POLITECNICO DI TORINO

Master’s Degree in Energy and Nuclear Engineering

Power upgrade of an onshore wind farm in Sicily: technical and economic aspects

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Abstract

In the last decades, the greater attention to environmental aspects, especially for what concerns the reduction of air pollution and greenhouse gas emissions, has caused a big development and spread of renewable energy systems. Also in Italy, at the beginning of the XXI century, many renewable plants are installed and are still today in operation. However, the evolution of energy conversion technologies and the fact that the expected lifetime of renewable energy systems is about 20÷30 years, imply that many of these plants are today no more efficient and competitive. For this reason, it is necessary to plan future interventions to be applied to these systems.

The case study discussed in this essay is the onshore wind farm Monte Mola located in Sicily and built by Asja Ambiente Italia Spa. The purpose of the work is to analyse and project its re-powering which consists in the complete removal of old wind turbines and their substitution with new ones.

In particular, the study, after a brief introduction on the wind resource and technology, follows all the various steps that are required for the correct design of the new plant. Starting from the analysis of the wind farm in operation, are firstly evaluated, according to regulations, all the constraints related to the area under investigation and the possible wind turbines to be installed. Then one or more possible plant's layouts are proposed and analysed, also from an anemometrical point of view, to highlight the optimum layout. Once the final layout is decided, an economic analysis is performed considering all cost items for turbines' investment and operation, but also for the construction of the civil and electrical engineering works.

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Acronyms

AC

Alternating Current

AEP

Annual Energy Production

a.g.l.

above ground level

a.s.l.

above sea level

AU

Autorizzazione Unica

CAPEX

Capital Expenditure

COP

Conference Of Parties

EBITDA

Earnings Before Interest, Taxes, Depreciation and Amortization

ETS

Emission Trading Scheme

GHG

Greenhouse Gases

GSE

Gestore Servizi Energetici

HAWT

Horizontal Axis Wind Turbine

IBA

Important Birds Area

IEC

International Electrotechnical Commission

IRR

Internal Rate of Return

LIDAR

Light Detection And Raging

MiTE

Ministero della Transizione Ecologica

NPV

Net Present Value

OPEX

Operational Expenditure

PAI

Piano di Assetto Idrogeologico

PAS

Procedura Abilitativa Semplificata

PBT

Pay Back Time

PCC

Point of Common Coupling

pdf

probability distribution function

PEARS

Piano Energetico Ambientale della Regione Sicilia

PLC

Programmable Logic Control

PNIEC

Piano Nazionale Integrato per l’Energia e il Clima

PNRR

Piano Nazionale di Ripresa e Resilienza

RES

Renewable Energy Sources

RTN

Rete Trasmissione Nazionale

SCADA

Supervisory Control and Data Acquisition

SIC

Sito di Importanza Comunitaria

SITR

Sistema Informativo Territoriale Regionale

SODAR

Sound Detection and Raging

TOC

Trivellazione Orizzontale Controllata

UTM

Universal Transverse of Mercator

VA

Verifica di Assoggettabiltà

VAWT

Vertical Axis Wind Turbine

VIA

Valutazione di Impatto Ambientale

WAsP

Wind Atlas Analysis and Assessment program

WTG

Wind Turbine Generator

WGS

World Geodetic System

ZPS

Zona di Protezione Speciale

ZSC

Zona Speciale di Conservazione

Chapter 1

Introduction to wind energy

In the last twenty-to-thirty years the greater attention to environmental and climate change aspects, due to the bigger increase of greenhouse gas and pollutant emissions, has ensured that many nations all over the world have though to common strategies and rules to contrast and take under control this problem. A first step in this direction is obtained with the drafting of the Kyoto Protocol (1997) which is basically the first international treaty that forces developed countries to reduce their emissions. Then various conferences, regarding the climate change problem, take place and one of the most important is the COP21 during which the Paris Agreement (2015) is subscribed. With this agreement, the countries, by drastically reducing their emissions, undertake to keep the total temperature increase, with respect to the pre-industrial levels, below 2 °C and possibly within 1,5 °C [1]. In this way they try to achieve, in 2050, net zero emissions and so a situation in which the few greenhouse gases emitted in the atmosphere are completely absorbed by forests, oceans or carbon capture technologies [2]. At the end of the past year, is held in Glasgow the COP26 in which more restrictive goals are introduced. It promotes the complete zeroing of net emissions by 2050 and the limitation of temperature increase below 1,5 °C by eliminating the use of coal, reducing deforestation, and increasing the exploitation of renewable energy. One of the main elements introduced with the Paris Agreement and reaffirmed in the COP26 is that each country has to publish a document which contains all the strategy to be adopted to mitigate and act to climate change.

Italy is aware of the potential benefits, coming from the diffusion of renewable energy and from the improvement of energy efficiency. Therefore, it actively participates to the various COPs and implements a set of strategies for the achievement of the goals regarding sustainability and decarbonization. In particular, Italy with the National Integrated Plan for Energy and Climate (PNIEC) establishes the national targets for 2030 on energy efficiency, renewable sources, reduction of CO_2 and GHG emissions, energy security, interconnections, energy market competitiveness and sustainable mobility [3], outlining for each of them the measures that will be implemented to ensure their achievement.

Table 1.1 - Energy and climate objectives of EU and Italy by 2020 and 2030 [3]

	2020 objectives		**2030 objectives**	
	UE	**Italy**	**UE**	**Italy (PNIEC)**
Renewable energy sources				
Share of RES in the final gross energy consumption	20%	17%	32%	30%
Share of RES in final gross energy consumption for trnsportation	10%		14%	22%
Share of RES in the final gross energy consumption for heating and cooling			+1,3% per year	
Energy efficiency				
Primary energy consumption reduction compared to PRIMES 2007 scenario	-20%	-24%	-32,5%	-43%
Final consumption savings	-1,5% per year (without trnsport)		-0,8% per year (with trnsport)	
Greenhouse gas emissions				
GHG reduction (with respect to 2005) for all ETS sectors	-21%		-43%	
GHG reduction (with respect to 2005) for all non-ETS sectors	-10%	-13%	-30%	-33%
Overall GHG reduction (with respect to 1990)	-20%		-40%	
Electricity interconnections				
Level of electricity interconnections	10%	8%	15%	10%
Capacity of electricity interconnections		9285 MW		14375 MW

As highlighted in the table above, Italy has the purpose to cover the 30% of the national gross energy consumption by means of RES, that have to be fully integrated into the system. The strong penetration of technologies for the electricity production from renewables, mainly photovoltaic and wind power, will allow to cover 55.0% of gross final electricity consumption with renewable energy, against 34.1% of 2017 [3]. In order to satisfy the targets on renewables, it will be necessary to plan new production and to preserve the existing one by promoting the revamping and repowering of old installations. This strategy will be specially adopted on existing wind power plants in which the obsolete and inefficient technologies are substituted with more developed and efficient machines.

1.1. Wind energy resource

Basically, wind is a movement of air masses, inside the atmosphere, with respect to the Earth surface. The main cause of this phenomenon is the presence of a temperature gradient due to a non-homogeneous heating of the surface. Thus, areas of high pressure and low pressure are generated, and they are influenced by the Earth's rotation. In fact, the mass of air does not move straightforwardly from a zone of high pressure to a zone of low pressure but is influenced by the Coriolis effect that deflects the wind to the right in the Northern hemisphere and to the left in the Southern one. When friction is low and isobars are straight, the air tends to flow parallel to isobars due to the presence of both pressure gradient and Coriolis force. Winds of this type are called geostrophic winds and can be found only at a certain height above the surface because, going down towards the terrain, the influence of the friction is significant and so the wind path is modified. In this sense it could be useful to define the atmospheric boundary layer as the zone near the ground that mixes the undisturbed wind layer and the zero-speed layer. The amplitude of the boundary layer, usually in the range ten meters to few kilometres, and the evolution of the wind profile are represented in Fig 1.1 and depend on diurnal heat coming from sun, moisture and ground characteristics like terrain elevation and surface roughness [4].

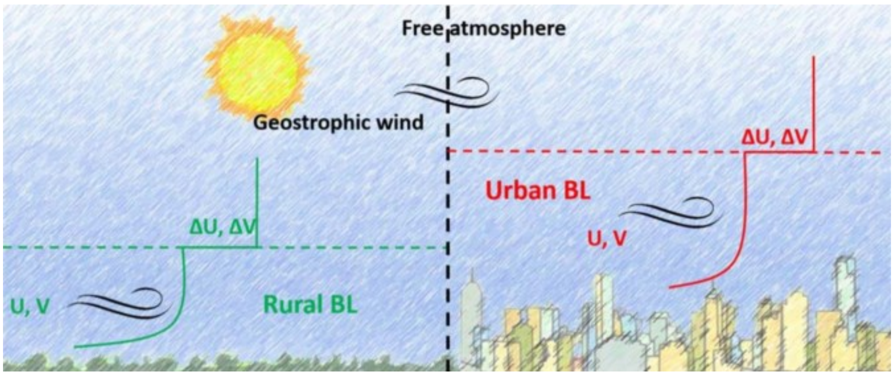

Figure 1.1 - Atmospheric boundary layer

The more the terrain is flat and without obstacles, the higher is the wind speed and the thinner is the boundary layer and this is beneficial. In fact, when we move from geostrophic wind to our local winds, we should consider turbulences since they decrease the turbine productivity. Turbulence consists in a flow characterized by fast and random fluctuations in pressure that result in variations of wind speed and direction. Its main causes are:

- orographic and surface roughness variations;
- heat transfer, especially thermal convection;
- steep terrain able to cause flow separation;
- presence of vegetation, buildings or any other obstacle.

This last point is particularly important in wind farms because each generator looks like an obstacle, and so a source of loss, for the other turbibnes.

The wind profile is also known as wind shear and it represents the speed variation with height. Normally it is positive and so the velocity increases with altitude due to the lower friction effects of the terrain [5]. Usually the wind speed measurements are performed at the mast, but often also velocities at different heights are needed. In such cases mathematical expressions of wind shear can be useful and the common used profiles are the logarithmic and the power law ones:

$$u(h, z_0) = u_{ref} \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{h_{ref}}{z_0}\right)} \tag{1.1}$$

$$u(h) = u_{ref} \left(\frac{h}{h_{ref}}\right)^{\alpha} \tag{1.2}$$

where z_0 $[mm]$ is the roughness parameter, h_{ref} $[m]$ is the mast altitude, u_{ref} $[m/s]$ is the wind speed at the reference height and α is the wind shear exponent [6].

Moreover the wind speed and direction change also in time, both in terms of daily and seasonal variations. In particular, at midlatitudes, usually winds are stonger from late autumn to spring and in the afternoon or evening. Due to these seasonal variations, in order to have an accurate evaluation of the wind resource, it is required a measurement campaign of about one year.

1.2. Wind energy measurement

Wind measurements are regulated by standards. The most important is the IEC 61400-12-1, which aim is to provide a suitable methodology to obtain wind measurements that are consistent, accurate and reproducible. Moreover, it defines some criteria for data quantity and quality and for electric measurements that are useful to evaluate the power production. Particularly a measurement, for the standard, is valid if performed with properly positioned instruments for at least 12 consecutive months and if the data availability is at least 90% [7]. The measured parameters must include obviously wind speed and direction, but also air temperature, pressure and humidity that are required for the evaluation of the air density. These measurements are performed by means of wind gauges and locally stored within a data logger. The data logger, with a sampling rate of about 1 Hz, records for all the parameters, excluding the wind direction, the maximum and minimum values, the average over a time interval of 10 minutes and the standard deviation. Then all these information are transferred to a central control system by means of cellular or radio signals.

1.2.1. Wind gauges

The device used for measuring the speed of an airflow is the anemometer. Nowadays there are various types of gauges on the market each of one with different characteristics and costs [5].

Cup anemometer (Fig. 1.4-a) consists in a vertical shaft to which three cups are connected and free to rotate since different drag drag forces are induced on the different cups by the incoming wind. This rotational motion, chearacterized by a velocity proportional to the airflow speed, is transformed into an electrical signal that can be sent to the data logger.

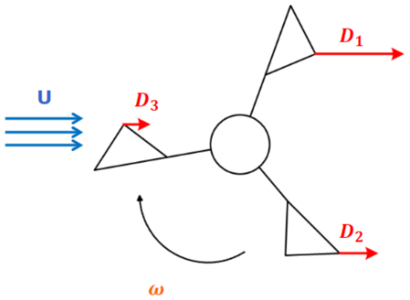

Figure 2.2 – Working principle of the cup anemometer

Because of the turbulent nature of the wind the anemometer has to present a fast response. This quality can be accounted by means of the so-called distance constant that has to be as low as possible. This type of sensor is the common installed today because it is simple, robust, quite cheap and characterized by a low power consumption. This last characteristic is really important especially for wind farm sites located in remote areas without access to electrical grid. The cup anemometer is not really precise in the wind gust evaluations because mechanical instruments speed up faster than slow down therefore, the measured mean wind speed is slightly larger than the true wind speeds. Moreover the decive requires a mast that contributes to the environmental impact. The presence of structural components, like the tower, causes a flow distortion that generates errors in the measurements. To reduce this problem it is recommended that the instrument is mounted at the top of the mast on a boom having a length of about 5 m. The figure below shows a different representation of the tower effect on wind measurements, represented as the ratio between the measured and the free-stream wind speed, as a function of distance and direction of the tower. The wind comes from the left and the flow fields are modelled using a CFD-type flow model. The optimum boom direction for a lattice mast is perpendicular to the prevailing wind direction, in this way the flow distortion is very small or close to zero. For a cylindrical mast the optimum boom direction is about 45° with respect to the prevailing wind direction.

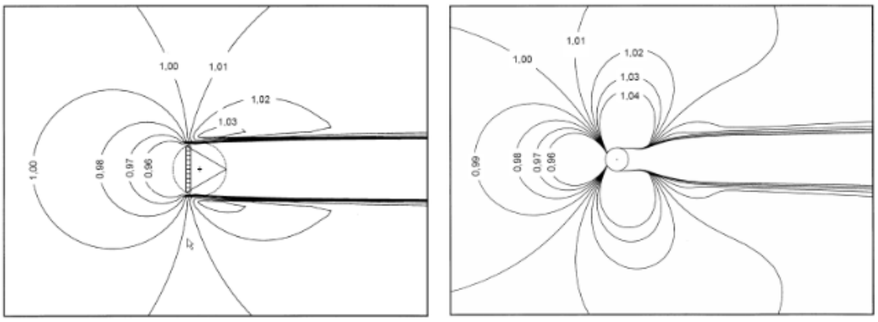

Figure 3.3 – Tower effects on lattice (left) and on a cylindrical (right) mast

Also the boom has a significant influence on the measured wind speed and therefore the standards recommend that the cup rotor has to be at a height, above the boom, of about 15÷25 times the boom diameter.

Propeller anemometer (Fig. 1.4-b) exploits a sort of turbine, installed on an horizontal shaft, that always points into the wind direction thanks to presence of the tail vane.

Sonic anemometer (Fig. 1.4-c) uses an ultrasonic pulses that is sent between a trasmitter and a receiver to perform a 3D wind speed measurement in a point. Since no moving parts are involved this gauge has a fast response to wind speed and direction changes and therefore it is more precise, but it is more expensive and requires more power supply than a cup anemometer.

Remote sensor devices detect the air flow, at a distance of few meters or kilometers, by exploiting the Doppler effect. By emitting a sound or a laser light signal and by evaluating the frequency shift between the emitted wave and the returned one after the collision with air particles, they are able to measure the wind speed on a surface. Two different types of sensors exist: the older one, today under dismission, is called SODAR (Sound detection and raging) while the most used today is LIDAR (Light detection and raging). LIDAR is more accurate and is able to perform real-time measurements some houndreds meters away and to evaluate the wake.

Figure 4.4 – Cup (a), propeller (b) and sonic (c) anemometers

To obtain reliable and useful data for the analysis, the anemometer has to present a certificate that guarantees the right calibration and installation of the instrument according to standards. Moreover, the data have to be controlled in terms of quality and validated by the analyst. In this preliminary phase the purpose is to detect all the failures that could occur in the datalogger, sensor and transmission system and that could generate corrupted data. Generally, the wrong acquisition of data may be caused to something, like ice and snow, that does not allow the sensible mechanism of the anemometer to rotate or to other breakdowns of the instrument. Therefore, it is important to periodically control the incoming data to verify if some faults are present to restore them as far as possible without losing too many data.

The collection of wind data by means of the anemometer is fundamental to correctly assess the wind climate of the site and to properly choose the turbine to be installed. Two different types of elaboration of the wind data can be performed.

1.2.2. Short-term elaboration

The short-term analysis is performed directly on recorded values of wind velocity, including gusts, which are evaluated every 10 minutes according to standards. By elaborating the wind data, are computed four important parameters which represent the basis for the wind classes definition. These wind classes determine which turbine is suitable for the normal operating conditions of the site under investigation.

Table 2.2 – IEC classification of wind turbines [6]

Wind turbine class		**I**	**II**	**III**	**S**
$\boldsymbol{V_{ave}}\ [\boldsymbol{m/s}]$		10	8,5	7,5	Defined by the constructor
$\boldsymbol{V_{ref}}\ [\boldsymbol{m/s}]$		50	42,5	37,5	
$\boldsymbol{V_{50,gust}}\ [\boldsymbol{m/s}]$		70	59,5	52,5	
$\boldsymbol{I_{ref}}$	**A**	0,16			
	B	0,14			
	C	0,12			

V_{ave} is the annual average wind speed at hub height. It is the primary parameter used for the selection of turbine: class I is for stronger winds and class III for lower winds. It is important also to underline that the higher is V_{ave}, the smaller has to be the rotor diameter because the turbine must withstand to bigger loads induced by wind.

V_{ref} is the 50-year extreme wind speed over 10 minutes. It represents the value of the highest wind speed, averaged over 10 min, with an annual probability of exceedance of 1/N where N is the recurrence period of 50 years.

$V_{50,gust}$ is the 50-year extreme gust over 3 seconds.

I_{ref} is the mean turbulence intensity at 15 m/s. Usually, turbulence intensity is evaluated for short periods and is calculated as the ratio between the standard deviation and the mean wind speed [8]:

$$I = \frac{\sigma}{\overline{V}} \tag{1.3}$$

Turbulence intensity generally decreases as the wind speed increments up to about 7÷10 m/s, above this level it becomes relatively constant. According to IEC 61400-1 three classes A, B and C of turbulences are defined and they correspond respectively to a high, medium, and low turbulence intensity.

In the analysis could be also important knowing the wind direction, especially during the design of the turbine layout of a wind farm, to avoid the so-called wake effect. Therefore, by means of the wind rose, the frequency of occurrence by direction is plotted. In this way, the graph displays the percentage of time in which the wind blows from a certain sector.

1.2.3. Long-term elaboration

The purpose of the long-term elaboration is to determine the probability distribution function that describes the arrangement of wind speeds over a relatively long period of time, for instance one year [6]. The construction of the histogram, describing this distribution, is performed by dividing the speed domain into bins having a width of 0,5÷1 m/s. For each bin, it is highlighted the number of times a wind of a certain intensity occurs.

The wind pdf is well approximated by the mathematical Weibull distribution function in which the probability density is given by the following expression:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \tag{1.4}$$

where $c\ [m/s]$ is the scale factor while k is the adimensional shape factor.

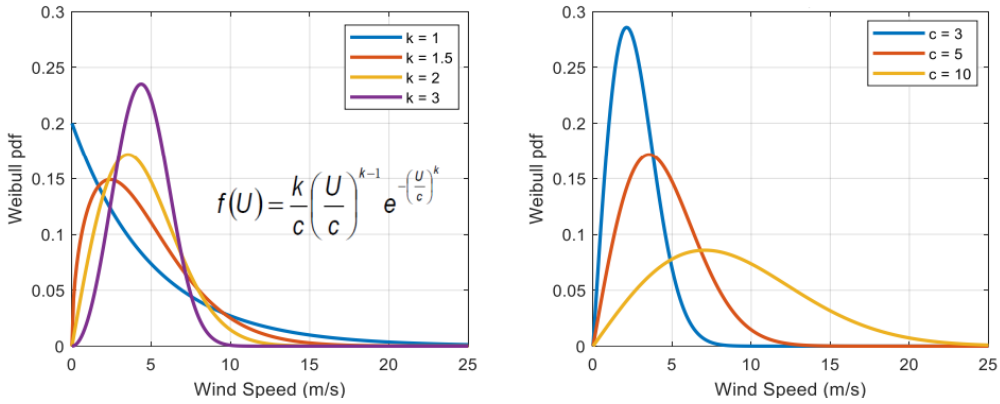

Figure 5.5 – Weibull distribution

The shape parameter influences the position of the peak of the curve: the more the peak is towards right, the higher is the wind speed. Usually, k is in the range 1,6÷2,4; when it is equal to 2 le function corresponds to a particular case: the Rayleigh distribution.

1.3. Wind energy technology

Wind turbine is the technology used to convert the kinetic energy of wind firstly into mechanical energy and then into electricity. It is a sustainable and clean technology characterized by a low carbon footprint since during the operation no CO_2 and GHG are emitted in the environment and the amount of pollutant emissions associated with wind turbines is relatively small and linked to the turbines and blades' production and transportation. Moreover, differently from traditional power stations using fossil fuels, wind turbines do not require water and use a fuel, the wind, that is almost free, costless, and not dependent on fluctuations of fuel prices. For a Nation it is important to invest on and exploit this technology because it is a good way to diversify the energy sources improving the national security and reducing the fuel and electricity importations from foreign countries. On the contrary many challenges are still present and are mainly due to the intermittency and unpredictability of wind. The problem can be potentially solved by temporarily storing the produced electricity and using it when needed, however storage technologies present some limitations that make this task quite difficult to perform. Other problems that have to be faced are the social acceptance of population, that is related to visual impact and noise pollution, and the disturbance of migration routes of birds.

1.3.1. Wind power history

For very long time, wind was the main source of energy exploited for transportation by using sailboats. Its use for other purposes started in Persia and China where the first vertical-axis wooden windmills were built. Then, in the Middle Ages, the Dutch windmills were largely spread in the Northern Europe and used for grinding grain and pumping water. This type of windmill consisted in a horizontal axis four-blades system connected to a vertical mast, located inside the structure, that can rotate to bring the blades perpendicular to the wind direction. The evolution of this technology was the so-called farm windmills characterized by a wind rose configuration for blades and a tail whose purpose was to point blades into the wind. During the 19th century a lot of windmills were installed all over the world also with the purpose to produce electricity from wind. In 1888 the first large size wind turbine for electricity generation was built by Charles Brush. The wooden rotor, having a diameter of 17 m, was connected to a direct current generator by means of a gearbox and was able to produce around 12 kW in good wind conditions [8]. Starting from 1920s, and especially after the oil crisis of 1970s, research and aerodynamic studies began to encourage the development of wind turbine technologies and to find the best solution to harvest energy from the wind.

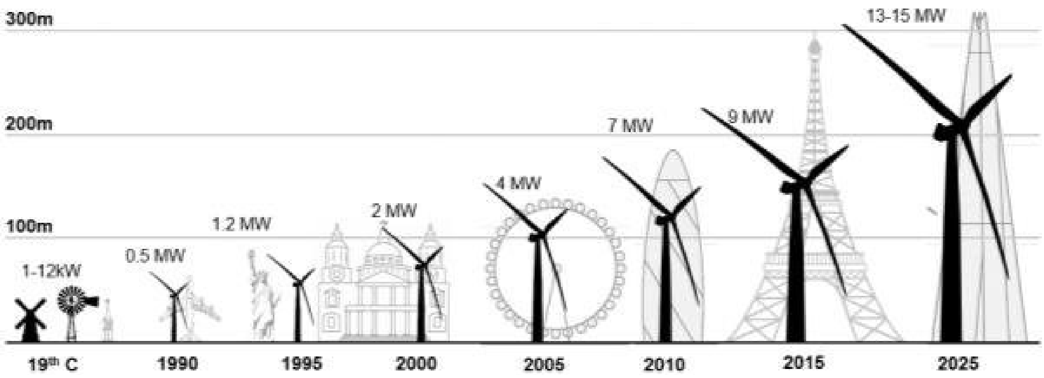

Figure 6.6 – Evolution of wind turbine technologies

Basically, two possible configurations are today adopted: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Over the years scale and competitiveness of wind turbines increase a lot and today turbine standardization consists in three-bladed horizontal axis up-wind turbines. The choice of adopting this configuration is mainly related to the turbine performances. In fact, HAWTs are more efficient than VAWTs and the up-wind arrangement allows the rotor to be not sheltered by the tower ensuring higher power harvesting and better performances even if the yaw control must be active. Regarding the number of blades, the solution of three blades seems to be the optimal one because by reducing the number of blades the impeller must rotate faster producing more noise and must withstand to higher loads due to the increment of blade’s dimensions and weight. On the contrary, in case of four blades the generator must be bigger and therefore the costs are higher [9].

1.3.2. Horizontal axis wind turbine

The common three-bladed horizontal axis up-wind turbines consist of three main sections that contain many components and auxiliary parts that allow the turbine to correctly work.

The support structure of wind turbines includes foundation and tower. The base of the turbine, dug into the soil, consists in a large and heavy block of concrete, with an iron gage, whose purpose is to resist to stresses and forces that act on the turbine. The towers of multimegawatt turbines are today 80÷150 m tall and are composed of different sections of steel bolted together. They are equipped with a ladder and a lift that take the operators on the top of the tower allowing them to enter directly in the nacelle. The connection between the nacelle and the tower is obtained by means of a yaw ring. This component, driven by a series of electrical or hydraulic motors, allows the orientation of the nacelle and of the rotor according with wind direction.

The nacelle contains a series of shaft, bearings, gearbox and brake, known as drivetrain, that is the mechanism used to transfer the harvested wind power to the generator. Usually, because the rotor shaft rotates at speed of 5÷30 rpm while the generator shaft at about 1000 rpm, a gearbox is required. However, it is possible also to have a direct-drive configuration in which no gearbox is present. In this case, the nacelle weight is strongly reduced, and higher efficiency and reliability are obtained, but the generator is more expensive. The generator, placed in the rear part of the nacelle, is the system which converts the kinetic energy of wind into electrical energy. Basically, it consists in an AC rotating electrical machines that can be of asynchronous (induction) or synchronous type.

In front of the nacelle, it is installed the hub which holds the blades and contains mechanisms required for the control of blades' pitch. The pitch regulation consists in turning the blades 90° around their axis and it is implemented when the wind is too high and so the turbine must be stopped for safety reasons or when maintenance must be performed. Blades are made of composite materials, like glass or carbon fibre, to be light and resistant in order to minimize structural stresses, which contribute to their deterioration. They present the form of an air foil, with a twist between root and tip, to be aerodynamic [10].

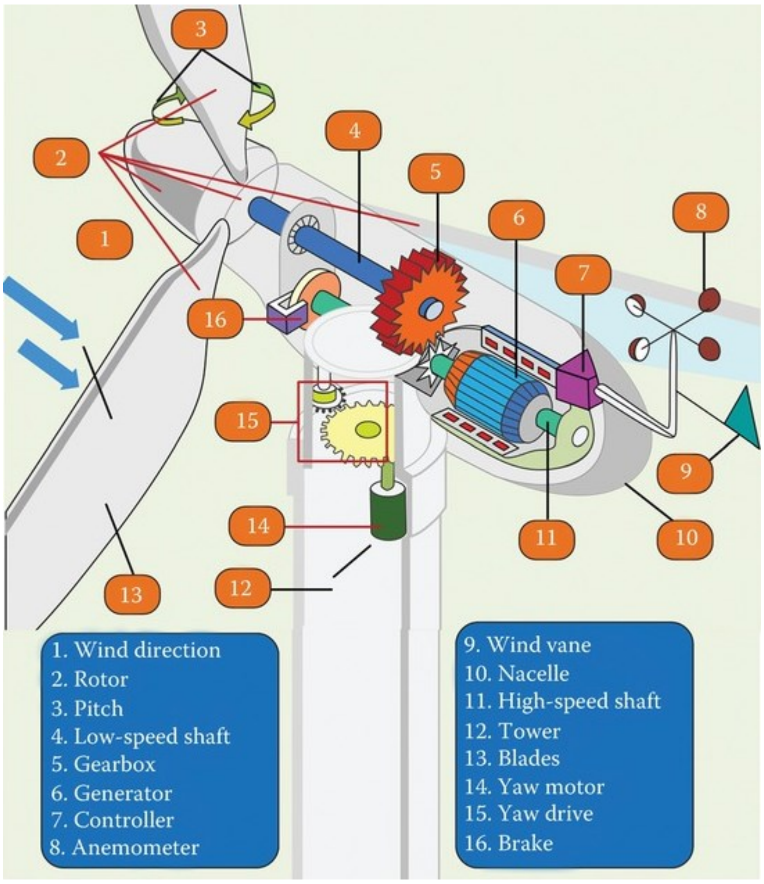

Figure 7.7 – Principal components of a horizontal axis wind turbines

The dimensions of the machines, also including the tower and blades, strongly depends on their size and IEC wind turbine classes. As already see in Tab. 1.2, in case of stronger wind resource turbines with lower IEC class have to be chosen, while where the wind are more weak generators of class IEC III are preferable. Generally, the higher is the yearly average wind speed, the smaller is the rotor diameter, and so the length of blades, with respect to the generator rated power. This feature is mainly related to the fact that the turbine hast to withstand to higher mechanical loads due to the strong wind conditions.

1.3.3. Vertical axis wind turbine

Vertical axis wind turbines can collect wind from any directions, but today are used only in small applications for low rated power (1÷10 kW) due to their low efficiency. The most diffuse VAWTs on the market are the Savonius and Darrieus which are quite cheap and easy to install, built and service. Savonius turbines are self-started but have pour aerodynamic performances, while Darrieus ones are more efficient but require a starting mechanism because blades are not able to generate a sufficient torque for rotation [9].

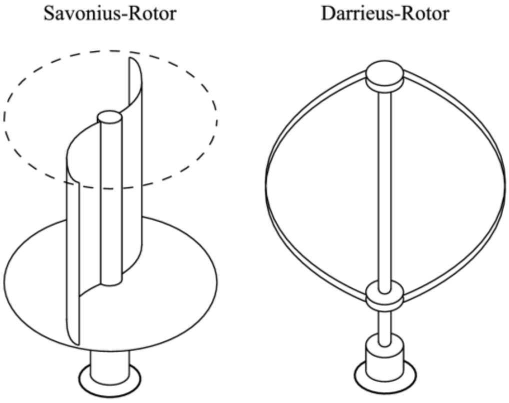

Figure 8.8 – Vertical axis wind turbines

Some studies have shown that the optimal solution in case of VAWT is to combine the two technologies and in particular to put the Savonius rotor inside the Darrieus rotor. The better solution in case of hybrid configuration is the two-bladed Savonius with three-bladed helical Darrieus. This model is not too complex and allows to obtain quite good performances and a self-started system [9].

1.4. Wind energy conversion

The primary aerodynamic forces acting on a wind turbine are lift and drag. Lift has a direction perpendicular to the incoming airflow and is a consequence of the pressure difference that is generated between the upper and lower surfaces of the blade. On the other hand, drag is parallel to the incoming airflow, so it tends to reduce its forward momentum [11], and is due to the pressure gradient, but also to viscous friction forces.

Horizontal axis and Darrieus wind turbines relay on lift, while Savonius wind turbines relay on drag.

