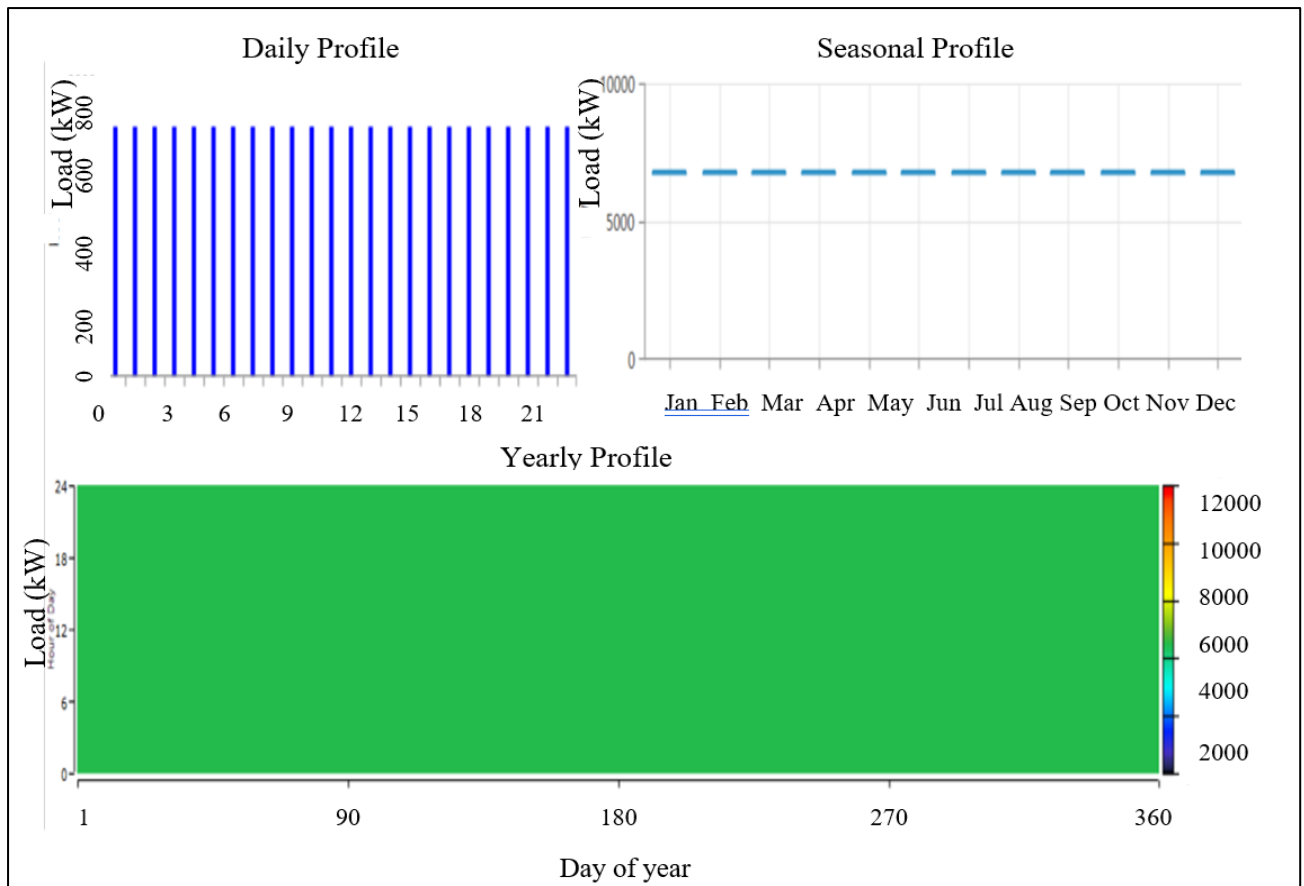


Figure 36: Defined electric load

A total of four turbines have been erected for this site. Specifications of each turbine is taken as recommended by the WAsP. Each turbine produces 2MW of electricity. Two turbines have a hub height of 60 m, while the other two have a hub height of 90 m.

