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Estimation of wind potential in Sardinia, quantitative computation and actual constraints analysis.

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1. Abstract

Wind energy is one of the renewable sources that can help to reduce the greenhouse emissions in Italy, in order to achieve the environmental goals defined at national and global levels. A widespread diffusion of wind turbines in the territory significantly affects several aspects of human lifestyle, as for instance the landscape and the noise level. To estimate how the wind resource can be exploited in today and future energetic mix, both at national and regional level, in this thesis an assessment of the electricity productivity of wind turbines is performed. The selected region of the study is Sardinia, the second biggest island in Italy. Different wind potentials are computed, more precisely the technical, the feasible, and the regulatory potential, which are based on the definition and application of several exclusion criteria. Moreover, a technical analysis of the actual electric infrastructure of the Region is conducted, and also an economic evaluation of each potential. The main result shows that all potentials have consistent annual production and "efficiency" (i.e., capacity factor), so the wind resource in the region can be exploited to sustain the renewable development in Italy according to the national targets.

2. Introduction

2.1. Objective of the study

The main objective of this thesis is to evaluate the theoretical annual electricity production using wind turbines in Sardinia, an Italian region. The quantity under investigation is called more properly potential, defined as electric energy produced by wind generators in a year. The growing concerns about climate change, and the necessity to modify the electric generation in Italy to reduce CO_2 emissions, lead to a relevant interest in the renewable sources. Differently from a thermoelectric plant, whose electric production is independent from the location where it is constructed, renewable sources need a detailed assessment for what concerns the optimal siting, in order to maximise the annual generation (and also the revenues). However, several factors must be considered while evaluating the siting of wind turbines, because certain areas must be excluded from the calculation for varied reasons. This exclusion is implemented considering some constraints, which correspond to portions of territory which cannot be included in the available area for wind turbine installation according to the legislation or other factors. Therefore, the calculation of the wind potential is strictly correlated to the choice of the constraints. Indeed, the potential is computed starting from the set of exclusion criteria, which has the biggest impact on the final result.

Considering what highlighted above, defining which areas must be excluded from the computation is the most crucial decision to make, and then define the correspondent constraint. This decision can vary a lot based on where the study is conducted, since different countries or regions give importance to diverse factors, therefore a common set of exclusion criteria does not exist. Concerning this point, in Italy the constraints that must be considered for installing a wind turbine are decided by the Regions, with some national guidelines and constraints (e.g., distance from single buildings, distance from airports) which have to be applied. Hence, the choice of which areas should be excluded from the wind potential calculations is very difficult and important and affects greatly the final results.

Focusing only on the study area, Sardinia, the previous problem is partially solved, since the regional laws define accurately which are the exclusion criteria, and so the potential can be calculated consequently. However, to provide some possible alternatives to the wind potential computation, other constraints are implemented and considered in this thesis, in order to obtain comparative results. In this way, the importance of the exclusion criteria choice is underlined, and also its impact on the wind potential. Alongside the definition of the exclusion criteria, also the choice about which turbines consider is important since the evolution of the technology can lead to significantly different wind potentials in the next future.

The importance of calculating the wind potential in Sardinia, together with the analysis of the constraints and turbines, is related to the energy security of the island. Indeed, a correct development of renewable sources, paired with a proper growth of electrical storages, can ensure a completely green electricity supply to the region, reducing the dependence on the mainland and on fossil fuels. Additionally, Sardinia can become a great exporter of electricity to foreign countries (mainly France) and to the peninsula, in order to increase the renewable electricity share in Italy. Nevertheless, several problems arise while considering a similar scenario. First of all, the electricity storage must be consistently developed, and also the electric connection to the mainland. Secondly, to guarantee a zero emissions generation a huge exploitation of renewable sources must be implemented. For what concerns the last point, the evaluation of the wind potential in Sardinia is surely fundamental to understand whether a zero emissions electric generation scenario can be achieved, and which actions could be made to pursue this purpose. Hence, the objective of this thesis is contextualised in this framework, to provide a tool to evaluate how the wind development in Sardinia can foster the renewable share in the national and regional electricity generation. Moreover, an analysis is performed regarding the various elements related to this assessment, so that the exclusion constraints, the turbine technologies, the electric infrastructure of the region, the economic factors for each potential.

2.2. Wind resource

2.2.1. Wind generation

Wind is the natural movement of air above the surface. Several types of wind exist, each of them with different strengths and durations. Globally, wind is generated by atmospheric circulation, which in turn is caused by two main factors: unequal global heating and Coriolis effect [1]. The first effect is created by a different amount of solar radiation which reaches the surface at Poles and Equator. Indeed, Sun rays needs to pass through a thicker atmosphere before hitting the surface at Poles than at Equator, due to inclination of Earth axis, so more heat is dissipated. This induces a net loss of heat near polar regions, while near Equator a net gain is present. The unbalance implies that the equatorial region is warmer than polar regions, therefore a movement of air is created which follows the temperature gradient. This phenomenon is shown in *Figure 1*.