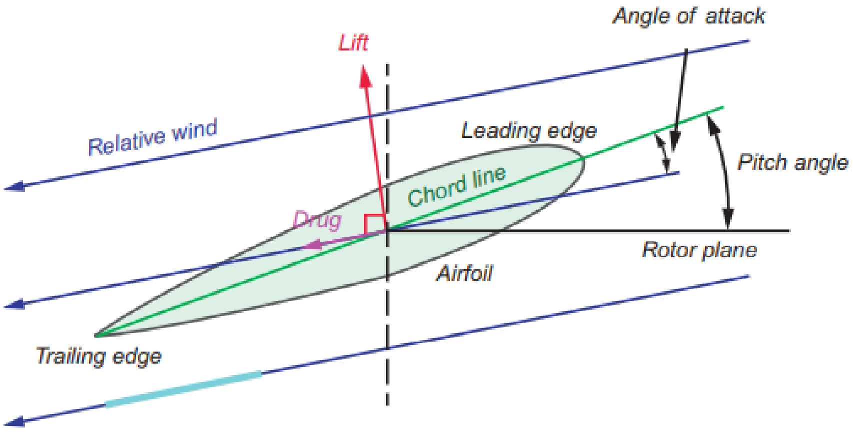

Figure 9.9 – Forces and angle of attack on a propeller blade

When the angle of attack between the airflow and the chord line of the blade is above a certain threshold, usually around 20°, there is a loss of lift that causes the separation of the flow, that becomes turbulent, and the so-called stall phenomenon.

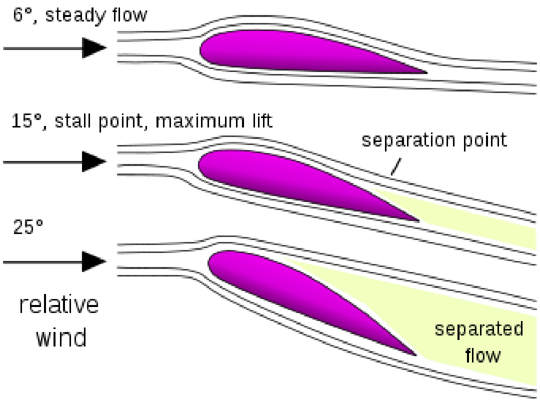

Figure 10.10 – Attached flow (normal operation), stall and separated flow

1.4.1. Power extraction

Wind turbines are able to produce electricity by exploiting the kinetic energy of the wind. Considering the wind as an air flow characterized by a constant density ρ $[kg/m^3]$ and a constant speed V $[m/s]$, the total power contained in the wind which could potentially be harvested by the turbine in the ideal case without considering any losses is given by the following equation:

$$P_w = \frac{1}{2}\,\rho\, A\, V^3 \tag{1.5}$$

The quantity A $[m^2]$ corresponds to the rotor swept area and, therefore, two different possible formulations are obtained in case of HAWT and VAWT:

$$P_{w,HAWT} = \frac{1}{2}\,\rho\,\pi\, R^2\, V^3 \tag{1.6}$$

$$P_{w,VAWT} = \frac{1}{2}\,\rho\, h\, D\, V^3 \tag{1.7}$$

where R $[m]$ is the radius of the HAWT, and h $[m]$ and D $[m]$ are respectively the height of the blade and the diameter of the VAWT [9].

However, the real exploited wind power is lower than the theoretical one due to the presence of losses that are mainly linked to the aerodynamic, mechanical and electrical fields.

The primary loss of energy is related to the continuity theory for which wind, crossing the rotor, should maintain a sufficient speed at the outlet without reaching the zero-speed condition. Moreover, a certain amount of power is also lost because the rotor turns itself, to point the blades in the wind direction, not immediately but with a certain delay [12]. For considering the just mentioned issues and the additional aerodynamic losses is introduced the aerodynamic power coefficient C_P that depends on the turbine and on the tip speed ratio λ:

$$\lambda = \frac{\Omega R}{V} \tag{1.8}$$

where Ω $[rad/s]$ is the angular velocity of the rotor, R $[m]$ is the rotor radius and V $[m/s]$ is the wind speed.

For this power coefficient Betz, in 1920, defined a theoretical limit, known as Betz limit, that corresponds to the maximum efficiency of an ideal wind rotor. The limit is evaluated considering the ideal situation in which there is no friction in the flow and no rotating-wake:

$$C_P = \frac{P}{\frac{1}{2}\,\rho\,A_D\,V^3} = 4a(1-a)^2 \tag{1.9}$$

where A_D $[m^2]$ is the area of the uniform actuator disk that mimics the wind turbine rotor, and a is the induction factor that is function of the wind speed V $[m/s]$ and of the wake velocity near the disk V_W $[m/s]$:

$$a = \frac{V - V_W}{V} \tag{1.10}$$

The maximum value of the power coefficient is obtained by evaluating its derivative with respect to the inductor factor:

$$\frac{dC_P}{da} = 4(1-a)(1-3a) = 0 \tag{1.11}$$

Evidence has shown that an ideal rotor is able to produce the maximum power if designed and operated in a way that the wind speed at the rotor is 2/3 of the undisturbed wind speed, so when $a = \frac{1}{3}$:

$$C_{P,max} = \frac{16}{27} = 0{,}5926 \tag{1.12}$$

This means that all wind turbines cannot harvest more than 59,3% of the available energy of wind [9].

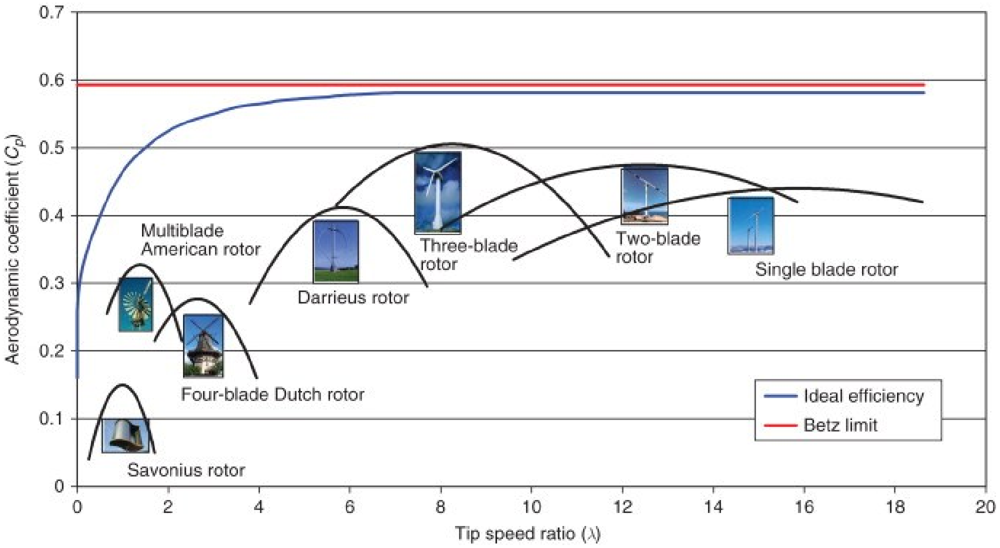

Figure 11.11 – Aerodynamic power coefficient for different wind turbine types and different tip speed ratios

The energy conversion of kinetic wind energy into electrical energy is performed by using a wind generator and other auxiliary components. Obviously to this process are associated various loss mechanisms that are considered by means of the gearbox efficiency, generator efficiency and electrical efficiency.

Considering all the possible losses occurring during the energy conversion, the actual power generated by a wind turbine can be evaluated as:

$$P = C_P \, \eta_{gear} \, \eta_{gen} \, \eta_{el} \, P_W = C_P \, \eta_{gear} \, \eta_{gen} \, \eta_{el} \, \frac{1}{2} \rho \, A \, V^3 \qquad (1.13)$$

1.4.2. Power curve

The equation 1.13 highlights how the output power of a wind turbine strongly depends on the wind speed. However, to be useful in the energy conversion process, the wind speed must be within a certain velocity range. This is because for low wind speeds, below the cut-in wind speed, blades are not able to rotate because friction losses of shafts and gearbox are big. On the contrary, for very high wind speeds, above the cut-out wind speed, the turbine must be stopped for safety reasons. Moreover, additional amount of wind energy is lost because, to guarantee the correct operation of the turbine, the power production is kept almost constant for wind velocity between rated and cut-out wind speed. The values of wind velocity corresponding to the cut-in and cut-out speeds depend on the wind turbine and especially on its IEC class. Generally lower-class wind turbines require higher wind speed to reach the rated power, but they can operate with higher cut-out speed. On the contrary, higher class wind turbines have big rotor so they can efficiently harvest power at low wind speed but must shut down at lower cut-out wind speed.

Considering constant air density, the power harvested by a wind turbine with respect to the wind speed can be easily summarized in the wind power curve. A generic simplified power curve is the blue one represented in Fig. 1.12, where it is also highlighted the influence of the aerodynamic power coefficient.

As already said, when the wind speed exceeds the cut-out threshold, the turbine is forced to shut down and the production stops until the wind speed condition returns acceptable. However, the restart of the turbine does not occur immediately when the wind velocity goes below the cut-out limit, but with a certain delay, as highlighted in Fig 1.13. The lag depends on the turbine technology, but usually a velocity drop of 3÷4 m/s is required. In this way a sort of hysteresis loop is generated with a subsequent loss of wind power. To reduce this power loss a solution largely adopted, especially in big wind farms, is to implement a control strategy that gradually reduces the power production when wind speed increases [13].

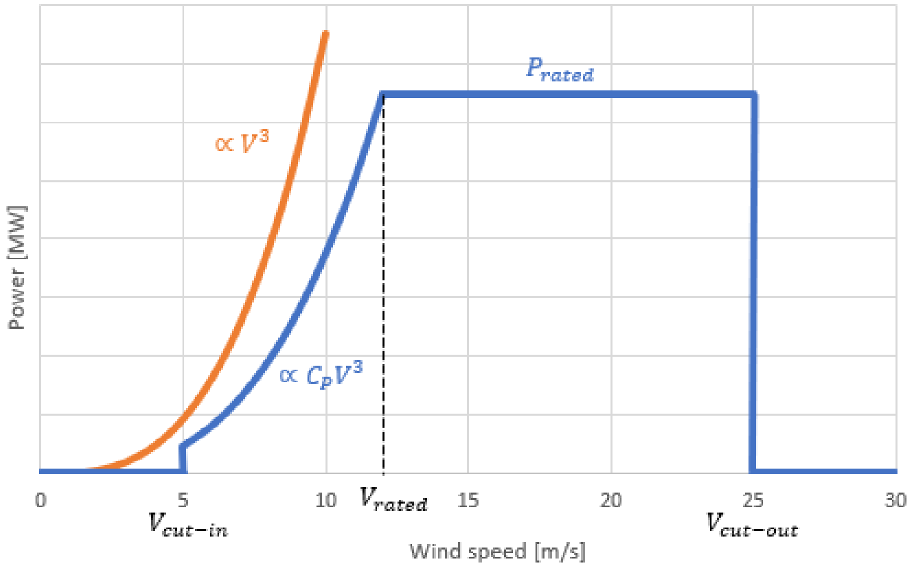

Figure 12.12 – Power curve

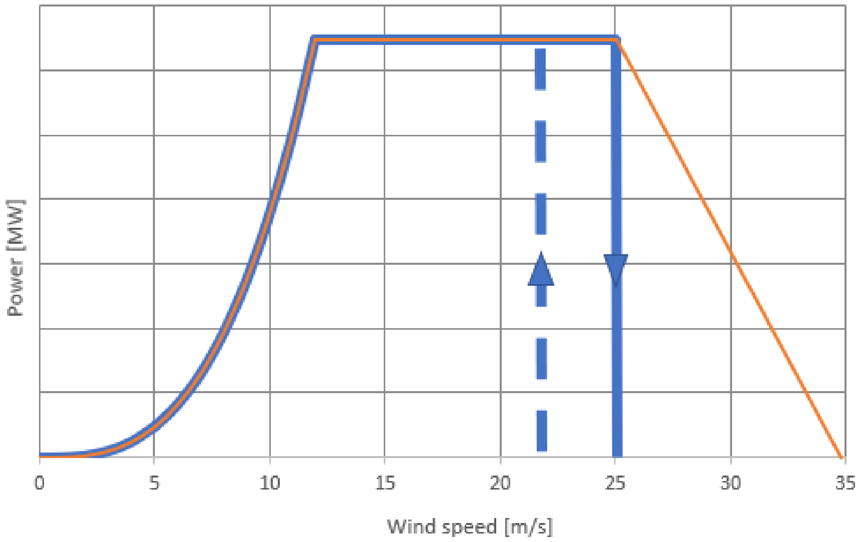

Figure 13.13 – Power curve with hysteresis loop (blue) and with smooth power reduction (orange)

1.4.3. Wind farm and wake effect

Even if the size and efficiency of wind turbine generators have been increased over the year, to extract and produce a considerable amount of power from wind it is necessary to install more turbines in the same site. Clusters of more wind turbines, interconnected by an electrical system and which deliver their combined electrical power production to the same point of common coupling (PCC), are known as wind farms. A wind park is usually controlled by the same control system, sometimes known as SCADA systems.

A wind turbine is always characterized by a wind shade downstream the rotor. In fact, the blades, while rotating, impart a wake spin, having opposite direction with respect to the rotor spin, that reduces the useful portion of the total energy content. This is also why the aerodynamic power coefficient of real turbines is always lower than the Betz limit.

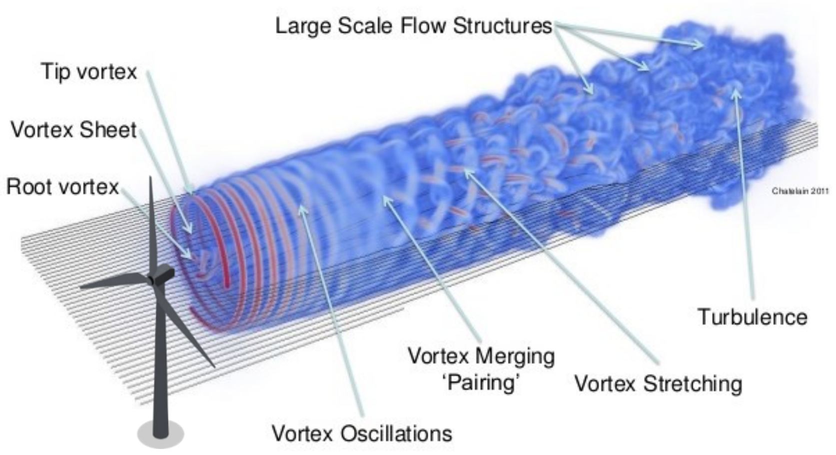

Figure 14.14 – Wake structure

At the rotor, the wake starts to rotate and then it mixes with the air flow. In such way the wake becomes more and more complex and less define until it is developed into a turbulent flow. This means that, if we consider a wind farm with a large number of turbines located on several parallel row in the in the prevailing wind direction, only the turbines windward receive a laminar air flow, while downwind turbines get a turbulent flow and so are able to produce less power. To reduce this effect, it is needed to install the turbines at a certain distance apart from each other. As a rule of thumb, turbines must be placed at a distance of 3÷5 rotor diameters in in the direction perpendicular to the prevailing winds and at a distance of 5÷9 rotor diameters in the prevailing wind direction [14].

Therefore, wake effects correspond to the loss of power production caused by the interaction of the turbines in the wind farm. For the evaluation of the wake effect, it is required to know the characteristics of the wind turbine, in terms of hub height, rotor diameter and thrust coefficient. Various models can today be used for the calculation of the wake effects.

The thrust coefficient is the actual thrust force F_t $[N]$ on the wind turbine tower divided by the total dynamic force of the wind over the rotor area:

$$C_t = \frac{F_t}{\frac{1}{2}\,\rho\, A_D\, V^3} = 4a(1-a) \tag{1.14}$$

The maximum value of the thrust coefficient is obtained by evaluating its derivative with respect to the inductor factor:

$$\frac{dC_t}{da} = 4 - 8a = 4(1-2a) = 0 \tag{1.15}$$

Theoretically, for an ideal rotor, the maximum value of the thrust coefficient is obtained when the induction factor is $a = \frac{1}{2}$.

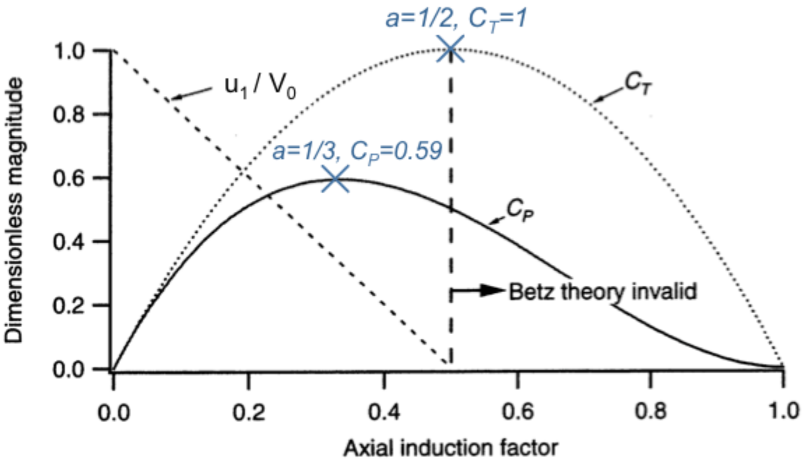

Figure 15.15 – Power and thrust coefficients

Increasing the induction factor, in the range $a = 0 \div 0{,}5$, the thrust coefficient increases and so at the outlet section the fluid velocity decreases while pressure increases. Consequently, the difference in speed between undisturbed wind and flow coming from the turbine becomes bigger. This is good for theory, but not for practical applications. In fact, when a speed differential is present, recirculation phenomena occur generating a turbulent flow, the wake [15]. To reduce recirculation and vorticity effects, winglets or swept profiles are used in turbine blades.

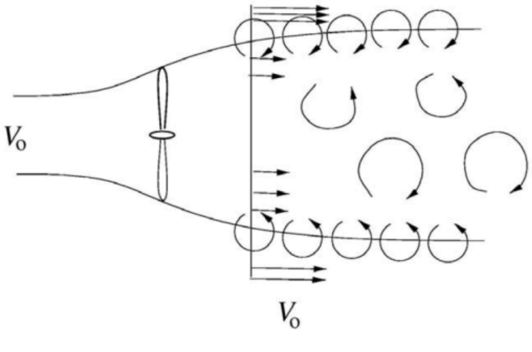

Figure 16.16 – Recirculation effects

Finally, it is important to notice that in the turbulent wake sate, so for induction factor greater than 0,4÷0,5, the thrust coefficient does not behave as descripted in the momentum Betz theory, but an empirical relationship has to be used. An example is the one developed, in 1930s, by Glauert who highlighted a steep increase of the thrust coefficient for $a > 0{,}4$ that is mainly due to flow separation and stall phenomena.

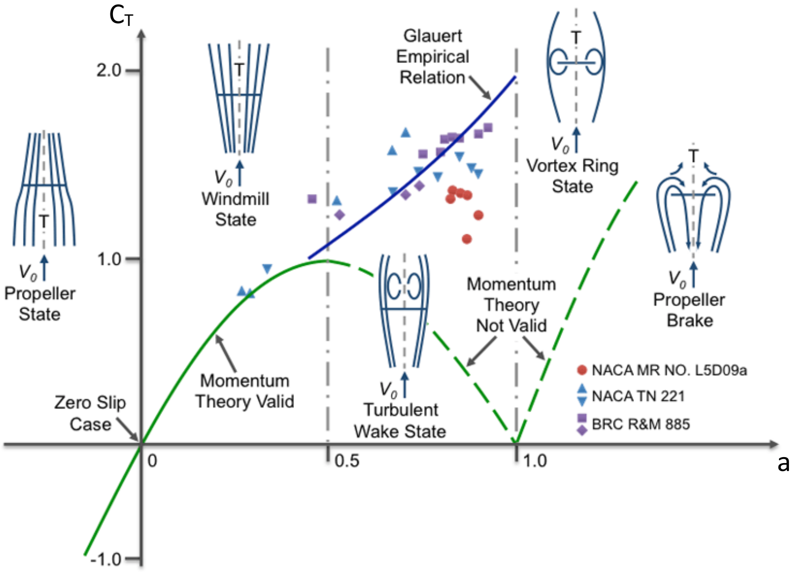

Figure 17.17 – Thrust coefficient: momentum Betz theory and Glauert empirical relation

Chapter 2

Power up-grade of wind plants

In Italy, starting from the end of XX and the beginning of XXI centuries, many onshore wind farms are installed on the national territories and especially in the Southern ones where the wind resource presents a better potential. The national trend, in terms of wind energy exploiting, is increased over the years. Today the national number of plants is increased reaching the value of 5777 for a total installed power of about 11322 MW.

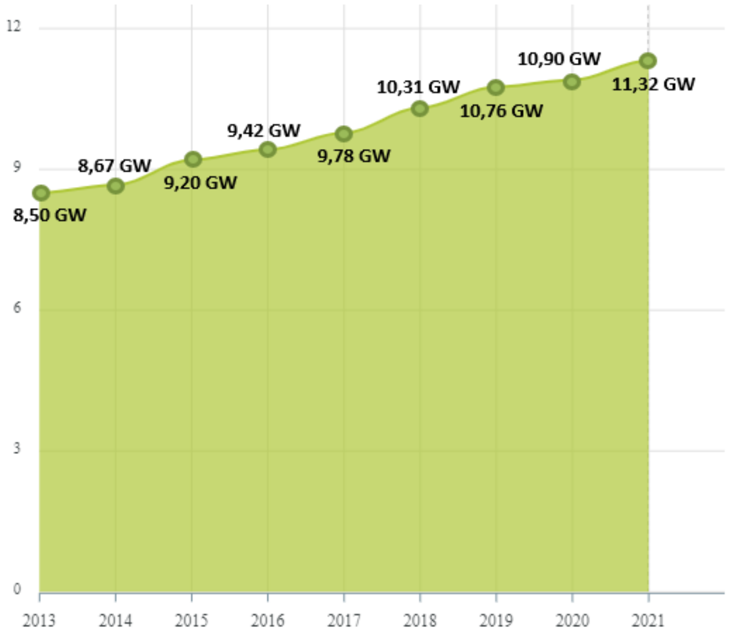

Figure 2.1 – Evolution of installed wind power [GW] in Italy

(Source: Terna - https://www.terna.it/it/sistema-elettrico/dispacciamento/fonti-rinnovabili)

Most of the national wind farms were installed in the early 2000s, so in the next years they are going towards the end of life since usually the life span of this type of plants is around 20-25 years. Furthermore, most of the plants benefit from the substitute incentive of the Green Certificates that are expected to expire by 2030. At the end of the incentive period, the plant operator will be free to evaluate the best solution to maximize the energy production without restrictions [16]. Consequently, many companies, owners of such plants, have to think about the decommissioning. The first, but not convenient possibility is to definitely stop the power production and remove all the wind turbines. This solution implies that the owner takes care of the removal and disposal of the installed machines. A better solution, that allows to the operator to continue to generate power in a more efficient way, is the power up-grade of the plant by installing new turbines (repowering) or by substituting turbine's components (revamping).

2.1. Repowering

Repowering implies the substitution of the entire old wind turbines with new more efficient ones having larger size and dimension. It is important to underline that when the machines were installed, decades ago, the technologies adopted were underdeveloped and inefficient. Moreover, on the market was present a small number of turbines which are mostly characterized by class IEC I since most of produces, such as Vestas, Siemens Gamesa and Nordex, were based on the Northern Europe where the wind blows strongly. Therefore, in the past, machines having a low IEC class were installed also in geographic areas where the wind resource is not so strong. Obviously, some years ago, this was acceptable because there were no other options for the wind exploitation, but today on the market are present many producers that design and sell a wide variety of wind turbine generators. This bigger offer allows the constructor of the wind farm to choose the best solution, for the specific case under evaluation, according to wind conditions and other constrains related to territory conformation and regulations.

In Italy, the above-mentioned situation is not rare because the wind resource is not so strong everywhere, even where the wind farms are built, and so theoretically turbines must be characterized by a wind class IEC III, but the oldest wind farms are realized with turbines having a wind class IEC I or II. For this reason the repowering process in our case can be a valid alternative for the wind parks that are going towards their end of life. In fact, the substitution of old generators with new ones and the design of a new plant layout allow the owner's plant to continue to exploit the site, that probably is characterized by good wind conditions, in a more efficient and profitable way. In this way it can be ensure an increase of the electricity production per unit area comparing to existing plant and a greater support to the country's electricity grid, with better power quality, even if the grid has to be reinforced according to the increment of the plant's capacity [17].

Additionally, it is important to notice that the re-exploitation of the same site for the new plant allows to optimize the layout and operation of new turbines, thanks to the good knowledge of the wind resource and of the site characteristics due to the plant managing for long time. This also gives the opportunity to exploit existing electrical and civil infrastructures by reducing the capital costs and the impact on the territory. Furthermore, the new turbines, having a bigger size and higher efficiency, permit to install a lower number of machines by reducing the investment cost, the environmental and visual impacts and the operation and maintenance costs [16]. The environmental impact with new bigger turbines is obviously larger in terms of soil occupancy, due to the huge dimensions of foundations, and of visual impact, due to larger rotor swept area and higher towers. However, these considerable sizes can be supposed to be balanced by the reduction of the machines' number. At the same time, the sound emissions are almost similar to the old ones, but the fact that the towers are taller implies that the noise level reaching the ground, where receivers are placed, is strongly reduced. Finally, the fact that the rotor of new turbines is characterized by a lower angular wind speed and the reduction of units installed, reduce the avian mortality even if the rotor swept area is larger.

Despite all the possible advantages, the main barrier to the repowering process is related to the fact that, compared to the time of authorization and construction of these plants, the legislation regarding the suitable areas for installation of renewable plants has undergone substantial changes becoming stricter. Therefore, before defining the new plant layout and actuating the substitution of machines, it is necessary to evaluate the constraints imposed by the current regulations. In fact, it is possible that during the years some areas, which in the past were not interesting from environmental or architectural perspective, today are considered protected. Furthermore, the increased dimensions of turbine's components represent a quite important problem to be faced since most of the windy sites, where plants were built, are located in remote areas at high altitude far from the coast and from the main seaports which are essential hubs for the on-site transport of the new wind turbines. The critical issues, in most cases, are related to the transport of blades, which are the bulkiest element in terms of length. This implies the search and use of roads with a little slope and a low number of curves having a reduced curvature radius. In case of tight curves, it is necessary to intervene by widening existing roads or creating new paths. Another viable solution in such cases, is to use the so-called blade-lifters, a special transport mechanism in which the blade is hooked to the root and can be transported in elevation. This solution is often adopted when it is required the passage through buildings of villages. At the same time, the increased dimensions can be a critical issue when elements limited in height, like bridges, overpasses or road presenting electrical or telephone overhead lines, are encountered during transportation. Finally, practical considerations for transportation must be exanimated also in terms of maximum loads that can be travelled on bridges and overpasses due to bigger weights of components, especially of nacelle and tower.

2.2. Revamping

Revamping consists in the substitution of some obsolete components of the wind turbine to improve the efficiency of the system without modifying the plant's layout. This process can be particularly interesting when the site presents problems, related to morphology and accessibility, that do not allow to implement a repowering intervention. Today the main revamping operation adopted is the "reblading" which consists in the substitution of the old blades with new ones having better performances, but same dimension. Other interventions can be the substitution of the programmable logic control (PLC) and the installation of the anemometer on the hub of the turbine.

An interesting and profitable opportunity, even in the short term, is represented by the possibility of replacing the blades ("reblading"). In fact, after 10÷15 years of operation, the blades start to show a relevant performance reduction caused by the constant exposure to atmospheric agents. Actually, the new blades present performing aerodynamic profiles adaptable to the wind conditions of the site and are built with stronger and lighter materials. The blades' substitution allows to extend the useful life of the plant by increasing the annual energy production without facing to a too expensive investment. It is estimated a gain in terms of annual energy generation in the range of 15÷20% [16]. The new blades' profiles are designed according to the specific wind conditions of the site. Therefore, it is necessary to upgrade the PLC to correct and adapt the control of the pitch angle to the new aerodynamic profile and extend the operating range of the machine. Usually this allows the wind turbine to operate in low wind conditions thus decreasing the cut-in wind speed. Finally, an additional option, in order to increment the performances by means of a limited investment, is to substitute or integrate the anemometer placed on the nacelle with another one installed on the turbine's hub. In this position the anemometer is not influenced by the turbulences generated by the rotor and so is able to measure the undisturbed incoming wind velocity in an accurate way. Therefore, due to a greater evaluation of wind speed and direction, it is possible to better regulate the orientation of the turbine and blades and so to harvest more energy.

Basically, the revamping, with respect to repowering, implies non-substantial changes in plant layout, dimension and operation and therefore the authorization process is easier and faster and investment costs are lower.

Chapter 3

Regulatory framework

The choice of the location and of the design configuration of the wind farm must be done according to the national and regional regulations. Usually, they have to be aimed at the recovery of degraded areas, if compatible with the wind resource, and at the creation of new values consistent with the environment context. The study about the inclusion of the plant in the ambient must foresee the analyses of protection levels, of landscape's characteristics, regarding both natural and human components, of the visual impact and of the historical evolution of territory.

The analysis of the environmental impact, especially in terms of visual perception, consists in the definition of the obstruction of the visual cones from priority points of view and of the variation of landscape value. To reduce the impact on the territory the turbines have to be installed, according to technical and productional constraints, at a proper distance far from naturalistic and architectural viewpoints also paying attention to not interrupt recognized historical units. Moreover, during the design of the plant layout, it is suggested to meet the geometries of the territory, by preferring homogeneous turbines' group instead of scattered solution, and to assume a relative distance between machines of about 5÷7 diameters on the prevailing wind direction and of 3÷5 diameters on the perpendicular direction [18].

Some measures, to reduce the impact on the landscape, are also adopted by turbines' manufacturer with the usage of neutral and anti-reflecting coating and the absence of transformer stations at the bottom of the tower. The effective and concrete impact on the environment, in terms of direct elimination of vegetation, is limited only to the portion of the terrain where turbine foundations are built.

In fact, the national legislation provides that cables for the energy transportation are putted underground and that are used existing roads for the construction and operating periods by only making some changes where required. Usually during the construction phase provisional enlargements and adaptations of roads are realised to allow the big trucks to reach the wind farm site. All these road modifications must then be restored at the end of the construction period. Always, according to the purpose of reducing the impact on the environment, at the end life of the plant decommission and site restoration in conditions like the original state have to be foreseen. In particular the concrete foundation structure must be embedded in the ground at a depth of at least 1m and the electrical lines must be removed and disposed according to the regulations.

3.1. National regulation

The procedures envisaged by the national legislation for the construction of plants powered by renewable sources, including wind farms, are essentially three. The applicability of these procedures is related to the power thresholds defined in Tab. 3.1.