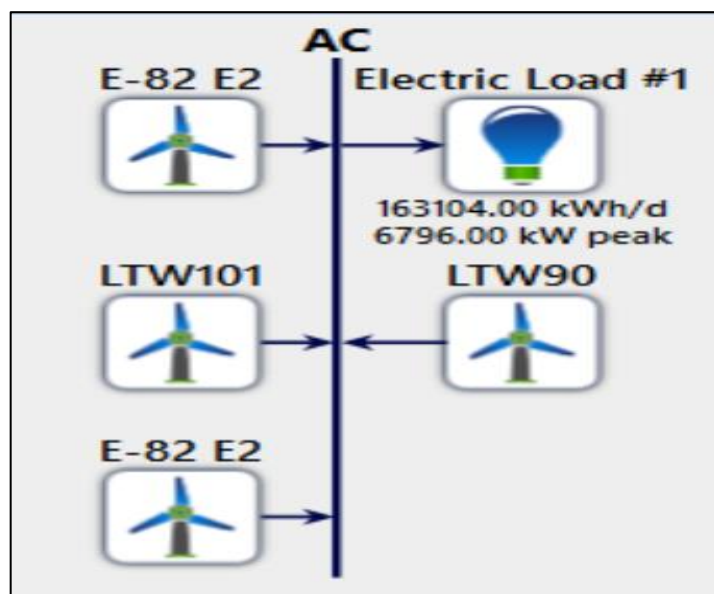


Figure 37: Installation of wind turbines

In most cases, turbine losses are not factored into the equation. However, WASP defined wake effects losses for each turbine. As a result, those losses are accounted for in this scenario. Other losses of 5% are also assumed because there will be other losses.


Power Curve	Turbine Losses	Maintenance Table
Availability Losses (%):	0	Wake Effects Losses (%) 2.0900
Turbine Performance Losses (%):	0	Electrical Losses (%) 0
Environmental Losses (%):	0	Curtailment Losses (%) 0
Other Losses (%):	5.00	
Overall Loss Factor (%):	6.985500	 Loss factors combine multiplicatively rather than additively.

Figure 38: Inclusion of turbine losses

A converter is added to convert the AC electricity provided by wind turbines into the DC power needed for storage. A storage system is required in the event of excessive electricity generation. Therefore a 1 MW capacity Li-Ion battery is used to store the excess energy.

The ‘optimized results’ tab tells about architecture, cost & component section. The result of this tool displays the number of components (turbines, batteries, converter) required to suffice the particular demand. It describes different combinations that are best suited for the scenario. HOMER Pro suggests 14 scenarios for this simulation. Our of them, 5 best scenarios are shown in below table. The quantity of wind turbines and Li-ion batteries, needed to meet the specific demand and required converter capacities are also indicated in the result section. It also calculates the cost of each component. But this thesis does not emphasize much on cost analysis, therefore cost analysis has not been added [43].

Table 21: Results in HOMER Pro (best combinations to suffice the desired demand)

	Equipment name	Capacity	Quantity
CASE I	Turbines	2 MW	4 (2 turbines with 60 m hub height and 2 turbines with 90 m hub height)
	Li- Ion battery	1 kWh	14
	Converter	785 kW	1

CASE II	Turbines	2 MW	3 (1 turbine with 60 m hub height and 2 turbines with 90 m hub height)
	Li- Ion battery	1 kWh	15
	Converter	1808 kW	1
CASE III	Turbines	2 MW	3 (1 turbine with 60 m hub height and 2 turbines with 90 m hub height)
	Li- Ion battery	1 kWh	17
	Converter	1352 kW	1
CASE IV	Turbines	2 MW	2 (with 90 m hub height)
	Li- Ion battery	1 kWh	28
	Converter	780 kW	1
CASE V	Turbines	2 MW	1 (with 90 m hub height)
	Li- Ion battery	1 kWh	65
	Converter	2027 kW	1

4.2.4. energyPRO

$$\begin{aligned}
 &\text{The new average wind speed} = \hspace{15em} (33) \\
 &= \text{initial wind speed} * (1 + \text{percentage difference in wind speed}) \\
 &= 7.6 * (1 + 0.033) = 7.8 \text{ m/s}
 \end{aligned}$$

Hence, the new wind speeds have been calculated by increasing wind speed by 2.7 %. For the simulation, energyPRO uses hourly wind speeds. However, for demonstrative purpose, monthly wind speed data is shown in the below table.

Table 22: Wind data extracted from external source [37] and Wind data derived based on simulations on WAsP.

Month	Mean wind speed data for Langeland (m/s)	Actual wind speed data derived for the specific meteo station based on the results of WAsP (m/s)
-------	--	--

January	8.4	8.7
February	8.2	8.4
March	9.0	9.3
April	7.0	7.2
May	7.6	7.8
June	6.7	6.9
July	7.0	7.2
August	6.5	6.6
September	7.8	8.0
October	7.7	7.9
November	7.2	7.4
December	8.4	8.7
Average wind speed	7.6	7.8

Hence, new wind speed is added in the tool. The below figure shows graph of wind speed data (in m/s) for the whole year. In this case, wind speed is more than the graph shown in figure 22. The graph clearly illustrates that wind speed is higher in the beginning and last months, and moderate in the middle.