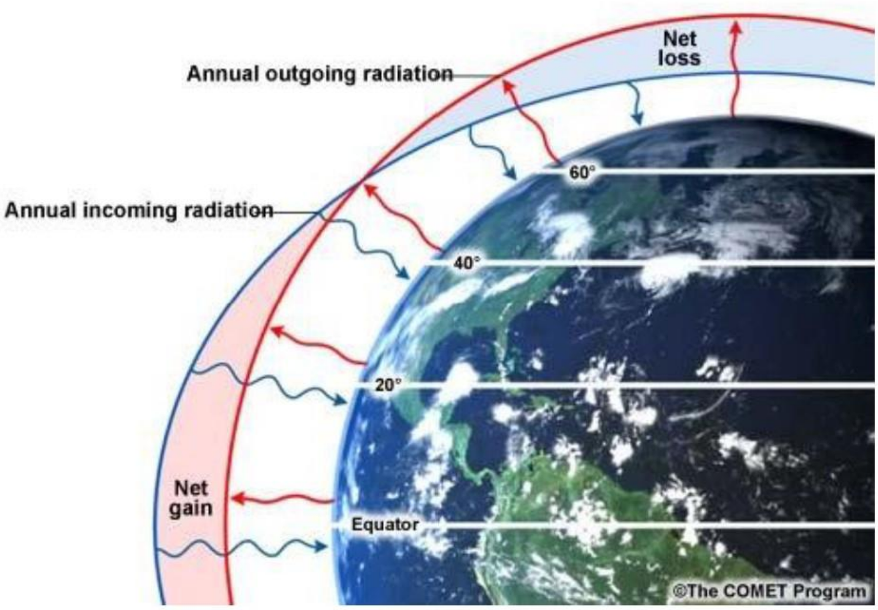


Figure 1 - Global radiation balance [2]

However, the flow of the air is not straight due to the second factor involved: the Coriolis effect. The Coriolis force is a fictitious force that acts on a body in motion within a rotating frame of reference, which causes a deflection of the body's path with respect to an inertial frame of reference. This effect is valid also for the Earth because it rotates faster at Equator than at Poles. Hence, the air moves from Equator towards Poles with different trajectories, generating three zones (more precisely cells, *Figure 2* [1]*)* for each hemisphere where the air motion remains nearly constant over years. As it is possible to observe in the figure below, the polar and Hadley cells are driven by temperature gradients, while the mid-latitude cell, or Ferrel cell, is a secondary circulation feature and it depends entirely on the other two cells. At an altitude above ground level of 1 kilometre (where friction is low), the air moves parallelly to isobars (geostrophic wind).

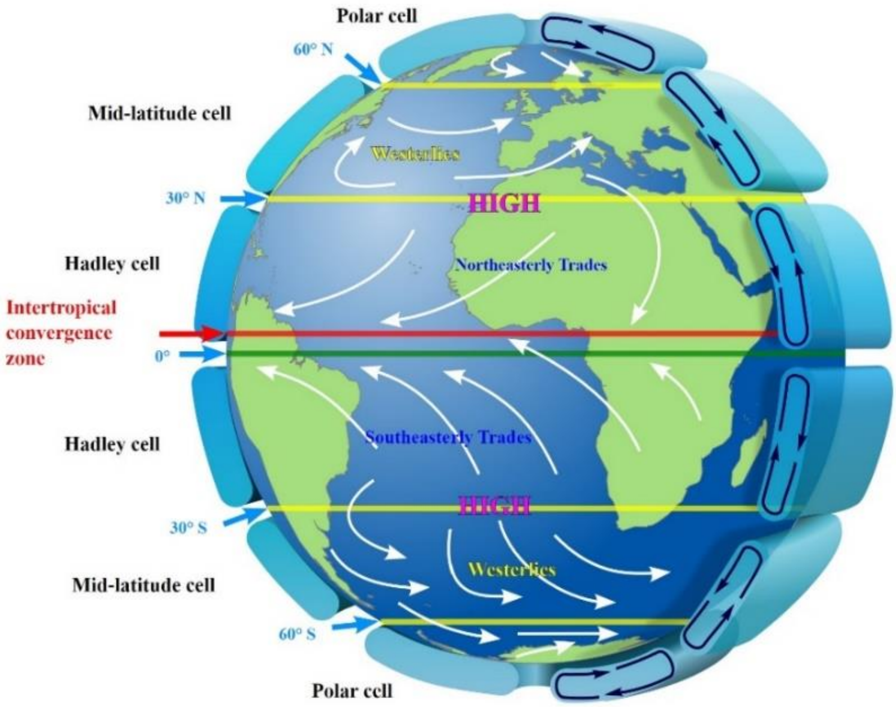


Figure 2 - Atmospheric circulation [1]

The global winds generated by above-mentioned factors are important to determine the predominant behaviour of winds in a given area, but other local elements can influence wind direction. Local winds are always created by temperature and pressure gradients, but at smaller scale. For example, sea or land breeze develops from temperature gradient between sea and mainland, which is opposite during the day and the night.