Table 3.1 – Authorization procedures according to the type of wind plant [16]

Type of wind plant	Authorization procedure
Plants characterized by a nominal power higher than 60 kW (the threshold can be extended, by the Regions, with related additional criteria, up to 1 MW of power)	Unique authorization (AU)
Plants characterized by a nominal power lower than 60 kW Anemometric towers for wind measurements over 36 months	Simplified authorization procedure (PAS)

Reconstruction works on existing wind farms that do not involve changes in the physical dimensions of the devices, in the volume of the structures and in the area of the plant	
Single wind generators, having total height shorter than 1.5 m and diameter lower than 1 m, installed on the roofs of existing buildings Anemometric towers for temporary wind measurements (up to 36 months) made with removable structures in areas not subject to restrictions	Communication to the Municipality

In the context of authorization procedures, always according to criteria such as the size of the system and the context in which the site is inserted, it is necessary to proceed with some assessments relating to the impact on the environment. In most cases it is necessary to proceed at least with a verification of eligibility (VA or screening) and sometimes with a complete environmental impact assessment (VIA). These procedures are regulated by the Legislative Decree n.104 of 16 June 2017. The first one has the aim to determine if the project must be or not subjected to the environmental impact assessment. The second one consists in the complete analysis of the environmental impacts in which specific technical-environmental studies are performed. In addition to the VA and VIA procedures, the Legislative Decree 104/2017 also introduces the possibility of proceeding with a simpler pre-screening that consists in the request for preliminary assessment of the procedural process to be initiated. The request is sent to the competent body, and, within 30 days, it must communicate if the changes, extensions and adjustments must be subjected to VA or VIA.

According to the total nominal power of the plant, the various authorization processes are managed by the state body MiTE, if the installed power is bigger than 30 MW, or directly by the Regions if the installed power is in the range 1÷30 MW.

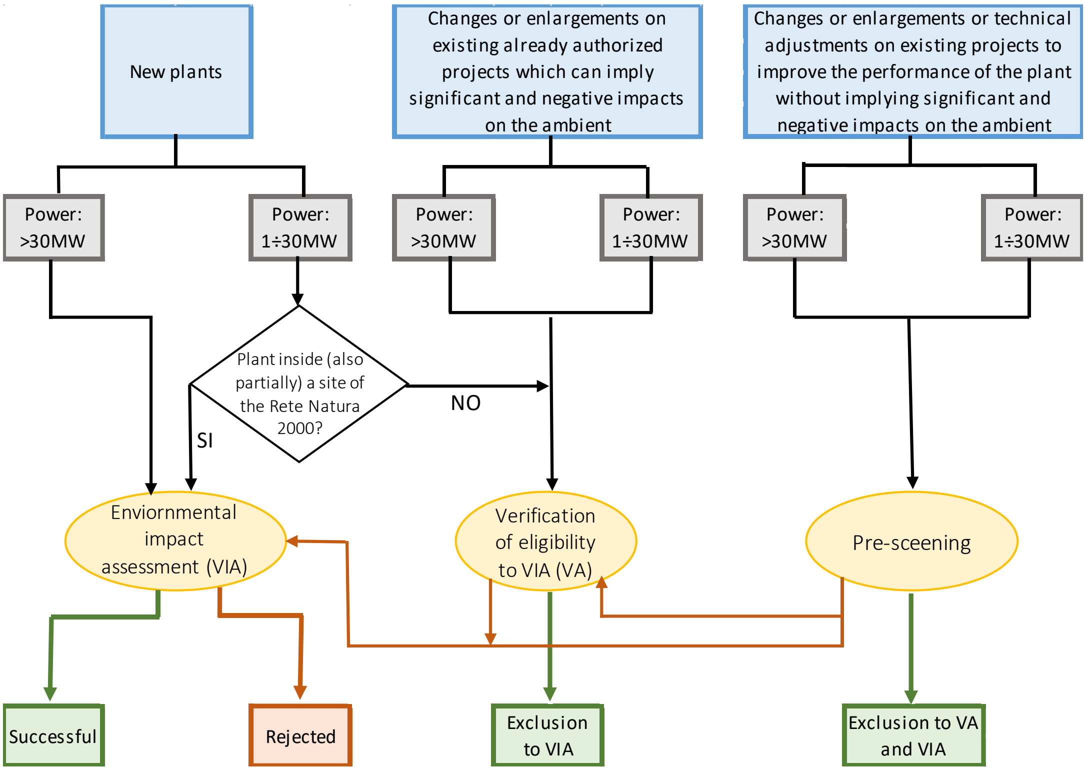

Figure 3.1 – Scheme of the procedural process for environmental assessment by type and size of plant [16]

3.1.1. Suitable and unsuitable areas

In order to obtain the authorization for the construction, the project must respect and satisfy some criteria, most of them regard the site location where the wind farm will be built. In particular the plant must not be located inside sites of particular cultural or landscape interest or subject to other types of technical constraints. The Art.142 of the Legislative Decree n.42 of 22 January 2004, also known as the *Code of cultural heritage and landscape*, provides a list of the protected areas and, in some cases, the relative buffer. Are subject to the provisions of this legal ground the following areas:

- coastal territories included in an area of 300 meters deep from the shoreline, also for the elevated lands on the sea;
- territories adjacent to lakes included in a zone of 300 meters deep from the shoreline, also for the elevated territories on the lakes;

- rivers and watercourses with a buffer zone of 150 meters from each embankment;
- mountains for the part exceeding 1600 meters above sea level for the Alpine chain and 1200 meters above sea level for the Apennine chain and the islands;
- glaciers;
- national or regional parks and reserves and all the sites included in the Natura 2000, as well as their external protection territories;
- territories covered by forests and woods, even if crossed or damaged by fire, and those subject to reforestation restrictions;
- areas assigned to agricultural universities and areas burdened by civic uses;
- wetlands defined with the Ramsar Convention;
- volcanoes;
- areas of archaeological interest [19].

In these zones the installation of plants is forbidden at the national level. However, each Region can provide additional not suitable areas according to more restricted technical constraints related to the specific characteristics of the environment. Furthermore, with the RED II Decree of 15 December 2021, it has been decided that suitable areas for the installation of RES must be defined, so that if the plant falls within these areas, the time required for the authorization procedures would be reduced by a third. Within 180 days from the decree coming into force, the MiTE must provide to the Regions some guidelines for the definition of such suitable areas. The criteria must be based on objective considerations and must prefer areas where there are already installed RES plants or degraded or industrialized areas. Then, within 180 days, the Regions must define these suitable areas which will be collected into a public national database. The decree, with the so-called burden sharing, also defines the distribution of installed power between regions and arranges for the implementation of new monitoring systems [20].

3.1.2. Provisions about repowering

To ensure a rapid development of the Recovery and Resilience National Plan (PNRR), it is essential to eliminate all the possible obstacles that could delay the investments and the implementation of projects. For this reason, in April 2022, it has been approved a law, that modifies the D.Lgs. 28/2011, with the useful simplifications to favour the energy transition. The decree accelerates investments regarding the green economy through the simplification of authorization procedures with reference to renewable sources, especially if located in suitable areas. Moreover, it also disposes the simplification of the repowering activity.

Regarding the wind energy plants, the law establishes that are not considered substantial and are authorized by simple communication, the interventions on wind farms, and on related works, which regardless the nominal power resulting from the changes, are made in the same area of the plant and which involve a minimum reduction in the number of wind turbines compared to those already existing or authorized. Always by respecting the current legislation on minimum distances of each wind turbine from housing units with habitability, regularly registered and permanently inhabited, and from inhabited centres identified by the urban planning instruments in force, as well as the compliance with the legislation on the disposal and recovery of wind turbines. The new wind turbines, because of the increase in their diameter, must have a limited maximum tip height, evaluated as the height from the ground that can be reached from the extremity of the blades [21]. Additionally, the decree specifies some definitions that must be considered and complied during the development of the project. Naming $d_1[m]$ the rotor diameter of the existing authorized wind turbines, n_1 the number of the existing installed aerogenerators, $d_2[m]$ the rotor diameter of the new wind turbines and $h_1[m]$ the tip height, with respect to the ground, of the existing authorized wind turbines, the following definitions are provided.

Wind plant site means:
a) if the plant is on a single route, the new one must be built on the same line with a maximum angular deviation of 20°, considering the same length plus a tolerance of 20% of the authorized plant length evaluated between the axes of the two extreme wind turbines
b) if the system is located on more directives, the overall planimetric surface of the new plant has to be within the perimeter identified by a line that joints, always forming convex angles, the points corresponding to the axes of the most external authorized wind turbines with an overall tolerance of 20%.

Minimum reduction of the number of aerogenerators means:
a) if the existing authorized wind turbines present a rotor diameter equal or lower than 70m, the number of new aerogenerators must be lower than

$$min\left(\frac{2}{3}n_1\,;\,n_1\frac{d_1}{d_2-d_1}\right) \tag{3.1}$$

b) if the existing authorized wind turbines present a rotor diameter bigger than 70m, the number of new aerogenerators must be lower than

$$n_1\frac{d_1}{d_2} \tag{3.2}$$

rounded up.

Maximum height of the new aerogenerators means:
the maximum tip height of new wind turbines has to be lower than

$$h_1\frac{d_2}{d_1} \tag{3.3}$$

3.2. Regional regulation

In Italy each Region periodically subscribes a regional environmental energy plan which regulates both structural and infrastructural interventions in the energy field. In February 2022 Sicily updates its energy plan PEARS in order to adapt the old version to the current needs of energy efficiency and energy transition and to the changed regulatory framework on authorization regimes considering also the recent innovations in the energy technology field. With reference to the wind sector, the production is expected to increase by a factor of 2,2 compared to normalized production in 2016 (2808 GWh), to reach a value of approximately 6177 GWh [22]. The authority provides that such increase in energy production must be achieved through the revamping and repowering of the existing plants and the creation of new realities.

Before 2010, in Sicily, were installed about 64 wind energy plants for a total installed capacity of 1383 MW. It is believed that these plants will reach the end of life within 2030. Consequently, to satisfy regional and national targets regarding energy production from RES, it is required that most of these farms have to be subjected to repowering or revamping processes. To encourage this kind of actions the regional bodies undertake to simplify and accelerate the authorization procedures. However, it is estimated that around 14 wind plants, for a total installed power of 333 MW, must be dismissed and disposed of because they are located in unsuitable and restricted areas. Repowering will be made on the remaining part of installed power, and it is assumed that this will increase the regional power capacity of about 1 GW allowing to reach a regional total production of 5140 GWh. Furthermore, new plants will be installed for a total capacity of about 500 MW. In this way in 2030 approximately 3000 MW are expected to be installed against the actual 1894 MW.

Table 3.2 – Wind power development by 2030 in Sicily [22]

Installed power (31/12/2019)	1893,5 MW
New power from repowering	1000 MW
Power to be dismissed	333 MW
Power from new plants	446 MW
Total power by 2030	3000 MW

3.2.1. Constrained areas

With the Regional Presidential Decree of 10 October 2017, Sicily classifies the wind energy plants in three main classes according to the nominal installed power: EO1 for those plants having a power lower than 20 kW, EO2 for those plants having a power in the range 20÷60 kW and EO3 for those plants having a power higher than 60 kW. According to the national legislation regarding the suitable and unsuitable areas for the construction of wind plants, the decree states that it is forbitten to install wind plants of type EO1, EO2 and EO3 in zones of environmental interest like SIC, ZPS, ZSC, IBA, Ramsar sites, national and regional natural parks, geosites and oasis of protection and a refuge for fauna [23]. At the same time, these plants can be realised, by paying particular attention, in zones subjected to hydrogeological constraints and characterized by prestigious agricultural productions.

Italy is a fragile territory strongly exposed to landslides, floods and subject to coastal erosion. For this reason, each Region edits its own plan for the hydrogeological structure (PAI) with the purpose to reduce the hydrogeological risk in order to safeguard the safety of people and minimize damage to the environment. Sicily, with the PAI, define a classification of the risk and of the danger both for geomorphologic and hydrogeologic aspects. The risk can be organized in four classes: R1 for moderate risk, R2 for medium risk, R3 for high risk and R4 for very high risk. On the other hand, the hazard can be divided in five classes: P0 for low danger, P1 for moderate danger, P2 for medium danger, P3 for high danger and P4 for very high danger. Whit danger is mean the probability that conditions of calamitous event occur in a given area. Especially, geomorphological hazard refers to instability phenomena in progress and therefore does not concern the danger of areas not affected by instability, while hydraulic hazard is related with the annual probability of exceeding a reference flow evaluated as a function of a specific return time (number of years in which the full flow rate is equalled or exceeded).

The Regional Presidential Decree of 10 October 2017 also gives some guidelines regarding the possibility to install wind plants in areas subjected to hydrogeological constraints. Given that EO2 and EO3 plants are considered of primary importance and EO1 plants are considered of secondary importance, in areas characterized by a PAI hazard of P4 and P3 the EO3 and EO2 plants cannot be realized while EO1 plants can be realized compatibly with a geomorphological verification. On the contrary, the plants of class EO1, EO2 and EO3 can be built in the areas identified by a PAI danger of P2, P1 and P0 if equipped with a proper geologic analysis.

Chapter 4

Monte Mola wind farm

Having a general view of the technologies and of the national and regional regulations regarding the exploitation of wind energy it is now possible to analyse a real case study.

The work is focused on the repowering project of an onshore wind farm built in Sicily during the 2000s by the company Asja Ambiente Spa. The plant is located in the municipality of Buseto Palizzolo (TP) exactly in the Monte Mola district south-east of the urban centre. It is about 7 km far from the city of Buseto Palizzolo and about 20 km far from the city of Trapani.

Figure 4.1 – Wind farm area

Mainly surrounded by arable fields for agriculture and grazing, the site has a moderately complex orography with gentle slopes and good exposure to prevailing winds. The altitude of the site is about 370÷440 m above sea level.

4.1. Wind farm in operation

The original authorized plant was built in 2006 and entered in operation in 2008, when all the additional works for the connection of the farm to the electrical national grid were completed. It is composed of eight production units, each consisting of a wind turbine generator V52-850kW by Vestas. The nominal power of each machine is 850 kW and therefore the total installed plant capacity is about 6,8 MW. In this way, it was expected an average gross energy production of about 12115 MWh per year with 1782 annual equivalent hours. Considering that no fossil fuels are used by the wind plant for the energy production, it was estimated a reduction of the pollutant and greenhouse gases emissions of about 5853 ton/year of CO_2, 17 ton/year of SO_2 and 23 ton/year of NO_2.

The plant is displaced over two principal directions. The planimetric surface of the plant, identified by the line that joints together the most external machine points, presents an area of about 380 m^2.

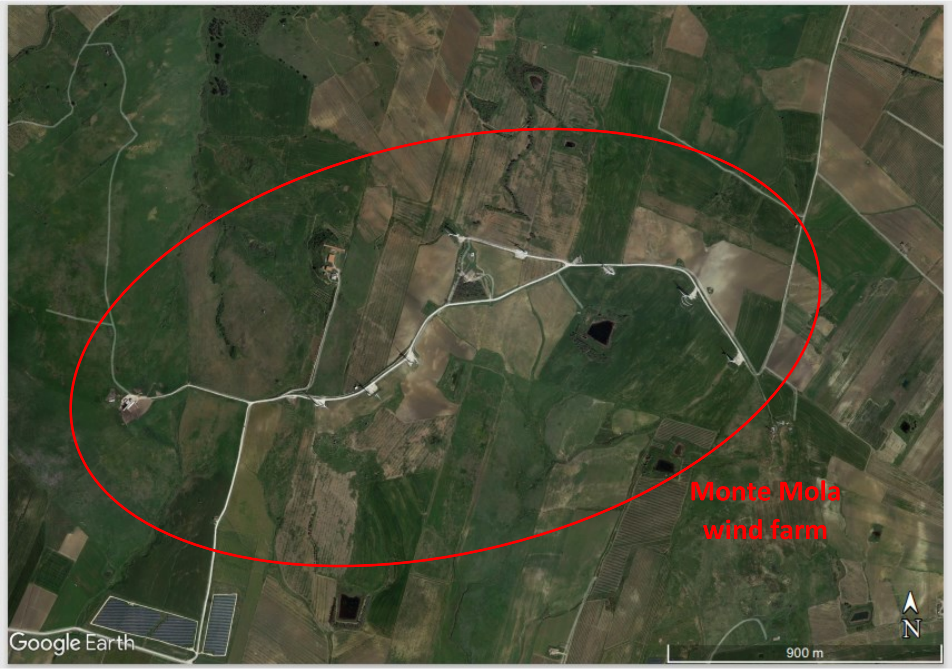

Figure 4.2 – Identification of the plant area on orthophoto

The V52-850kW is a classical pitch regulated upwind turbine with active yaw and a three-blade rotor having a diameter of 52 m. Each blade, made of glass-fibre reinforced epoxy, is 25,3 m long and weights approximately 1900 kg. The rotor is installed on a tapered tubular multiple-parted steel tower having a hub height of 49 m. At the top, where is mounted the nacelle containing the 4-poles asynchronous electrical generator and the gearbox characterized by a multiplayer ratio of 1:75, the tower diameter is about 2 m. At the bottom, where is located the transformer (1000kVA 20kV/690V – 50Hz), the tower diameter is about 3,3 m.

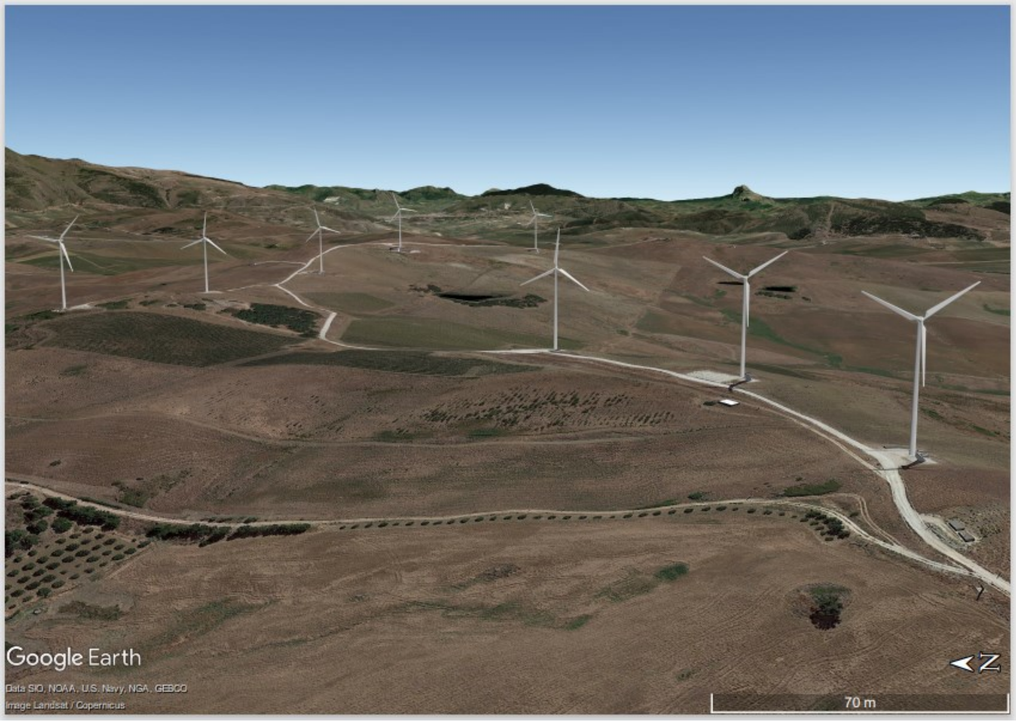

Figure 4.3 – Monte Mola wind farm

The installed wind turbine generators are characterized by a wind class IEC IA. The relative power curve is the one represented in Fig. 4.4 and it presents a cut-in wind speed of 4 m/s and a cut-out wind speed of 25 m/s. These turbines are today out of production and anyway are not really suitable for Italian sites since they are design for strong wind conditions like the ones of North of Europe.

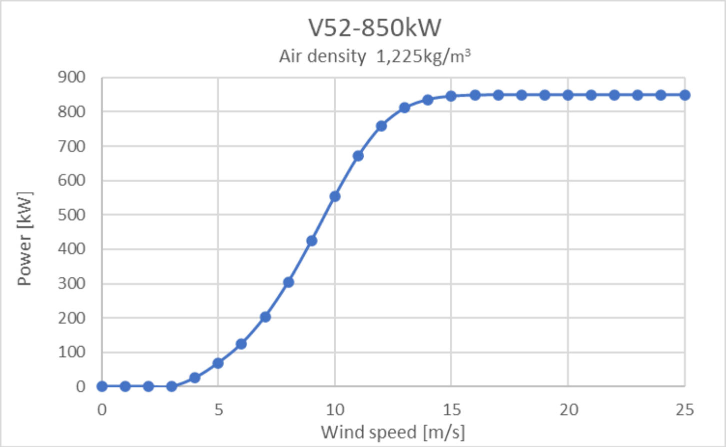

Figure 4.4 – V52-850kW power curve

In 2017 the farm was expanded by adding a new wind turbine presenting a unitary power of 1,7 MW. It consists in a Vestas asynchronous 4-pole generator with wound rotor, the V80-2.0MW. Even this machine is a pitch regulated variable speed upwind turbine with active yaw. It presents a three-blade rotor, having a diameter of 80 m, that is mounted on four-parted tapered tower 78 m high. The bigger dimensions of the rotor imply longer and heavier blades: each one is 39 m long and 6500 kg heavy. This results in a larger visual impact, but also in a greater power extraction from wind. Moreover, an additional advantage of this turbine type is the higher wind class, IEC IIA that fits better also with sites where the wind resource is not so strong. The power curve of the turbine is represented below.

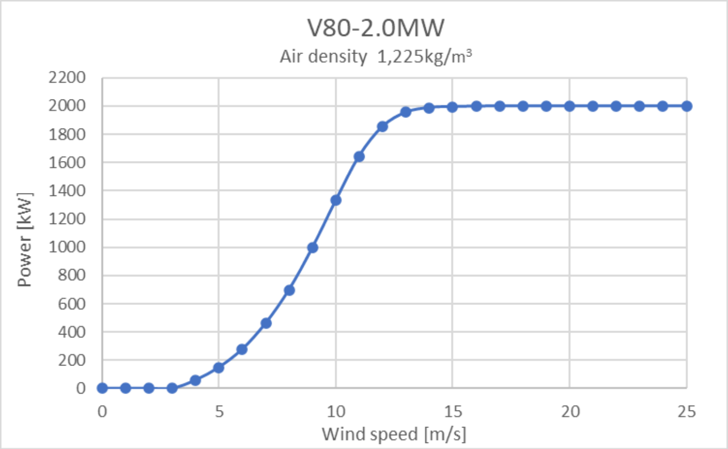

Figure 4.5 – V80-2.0MW power curve

The plant is also equipped with an anemometric tower whose purpose is to monitor the wind resource and therefore the energy production. The lattice tower has a height of 50 m and is equipped with two pairs of sensors, the first to measure the intensity of the wind (anemometer) and the second to identify the direction of the wind (weathervane). Data recording is carried out by a data logger in which the data is stored and subsequently sent to offices for the processing. More recent anemometric towers are today also equipped with some sensors for the measurements of air temperature and humidity. This information is important for the evaluation of the air density that influences the power production of the turbines.

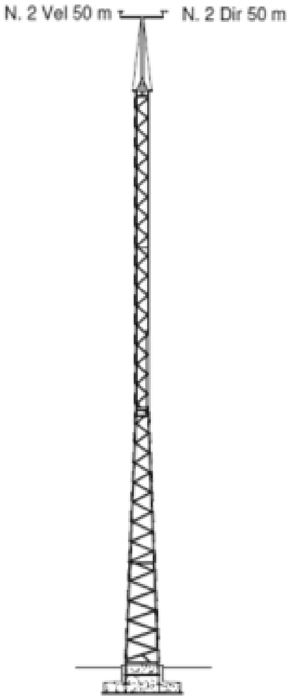

Figure 4.6 – Anemometric tower

Below is reported a table highlighting the coordinates of the wind turbines and a picture showing the layout of the plant.

Table 4.1 – Wind turbines and anemometer coordinates

Plane coordinates in datum WGS84 e UTM system (time zone 33)

		UTM-WGS84 (33S)[1]	
N. WTG	**Type WTG**	**East**	**North**
Anemometer	-	303624	4203713
MM01	V52-850kW	303107	4203260
MM02	V52-850kW	303276	4203292
MM03	V52-850kW	303407	4203389
MM04	V52-850kW	303574	4203786
MM05	V52-850kW	303787	4203726
MM06	V52-850kW	304060	4203654
MM07	V52-850kW	304304	4203576
MM08	V52-850kW	304436	4203370
MO01	V80-2.0MW	302617	4203329

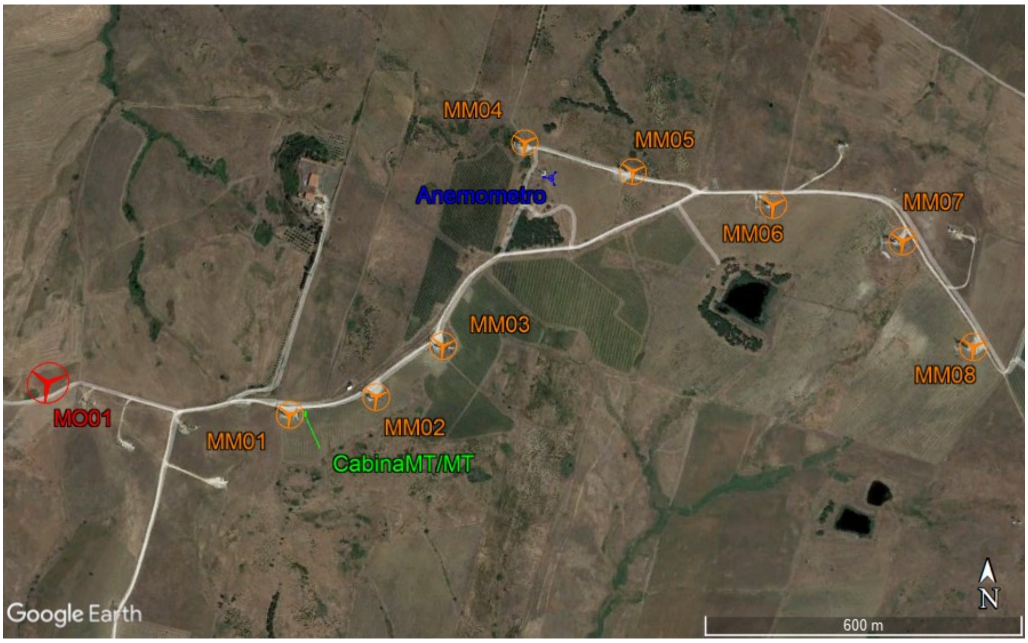

Figure 4.7 – Monte Mola wind farm layout

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[1] The UTM (Universal Transverse Mercator) is a plane coordinate system associated with both the ED50 and WGS84. It adopts the Gauss representation considering the entire globe as divided into 60 time zones of 6 degrees each. The time zones are numbered from 1 to 60 towards east starting from Greenwich antemeridian. The entire italian territory is between 3 time zones: 32, 33 and 34.

4.1.1. Energy production

Since the beginning of the plant operation, until the end of 2021, Monte Mola wind farm accounts for a cumulative net energy production of about 160274 MWh. On average, the AEP of the plant is around 11930 MWh/year and its variability in the different years mainly depends on the variability of the wind resource. In Tab. 4.2 and in Fig. 4.8 is highlighted the evolution of the net AEP during the lifetime of the plant. Knowing the net AEP, it is possible to calculate the equivalent hours as the ratio between the net annual energy production and the plant capacity:

$$h_{eq} = \frac{AEP}{P_{nom}} \tag{4.1}$$

The equivalent hours indicate the total number of hours in a year in which the plant would operate if it worked at the rated power.

Table 4.2 – Net annual energy production and equivalent hours

Year	Net AEP [MWh]	Net h_{eq} [h]
2008[2]	5176	761
2009	11904	1751
2010	13334	1961
2011	10815	1590
2012	11770	1731
2013	12754	1876
2014	11688	1719
2015	10711	1575
2016	12786	1880
2017	12344	1815

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[2] Data collected starting from July. For this reason, in 2008, the AEP and h_{eq} are much lower than in the other years.

2018	12254	1802
2019	12725	1871
2020	10313	1517
2021	11700	1721
Average on the period 2009-2021	11931	1755

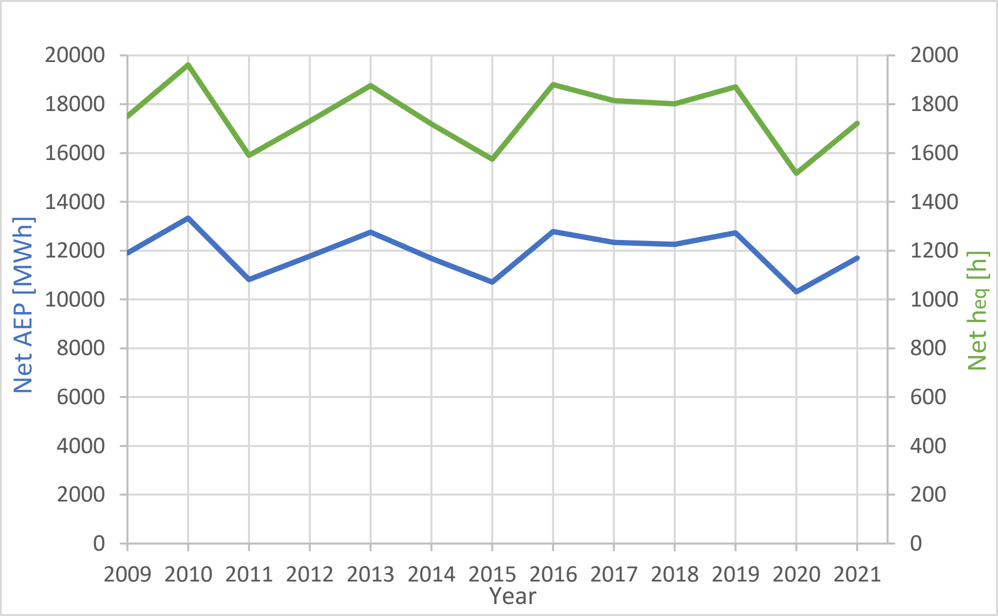

Figure 4.8 – Net annual energy production and equivalent hours

By knowing the annual equivalent hours, it is possible to highlight the real plant efficiency that is represented by the capacity factor CF. The capacity factor is an indicator that identifies the relationship between the energy produced in a time interval and that which could have been produced if the plant operates, in the same time interval, at nominal power. In practice it can be calculated as the ratio between the annual number of equivalent hours and the total number of hours in a year:

$$CF = \frac{h_{eq}}{8760} \tag{4.2}$$

Considering the Monte Mola wind farm, that is characterized by an average number of equivalent hours of about 1755 h, the capacity factor of the plant is equal to 0,20. This value is slightly below the national one. In fact, in Italy, the current capacity factor of the entire national wind farm is 25%, corresponding to approximately 2200 h of plant operation per year at nominal power. The fact that the wind farm under evaluation presents a quite low CF is related to the turbine type that is not suitable for the site. For this reason, the repowering idea could be interesting: it is expected that, with the new turbines, the capacity factor of the wind farm will increase.

4.2. Repowering of the wind farm

The height wind turbines installed in Monte Mola in 2008 are today approaching to their end of life and the incentives granted by the network manager are going to expire in next years. For these reasons, the company Asja Ambiente Italia Spa has decided to undertake a repowering activity on the wind farm. The purpose is to completely substitute the V52-850kW turbines with more performable machines. The only wind turbine that will not be removed but will be left in operation is the V80-2.0MW since it is installed recently and therefore is still able to produce energy in an efficient way.