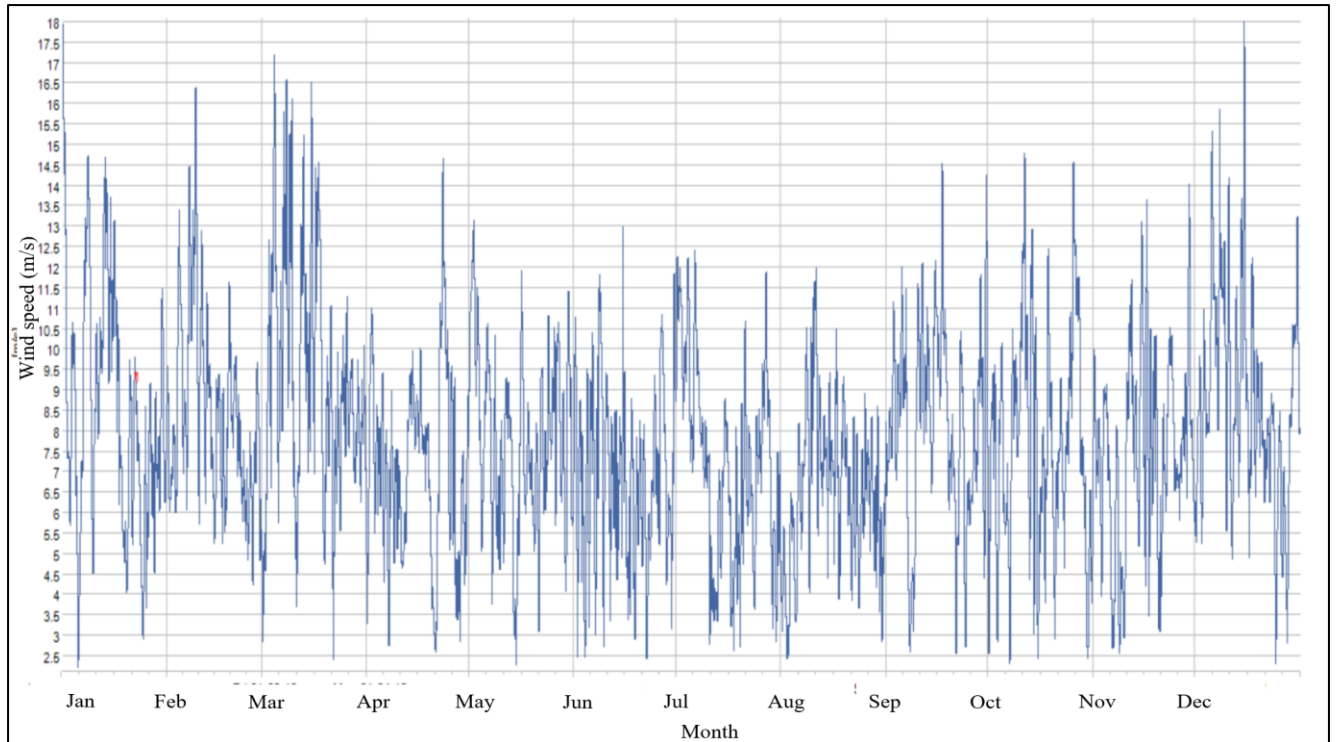


Figure 39: Graph of wind data for wind facility at Langeland

The power curve, in the below figure is similar as shown in figure 23. The cut-in and cut-out wind speeds are 2 m/s and 27 m/s respectively. The chosen wind turbine facility is suitable since wind speed for this location is in between the cut-in and cut-out wind speed range.

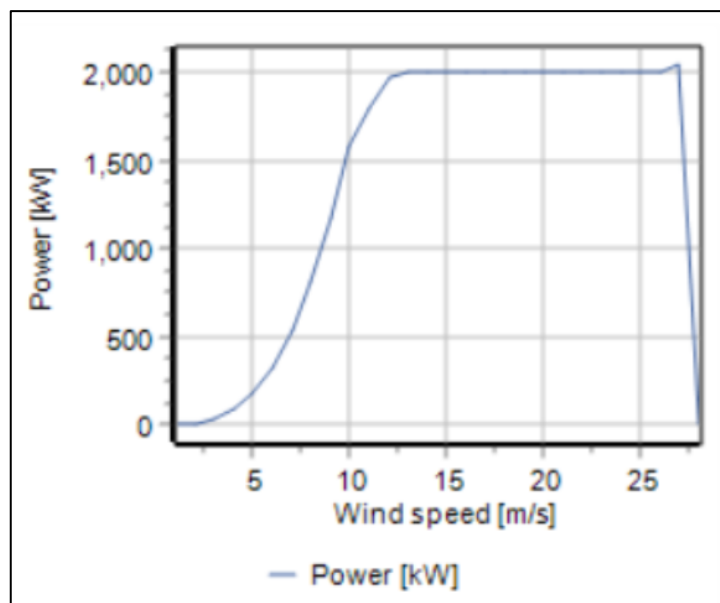


Figure 40: Power curve for chosen wind facility

For this scenario, the electricity demand is kept same as figure 24, which is 3.5 MW. The figure, shown below is the schematic after four wind turbines with the specified parameters and new electricity demand of 3.5 MW have been added.