Another key factor to consider in order to define the wind behaviour is the roughness of terrain and, consequently, the turbulence. The terrain roughness creates the wind shear, which is a difference in wind speed at different heights above the ground. Lower roughness implies higher speeds, as for example over the sea or very smooth surface (e.g., ice or mud). The wind speed is also linked to distance from the ground since the influence of the obstacles on the terrain diminishes as height increases. The presence of an obstacle generates a turbulent flow of the air near the terrain, which affects the productivity of a wind generator. This influence is related to the height of the obstacle, as shown in *Figure 3* [3]. As it is possible to observe, the turbulence is generated also upwind with respect to the obstacle, and it alters the air flow quite far in downwind direction.

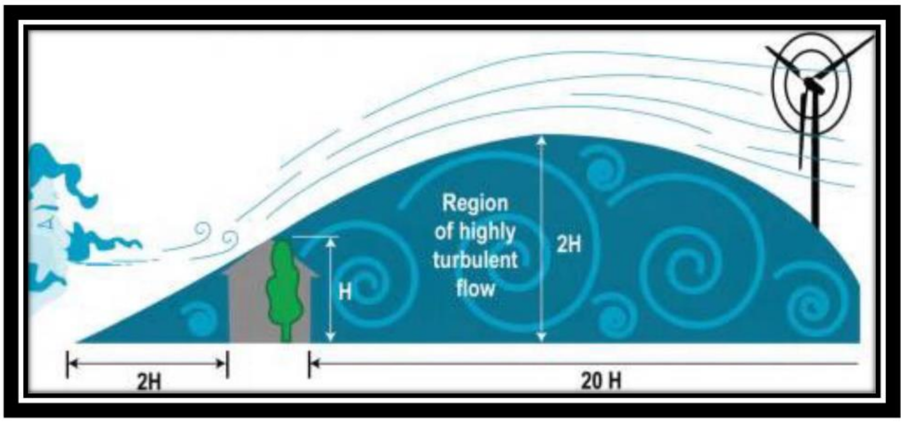


Figure 3 - Influence of obstacle for turbulence

Various sources of turbulence are identifiable, and they can be divided into two groups: modifying and local factors. The first category includes elements as orographic variation and surface roughness changes, hence related to the shape of landscape. The second category includes locally relevant effects, as for instance thermal convection, obstacles (e.g., trees or buildings), steep terrain, wind turbines.

Considering all the effects briefly described above, it is possible to analyse the best location where to install a wind turbine. Moreover, some wind atlases have been developed through years in which the average wind speed is provided for a certain area, at different distances from the ground. These data are useful not only to identify the windiest site, but also to determine which turbine could be employed. Below are shown the wind map for Italy (*Figure 4*) and Sardinia (*Figure 5*) [4], at 100 metres above the surface.

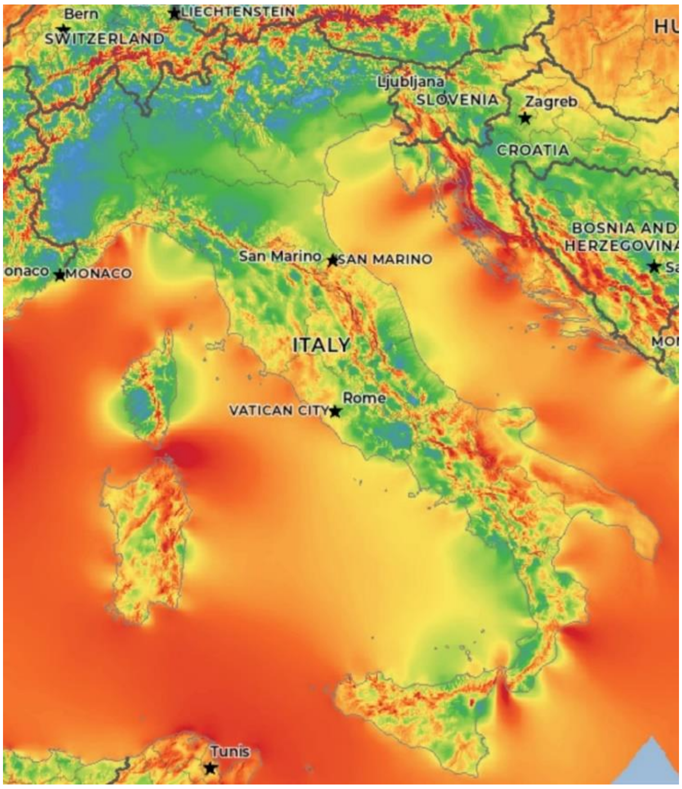


Figure 4 - Wind map for Italy [4]