This chapter is focused on the initial steps of the project: from the identification of the machine points of the new wind turbines to the productivity analysis. The discussion covers only the preliminary phase of the entire work that will be required for the installation of the new machines. As a general information, the analysis developed in this essay, assisted with additional environmental and technical studies, is the basis of the executive project that is requested for obtaining the authorization and for the construction of the plant itself.

It is important to underline that, until the new wind turbines will be installed, the V52-850kW will continue to operate and harvest energy from wind avoiding the interruption of power production. Once the new WTG are ready to work, the old ones and all the useless equipment will be removed and dismissed in order to restore the area to its initial state. The resulting wastes will have to be managed and disposed of according to the D.Lgs. 3 April 2006, n. 152 – *Part IV: Regulations on waste management and remediation of polluted sites*.

4.2.1. Constraints and regulatory aspects

The first step of the project is to evaluate the natural and technical constraints of the site area. For what concerns Sicily this information can be found on the SITR website.

As highlighted in Fig. 4.9 the area under investigation presents a lot of constraints. The plant is located outside areas with archaeological restrictions, protected natural zones and Natura2000 sites. Particularly it is placed about 1,5 km far from the northern ZSC, about 4,5 km from the southern ZSC and about 6,5 km away from the eastern ZPS and IBA area. Even most of the woods, as defined by the L.R. 16/96 and by the D.Lgs. 227/2001, are quite far from the plant site. This is important not only from a legislative point of view, but also because trees and forests can affect the power production since they can act as a sort of obstacle for the incoming wind. The area is also characterized by many small water basins and several surface and underground water bodies. Some of them also present a buffer zone, identified in the picture with the light blue oblique hatching, that is considered a landscape heritage in which the construction is not allowed. The area is not subject to hydrogeological constraints but presents some areas having a medium (R2) and high (R3) geomorphological risk and a moderate (P1) and medium (P2) geomorphological danger.

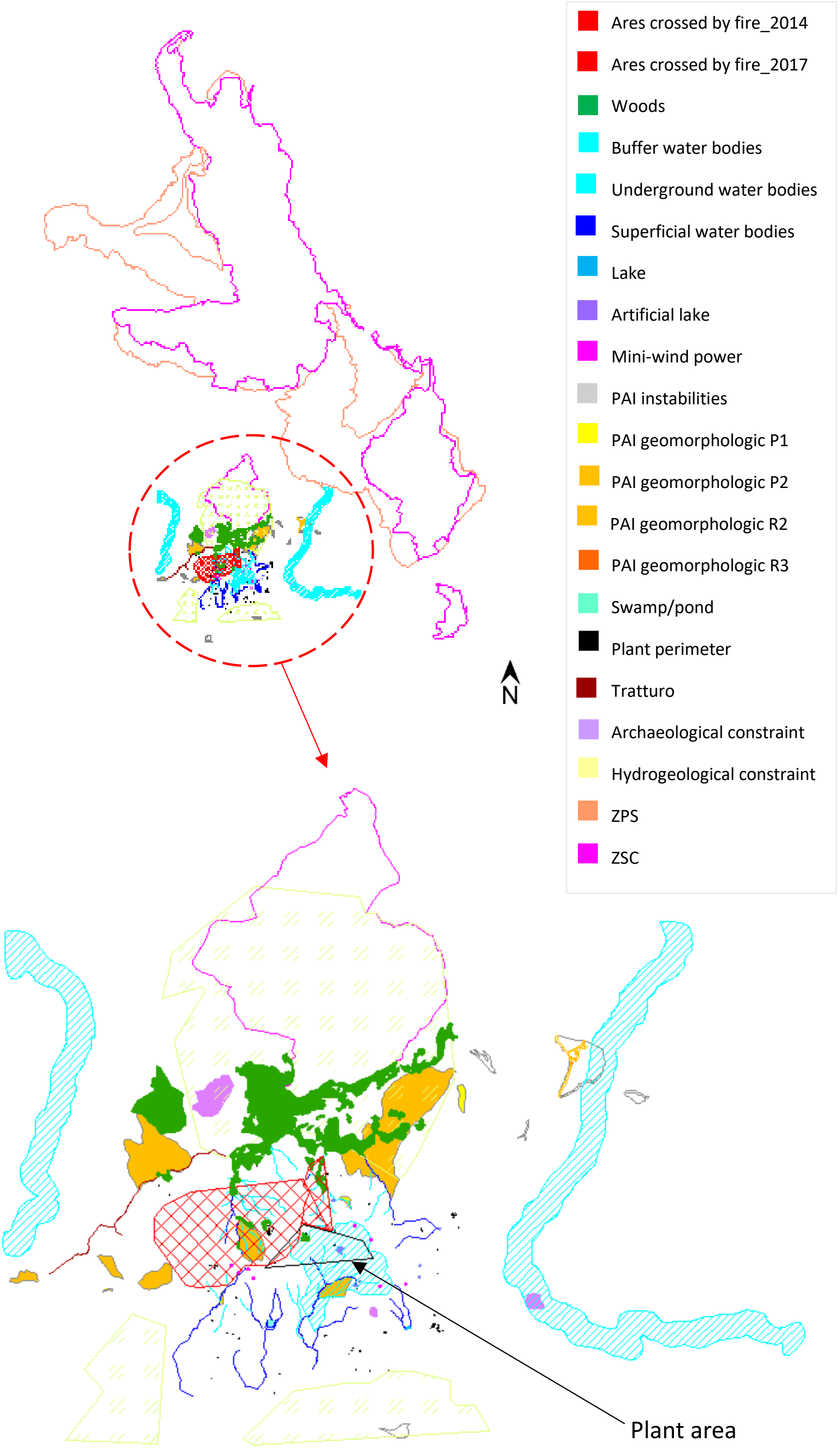

Figure 4.9 – Constrained areas

Moreover, the figure also contains information not directly related to environmental, landscape or cultural constraints. With the little pink circles are identified the machines of a mini-wind power plant that was built in the last five years, but never came into operation. While with the red areas are represented the surfaces crossed by the fire. In fact, the national legislation L. 353/2000 prohibits, for at least 15 years, the construction of unnecessary works and the changes in the intended use of the area affected by the fire, with respect to the urban use prior to the combustion event.

As already seen in Chapter 3, the national legislation also prescribes some rules regarding the location, the number, and the dimensions of the new wind turbines in case of a repowering project.

The Monte Mola wind farm can be considered a plant disposed on several lines; therefore, the site of the repowered farm must be the same of the existing one. The only difference is that the surface can be enlarged of a 20%. In the next figure it is highlighted the perimeter of the plant in operation and the enlarged one within which the new turbines must be installed.

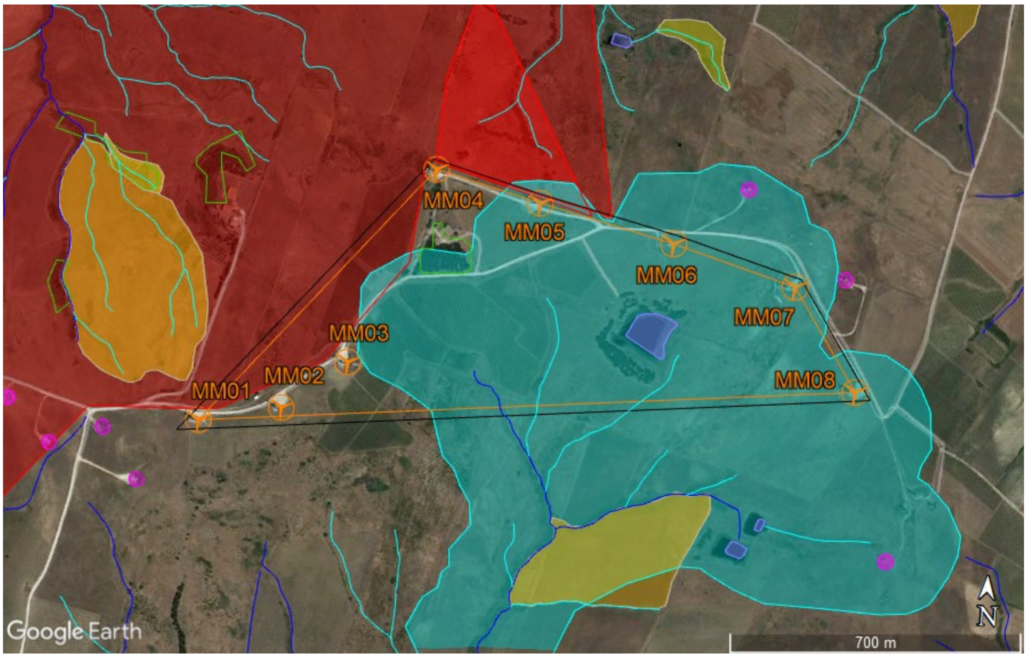

Figure 4.10 – Perimeter of the wind farm in operation (orange line) and the enlarged one exploitable for the repowering (black line)

For what concerns the constraints regarding the number and dimensions of the new aerogenerators we have to consider that the existing wind turbine generators, to be removed, presents a rotor diameter lower than 70 m. Specifically the installed V52-850kW turbines present a rotor diameter d_1 of 52 m and a hub height of about 49 m. Therefore, the tip height h_1, understood as the maximum height from the ground that can be reached by the end of the blades, of the existing machines is equal to 75 m.

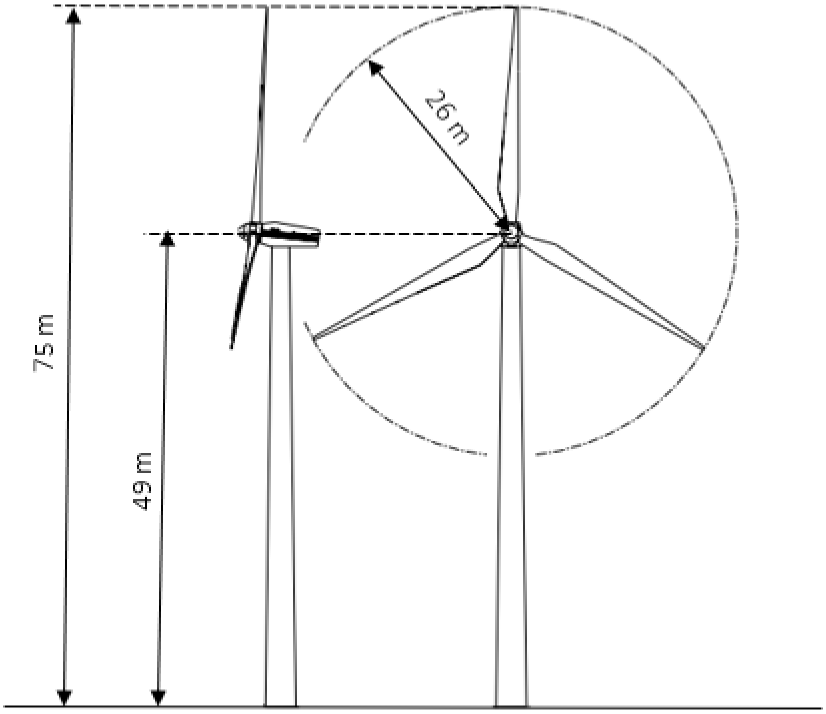

Figure 4.11 – Dimensions of the V52-850kW wind turbine

As already seen, the main purpose of the repowering activity is to increase the total installed power by reducing the number of machines and therefore the visual impact. For Monte Mola wind farm the number of the new aerogenerators must not exceed the minimum between $\frac{2}{3}n_1$ and $\frac{d_1}{d_2-d_1}n_1$, where n_1 is the number of current authorized machines and d_2 is the rotor diameter of the new wind turbines. At the same time, the increasing dimensions in terms of rotor diameter and tower height could change the appearance of the landscape, therefore too high machines are prohibited. Even in this case the maximum tip height of new aerogenerators depends on the tip height and rotor diameter of current authorized machines and on the rotor diameter of the new wind turbines, as highlighted in the equation 3.3. It is particularly important to consider these last constraints during the choice of the aerogenerators since they depend on the model of WTG that will be installed and especially on the rotor diameter.

Most of the wind turbine producers offer on the market several turbine models characterized by different characteristics in terms of IEC wind class, operability temperature range and dimensions. For what concern the dimensions, the turbine manufacturers provide, for most of the wind turbine generators, more towers presenting different heights. In this way it is possible to respect the imposed constraints and chose the solution that best fits the specific conditions of the site.

As a first step many turbines, that satisfy the requirement about the maximum tip height, are selected from the three major manufactures of wind turbine generators. Knowing their rotor diameter, it is evaluated the maximum number of installable machines with the repowering. As highlighted in Tab. 4.3 the maximum theoretical number of WTGs installable with the repowering in the area is 4 or 5 according to the different turbine model.

Table 4.3 – WTG analysis: tip height and number of machines

Rotor diameter [m]	Repowering constraints		WTG model	Nominal power [MW]	Tower height [m]	Tip height [m]
	Number of WTG	Tip height [m]				
126	5	181,73	V126-3.6MW	3,6	117	180
136	5	196,15	V136-3.45MW	3,45	112	180
			V136-4.0MW	4	112	180
			V136-4.2MW	4,2	112	180
			V136-4.5MW	4,5	112	180
145	4	209,13	SG145-5.0MW	5	127,5	200
149	4	214,9	N149-4.5MW	4,5	125	199,5
			N149-4.5MW	4,5	135	209,5

150	4	216,35	V150-4.0MW	4	105	180
			V150-4.2MW	4,2	105	180
			V150-4.5MW	4,5	105	180
			V150-5.6MW	5,6	125	200
155	4	223,56	V155-3.6MW	3,6	118	195,5
			SG155-4.7MW	4,7	120,5	198
162	4	233,65	V162-5.6MW	5,6	125	206
			V162-6.0MW	6	125	206
			V162-6.2MW	6,2	125	206
163	4	235,1	N163-5.9MW	5,9	118	199,5
170	4	245,19	SG170-6.2MW	6,2	115	200

4.2.2. Possible plant layouts

Taking into account all the constraints and considerations just described in the previous paragraph, three layouts, characterized by four or three wind turbines, are proposed for the repowering of the farm.

Firstly, it must be considered that the repowered plant must be located in the same site of the existing wind farm and that the aerogenerators, possibly, have to present a relative distance of about three times the rotor diameter. However, the choice of the location of the new wind turbines strongly depends on the regulatory constraints, and especially, to the ones linked to the areas crossed by fire and to the river buffer zone, as shown in Fig. 4.10. Additionally, it is also influenced by the presence of the existing machines and of the relative connected works. In fact, during the positioning of the new machine points, it is advisable to install the new turbines near the oldest ones in the same cadastral parcel to exploit entirely or partially the existing pad and to not change the owner of the land. In this way it is possible to reduce costs because less new infrastructures must be built. Moreover, it is preferable to avoid the overlap of the foundations to reduce the economic impact: if no overlapping occurs the old foundations will be removed only for 1m deep, otherwise they must be removed for the entire depth with higher costs.

In the next table and figures are described the possible layouts that will be analysed from an anemometric point of view to highlight which is the optimal one. In the tables are reported the coordinates of each machine point, while in the figures are graphically represented the turbine sites by means of some circles. The black dots represent the tower foundations. Since each type of turbine and tower presents different dimensions, for the moment a diameter of 15 m has been conservatively assumed. When a single turbine will be chosen a more accurate evaluation and study of the foundation must be performed. The smaller coloured circles represent the overall dimensions of the turbine rotor, while the bigger ones present a radius equal to three times the rotor diameter and are used to verify that the distance between turbines is appropriate. Each couple of concentric coloured circles is representative of a particular turbine rotor diameter. In the in the legend of the figures the number after "WTG_" indicates the rotor diameter in meters.

Table 4.4 – 4 WTG Layout A: wind turbines coordinates
Plane coordinates in datum WGS84 e UTM system (time zone 33)

N. WTG	UTM-WGS84 (33S)[1]		Altitude a.s.l.
	East	North	[m]
01	303095	4203241	384,6
02A	303418	4203398	390,4
03	303674	4203768	400
04	304369	4203477	420

Table 4.5 –4 WTG Layout B: wind turbines coordinates
Plane coordinates in datum WGS84 e UTM system (time zone 33)

N. WTG	UTM-WGS84 (33S)[1]		Altitude a.s.l.
	East	North	[m]
01	303095	4203241	384,6
02B	303543	4203278	369,4
03	303674	4203768	400
04	304369	4203477	420

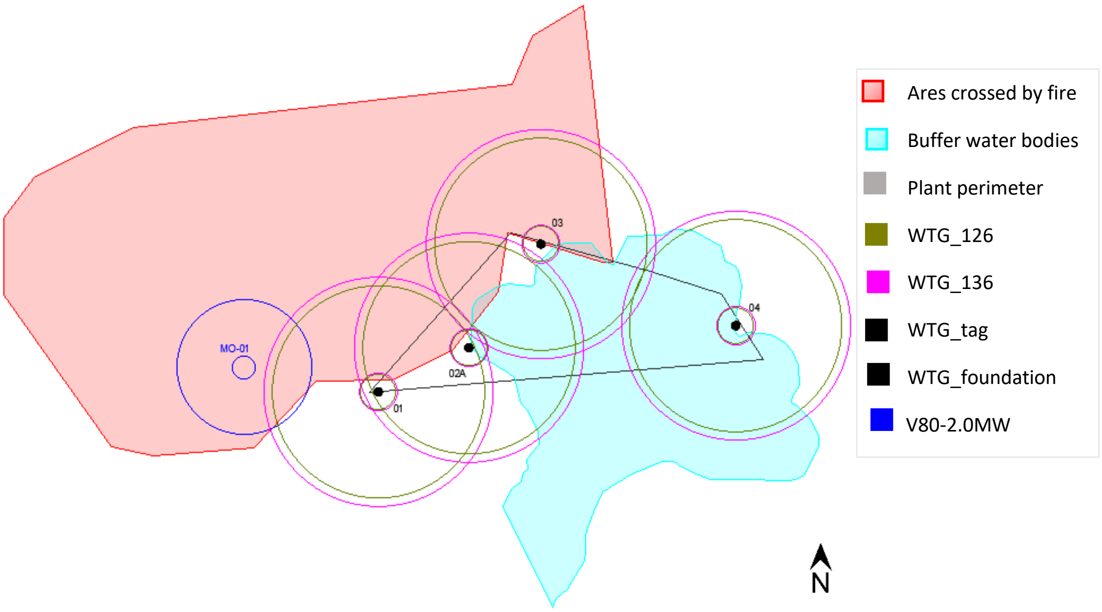

Figure 4.12 – 4 WTG Layout A: wind turbines position

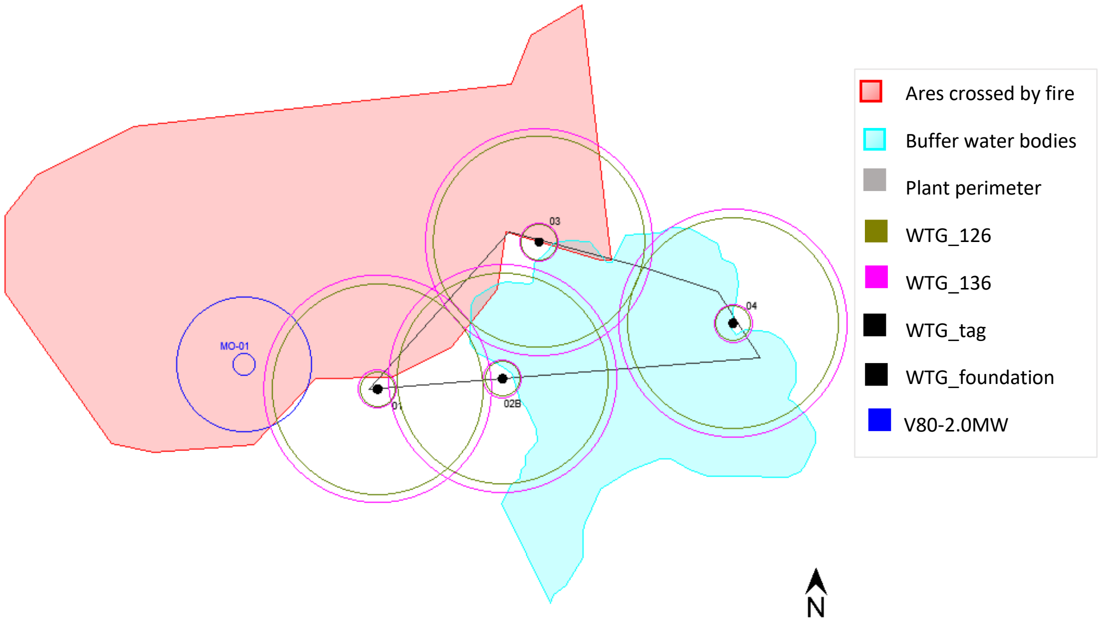

Figure 4.13 – 4 WTG Layout B: wind turbines position

The two proposed arrangements differ only for a single wind turbine position. The WTG 02A is located further north at a higher altitude, about 390 m a.s.l., but is closer to the turbines 01 and 03 and therefore greater visual impact and wake losses are probably created. On the contrary, the WTG 02B is placed at a lower altitude, about 370 m a.s.l., so the wind resource is weaker, but this position allows a bigger distance between the turbines.

The third and last hypothesized layout is proposed for the turbines presenting big rotor diameters, larger than 145 m, that do not allow a proper distance between the various machines. By eliminating the WTG02 we ensure a distance of three rotor diameters between turbines and reduce the investment costs. With the following anemometric analysis, we are able to decide which layout is the optimal one.

Table 4.6 – 3 WTG Layout: wind turbines coordinates
Plane coordinates in datum WGS84 e UTM system (time zone 33)

	UTM-WGS84 (33S)[1]	
N. WTG	**East**	**North**
01	303095	4203241
03	303674	4203768
04	304369	4203477

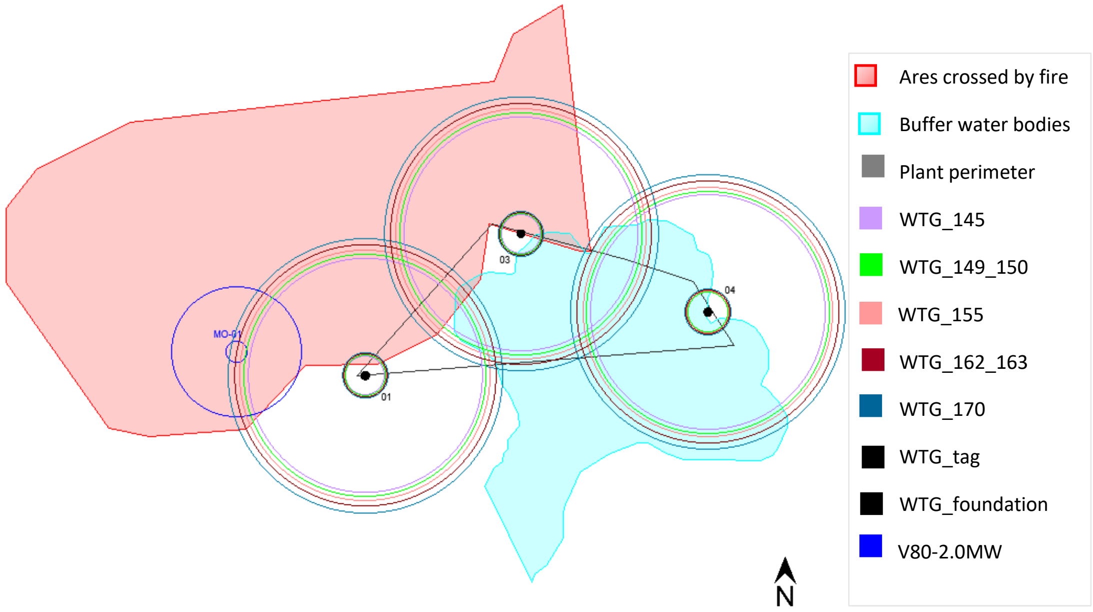

Figure 4.14 – 3 WTG Layout: wind turbines position

4.2.3. Wind data analysis

To perform the productivity analysis and, therefore, to evaluate the annual energy production and the equivalent hours of the repowered plant it is necessary to accomplish a complete analysis of the wind data. The more the data present a good quality and are representative of a long time period, the more the anemometric analysis and the result will be accurate and precise. The standard IEC 61400-12-1 prescribes wind measurements for at least 12 consecutive months. Fortunately, the time series of wind data we have is much longer because the authorized plant is equipped with an anemometric tower for wind measurements. The tower was installed during the construction of the existing wind farm and, since the beginning of 2007, it measured almost continuatively the wind data.

Figure 4.15 – Anemometric tower and wind sensors

The anemometric tower, shown in Fig. 4.15 and located at a height of 420 m a.s.l., is of lattice type and is 50 m tall. On the top are installed two cup anemometers for measuring the wind speed velocity and two windvanes for evaluating the wind direction. All the sensors are linked to the tower by means of four arms 120 cm long to reduce the interferences with the tower itself. To ensure a good wind data evaluation the sensors are calibrated according to the

Measnet standard procedures. Each of the sensor is connected to a specific channel of the data logger as exhibit in the following picture. For a proper recording of the measured data, it must be sure that each sensor is linked to the right channel. In particular, the north anemometer is connected to CH1 and the south one to CH2, while the east windvane is joined to CH7 and the west one to CH8.

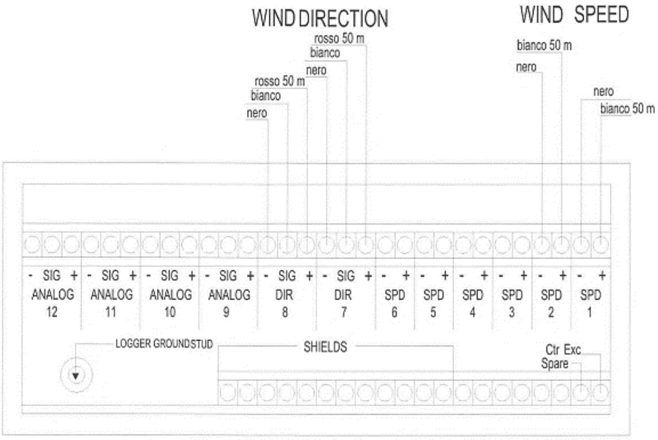

Figure 4.16 – Connection of wind sensors to the channels of the data logger

As already discussed in the introductory part of this work, the anemometric instruments measure wind data continuously. However, the wind analysis, according with standards, is performed with 10-min average data therefore they must be recorded in this format. The measured wind data at the wind farm site are collected and stored by the data logger Nomad2, in the first years of operation, and then by the data logger Campbell, the one still used today. These data can be downloaded remotely in the logger's raw binary format and then are converted to a text file. To correctly read and studied the wind data a software called *Windographer3* is used. The software allows to perform the data validation. This task, which purpose is to detect, flag and then exclude from statistic calculations the invalid or corrupted data, is executed in two following steps. Initially, by means of algorithms, some rules are defined to obtain an automated screening. Then, a manual validation is performed to decide case-by-case what to do with the suspect values.

Once *Windographer3* is opened and the anemometric tower is correctly set specifying its height, coordinates and channels, the files containing the wind data are added. Our time series of data is sufficiently long, about 15 years: from the end of January 2007 to the beginning of April 2022. The second requirement of IEC 61400-12-1, regarding the data availability higher than 90%, has to be checked before starting data filtering. The indicator used for this verification is the data recovery rate:

$$DRR = \frac{N_{valid}}{N_{possible}} \cdot 100\% \tag{4.4}$$

where N_{valid} is the number of valid data points in the time interval while $N_{possible}$ is the possible number of data points in the time interval. Therefore, the DRR reflects the success of the measurement campaign at recording all the measurements that it could have captured. It differs from the data coverage rate, which compares the valid time steps in some interval to the total number of time steps in that interval:

$$DRR = \frac{N_{valid}}{N_{total}} \cdot 100\% \tag{4.5}$$

where N_{total} is the total number of time steps in the entire time interval (normally equal to 52560, in leap years equal to 52704).

These two indicators are calculated and reported in Tab. 4.6 where is highlighted that, for the case study, the data availability is higher than 90% for both the sensors. As specified in the title of the table, the reported values refer to the wind data before being filtered. After the application of the flags, it is expected that the percentages related to the DCR and DRR are reduced because, with the cleaning procedure, the number of valid data N_{valid} is reduced.

Table 4.7 – Data coverage rate and data recovery rate of the two anemometers before filtering data

	Cup anemometer North				**Cup anemometer South**			
	Possible data points	**Valid data points**	**DCR [%]**	**DRR [%]**	**Possible data points**	**Valid data points**	**DCR [%]**	**DRR [%]**
2007	48306	48300	91,89	99,99	48306	48300	91,89	99,99
2008	52704	52698	99,99	99,99	52704	52698	99,99	99,99
2009	52560	52548	99,98	99,98	52560	52548	99,98	99,98
2010	52560	52560	100	100	52560	32256	61,37	61,37
2011	52560	52560	100	100	52560	52560	100	100
2012	52704	34629	65,7	65,7	52704	45141	85,65	85,65
2013	52560	47171	89,75	89,75	52560	47171	89,75	89,75
2014	52560	39057	74,31	74,31	52560	39057	74,31	74,31
2015	52560	52560	100	100	52560	52560	100	100
2016	52704	52704	100	100	52704	52704	100	100
2017	52560	52560	100	100	52560	52560	100	100
2018	52560	52560	100	100	52560	52560	100	100
2019	52560	52539	99,96	99,96	52560	52539	99,96	99,96
2020	52704	52694	99,98	99,98	52704	52694	99,98	99,98
2021	52560	52560	100	100	52560	52560	100	100
2022	13912	13912	26,47[3]	100	13912	13912	26,47[3]	100
All Data	798634	761612	90,50	95,36	798634	75182	89,34	94,14

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[3] This value is lower than the annual average of previous years because data collection lasts after only three months, i.e. at the beginning of April 2022

During the years, the two anemometers present some differences in the DRR and DCR values because it may have happened that sometimes one of the two instruments works while the other one is forced to stop for technical problems. A clear example of this situation, represented in Fig. 4.17, is the year 2010 where the Northern anemometer measured wind speed continuously for the entire year, while the Southern one recorded data only for a reduced portion of the year.