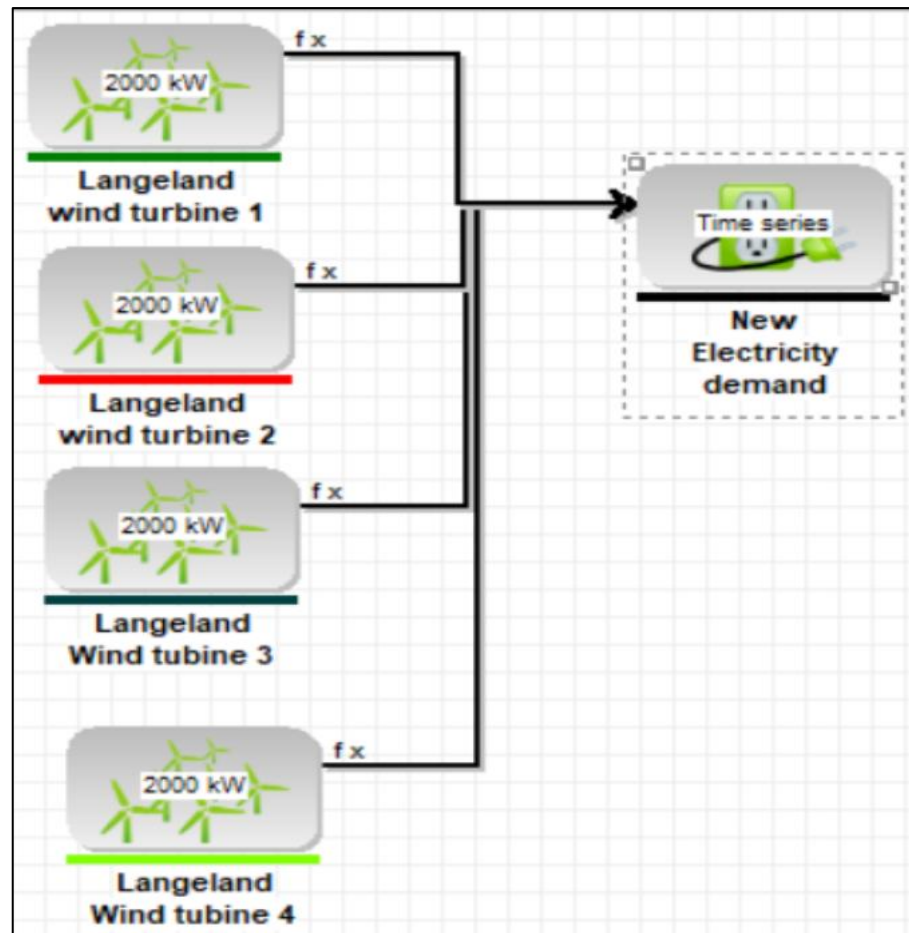


Figure 41: Schematic of overview of wind turbines and new electricity demand

After simulating the energy facility containing 4 wind turbines with specific parameters, the graph of electricity generation shown below is created. It depicts the total amount of power generated (in MW) by each turbine over the course of a year, with four alternative colour coding schemes. The electricity consumption of 3.5 MW is indicated by the yellow colour line.