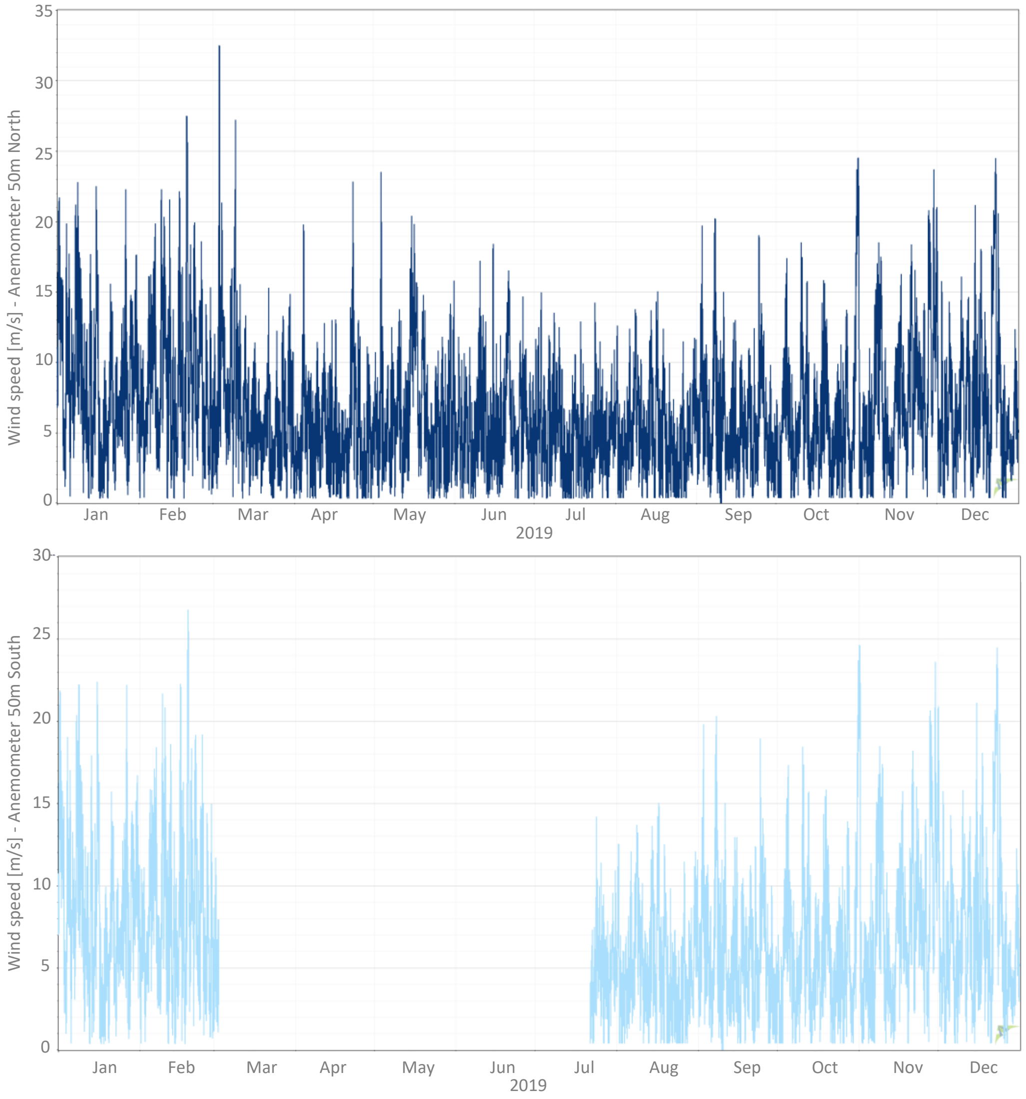


Figure 4.17 – Recorded values of wind speed from North anemometer (A) and South anemometer (B) in 2010

On *Windographer3*, for the automatic flagging of invalid data, are set various rules. Firstly, are automatically excluded the null values since it is practically impossible that the mean wind speed, over a 10-min time step, is equal to 0 m/s. When such values are recorded, it means that there was something that prevented the rotation of the sensible part of the anemometer. A common situation of this type occurs in winter when ice and snow accumulate around the instrument. In hotter months, the zero

speed values can be due to the presence of other rotation impediments as dirt or nests. On the software these events are flagged with the *icing* wording and are highlighted with an orange dot as in the following figure.

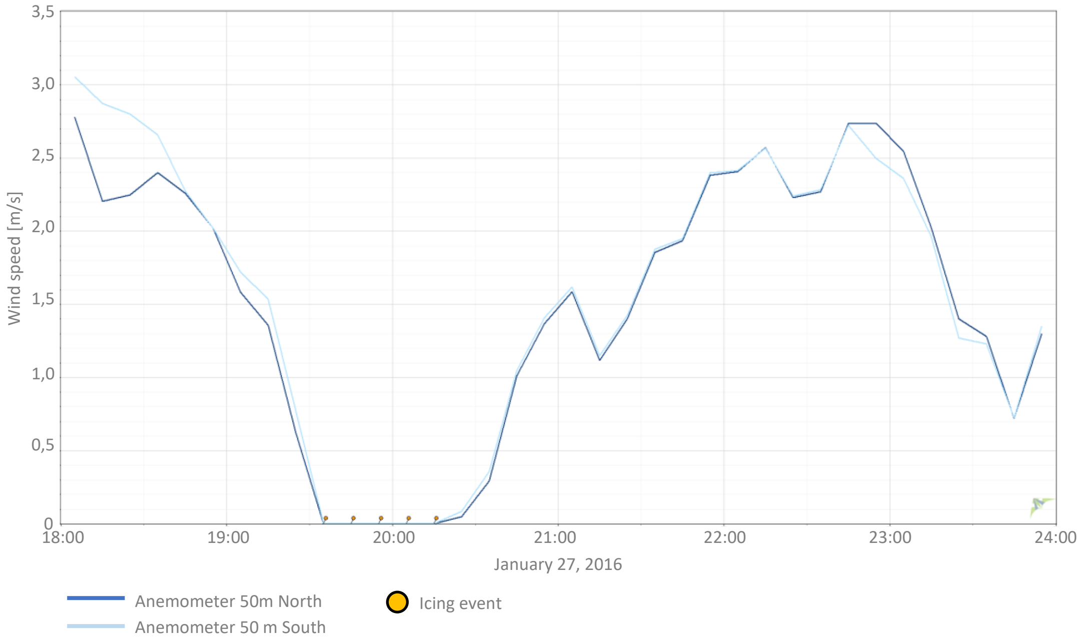


Figure 4.18 – Flag of an icing event

With the same reasoning too high values of wind speed must be rejected: as a practical rule we have chosen to exclude those velocities higher than 30 m/s. However, in this case it is possible that, in particular situations of strong winds or storms, the wind exceeds the limit. For this reason, after the application of this type of flag, the entire measuring period is controlled situation-by-situation to verify the correct flag assignment. In the next two figures are shown an example of the two possibilities. In the first picture the value corresponding to 50 m/s is rejected because it seems quite strange since immediately before and immediately after the mean wind speed is around 5 m/s. On the contrary, in the second figure, there is a time step presenting a wind speed slightly higher than 30 m/s that can be considered in the analysis and not flagged. The reason of this choice is since there is a progressive increase, and then decrease, of the wind speed in this second case.

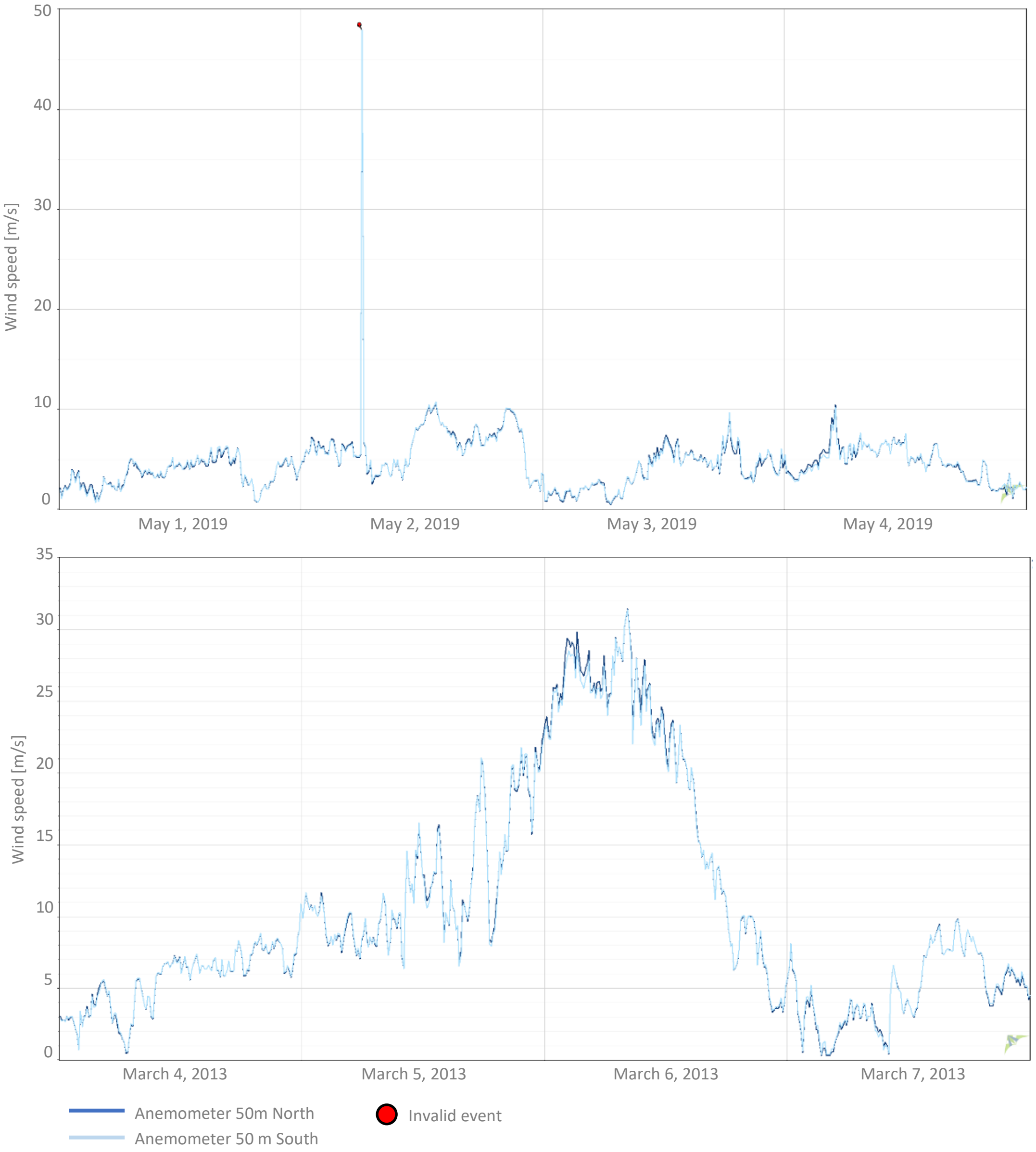


Figure 4.19 – Strong wind speed event flagged and not-flagged

By looking at Fig. 4.19 it seems that the wind data series recorded by the two anemometers follow almost the same trend. This is partially true because with a deep observation of the time series it could happens that the measured velocity values differ for several m/s. In this sense data validation can be performed by applying an additional rule having the purpose to detect and then exclude the higher recorded values when the difference in wind velocity between the two anemometers is greater than a certain threshold. In the case study, with the two sensors positioned at the same height, we estimate a limit value of 1 m/s. If the sensors are located at different heights the limits for the validation criteria have to be modified according to the specific situation.

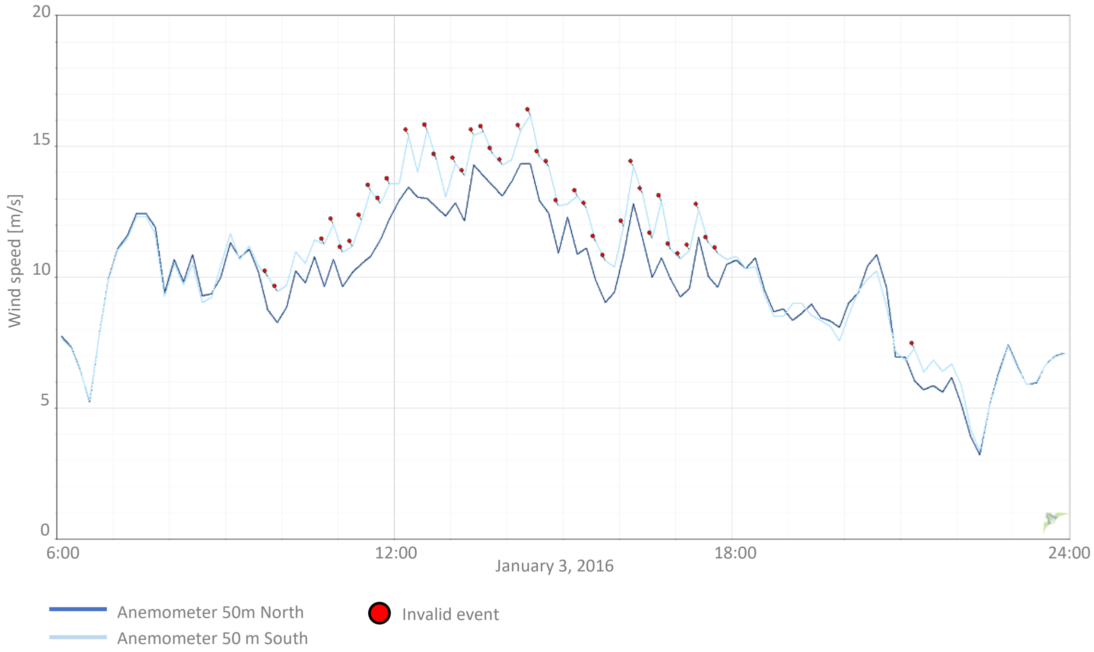


Figure 4.20 – Flag of data measured by the South anemometer since they differ for more than 1 m/s from the ones measured by the North anemometer

The choice of which of the two data series to flag can be arbitrary, however, to be more conservative in the analysis, we decide to impose the elimination of the higher values. Nevertheless, a manual visual inspection must be also performed in order to verify that the removal of such data is reasonable. In fact, in particular cases, it could happen that due to some failures in one of the two measurement instruments the values to be excluded in the analysis are the lower ones. An example of this situation is represented in the next figure. The trend of wind speed during the day is growing, but around 12:00 the South anemometer registers a sharp drop of wind speed, close to 0 m/s, while the North anemometer records data more coherent with the general daily situation. For this reason, in this time step, we decide to reverse the flag and eliminate the smallest data.

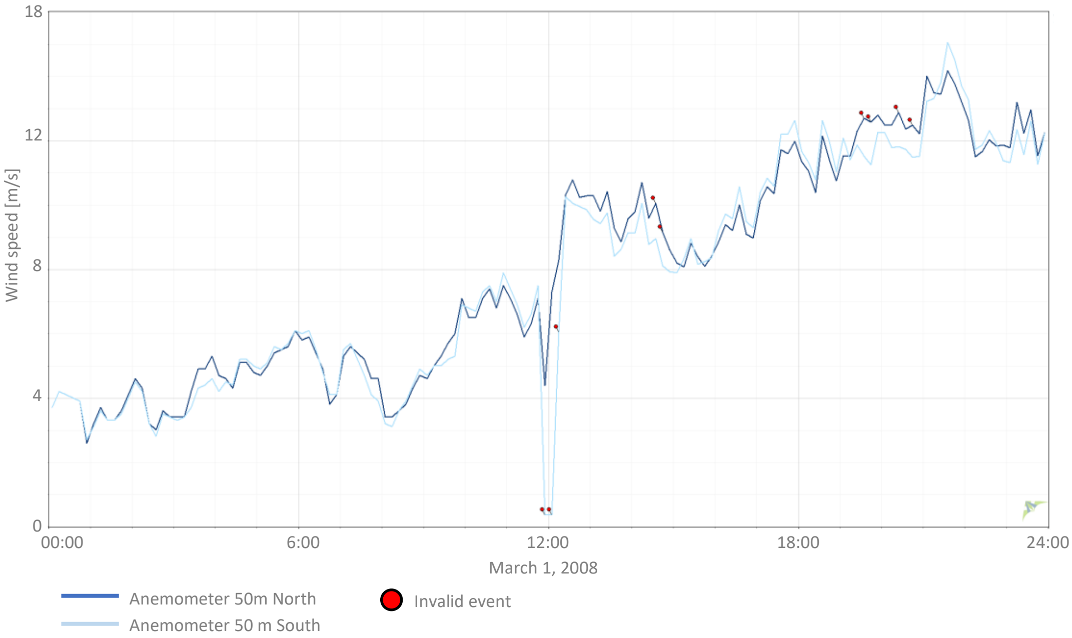


Figure 4.21 – Particular situation with inverted flag

For a complete and accurate data validation a final visual check must be performed to detect, and then manually flag, those time intervals in which the recorded values remain constant, at a certain value, for more successive and contiguous time steps. As a rule of thumb, we decide to flag data once no variations in wind speed records occur for at least 5÷6 time steps, that means for at least one hour. In fact, it is practically impossible, or in any case difficult, that zero changes in the average wind speed are registered for so long time. In Fig. 4.22 are reported two examples of this situation. In the first case, probably for a general malfunction of the device, both the two anemometers register for long time a constant wind speed value. In the reported graph the flags related to these data are not represented, but the relative information is in any case excluded from the wind analysis. In the second case, only one of the two anemometers does not properly work and so only the corresponding data are exclude while the others are still considered valid.

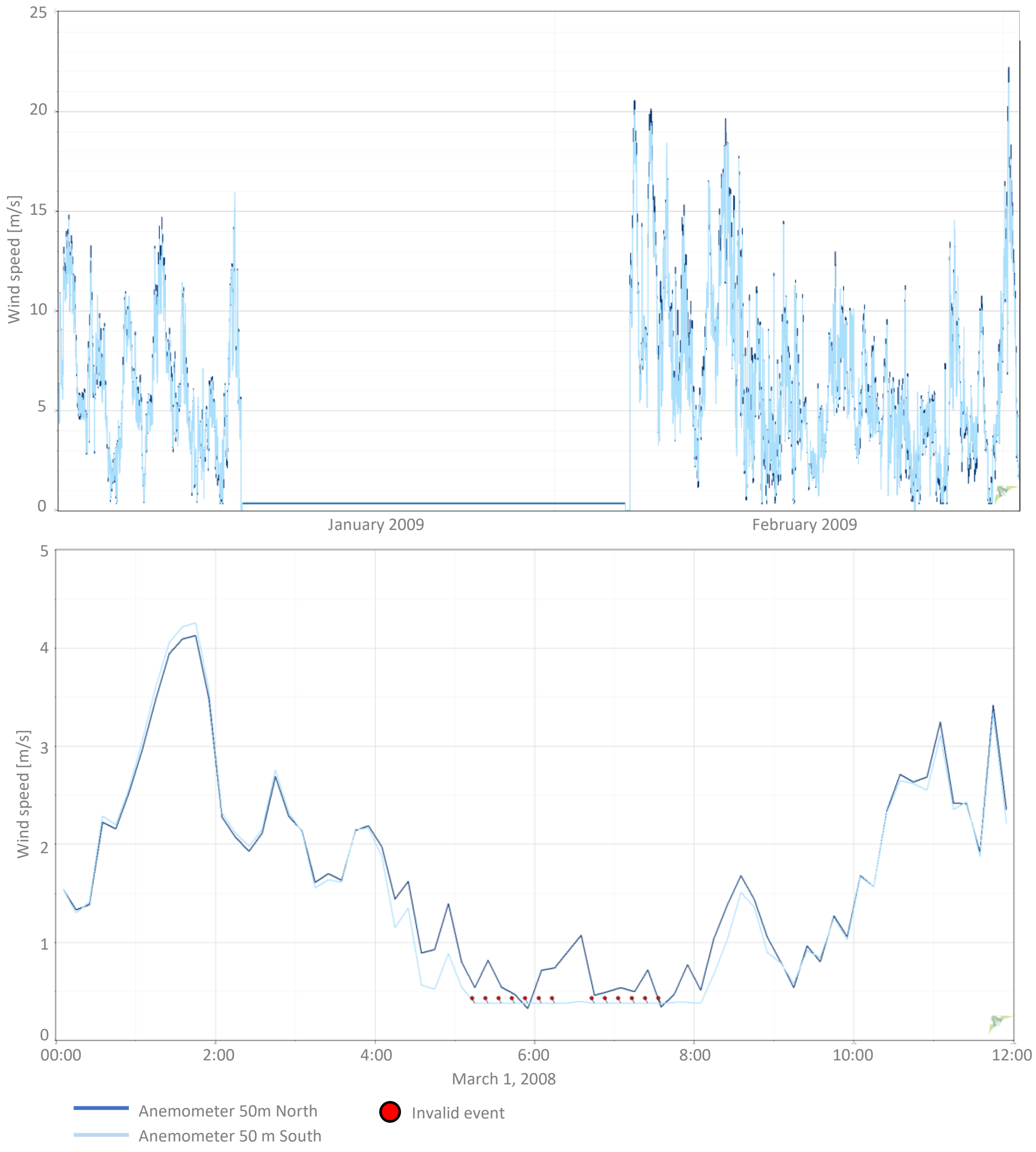


Figure 4.22 – Flag data having constant wind speed for long time

As shown in these above figures, the data obtained during the anemometric campaign were detected by the two pairs of speed sensors installed on the anemometric tower. This double registration often allows not to have completely data loss in case of breakage or malfunction of one of the measuring devices. The good quality of the measurement can be observed, before the filtering process, by looking at the excellent correlation coefficient $r^2 \cong 0{,}940$. After the data validation the correlation coefficient increases a bit, reaching a value of

$r^2 \cong 0{,}997$, because the spread measurements that differ too much from tendency line are removed during the data filtration. This behaviour can be graphically highlighted with the following graphs.

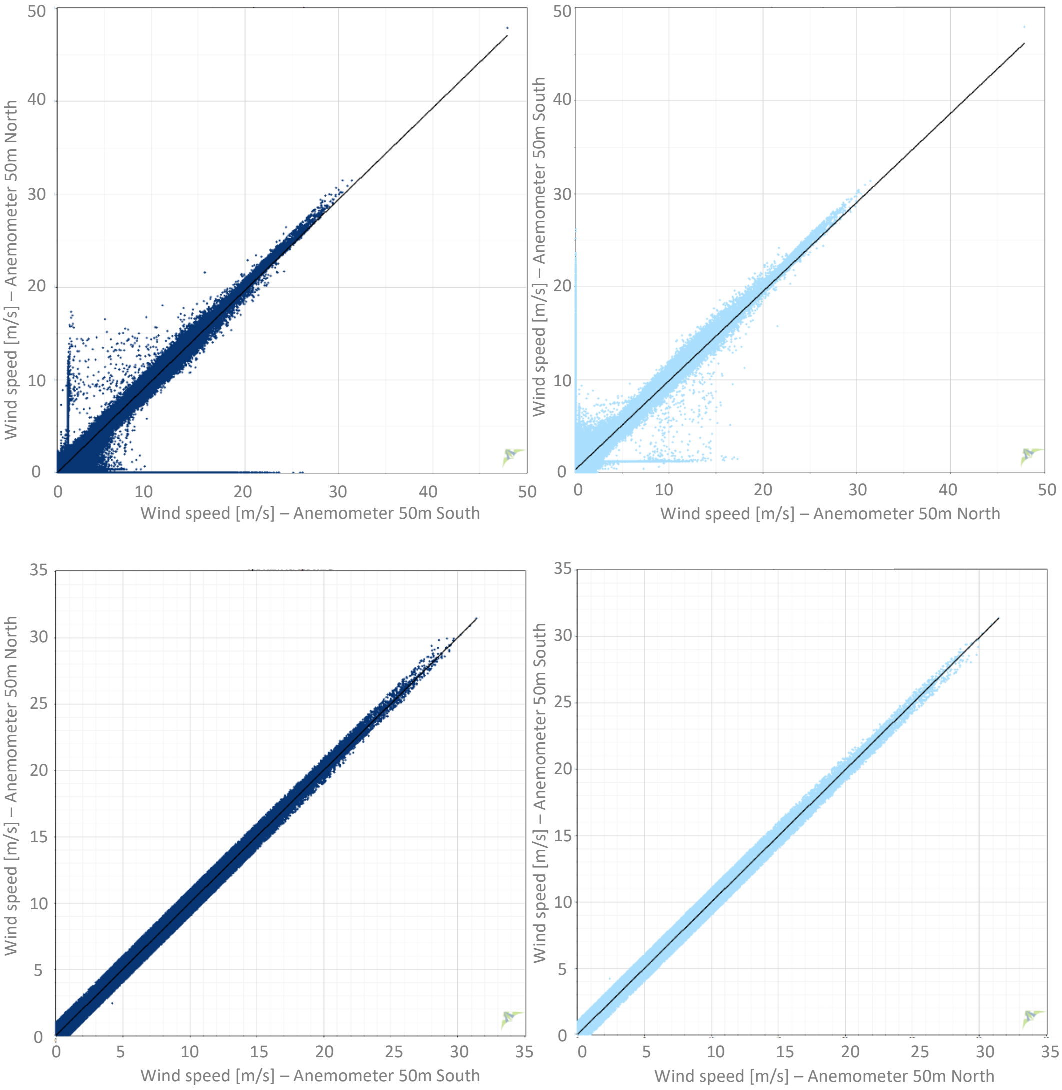


Figure 4.23 – Data quality before and after the filtering process

With the validation of the acquired data, it is possible to establish the frequency and occurrence distribution and the incoming sectors of the prevailing winds, with the aim of finding the optimal location of the wind turbine generators. As shown in the distribution roses statistically derived from the two windvanes, the northern area of the province of Trapani is highly influenced by winds from the west (270°) and north-east (30°) sectors. These winds are attributable to the currents coming directly from the sea.

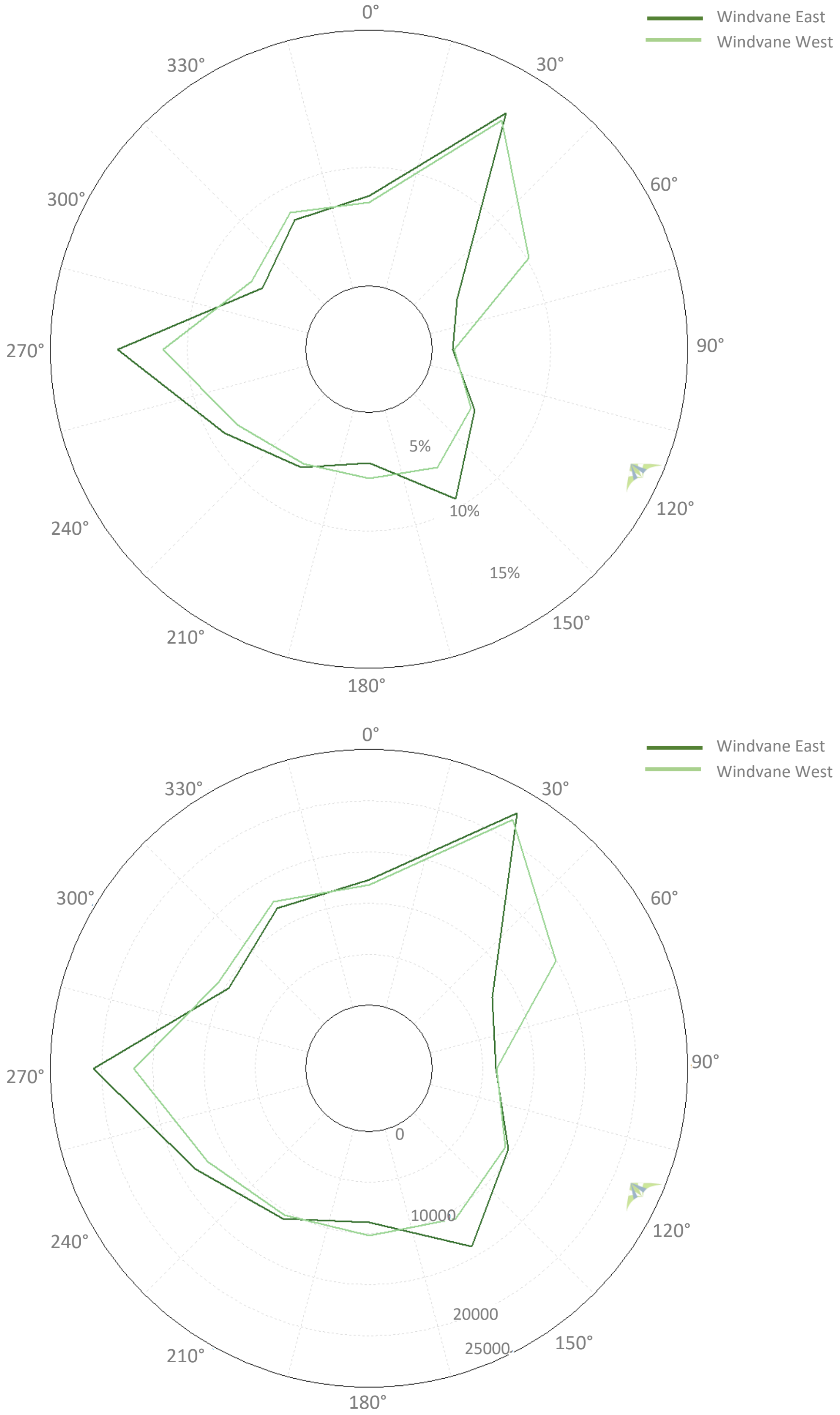


Figure 4.24 – Wind direction frequency [%] and occurrences [h]

At the same time *Windographer3* statistically evaluates the probability distribution function of the site. Here are reported the pdf and the corresponding Weibull approximations that are characterized by different scale factor c and shape factor k according to the considered anemometer.

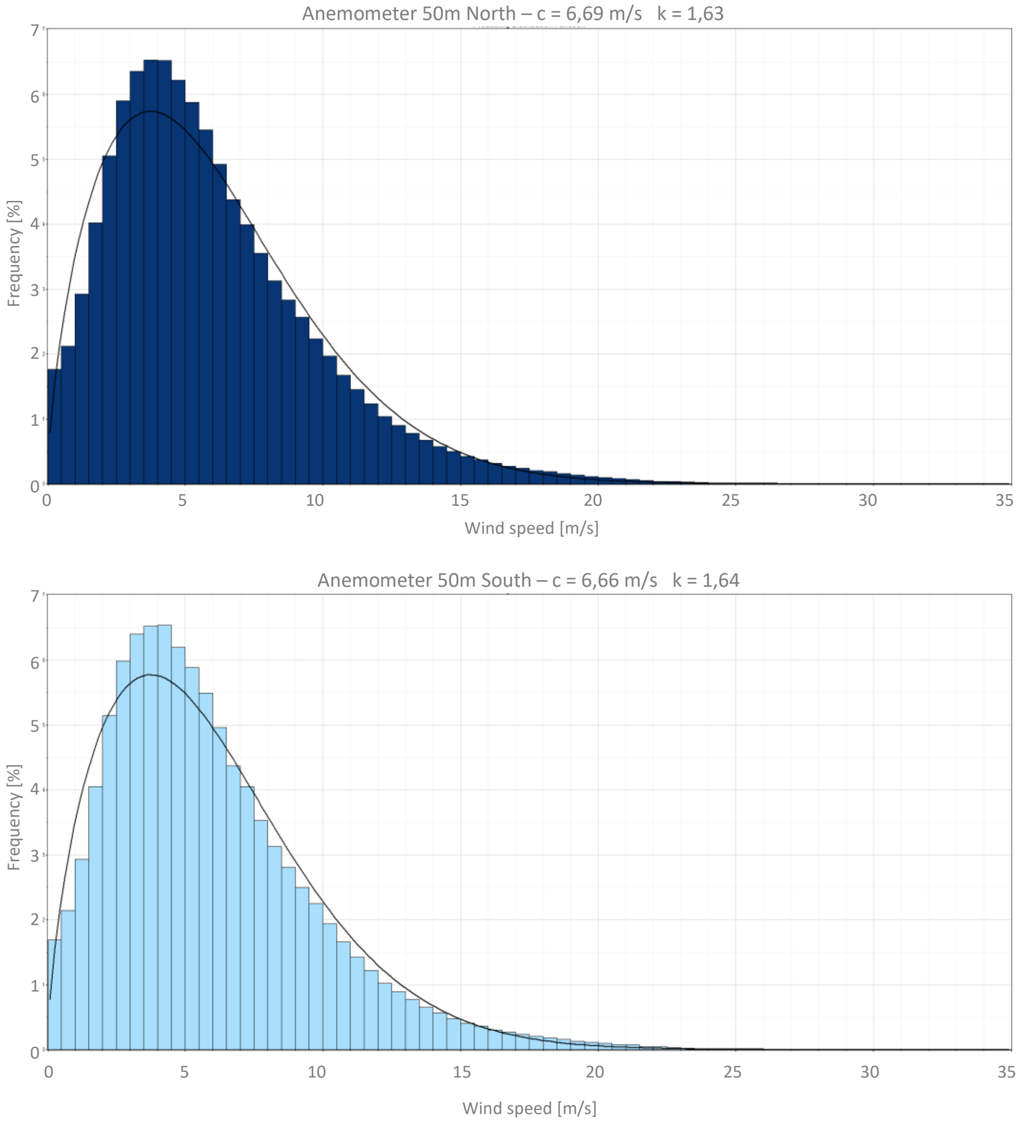


Figure 4.25 – Probability distribution function

The annual average wind speed of the site is around 6,0 m/s at a height of 50 m above the ground. This information allows to establish the power density of the site and, consequently, the wind power class which is important for identifying the potential energy of the flow on the ground. In the case study the resulting power density is about 316 W/m^2 which corresponds to a site of class 3 (fair) that offers a good supply of the wind resource.

In Fig 4.25 are reported the daily wind speed profiles for the various months. It is immediately clear as in winter months, from November to March, the average wind speed is higher than in the hotter season, from June to September. However, the monthly trend is always almost the same: higher wind velocities are registered in the central hours of the day when the sun is high in the sky.

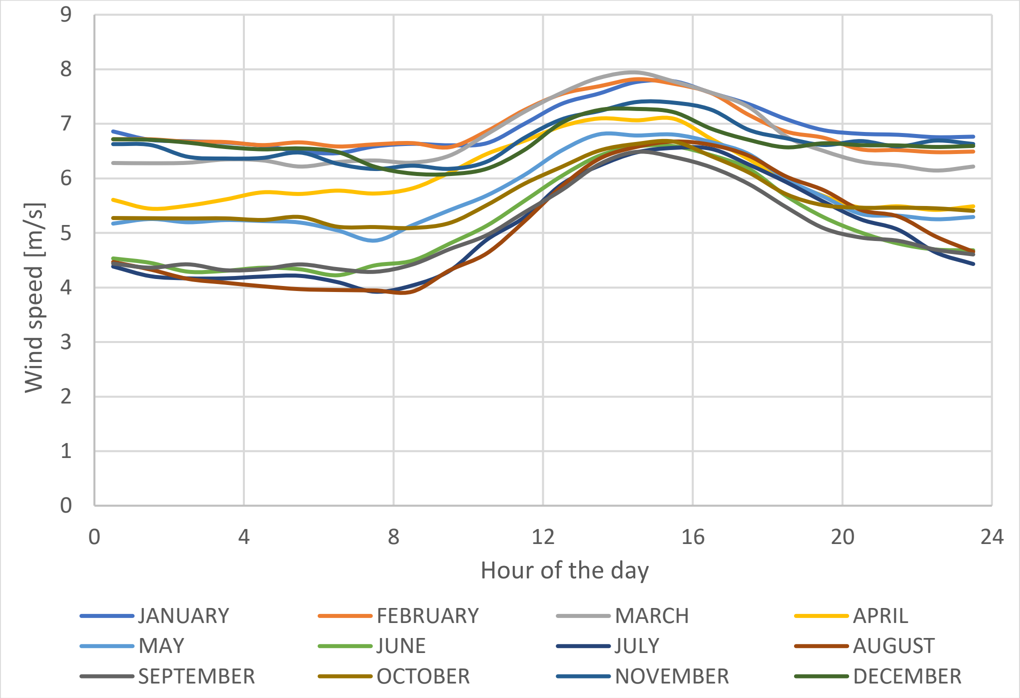


Figure 4.26 – Daily wind speed profiles for different months

4.2.4. Expected power production

For the power production and energy yield calculations, and therefore for the selection of the optimal plant layout, it is used the wind analysis and assessment software *WAsP11*. The software operates only in the microscale range and so it exploits microscale flow models. For this reason, wind phenomena at larger scales are not considered by the software. From the temporal perspective, *WAsP* analyses are based on 10-minute averaged wind data that provide long-term wind statistics.

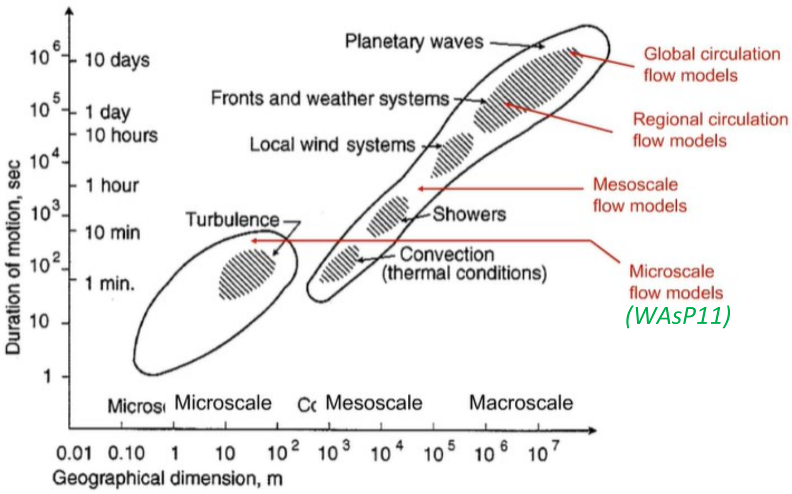


Figure 4.27 – Flow models

For the analyses *WAsP11* requires some input information for the complete description of the situation under evaluation. Particularly are essential a terrain analysis in terms of orography and roughness vector maps, a generalized wind climate where the location and data of the meteorological station are specified and a turbine site and characterization in terms of location and power and thrust curves.

The terrain topography describes systematically the most important features of the surrounding terrain which are elevation, also known as orography, surface roughness, and near-by sheltering obstacles. The effects on the atmospheric flow of these three terrain features are not entirely independent, but *WAsP* allows the user to evaluate them separately. In the case study no obstacle effects are considered, while orography and roughness, that strongly influence the wind resource, are modelled through digital maps created and edited by means of *WAsP Map Editor*.

Orography describes the elevation variations in the large-scale geometry of the terrain surface. The information about terrain elevation is important because the wind intensity varies a lot with altitude. Generally, near the crest of hills and ridges the wind accelerates, while near the foot of hills and ridges and in valleys it normally decelerates. However, it is important underline that the resulting orographic effects on the wind flow observed beyond 10 km are very small. In a *WAsP* terrain map, the orography is represented by heigh contour lines which are lines of constant elevation above mean seal level.

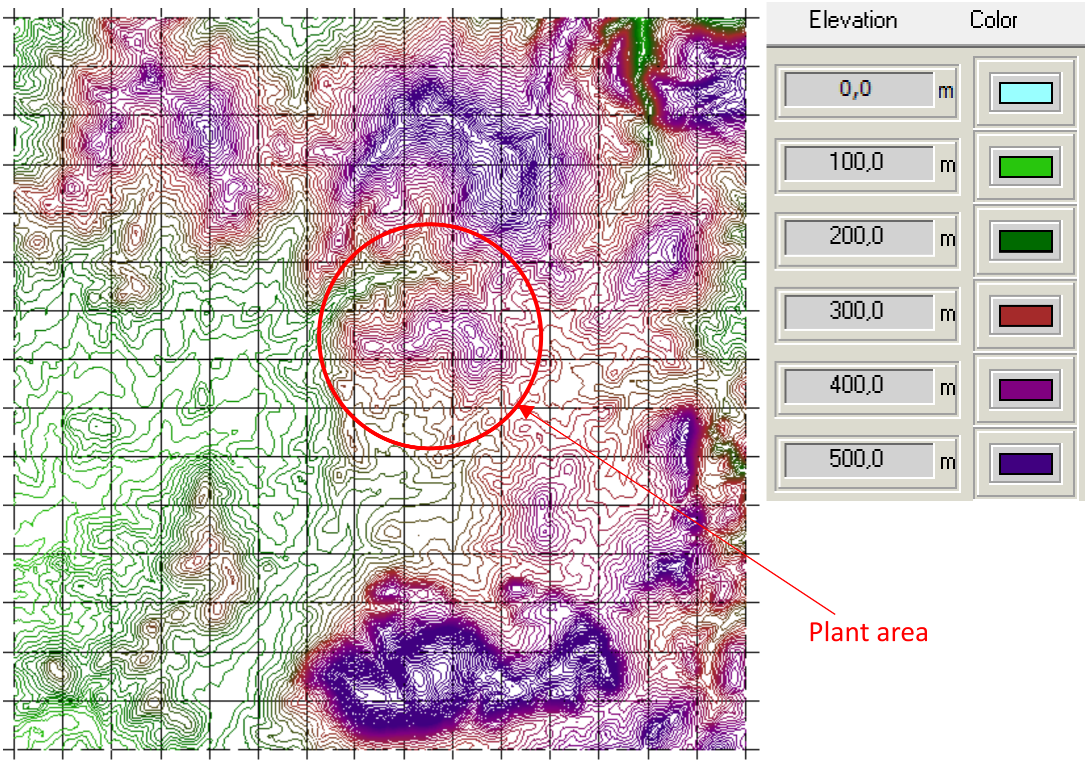


Figure 4.28 – Orography vector map of Monte Mola

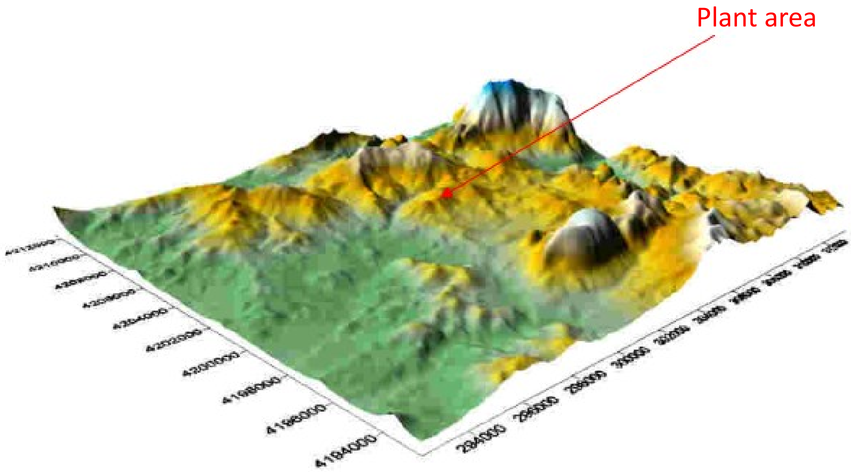


Figure 4.29 – Orography 3D map of Monte Mola

WAsP cannot predict recirculation zones and detached flow phenomena. So, when the terrain slopes are steeper than 30÷40%, the wind cannot follow the terrain surface and seems to move over a virtual hill having less steep slope, as shown in the figure.

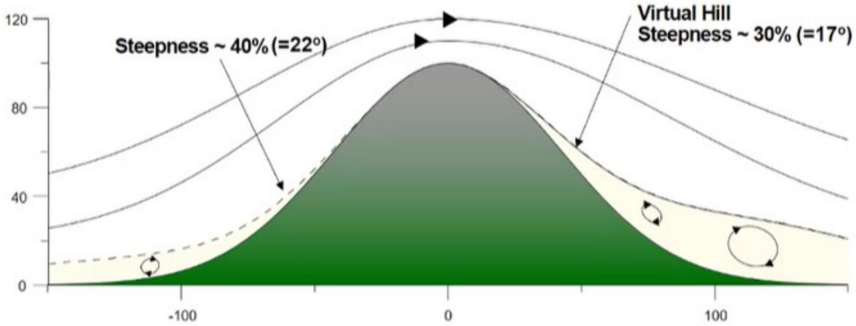


Figure 4.30 – Virtual hill generation in case of too steep terrain

The software model forces the flow to follow the terrain surface without creating recirculation zones and therefore tends to over-estimate the speed in complex terrain with steep hills. Fortunately, this model works quite well with the actual situation since the site is characterized by a gentle orography.

Roughness length of the terrain surface includes small-scale and large-scale variations in land cover. Each terrain surface type may be referred to a roughness class and there is a relation between the roughness class and the roughness length scale. Water surfaces correspond to class 0: the roughness of water is about 0,2 mm, but in *WAsP* z_0 for water must be set equal to 0 m since the software automatically converts this value to the more realistic value according also to wind conditions. Forests and urban districts correspond to roughness class 3 and the default roughness length for this class is 0,4 m. Obviously landscapes and roughness lengths change throughout the year, following the growing cycle of vegetation and the fact that snow affects the surface roughness. In *WAsP* however we consider only the average annual roughness length. A more detailed classification of roughness class and length according to the different terrain type is highlighted in the following table:

Table 4.8 – Roughness class and length for different terrain types

	Class	**Real z_0 [m]**	**WAsP z_0 [m]**
Sparse forest	4	1,0÷3	>1
City		1,0	
Dense forest		0,8	
Suburbs	3	0,5	
Shelter belts		0,4	
Many trees and/or bushes	2	0,2	
Farmland with closed appearance		0,1	
Farmland with open appearance	1	0,05	
Farmland with few buildings and trees		0,03	
Airport area with few buildings and trees		0,02	
Airport runway areas	0	0,01	
Mown grass		0,008	
Bare soil (smooth)		0,005	
Snow surfaces (smooth)		0,001	0,003
Sand surfaces (smooth)		0,0003	0,003
Water areas		0,0002	0

In a WAsP terrain map, the land cover is represented by roughness change lines which are lines separating areas of different roughness. If no roughness map is given to *WAsP*, the software automatically assigns a value of 0,3 m to all the area. In the specific case study, the site is characterized by an open farmland with few buildings and trees so to the entire zone is assigned a z_0 of 0,03 m. However, some zones, close to the wind farm site, are characterized by a more concentrated vegetation. Therefore, in the roughness map, are added some areas presenting an internal roughness length of 0,2 m because some trees and bushes are present, and others having z_0 equal to 0,8 m where dense forests are present.

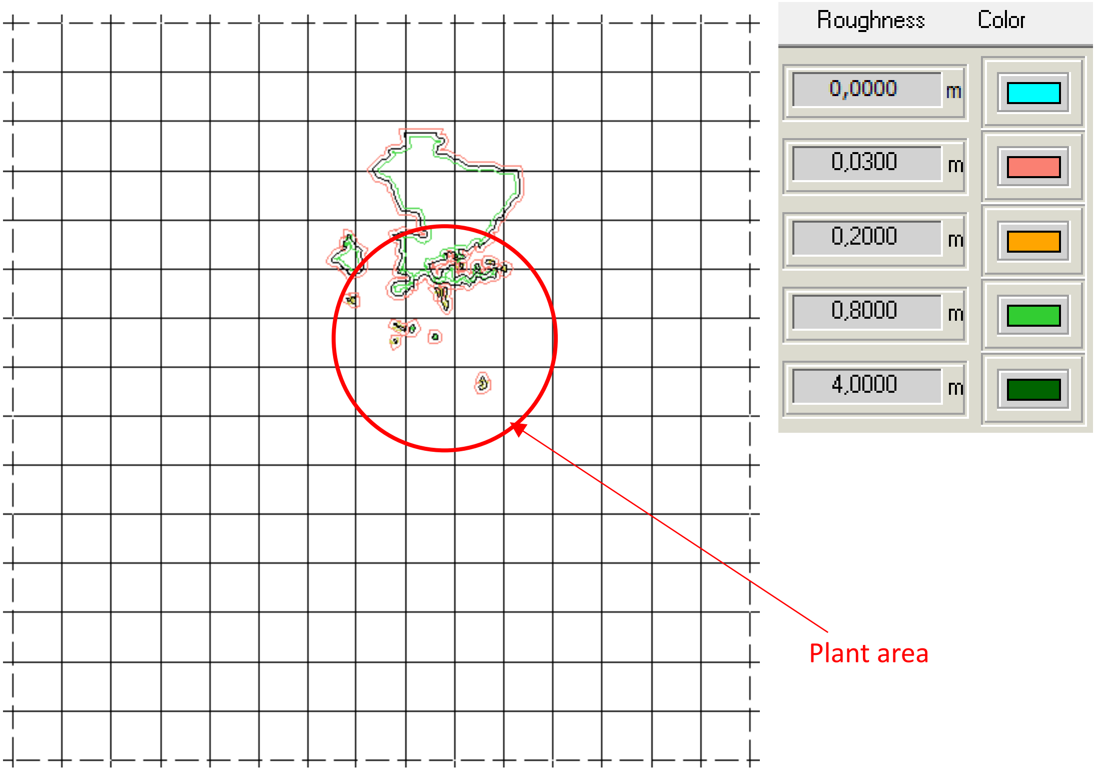


Figure 4.31 – Roughness vector map of Monte Mola

The two maps created with *WAsP Map Editor* are superimposed and the resulting vector map is a full description of the terrain.

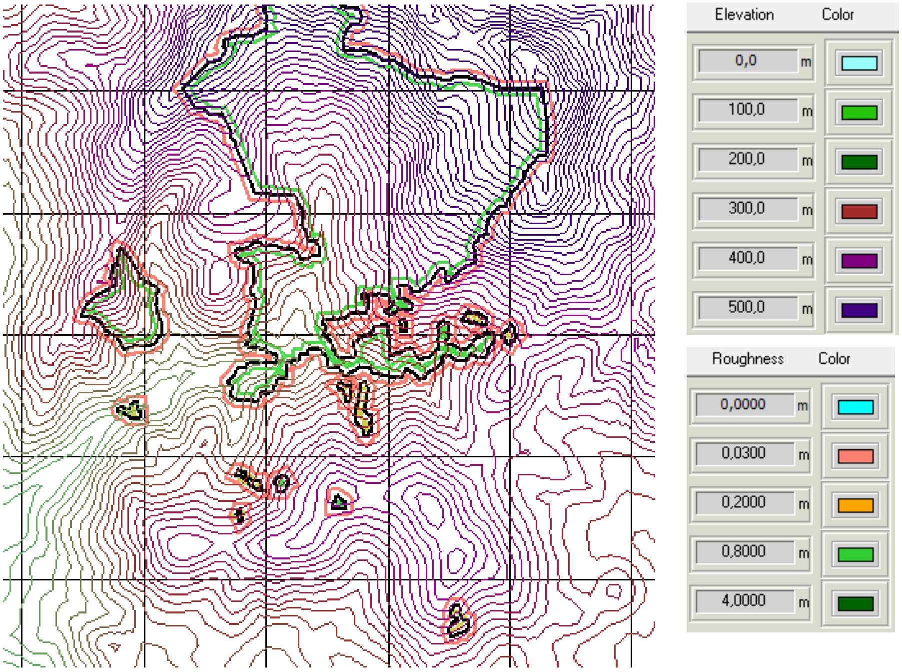


Figure 4.32 – Orography and roughness vector map of Monte Mola

Regarding the wind climate, it is creating by coupling the wind information obtained with *Windographer3* with the description of the site, in terms of terrain orography and roughness, where we want to perform the resource assessment. The time series of wind speed and direction information are used to estimate the observed wind climate.

Table 4.9 – Observed wind climate

Sector		**Wind climate**				**Power (at 1,225 kg/m^3)**
number	**angle [°]**	**frequency [%]**	**Weibull-c [m/s]**	**Weibull-k**	**mean speed [m/s]**	**power density [W/m^2]**
1	0	7,7	5,8	1,52	5,23	234
2	30	13,1	8	2,3	7,1	369
3	60	7,8	6,3	1,97	5,55	203
4	90	4,8	5,1	1,63	4,52	137
5	120	5,8	6,8	1,41	6,16	428
6	150	6,7	8,1	1,39	7,41	763
7	180	5,4	8,3	1,64	7,44	606
8	210	6,5	6,6	1,58	5,88	314
9	240	8,3	6,5	1,63	5,85	297
10	270	11,3	6,7	1,61	5,98	322
11	300	9,6	5,2	1,31	4,81	232
12	330	13,1	5	1,3	4,58	201
All (emergent)		-	-	-	5,84	327

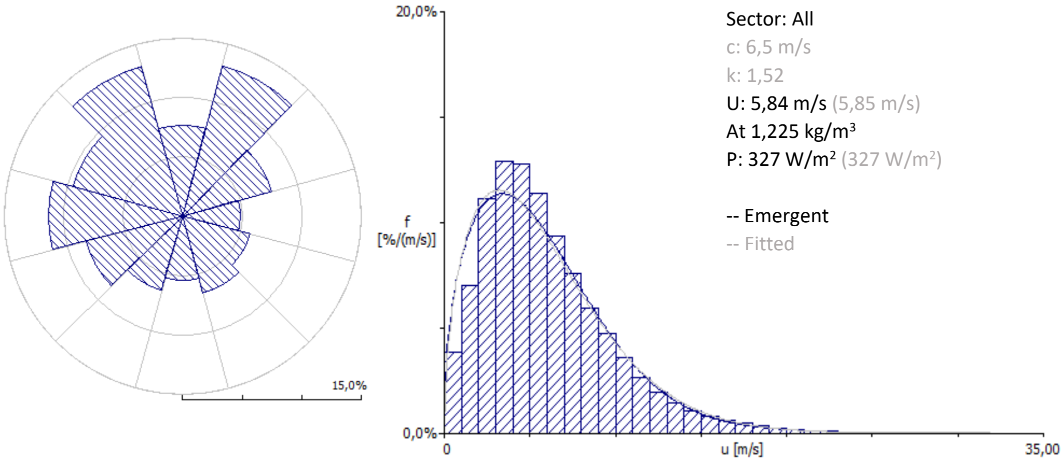


Figure 4.33 – Wind climate on WAsP11

Then, the local terrain effects have been removed and the wind climate is referenced to certain standard conditions providing the generalised wind climate. It is specified for five standard heights above ground level and five roughness classes. These standard conditions should span the characteristics of all calculation sites in the project, but *WAsP* interpolates between these conditions in order to provide reliable results.

Table 4.10– Generalised wind climate

	R-class 0 (0,000 m)	R-class 1 (0,030 m)	R-class 2 (0,100 m)	R-class 3 (0,400 m)	R-class 4 (1,500 m)
Height 1 (10 m a.g.l.)	4,99 m/s	3,62 m/s	3,17 m/s	2,51 m/s	1,69 m/s
Height 2 (25 m a.g.l.)	5,47 m/s	4,33 m/s	3,91 m/s	3,31 m/s	2,55 m/s
Height 3 (50 m a.g.l.)	5,88 m/s	5,00 m/s	4,58 m/s	3,99 m/s	3,28 m/s
Height 4 (100 m a.g.l.)	6,39 m/s	5,92 m/s	5,45 m/s	4,83 m/s	4,12 m/s
Height 5 (200 m a.g.l.)	7,02 m/s	7,22 m/s	6,65 m/s	5,94 m/s	5,17 m/s

The generalised wind climate, combined with the description of the site, provides the predicted wind climate that is representative for the specified wind turbine hub height. This climate, by adding the turbine's power curve, gives the information about the annual energy production (AEP) of a specific wind turbine at that site. When the farm layout is added the wake losses can be estimated and so the gross and net AEP of the site can be calculated.

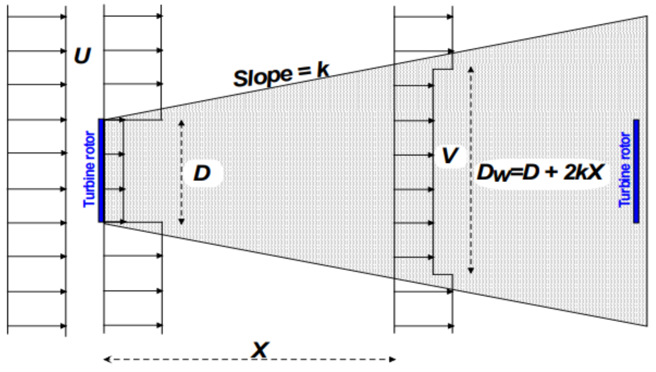
Each wind turbine generator is characterized by specific power and thrust curves that are usually provided by the turbines' manufacturers. These curves depend on the wind turbine model but also on the air density: the higher it is, the more energy can be extracted from wind. Most of the power and thrust curves are given for different air densities, therefore in the analysis it is also important to properly estimate this parameter. The air density is site dependant. *WAsP11* provides an air density calculator which evaluate it as a function of the air temperature and altitude. In the specific case of Monte Mola, the average annual air temperature is about 16°C while the considered altitude is around 470 m a.s.l.

because the anemometric tower is 50 m tall and is located on a height of 420 m a.s.l., so the resulting mean air density of the site is about 1,15 kg/m^3.

As already explain in the introductory part, a wind farm is a collection of wind turbines that are interconnected by an electrical system and that deliver their combined electrical power production to the same point of common coupling. In *WAsP* a wind farm consists in a set of turbine sites which can present different map location, hub height and wind turbine type. The main goal of the software is to provide the annual energy production, but it also gives the opportunity to evaluate the reductions in power yield for each turbine caused by the interference from the neighbour machines. These reductions are called wake losses. *WAsP11* provides a simple wake model which is designed to estimate the speed deficit in the wind turbine wake, but it provides no information on the structure of the flow or on the turbulence. The wake is modelled as a simple cone in which the wind speed is reduced. The velocity decrease, downwind the turbine, depends on the rotor diameter, the slope of wake cone, the downstream distance from the rotor and the thrust curve of the turbine:

$$\delta V = U - V = U(1 - \sqrt{1 - C_t})\left(\frac{D}{D + 2kX}\right)^2 \qquad (4.6)$$

where D is the rotor diameter, X is the downstream distance from the rotor, k is the decay constant, Ct is the thrust coefficient and U is the upstream undisturbed wind speed.



k : wake decay constant

The shape of the cone changes with the flow turbulence, therefore it is recommended to use different constants for off-shore (k=0,050) and on-shore (k=0,075) wind farms.

Figure 4.34 – WAsP11 wake model

This wake model is designed for small and medium-sized wind farm with an extent of about 2÷5 km. For very large wind farm it tends to underestimate the wake losses and therefore to overestimate the production of the wind farm. The wake model provides reliable results if the distance between neighbouring turbines in the farm is at least 4 rotor diameters.

By subtracting the wake losses from the gross AEP of the wind farm it is possible to calculate the potential energy production of the wind farm. The potential AEP calculated by *WAsP11* is the ideal annual energy production that can be produced by the wind farm when the wake losses and a 10% of additional technical losses are considered. This production evaluation is also referred to the P50-value. Being the best estimate, we might expect that there is a 50% of probability that it will be higher or lower than the real production level. This is the more optimistic estimate of the electricity production that will be fed into the electrical grid, and it can be used in the financial and economic modelling of the wind farm. However, financing bodies often require a lower risk and therefore ask for P75 or P90-values to get a probability of 75% or 90% that also considers the uncertainty of the prediction. For the P75-value a reduction of 13,5% with respect to the P50-value is hypnotised while for the P90-value it is considered an additional decrease of 9%.

By means of *WAsP11* we perform the anemometric analysis to estimate the wind farm productivity and then chose the optimal solution for the repowering. The results are collected in the following tables. For each single wind turbine are reported the annual gross and net energy productions and the wake losses as a percentage of the gross power yield. Then additional parameters are evaluated for the entire repowered wind farm and therefore without considering the MO01 machine that is already installed and that will not be dismissed. In particular, are calculated the P50 gross annual energy production as the sum of the net AEP of each single turbine, the P50 net annual energy production considering a 10% of electrical and technical losses with respect to the gross AEP and the equivalent hours for the different probability scenarios.

Table 4.11 – Anemometric results: 4WTG V126-3.6MW

	V126-3.6MW	V80-2.0MW
Number of turbines	4	1
Hub height [m]	117	80
Unit power [MW]	3,6	2
Total power [MW]	14,4	2

		Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
							P50	**P75**	**P90**
Layout A	01	11,589	11,074	4,44	44,662	40,196	2791	2414	2197
	02A	11,400	10,607	6,96					
	03	11,577	11,228	3,02					
	04	12,028	11,753	2,29					
	MO01	4,304	4,228	1,75					
Layout B	01	11,589	11,199	3,37	44,37	39,933	2773	2399	2183
	02B	10,878	10,197	6,26					
	03	11,577	11,234	2,96					
	04	12,028	11,740	2,40					
	MO01	4,304	4,235	1,61					

Table 4.12 – Anemometric results: 4WTG V136-3.45MW

	V136-3.45MW	V80-2.0MW
Number of turbines	4	1
Hub height [m]	112	80
Unit power [MW]	3,45	2
Total power [MW]	13,8	2

		Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
							P50	**P75**	**P90**
Layout A	01	12,097	11,535	4,65	46,487	41,838	3032	2622	2386
	02A	11,911	11,046	7,26					
	03	12,088	11,701	3,20					
	04	12,519	12,205	2,51					
	MO01	4,304	4,224	1,85					
Layout B	01	12,097	11,661	3,61	46,202	41,582	3013	2606	2372
	02B	11,397	10,639	6,65					
	03	12,088	11,708	3,15					
	04	12,519	12,194	2,60					
	MO01	4,304	4,230	1,72					

Table 4.13 – Anemometric results: 4WTG V136-4.0MW

	V136-4.0MW	V80-2.0MW
Number of turbines	4	1
Hub height [m]	112	80
Unit power [MW]	4,0	2
Total power [MW]	16	2

		Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
							P50	**P75**	**P90**
Layout A	01	13,097	12,468	4,80	50,223	45,201	2825	2444	2224
	02A	12,870	11,893	7,59					
	03	13,072	12,635	3,35					
	04	13,585	13,227	2,63					
	MO01	4,304	4,219	1,97					
Layout B	01	13,097	12,607	3,74	49,860	44,874	2805	2426	2208
	02B	12,253	11,401	6,96					
	03	13,072	12,639	3,31					
	04	13,585	13,213	2,74					
	MO01	4,304	4,225	1,83					

Table 4.14 – Anemometric results: 4WTG V136-4.2MW

	V136-4.2MW	V80-2.0MW
Number of turbines	4	1
Hub height [m]	112	80
Unit power [MW]	4,2	2
Total power [MW]	16,8	2

		Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
							P50	**P75**	**P90**
Layout A	01	13,347	12,706	4,81	51,184	46,066	2742	2372	2158
	02A	13,110	12,111	7,62					
	03	13,322	12,874	3,36					
	04	13,859	13,493	2,64					
	MO01	4,304	4,218	1,99					
Layout B	01	13,347	12,847	3,75	50,803	45,723	2722	2354	2142
	02B	12,469	11,599	6,98					
	03	13,322	12,879	3,33					
	04	13,859	13,478	2,75					
	MO01	4,304	4,224	1,85					

Table 4.15 – Anemometric results: 4WTG V136-4.5MW

	V136-4.5MW	V80-2.0MW
Number of turbines	4	1
Hub height [m]	112	80
Unit power [MW]	4,5	2
Total power [MW]	18	2

		Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
							P50	**P75**	**P90**
Layout A	01	13,724	13,064	4,81	52,622	47,360	2631	2276	2071
	02A	13,470	12,438	7,66					
	03	13,694	13,232	3,38					
	04	14,266	13,888	2,65					
	MO01	4,304	4,217	2,02					
Layout B	01	13,724	13,209	3,76	52,208	46,987	2610	2258	2055
	02B	12,788	11,892	7,01					
	03	13,694	13,236	3,35					
	04	14,266	13,871	2,77					
	MO01	4,304	4,223	1,87					

So far are simulated the wind turbine generators having a small rotor diameter and therefore are evaluated the two layouts characterized by four machines. From the tables it is clear how, regardless the wind turbine model, the best solution is the layout A since it allows to reach higher equivalent hours and annual energy production. This is mainly because the machines 02A is located at a higher altitude with respect to the machines 02B. In fact, this elevation difference, of about 20 m, allows to harvest a stronger wind resource.