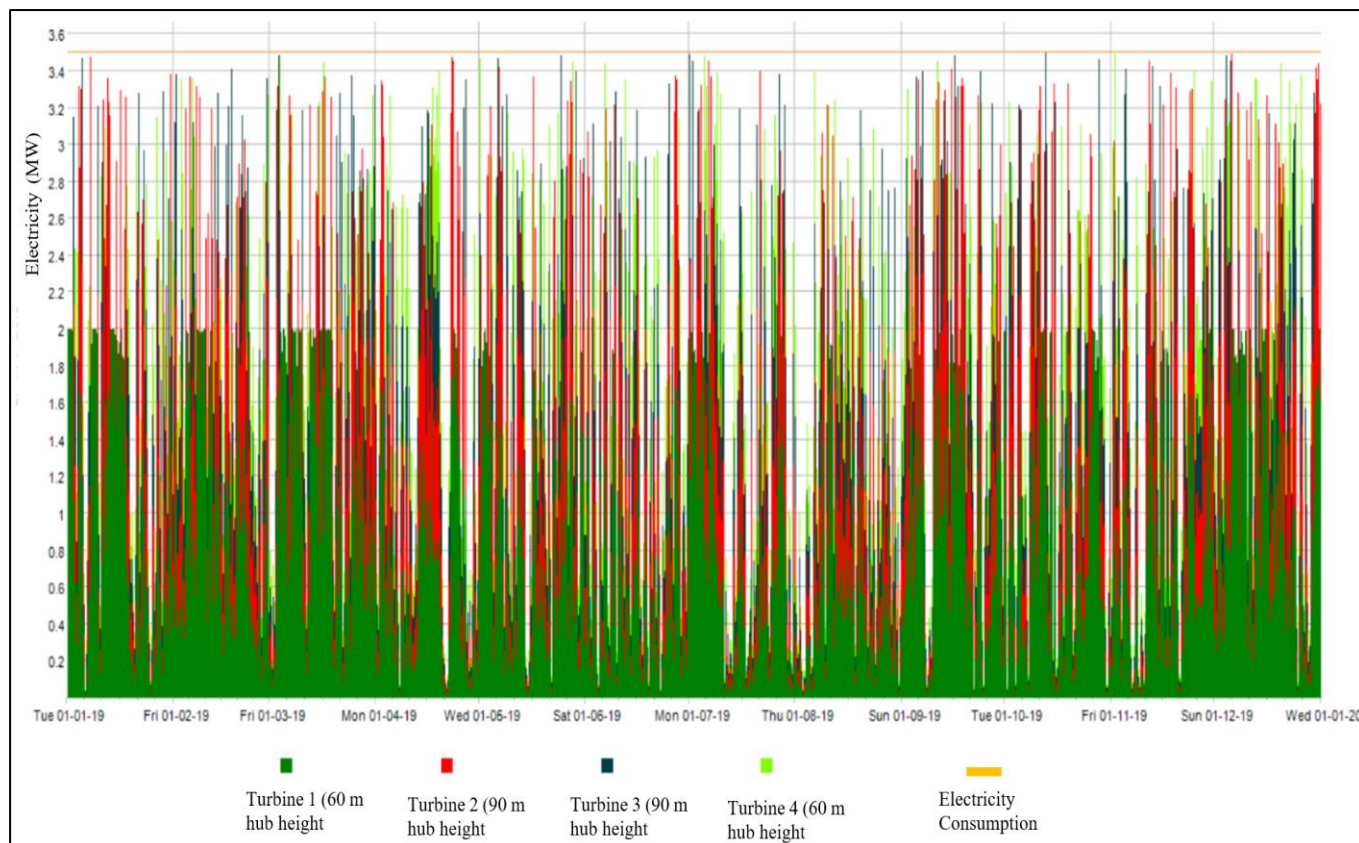


Figure 42: Graph of electricity production by the energy units (MW)

The findings of the energyPRO software for the specified scenario are shown in the table below. The total electricality produced by all energy units is 31.4 GWh, while the electricity consumption is 30.7 GWh. The results show that four turbines will be sufficient to meet the demand. The amount of electricity generated by each turbine is also displayed in the results section. All of the results are displayed on a monthly and yearly basis, both.

Table 23: Results of energyPRO

Month	Energy demand (MWh)	Energy produced by energy units (MWh)	Energy produced by turbine 1	Energy produced by turbine 2	Energy produced by turbine 3	Energy produced by turbine 4
January	2601.6	3,140.5	796.9	796.9	773.4	773.4
February	2349.9	2,705.7	689.9	689.9	663	663
March	2601.6	3,576.3	907.3	907.3	880.8	880.8
April	2524.7	2,100.4	537.4	537.4	512.8	512.8

May	2601.6	2,653.4	678	678	648.7	648.7
June	2524.7	1,944	497.9	497.9	474.2	474.2
July	2601.6	2,280	582.5	582.5	557.5	557.5
August	2601.6	1,718.1	440.8	440.8	418.3	418.3
September	2524.7	2,940.9	749.9	749.9	720.6	720.6
October	2601.6	2,633.3	671	671	645.7	645.7
November	2524.7	2,373.2	606.8	606.8	579.8	579.8
December	2601.6	3,292.6	837.8	837.8	808.5	808.5
Total	30,660	31,358.5	7,996.0	7,996.0	7683.3	7683.3

5. Discussion

- An approach to obtain precise results by using tools interdependently

After each tool had been successfully simulated, the findings were analysed. To gather the precise information about installing an effective & efficient wind turbine facility, all the wind resources modelling tools can be used interdependently. WindStation, as indicated in the figure below, requires wind inputs for the entire site (wind turbine data, temperature, direction, and turbulence) and after the simulation, it provides wind speed, wind direction and turbulence intensity at various heights. This output can be utilised to determine the turbine facility's hub height and direction of turbine rotor in order to extract the most of energy. This way, the output of WindStation helps in providing inputs to the WAsP tool. The outcomes of simulation on WAsP software provide mean wind speed, annual energy production by wind turbine facility, wake effect (wake loss) in wind turbine performance by the impact of turbines on each-other. This information aids in determining the number of turbines to be erected at that specific location, as well as the essential distance between turbines to minimise wake loss. This information can be used to feed into the HOMER Pro software, which requires inputs such as wind speed, number of turbines, hub height and turbine losses etc. As a result, this allows HOMER Pro to deliver accurate information (close to the actual scenario) about the number of components (turbines, batteries) and their capacity needed to meet a specific demand.

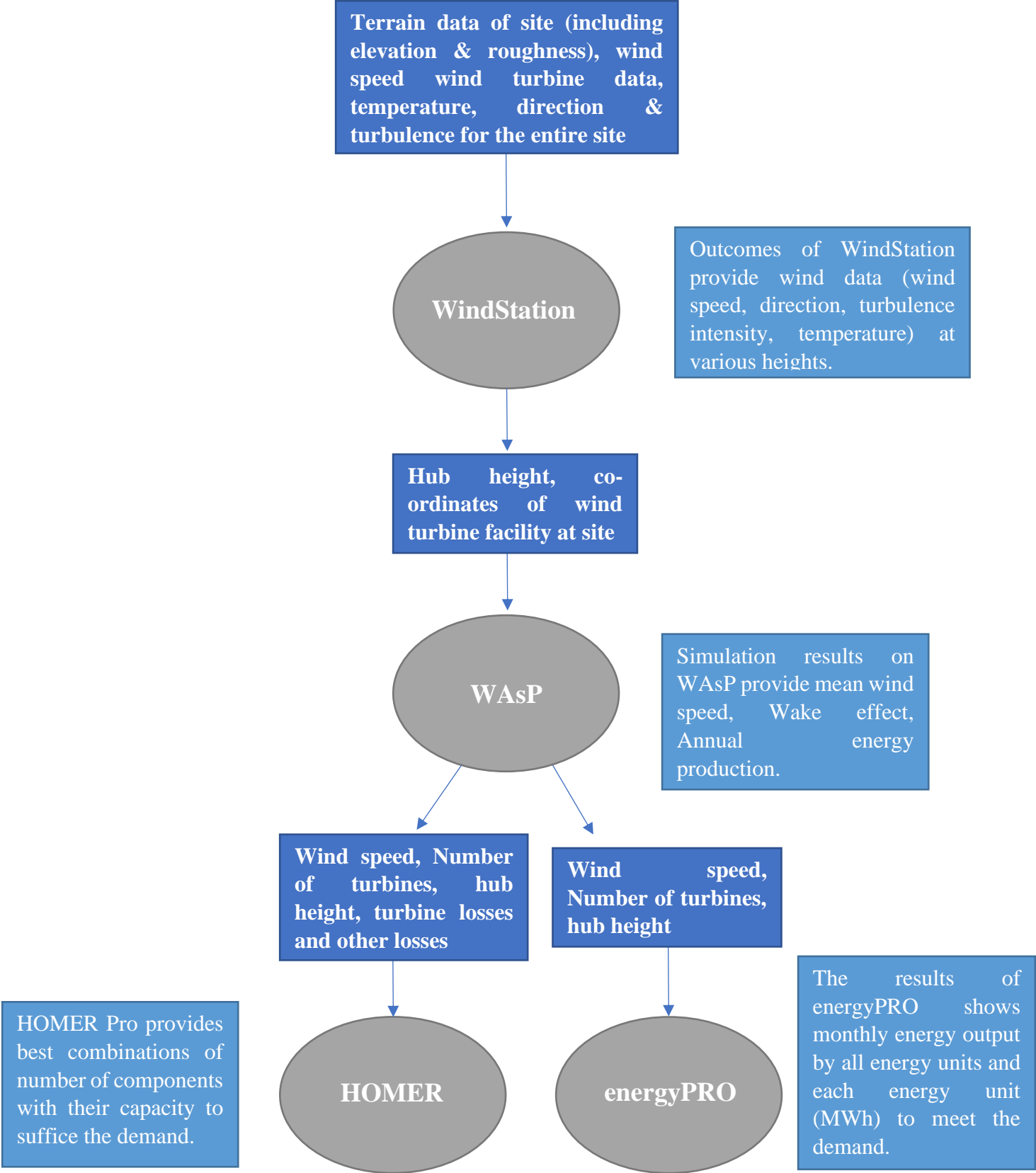
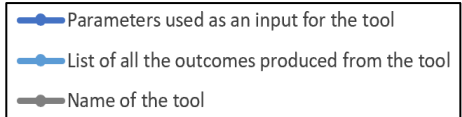