Similar evaluations are now proposed for the aerogenerators presenting bigger rotor diameter for which a layout of three turbines is assumed to satisfy the requirement of having a distance of at least three rotor diameters between turbines and to have not too high wake losses. As a rule of thumb, the wake losses must be lower than 10 %. As highlighted in the tables above, with a layout of four machines, the WTG 02 is subjected to quite high wake losses, about 7÷8%. With bigger turbines it is expected that this percentage increases and for this reason it is chosen to design a wind farm with only three turbines.

Table 4.16 – Anemometric results: 3WTG V150-4.0MW

	V150-4.0MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	105	80
Unit power [MW]	4,0	2
Total power [MW]	12	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	14,156	13,766	2,76	41,970	37,773	3148	2723	2478
03	14,134	13,843	2,06					
04	14,643	14,361	1,92					
MO01	4,304	4,227	1,78					

Table 4.17 – Anemometric results: 3WTG V150-4.2MW

	V150-4.2MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	105	80
Unit power [MW]	4,2	2
Total power [MW]	12,6	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	14,466	14,064	2,78	42,900	38,610	3064	2651	2412
03	14,446	14,146	2,08					
04	14,980	14,690	1,93					
MO01	4,304	4,226	1,81					

Table 4.18 – Anemometric results: 3WTG V150-4.5MW

	V150-4.5MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	105	80
Unit power [MW]	4,5	2
Total power [MW]	13,5	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	14,904	14,483	2,83	44,210	39,789	2947	2549	2320
03	14,886	14,573	2,10					
04	15,456	15,154	1,95					
MO01	4,304	4,225	1,84					

Table 4.19 – Anemometric results: 3WTG V150-5.6MW

	V150-5.6MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]		80
Unit power [MW]	5,6	2
Total power [MW]	16,8	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	17,737	17,242	2,79	52,631	47,368	2820	2439	2219
03	17,743	17,359	2,16					
04	18,401	18,03	2,02					
MO01	4,304	4,223	1,89					

Table 4.20 – Anemometric results: 3WTG V155-3.6MW

	V155-3.6MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	118	80
Unit power [MW]	3,6	2
Total power [MW]	10,8	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	13,411	13,086	2,42	39,771	35,794	3314	2867	2609
03	13,425	13,174	1,87					
04	13,757	13,511	1,79					
MO01	4,304	4,236	1,57					

Table 4.21 – Anemometric results: 3WTG V162-5.6MW

	V162-5.6MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	125	80
Unit power [MW]	5,6	2
Total power [MW]	16,8	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP_{grs} [GWh]**	**AEP_{net} [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	19,165	18,617	2,86	56,751	51,076	3040	2630	2393
03	19,168	18,736	2,26					
04	19,826	19,398	2,16					
MO01	4,304	4,219	1,97					

Table 4.22 – Anemometric results: 3WTG V162-6.0MW

	V162-6.0MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	125	80
Unit power [MW]	6,0	2
Total power [MW]	18	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**$\mathrm{AEP}_{\mathrm{grs}}$ [GWh]**	**$\mathrm{AEP}_{\mathrm{net}}$ [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	19,815	19,235	2,93	58,671	52,804	2934	2538	2309
03	19,823	19,366	2,30					
04	20,522	20,070	2,20					
MO01	4,304	4,217	2,03					

Table 4.23 – Anemometric results: 3WTG V162-6.2MW

	V162-6.2MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	125	80
Unit power [MW]	6,2	2
Total power [MW]	18,6	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**$\mathrm{AEP}_{\mathrm{grs}}$ [GWh]**	**$\mathrm{AEP}_{\mathrm{net}}$ [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	20,151	19,550	2,98	59,651	53,686	2886	2497	2272
03	20,161	19,688	2,35					
04	20,880	20,413	2,24					
MO01	4,304	4,215	2,06					

Table 4.24 – Anemometric results: 3WTG N149-4.5MW

	N149-4.5MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	125	80
Unit power [MW]	4,5	2
Total power [MW]	13,5	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**$\mathrm{AEP}_{\mathrm{grs}}$ [GWh]**	**$\mathrm{AEP}_{\mathrm{net}}$ [GWh]**	**h_{eq} [h]**		
						P50	**P75**	**P90**
01	15,822	15,426	2,51	46,984	42,286	3132	2709	2466
03	15,813	15,507	1,94					
04	16,348	16,051	1,82					
MO01	4,304	4,228	1,76					

Table 4.25 – Anemometric results: 3WTG N163-5.9MW

	N163-5.9MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	118	80
Unit power [MW]	5,9	2
Total power [MW]	17,7	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
						P50	**P75**	**P90**
01	19,147	18,591	2,9	56,726	51,053	2884	2495	2270
03	19,129	18,700	2,24					
04	19,856	19,435	2,12					
MO01	4,304	4,215	2,07					

Table 4.26 – Anemometric results: 3WTG SG145-5.0MW

	SG145-5.0MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	127,5	80
Unit power [MW]	5,0	2
Total power [MW]	15	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
						P50	**P75**	**P90**
01	16,528	16,113	2,51	49,103	44,193	2946	2548	2319
03	16,518	16,193	1,96					
04	17,111	16,797	1,84					
MO01	4,304	4,230	1,72					

Table 4.27 – Anemometric results: 3WTG SG155-4.7MW

	SG155-4.7MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	120,5	80
Unit power [MW]	4,7	2
Total power [MW]	16,1	2

	Gross [GWh]	**Net [GWh]**	**Wake [%]**	**AEP$_{grs}$ [GWh]**	**AEP$_{net}$ [GWh]**	**h$_{eq}$ [h]**		
						P50	**P75**	**P90**
01	16,491	16,047	2,69	48,876	43,988	3120	2699	2456
03	16,470	16,125	2,09					
04	17,041	16,704	1,98					
MO01	4,304	4,225	1,84					

Table 4.28 – Anemometric results: 3WTG SG170-6.2MW

	SG170-6.2MW	V80-2.0MW
Number of turbines	3	1
Hub height [m]	115	80
Unit power [MW]	6,2	2
Total power [MW]	18,6	2

	Gross [GWh]	Net [GWh]	Wake [%]	AEP$_{grs}$ [GWh]	AEP$_{net}$ [GWh]	h$_{eq}$ [h]		
						P50	P75	P90
01	19,851	19,173	3,42	58,569	52,712	2834	2451	2231
03	19,812	19,294	2,61					
04	20,618	20,102	2,50					
MO01	4,304	4,203	2,33					

4.2.5. Optimal layout

Once the data regarding the expected productivity of the wind farm are calculated by means of *WAsP11*, they are collected in a table to visualize in a simpler way which solution and layout is the optimal solution for the repowering. The choice is performed by looking at the highest net annual energy production and equivalent hours. In the tables are summarized the main characteristics of the wind turbine chosen for the analysis and the P75 net AEP and h_{eq}.

Table 4.29 – Summary of turbine characteristics and P75 net AEP and h_{eq}

							P75	
	D$_{rot}$ [m]	H$_{hub}$ [m]	H$_{tip}$ [m]	P$_{nom}$ [MW]	N WTG	P$_{tot}$ [MW]	h$_{eq}$ net [h]	AEP net [GWh]
V126-3.6MW	126	117	180	3,6	4	14,4	2415	34,769
V136-3.45MW	136	112	180	3,45	4	13,8	2622	36,190
V136-4.0MW	136	112	180	4,0	4	16	2444	39,099
V136-4.2MW	136	112	180	4,2	4	16,8	2372	39,847
V136-4.5MW	136	112	180	4,5	4	18	2276	40,966

V150-4.0MW	150	105	180	4,0	3	12	2723	32,674
V150-4.2MW	150	105	180	4,2	3	12,6	2651	33,398
V150-4.5MW	150	105	180	4,5	3	13,5	2549	34,417
V150-5.6MW	150	125	200	5,6	3	16,8	2439	40,973
V155-3.6MW	155	118	195,5	3,6	3	10,8	2867	30,962
V162-5.6MW	162	125	206	5,6	3	16,8	2630	44,181
V162-6.0MW	162	125	206	6,0	3	18	2538	45,675
V162-6.2MW	162	125	206	6,2	3	18,6	2497	46,438
N149-4.5MW	125	108	170,5	4,5	3	13,5	2709	36,577
N163-5.9MW	163	118	199,5	5,9	3	17,7	2495	44,161
SG155-4.7MW	155	120,5	198	4,7	3	14,1	2699	38,050
SG145-5.0MW	145	127,5	200	5,0	3	15	2709	40,641
SG170-6.2MW	170	115	200	6,2	3	18,6	2451	45,596

It is expected that the bigger turbines cost much more than the smaller ones, but the higher is the number of WTG, the higher will be the investment cost. For this reason, it is decided to select two possible layouts for the repowering activity, one considering four wind turbine generators and another considering three machines. Then, in the following paragraph, an economic analysis will be performed in order to evaluate which solution is the optimal one also in monetary terms.

Comparing the layouts presenting four wind turbines, the selected solution is the one characterized by the V136-4.2MW machines. This wind turbine presents a quite high P75 annual energy production, about 39,85 GWh, and a great number of equivalent hours, around 2372 h. As highlighted in the graph in Fig. 4.35, the

V136-4.2MW solution is the optimal one, together with the V136-4.5MW. However, this last option is not chosen because the corresponding investment cost is higher than the one of the 4.2MW machines while the difference in the total AEP and h_{eq} is not so significant.

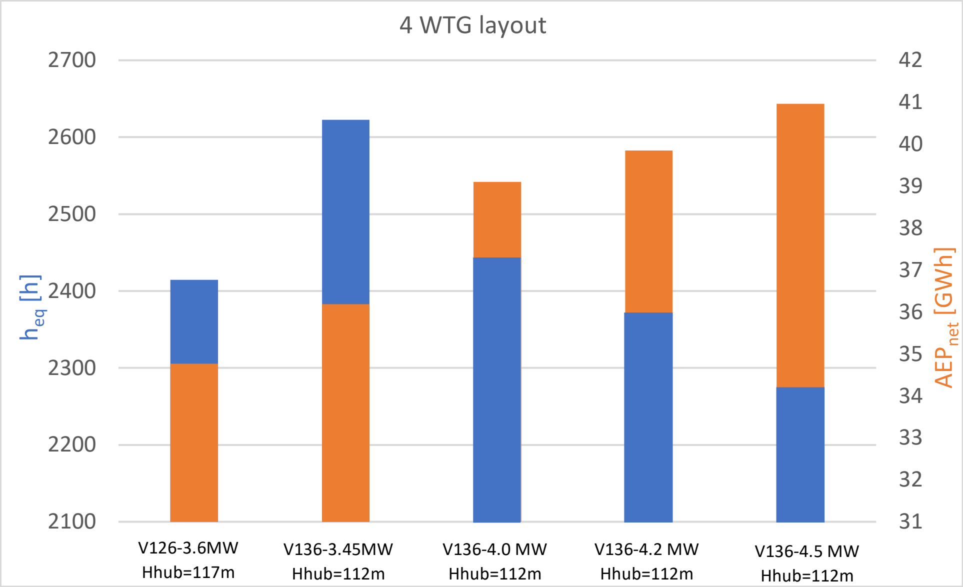


Figure 4.35 – P75 net AEP and h_{eq} for 4WTG layout

The bigger are the rotor dimensions and the machine nominal capacity, the higher is the total net annual energy production even if the equivalent hours are smaller. The reason is due to the fact that wind turbines characterized by smaller capacity are able to reach the nominal power for lower wind speeds, typical of Italian sites, but they are forced to shut down at lower cut-out velocities. This behaviour can be easily shown by looking to the different power curves represented in Fig. 3.36. In the same figure it is possible to understand also why the V136-4.5MW and V136-4.2MW turbines present quite similar productivity, but a difference of around 1000 equivalent hours, even if their nominal capacity is almost the same. In fact, the 4.2MW machine can produce energy at the rated power for a big wind speed range, from 14 m/s to 27 m/s, and then is shut down. On the other hand, the 4.5MW machine works at its rated power for a smaller velocity range, from 15,5 m/s to 21 m/s, and then the power production is progressively reduced until 32 m/s wind speed when the wind turbine is shut down for safety.

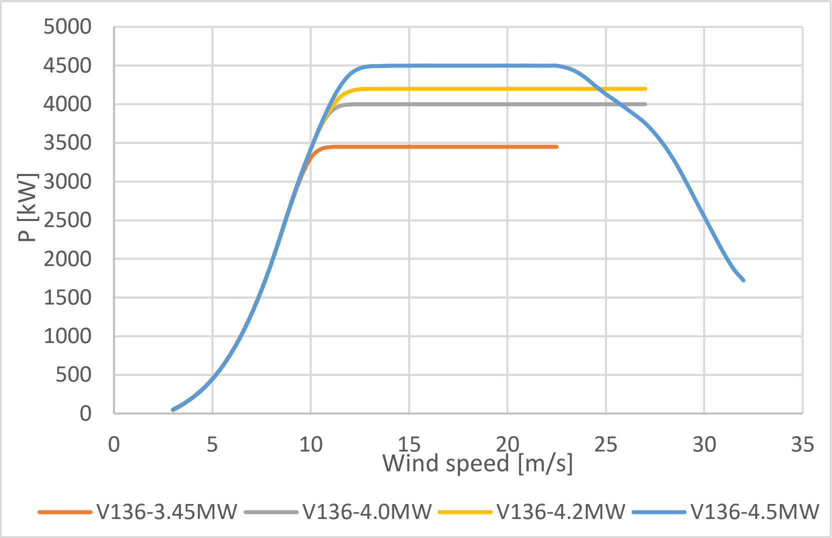


Figure 4.36 – Comparison of V136 power curves

Similar considerations are then performed by looking at bigger wind turbines for which a layout with only three machines is hypothesized.

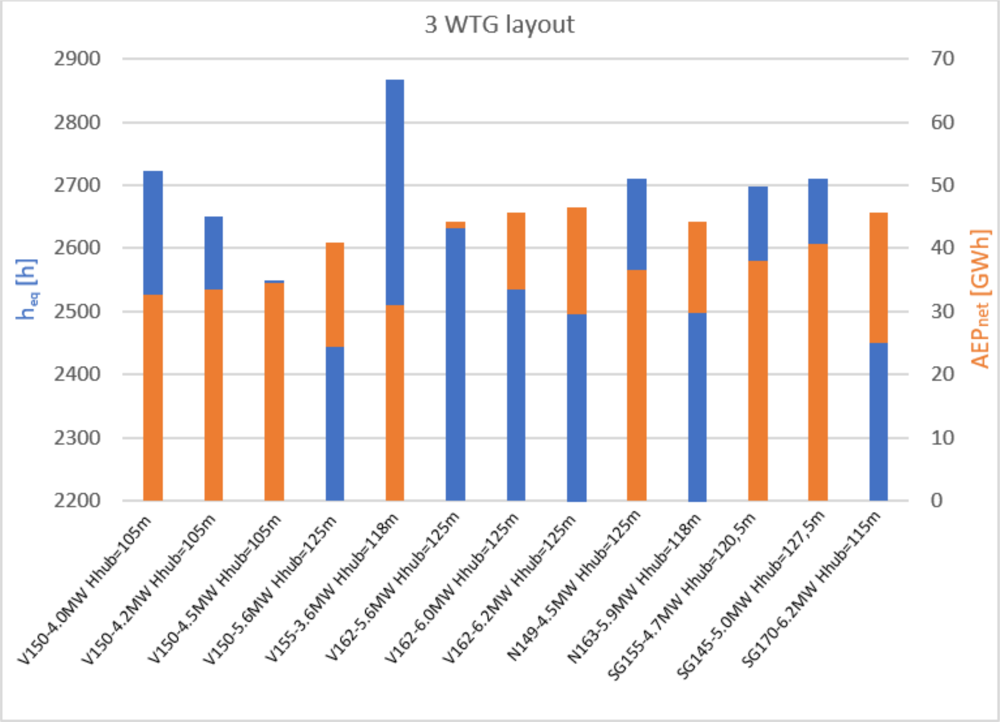


Table 4.30 – Summary of turbine net AEP and h_{eq}

Considering the various options, the best solutions are the wind turbines presenting the higher rated power and therefore the bigger net annual energy production, even if smaller machines present higher net equivalent hours. Taking into account these considerations, the greater productivity, with a good number of equivalent hours, is obtained with the Vestas V162-6.2MW, the Nordex N163-5.9MW and the Siemens Gamesa SG170-6.2MW.

Figure 4.37 – P75 net AEP and h_{eq} for 3WTG layout

				P75	
	D_{rot} [m]	H_{hub} [m]	H_{tip} [m]	h_{eq} net [h]	AEP net [GWh]
V162-6.2MW	162	125	206	2497	46,438
N163-5.9MW	163	118	200	2495	44,161
SG170-6.2MW	170	115	200	2451	45,596

From the table it is clear that the wind turbines characterized by the highest annual productivity are the V162-6.2MW and the SG170-6.2MW. In fact, these machines present the bigger dimensions. The Siemens Gamesa has a very big rotor diameter which allows a big wind energy harvesting, on the other hand the Vestas has a smaller diameter, but a taller hub height that allows the rotor to reach a higher altitude where wind is stronger. For the repowering of the Monte Mola wind farm, and in particular for the layout with four wind turbines, are selected the SG170-6.2MW machines because the turbine cost is lower.

For the two selected layouts, the one characterized by the four V136-4.2MW turbines having a hub height of 112 m and the other composed by the three SG170-6.2MW turbines presenting a tower 115 m tall, are reported some images describing the main characteristics. For each turbine are described the net AEP and wake losses by means of a yellow and a red wind rose respectively. As expected, due to the prevailing wind direction, the WTG02 in the layout with four turbines is subjected to the highest wake losses caused by the presence of the other machines. These roses are reported on resource grid maps representing the mean wind speed in m/s and the mean power density in W/m^2 of the site at the height of the turbines' hubs.

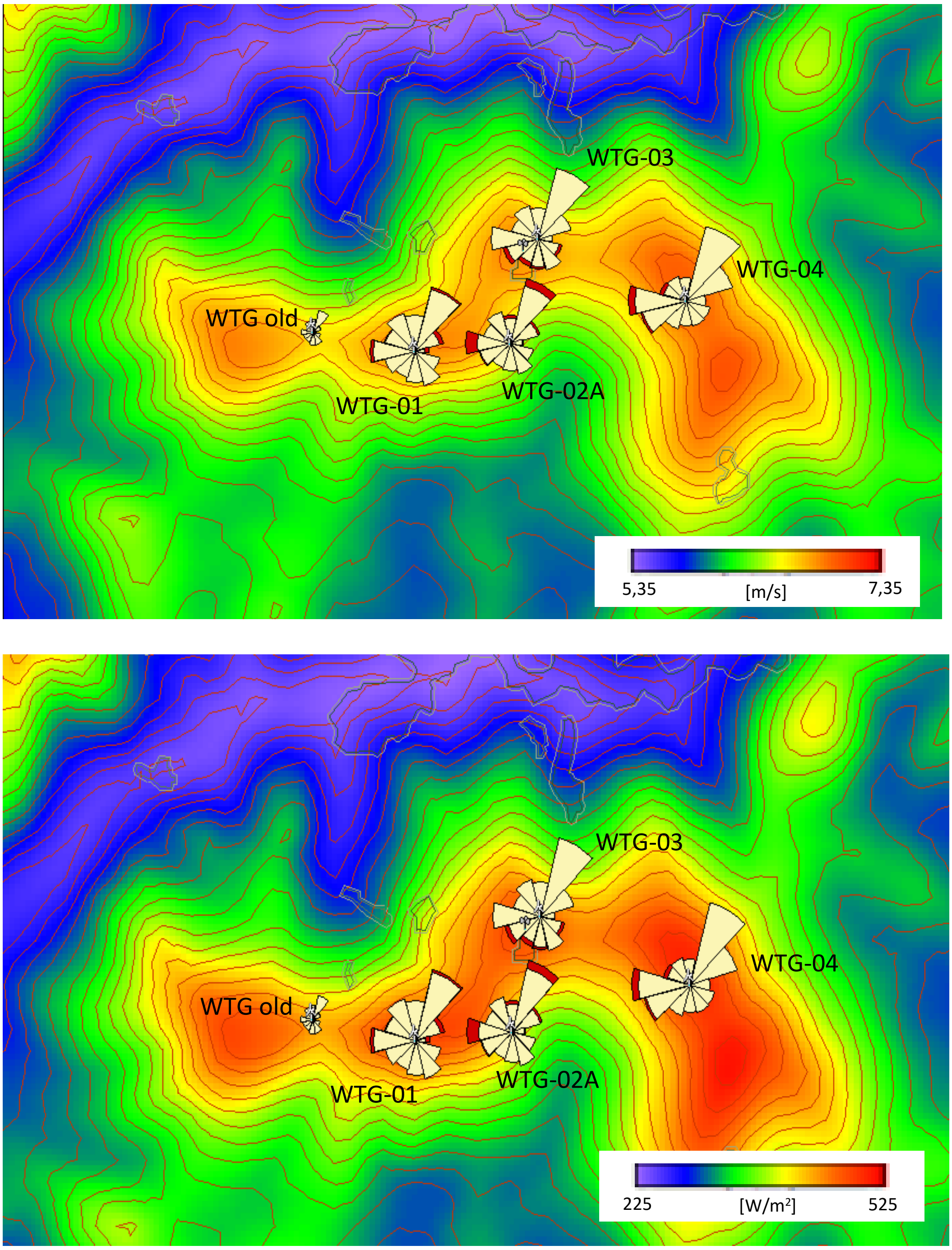


Figure 4.38 – Net AEP and wake losses for 4WTG layout on mean wind speed and power density maps

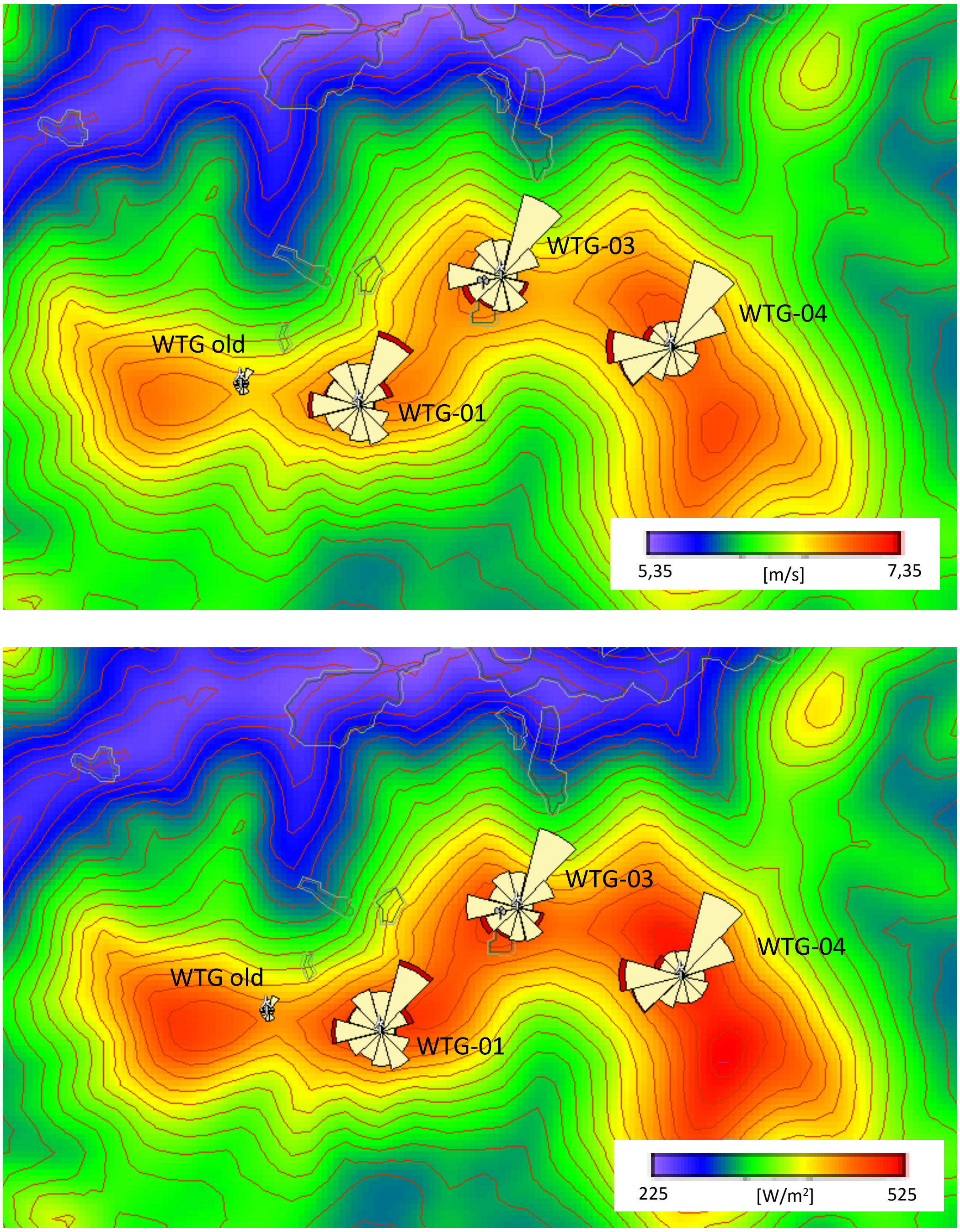


Figure 4.39 – Net AEP and wake losses for 3WTG layout on mean wind speed and power density maps

Another interesting comparison between the two possible layouts is the one regarding the different visual impact. The SG170-6.2MW turbines have bigger rotor diameter and a little bit taller tower, therefore the solution adopting these machines presents a greater impact on the landscape and are visible from a farer distance. However, it has to be considered that the V136-4.2MW solution is characterized by one more wind turbine that obviously influences the panorama.

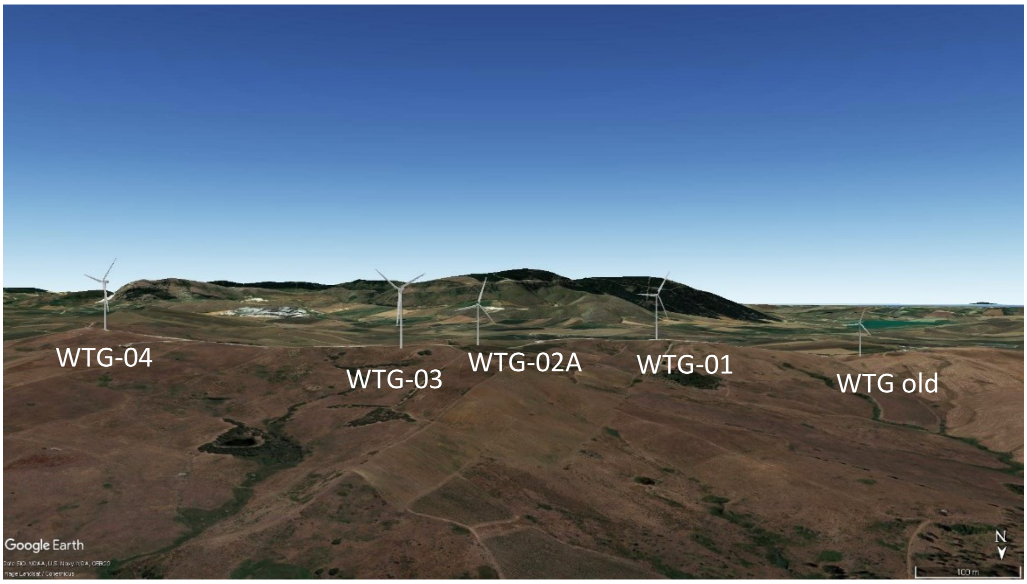


Figure 4.40 – 4WTG layout: visual impact

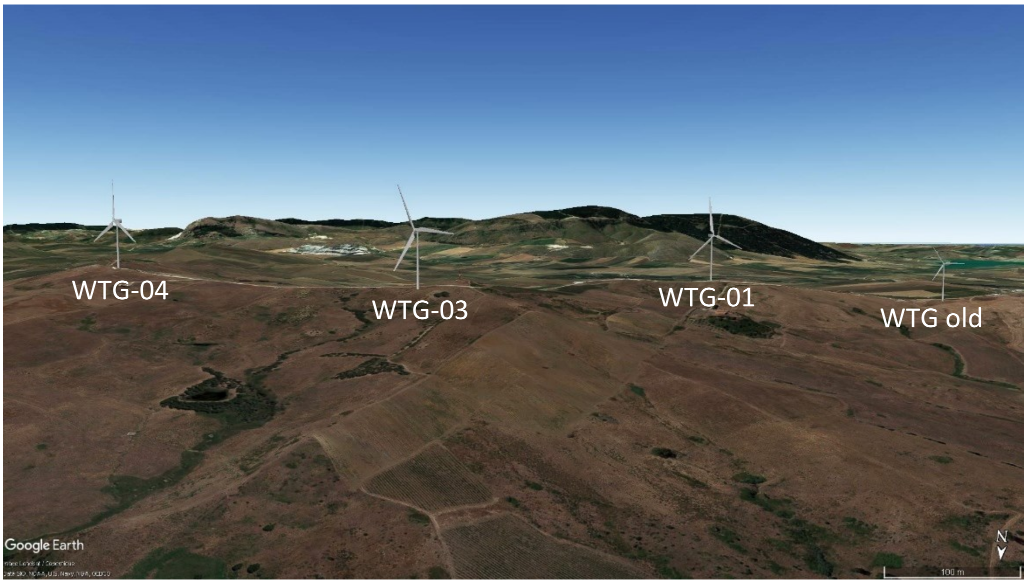


Figure 4.41 – 3WTG layout: visual impact

4.2.6. Economic analysis

The final part of the work is focused on the economic evaluation of the project to evaluate if the repowering activity is profitable and convenient and in that case which of the two proposed layout is the optimal one also in an economic perspective, that means which one has the lower investment and operational costs and highest revenues. The economic analysis must be performed by considering all the possible cost items, including the investment and maintenance costs of the turbines and all the costs for the realization and dismission of the necessary roads and auxiliary infrastructures. These costs are evaluated by estimating numeric or metric calculations for each specific item and considering the prices reported on the regional price list. The analysis is performed according to the economic model of the software *PriMus* and also considering the past expenditures of other plants already built in the recent years.

The first required information is the one regarding the costs of the wind turbine, both in terms of investment and operational costs. These costs are obtained from the turbines' manufacturers that adapt these costs also in function of the geographical area where the plant is located. As shown in the table the cost of each single aerogenerators depends on the dimension: bigger wind turbines present higher investment and maintenance costs. Operational and maintenance costs depend on how many years have passed since installation: in the initial years the costs are lower because a limited request of maintenance is expected since the machines are new.