Figure 43: Steps of using all tools together to create an efficient wind turbine facility

Hence, the simulation results can be fine-tuned by combining the tools and using them interdependently. The main factors that had a significant impact on the outcomes are listed below:

1. Sufficient distance between the turbines to minimise the wake effect
 2. Deciding hub height based on wind profile in vertical and horizontal plane.
 3. Facing of turbines in the direction where wind is predominant.
- Comparison of wind speeds pre-defined in HOMER Pro tool with the wind speeds derived based on simulations in WindStation and WAsP for the specific location of wind farm

The wind speed data pre-programmed in the HOMER Pro tools differs from the wind data generated from WAsP for the specific meteo station as shown in table 20. HOMER Pro considers the flat terrain of location. It does not take into account the elevation, roughness and other factors of site. It also provides wind statistics for the entire site. Wind, on the other hand, varies depending on various parameters. WAsP and WindStation are detailed modelling tools that take into account a lot of elements that simple modelling tools do not. The graph below depicts the difference between the wind speed which is extracted from HOMER Pro tool and the wind speed calculated using simulations on WindStation and WAsP. Between these two situations, there is approximately 3.3 % difference in mean wind speeds.

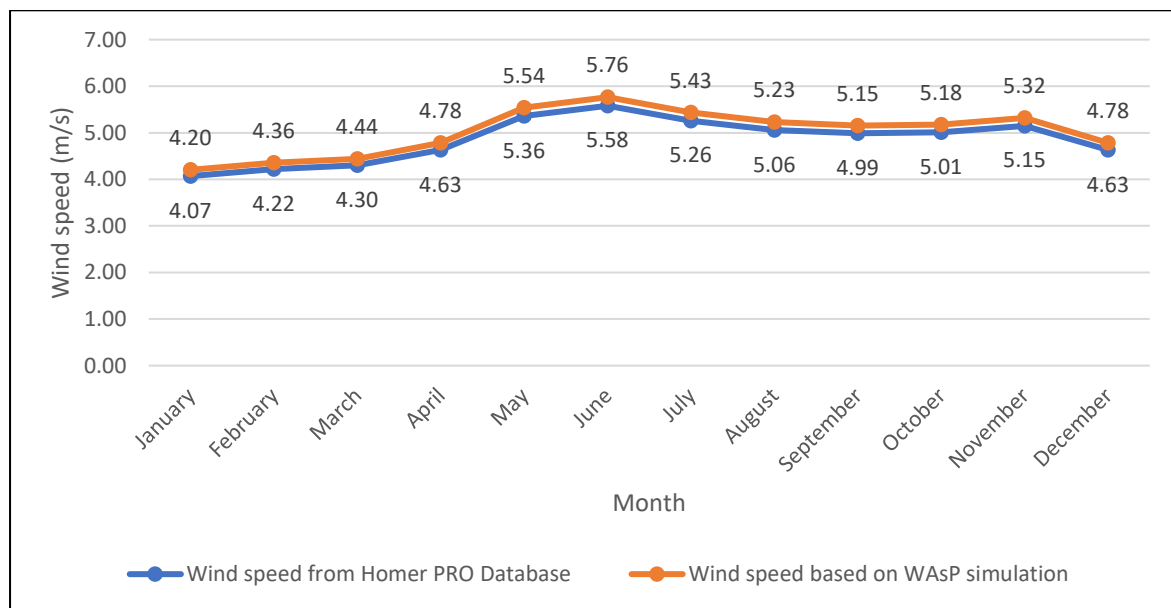


Figure 44: Graph showing variation between Wind speed extracted from HOMER Pro database and Wind speed calculated using WindStation and WAsP simulation for the particular wind farm location

- Comparison of wind data for energyPRO tool taken from external source with the wind speeds derived based on simulations in WindStation and WAsP for the specific location of wind farm

The electricity production by four wind turbines at Langeland is shown in section 4.1.4 result section, where yearly electricity production is 29.6 GWh and annual electricity demand is 20.7 GWh. As a result, the supply is unable to meet the demand, resulting in a demand-supply imbalance. This simulation considers wind data of external source, which generally contains a fix data for a particular location irrespective of the area of site, distance between turbines, elevation, roughness. In section 4.2.4, wind data is extracted after the simulation on WAsP and WindStation. The height of turbines, elevation, and roughness are all put into consideration by WindStation. The WAsP tool takes into account the distance between turbines, as well as the direction, turbulence severity, and wake losses. As an outcome, all losses have been reduced in this scenario by selecting the most appropriate hub height, turbine distance, and directions, which extracts the larger amount of energy from wind and yields 31.4 GWh of annual energy. It has the capacity to meet the given annual demand of 30.7 GWh. The below figure shows the difference in mean wind speeds when comparing these two scenarios.