Table 4.31 – Turbine costs

	CAPEX		**OPEX**		
	WTG	**Plant**	**WTG year 1-2**	**WTG year 3-5**	**WTG year 6-10**
SG170-6.2MW	€ 5.115.000	€ 15.465.000	€ 50.000	€ 68.000	€ 74.000
V136-4.2MW	€ 3.695.000	€ 14.780.000	€ 36.500,00	€ 55.900	€ 55.900

The other costs to be considered in the CAPEX are those regarding surrounding works that are necessary to prepare the site to the construction of the plant and the installation of the wind turbines. They consist in civil, electrical and auxiliary works, which are summarized in the following table. The various costs include both the required materials and the works. The higher costs are the ones about the civil works and especially to the construction of the turbines' foundation since a huge amount of concrete and iron is required and these two materials present very high unitary costs that still increase in the last months due to the particular European situation.

Table 4.32 – Civil, electrical and disposal costs from numeric and metric computations

		SG170-6.2MW	**V136-4.2MW**
Civil works	Roads and pads	€ 771.567	€ 643.141
	Foundations	€ 2.514.683	€ 2.718.713
Electric Works	Wiring	€ 675.524	€ 679.564
	Joints	€ 11.400	€ 9.075
	Terminals	€ 7.218	€ 8.238
	Optical fibre	€ 20.933	€ 21.128
	Copper rope	€ 28.556	€ 31.026
	TOC	€ 221.960	€ 221.960
	Generic works	€ 1.335.863	€ 1.337.856
Disposal Works	Roads and pads	€ 11.760	
	Foundations	€ 238.053	
	Electrical works	€ 39.060	

The main items regarding the civil works are reported in the above table. The first works to realize are the roads. Since the plant will be built in the same area of the existing one almost all the viability already exists and so only some adjustments must be performed. The roads have to present a global width of 5 m and the excavation required has to be 0,3 m deep in order to allow the stratification of the various materials, having different granulation sizes, to create the road foundation. In case of roads with too tight turns or obstacles, that do not allow the passage of the big exceptional transports, temporary by-pass or enlargements must be foreseen. These changes must be designed considering the specific curvature radius of the transports which is basically equal to the length of the blades: 80 m for the SG170-6.2MW and 65 m for the V136-4.2MW. Once the roads are adjusted it is possible to reach each turbine site and start with the foundations and pads construction. The wind turbine foundations consist in blocks of concrete equipped with iron that must be realized following a specific civil project. Usually, foundations present 28 poles plus 2 test poles that are insert deeper in the terrain to guarantee stability to the tower. In the centre of the foundation, it is added an anchor cage which ensures a good anchorage of the turbine's tower to the foundation.

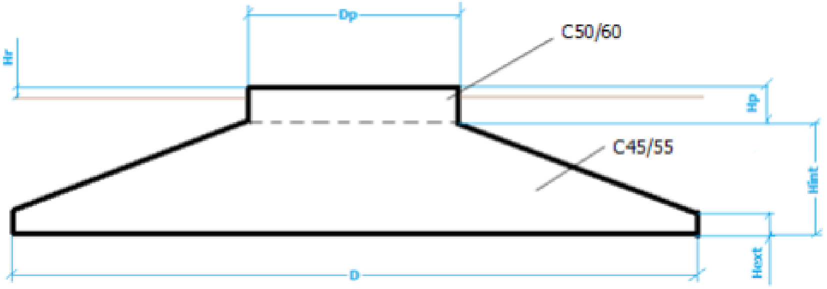


Figure 4.42 – Foundation scheme

Table 4.33 – Foundation dimensions

	SG170-6.2MW	V136-4.2MW
D [m]	23,0	20,0
Hext [m]	0,5	0,5
Hint [m]	3,5	2,7
Dp [m]	6,0	5,5
Hp [m]	0,6	0,5

The dimensions of the foundation depend on the turbine type as highlighted in the Tab 4.33. Similarly, also the pads present specific dimensions. Generally different pads are required: a definitive pad that will remain to facilitate the access and movements around the turbine, a temporary pad, that will be removed at the end of the works, which used to install the crane useful for the assembly of the tower and rotor and a temporary storage pad for holding the blades before their assembly.

In the following figures are reported the civil works that have to be realized in the two possible layouts. Obviously, the bigger are the wind turbines the bigger are the corresponding civil works. However, in the actual case study it has to be considered that the smaller V136-4.2MW layout present one more machine and so surely one more foundation and pad.

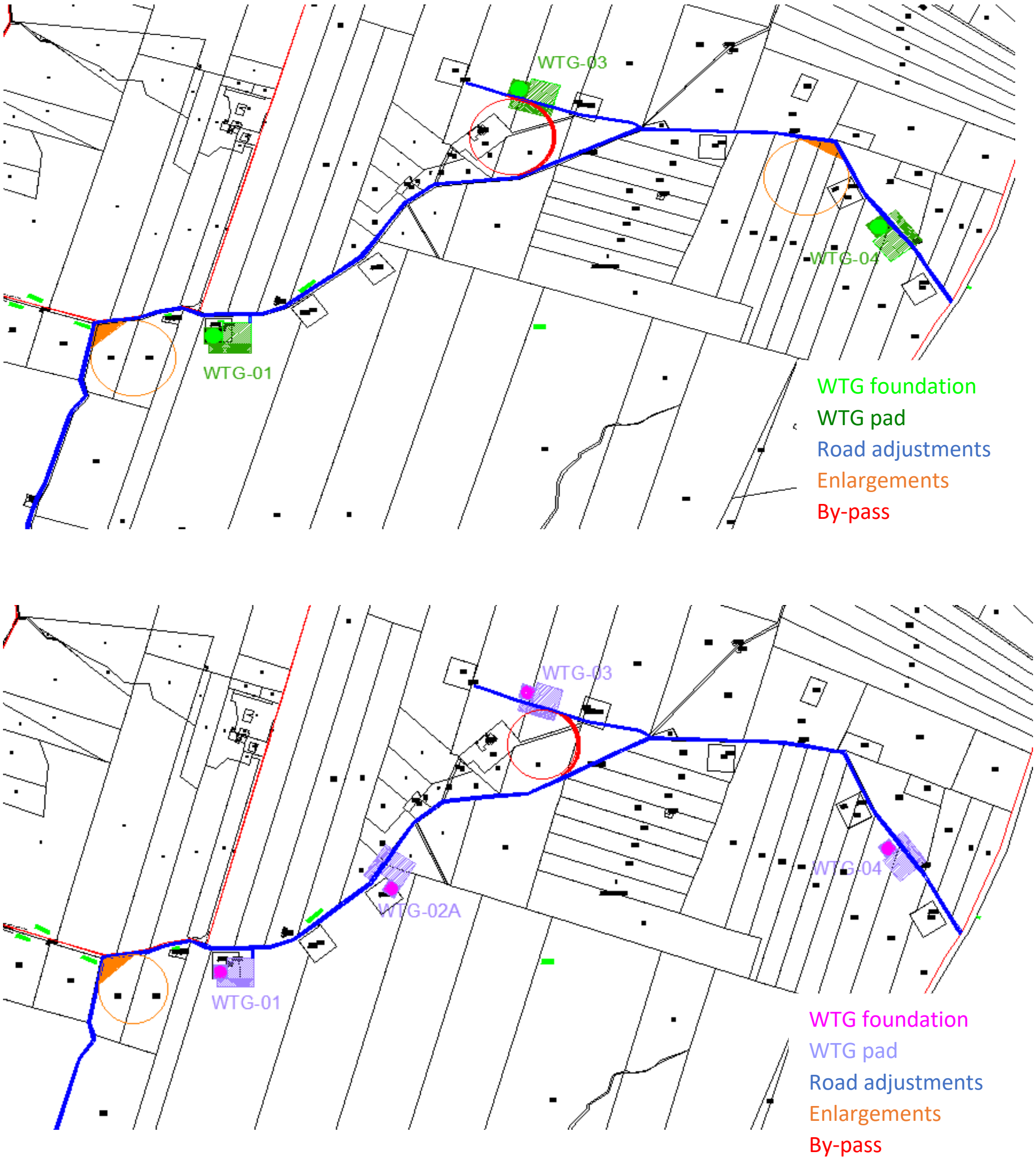


Figure 4.43 – Monte Mola civil works (3 WTG SG170-6.2MW and 4 WTG V136-4.2MW)

The second class of costs is the one about the electric works. The main work consists in the excavation and laying of the medium voltage cable which connects the various turbines and then the wind farm to the user electrical substation and of the high voltage cable used to connect the substation to the national electrical transmission (RTN) network. Out from the wind farm, the path followed by the cables is the same for the two possible layouts: the medium voltage cable is about 11,5 km long while the high voltage cable is about 100 m long. In the figure a hypothetical cable path is represented.

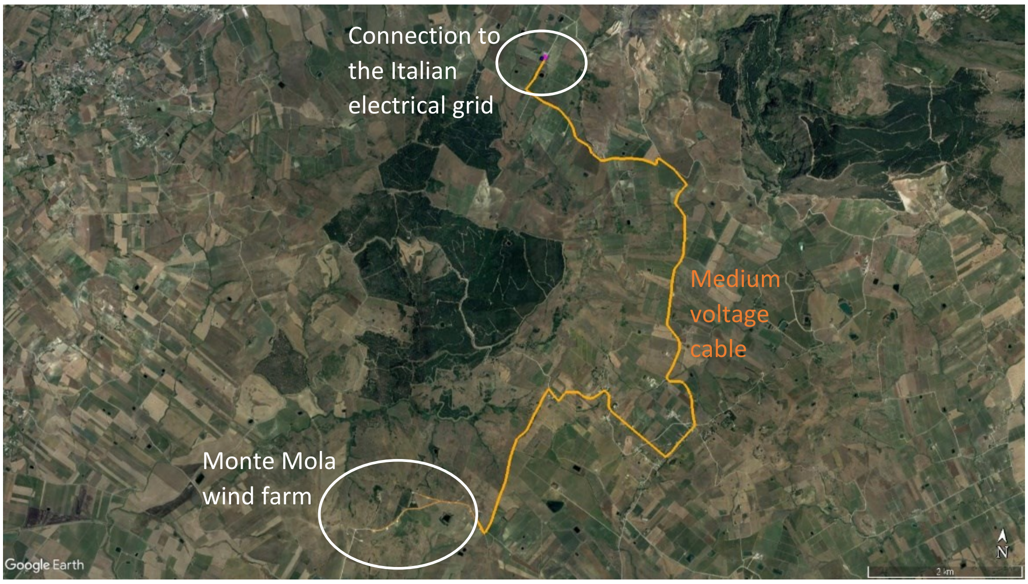


Figure 4.44 – Medium and high voltage cables from the wind farm to the network connection point

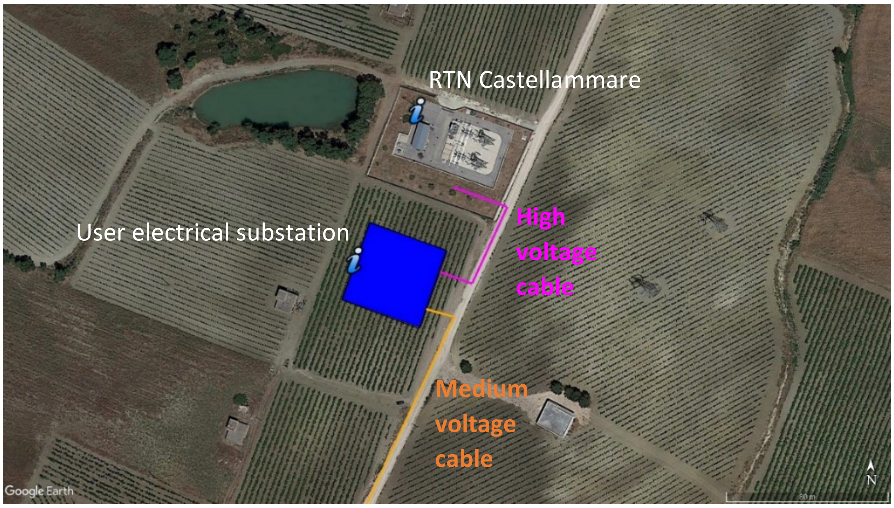
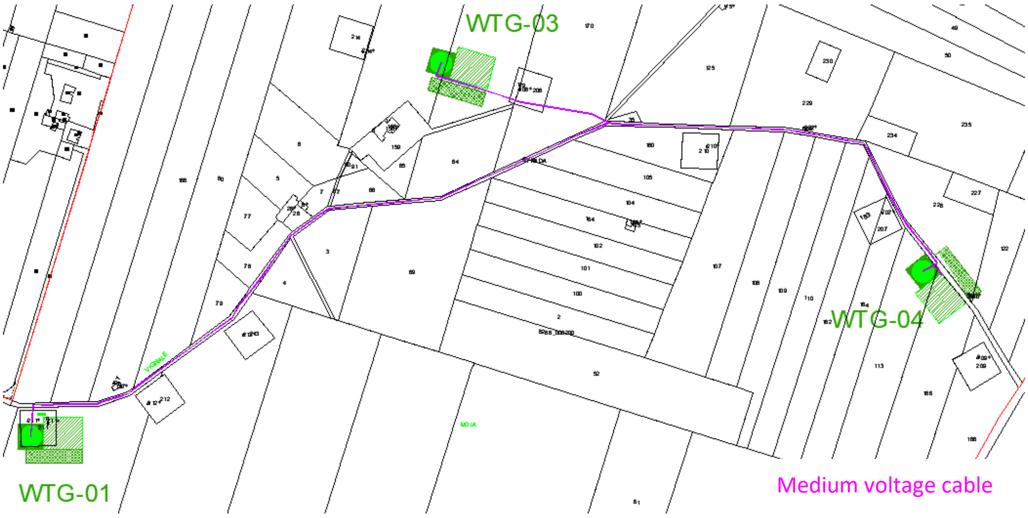


Figure 4.45 – Connection to the Italian electrical grid

The user electrical substation is not still present and so has to be constructed during the plant realization. At the same time also the RTN station probably must be adequate by adding a new electric stall to accept a bigger amount of incoming MW of power. Those activities imply some costs that are considering during the drafting of the CAPEX. Another important electrical cost item is the controlled horizontal drilling TOC which is necessary when the cable path encounters an obstacle, for example, a bridge or impluvium to be crossed. This kind of drilling presents higher cost with respect to the one performed directly on the surface because more complex machines are required. In the Monte Mola repowering project are required about 30 TOC for a total length of around 1300 m. These numbers are estimated simply by looking at the cable path on *GoogleEarth*, but obviously, once the project obtains the authorization for the construction, more accurate investigations will be performed.

In Fig. 4.46 is represented the medium voltage cable path for the two layouts. In the figure the optical fibre and copper rope are not highlighted because they almost follow the same path of the cable. The copper rope, for grounding, connects the various turbines and the anemometer while the optical fibre connects the aerogenerators and the anemometer to the user electrical substation and it is used for the transport of information about meteorological and turbines' data.



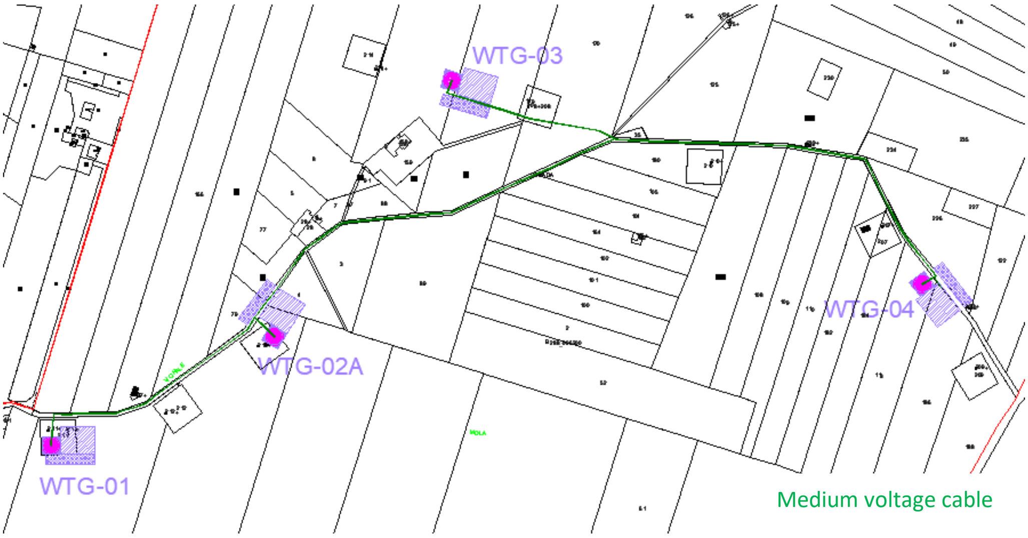


Figure 4.46 – Monte Mola electric works inside the wind park (3 WTG SG170-6.2MW and 4 WTG V136-4.2MW)

Out of the wind farm the cable path is the same therefore the difference in electric connection is inside because the wind turbines are connected in an in-and-out configuration and so, the fact that the number of wind turbine is different, implies also different cable path and length. Variations are also present in the cables dimensioning since the cable section depends on the power transported by the wire. In the following tables are reported, for both the two layouts, the geometric characteristics of each cable and the expected electrical losses. Moreover, are also added information about the number of required joints, that are needed every 1 km of cable since the commercial coils usually have a maximum length of 1000 m, and about the number of medium voltage terminals for the connection of the wire to the machine. It is important to notice that for each cable section are required three wires because the electrical system has a three-phase configuration.

Table 4.34 – SG170-6.2MW: Cable dimensioning, joints and terminals

Cable MT - ARE4H5(AR)E - 18/30 kV				**ACCESSORIES MT**	
	Length [m]	**Section [mm^2]**	**Voltage drop [%]**	**Terminals MT**	**Joints MT**
WTG01 - WTG03	1315	95	0,43	2 kits type C 400A/630A	1 kit

WTG03 - WTG04	920	240	0,26	2 kits type C 400A/630A	-
WTG04 - CAB SM	50	500	2,87	1 kit type C 400A/630A 1 kit auto/heat shrink	-
CAB SM - SSE	11.500	500	-	1 kit type C 400A/630A 1 kit auto /heat shrink	11 kit

Table 4.35 – V136-4.2MW: Cable dimensioning, joints and terminals

Cable MT - ARE4H5(AR)E - 18/30 kV				**ACCESSORIES MT**	
	Length [m]	**Section [mm^2]**	**Voltage drop [%]**	**Terminals MT**	**Joints MT**
WTG01 - WTG02	470	95	0,10	2 kits type C 400A/630A	-
WTG02-WTG03	975	120	0,35	2 kits type C 400A/630A	-
WTG03 - WTG04	920	240	0,27	2 kits type C 400A/630A	-
WTG04 - CAB SM	50	400	3,09	1 kit type C 400A/630A 1 kit auto/heat shrink	-
CAB SM - SSE	11.500	400	-	1 kit type C 400A/630A 1 kit auto /heat shrink	11 kit

The higher are the power to be transported and the cable length, the bigger has to be the section of the cable in order to obtain lower the voltage drop, but the higher are the difficulties in the laying of the cables and the costs.

Until now are performed the metric and numeric computations for the new plant that will be constructed. However, to all this works must be added also those regarding the disposal of the existing wind farm in operation for the restoration of the sites to the pre-construction state. In this sense, the existing pads must be removed, and the foundations destroyed for the first meter of depth. At the same time the old wind turbines have to be dissembled and also the old electrical cables have to be removed. The resulting waste materials must be disposed of in local authorized landfills even if, in any case, the recycling of products will be promoted as far as possible in a circular economy perspective in order to respect the environment. In particular, an attempt will be made to sell the wind turbines to third-party companies in order to cover the costs of dismantling of the machines without producing too many wastes. Once all the useless old infrastructures are removed it is necessary to proceed with the remodelling of the land to its original state and the restoration of the vegetation.

The metric and numeric computations performed so far provide information about the various cost items, as shown in Tab. 4.32. For the CAPEX other cost items are also added in order to consider all the possible source of expenditures.

Table 4.36 – CAPEX summary

	SG170-6.2MW	**V136-4.2MW**
Engineering, preparatory surveys and design costs	€ 521.557	€ 564.280
Civil Works	€ 5.788.895	€ 5.866.712
Electrical Works (including electrical substation)	€ 3.859.291	€ 3.863.304
Wind Tubines	€ 15.465.000	€ 14.780.000
Safety costs	€ 153.313	€ 160.184
Connection Costs	€ 26.789	€ 24.185
Total investment	€ 25.814.845	€ 25.258.666

Globally the higher investment is obtained by installing three wind turbines SG170-6.2MW. However, by looking the investment cost for each MW of installing power it results a lower cost: 1.387.895 €/MW for the SG170-6.2MW and 1.503.492 €/MW for the V136-4.2MW.

For establishing which is the better layout an accurate business plan must be performed. For the project, we have relied on a consolidated financial model, focused on the first 20 years of the plant operation, which is provided by Asja Ambiente Italia.

The first index to be introduced is the EBITDA one, defined as Earnings Before Interest, Taxes, Depreciation and Amortization. It accounts for the cash flow obtained by the company without consider interest, taxes, depreciation and amortization items and is calculated by subtracting the annual expenses, and so the OPEX, to the revenues obtained from the sale of electricity which tariff at €/MWh is variable according to the different year and period of the day:

$$EBITDA = revenues - OPEX \tag{4.7}$$

In the analysis it is considered an average revenue for the sale of electricity on the market of about 70,7 €/MWh and an average expenditure to produce this energy of about 46,0 €/MWh for the case with four V136-4.2MW wind turbines and of about 40,2 €/MWh for the layout with three SG170-6.2MW machines.

However, for a better and more accurate evaluation of the project convenience it is required to also consider the taxes that are evaluated as a function of the revenues coming from the electricity selling. In this way it is obtained the income entering the company's coffers each year:

$$Incoming\ profit = EBITDA - taxes \tag{4.8}$$

In reality, the incoming profit calculated in this way will not be immediately usable by the company, but firstly will be used to repay the initial investment. Only when this expenditure has been recovered, the profit becomes a real gain therefore the recovered time has to be the lower as possible.

Generally, the incoming profit is also known as Cash Flow and it is useful for the calculation of the Cumulated Cash Flow which indicates how much money is still needed to entirely recover the CAPEX. It is calculated by summing every year the incoming profits to the CAPEX which is considered negative. The final value of the Cumulated Cash Flow, if positive, indicates the final earning obtained from the investment.

$$Cumulative\ Cash\ Flow_n = -CAPEX + \sum_{t=0}^{n} Cash\ Flow \tag{4.9}$$

The evaluation of this parameter allows also to obtain the so-called Pay Back Time PBT which corresponds to the time in which the initial investment is completely recovered. This parameter, together with the Internal Rate of Return IRR, is fundamental to establish the economic interesting of a certain project. The IRR index is mathematically defined as the discount rate which makes the

Net Present Value NPV of a series of cash flows equal to zero. With discount rate is mean that interest rate used to transfer a certain capital expenditure from the actual time to a future time to have a financially equivalent capital both in the present and in the future. This means that for knowing the IRR it is required the NPV which can be calculated in this way:

$$NPV = \sum_{t=0}^{n} \frac{Cumulative\ Cash\ Flow}{(1+i)^t} \tag{4.10}$$

When, by varying the discount rate i, the NPV is equal to zero, the correct value of IIR is found. The IRR index usually has to be higher of a certain value to have a profitable investment and so to consider the project interesting and realizable.

The financial modelling exploited in the analysis considers all these indices and parameters, but a better clarification must be done on the initial CAPEX. As already explain, the CAPEX indicates the investment that a company must pay to realize a project. This capital can be directly and entirely paid by the company or can be partially entrusted to a bank. According to these two possibilities the financial modelling varies a bit. In the first case, the CAPEX is entirely covered by the company and therefore the real convenience of the project can be evaluated since the considered values refer exclusively to the plant. On the contrary, in the second case, the company is helped by a bank and therefore in the economic model must be considered also those parameters required by the second investor like the mortgage payments and the interests. It is important to highlight that exploiting an external bank to partially cover the investment is always convenient since the company does not pay too much also by reducing the economic risks linked to the investment. Obviously even this solution presents some difficulties and risks that can be easily keeping under control by subscribing a good contract with the bank. In particular, must be defined the percentage of the capital entrusted to the bank (leverage), the duration of the loan and the imposed interest rate. For the analysis it is considered a leverage of 70%, a loan duration of 10 years and an interest rate of 3%.

In the following table a summary of the results of the economic analysis is reported, while in the figures the cumulative cash flows of the two possible projects are compared.

Table 4.37 – Results of the economic analysis

		SG170-6.2MW	**V136-4.2MW**
Installed power		18,6 MW	16,8 MW
Equivalent hours		2.451 h	2.372 h
CAPEX		26.229.845 €	25.673.666 €
OPEX		472.200 €	498.080 €
Cumulative Cash Flow		10.433.555 €	5.941.592 €
Net Present Value		4.779.732 €	2.721.912 €
Internal Rate of Return	**Unlevered**	6,1 %	4,6 %
	Levered	9,2 %	6,4 %
Pay Back Time	**Unlevered**	12 y	14 y
	Levered	13 y	15 y

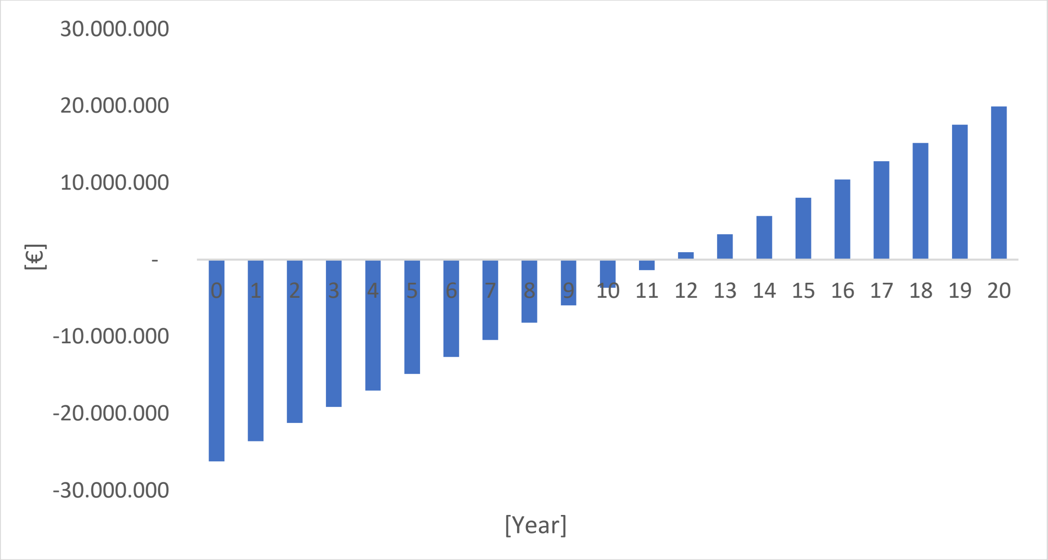


Figure 4.47 – SG170-6.2MW: Unlevered Cumulative Cash Flow

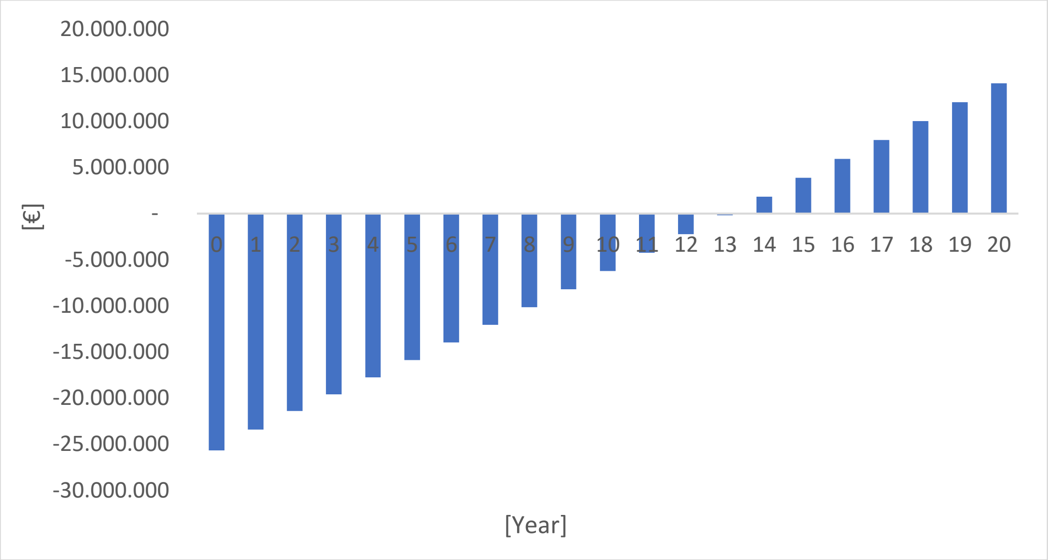


Figure 4.48 – V136-4.2MW: Unlevered Cumulative Cash Flow

As highlighted in the table and in the graph the layout presenting three SG170-6.2MW wind turbines is the optimal one because it allows a faster recover of the investment even if it is higher. Such solution presents also a greater IIR, of about 6,1%, which, in any case, is not so high compared to other wind projects developed by Asja Ambiente Italia Spa. However, it is important to notice that it increases of about +3% by asking the help of an external bank, so that the repowering project could be really interesting.

Chapter 5

Conclusions

The goal of this work is that of understanding which is the optimal solution to adopt for the repowering of the existing and operating wind farm of Monte Mola that is going towards its end of life. The entire analysis is focused on the highlighting of which layout and turbines ensure the best performances both in technical and economic terms. The main purpose is to improve the performances of the plant and so to increase the annual energy production.

The analysis has shown that the more profitable solution for the power upgrade of the wind farm is the one presenting a layout with three wind turbines SG170-6.2MW. In this way the actual installed power of about 6,8 MW, obtained with eight aerogenerators, will be increased of about 274% reaching around 18,6 MW only with the usage of three machines. This inevitably reduces the impact on the environment in terms of civil and electrical works and also in terms of visual impact even if the bigger dimensions of the turbines make machines more visible from far distance. However, this last point in the specific case study has a lower importance since the plant area is in the Sicilian hinterland where there are no points of particular architectural, naturalistic and landscape interest. In this work all the analysis are preliminary, once the project will reach the approvement by the company department to develop the project, new and more accurate studies have to be performed. Even if no important naturalistic sites are present in the area, some studies must be developed to understand, for example, how the new machines can impact on the flora and fauna of the place and particularly on the migratory routes of birds.

From a technical perspective the incoming benefits of the project regard the increase of the number of equivalent hours and of the annual energy production that respectively reach quite high values with respect to the present situation. In fact, on average, yearly the plant in operation presents about 1755 h_{eq} and an AEP of 11930 MWh, while the expected AEP of the new repowered plant is about 45595 MWh per year with 2451 h_{eq}.

The convenience of the repowering project is clear by looking at these values reported just above, however the economic analysis has shown a quite big initial investment that is not so easy to be recovered in short time. The causes of the big investment are mainly related to the increases of costs linked to material and transports. The hope is that in the course of the two/three years, that it is expected to wait for the obtaining of the national authorization for the construction of the plant, the prices of these items will decrease making the investment more convenient.

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