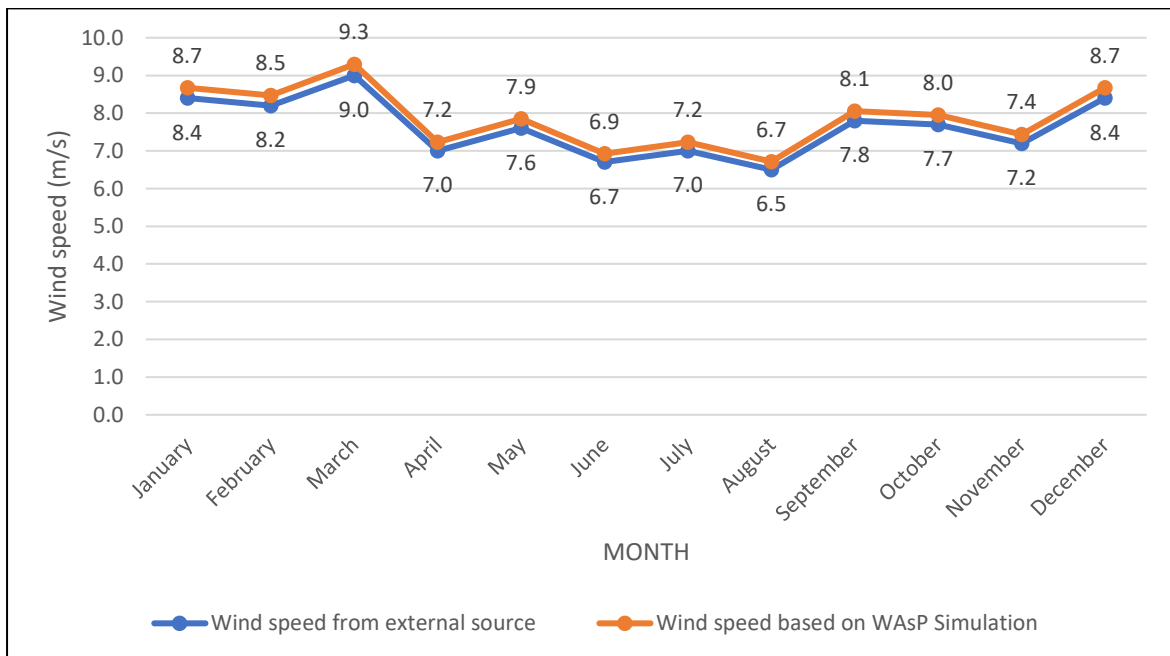


Figure 45: Graph showing variation between Wind speed taken from external source via conventional way and Wind speed extracted using WindStation and WAsP simulation for the specific wind facility

6. Conclusion

This thesis demonstrates that simulations performed on wind resources modelling tools considering parameters interdependently generate more accurate results. Simplified modelling tools (HOMER Pro, energyPRO) exclude factors like roughness, elevation, turbulence, and temperature. They also fail to consider turbine losses (5% in this scenario) in calculations thus producing deviated results. However, detailed modelling tools like WAsP, and WindStation consider these parameters. In section 3.1.4, when calculations are performed on Homer PRO independently, the wind speed is considered as 4.2 m/s which is the average wind speed of Langeland region. While in section 3.2.4 on using the softwares interdependently, the actual wind speed at turbine installation location is found to be 4.7 m/s. This goes on to affect the amount of energy units required to match the demand. Similarly, in eneryPro, a 3.3% deviation in wind speeds is found which further alters the energy output generated to suffice the demand.

The main factors that have a significant impact on the outcomes are as follows:

- Sufficient distance between the turbines to minimise the wake effect
- Deciding hub height based on wind profile in vertical and horizontal plane
- Facing of turbines in the direction where wind flow is predominant
- Elevation and roughness of terrain
- Turbulence and temperature

7. Future Scope

- With more resources, further research like cost analysis of energy systems can be conducted.
- This report focuses on wind generation modelling tools to produce more accurate results by using simplified and detailed modelling tools together. The similar process can be applied for solar energy systems, biomass energy, and hydro power systems.
- Two simplified modelling tools (HOMER Pro, energyPRO) and two detailed modelling tools (WAsP, WindStation) are used for this demonstration. This process can be used to evaluate similar such modelling tools like windPRO and EnergyPLAN.

8. References

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