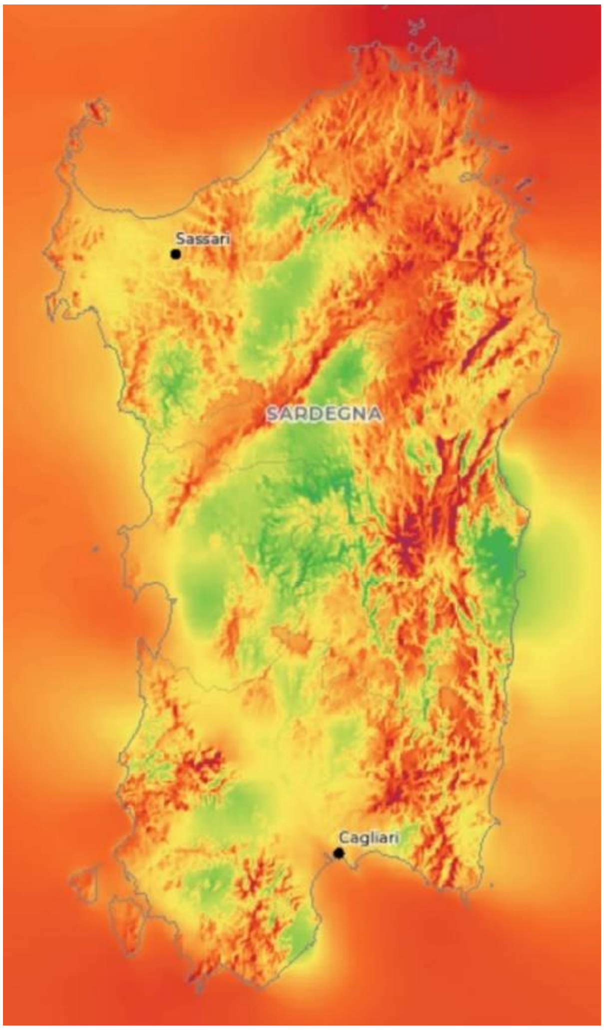


Figure 5 - Wind map for Sardinia [4]

2.2.2. Wind power history

Having discussed how the wind is generated in the atmosphere and how it is affected by global and local effects, a brief digression can be done to explain the methods that have been invented in the human history to exploit this natural resource.

The story of wind power started with the construction of sailboats around 6000 BC, but the first massive use of this type of means of transport dates back to ancient Egypt, around 4000 BC, before a rapid development among Greeks, Arabs, and Phoenician [5].

Considering specifically wind machinery, the first example of a windmill dates back to ancient Persia, between 500 and 900 A.D., in the modern Iran. These vertical axis windmills were built of clay, straw, and wood, and the rectangular sails were connected to a vertical shaft which rotated a grinding stone for milling [6]. The region where these machines were constructed is characterised by intense winds (up to 120 km/h), so the windmills have been developed to withstand these storms and at the same time to harvest energy to produce flour. Moreover, being placed in the highest location, they also protected the villages from the storms. Some of these windmills are operative still nowadays.

Then, the use of windmills spread out in the Middle East and Central Asia, and later in China and India. At the end of the 12^{th} century, horizontal axis windmills were extensively used in the North-western Europe, with a design completely different with respect to the machines developed in the Middle East. In the 14^{th} century, Dutch windmills were used to drain the delta of Rhine river. Some centuries later, several windmills were installed in rural America to operate irrigation pumps, with several companies involved in this business.

The first example of proper wind turbine, so that designed to generate electricity, is dated July 1887, developed in Scotland by James Blyth, professor at Anderson's College [7]. This turbine was 10 m high, and it was used to charge accumulators which in turn power the lighting of the professor's house. He successively designed a bigger wind turbine to power some public buildings in Montrose, but this invention did not increase the attentions toward the wind technology since it was not considered economically feasible.

In the same years (1887-1888) in Cleveland, Ohio, a larger wind turbine was designed by Charles F. Brush, with a rotor diameter equal to 17 m and a tower height of 18 m [7]. Despite the dimensions, the turbine only produced 12 kW because of its low rotational speed, due to 144 blades. However, the turbine remains in operation until 1900, and it was abandoned in 1908.

In 1891, a Danish scientist named Poul la Cour constructed a wind turbine to generate the electricity required for the water electrolysis, in order to produce hydrogen [7]. He also invented a regulator to generate a steady power supply, and in 1895 transformed the windmill in a prototype electrical power plant to provide power for public lighting to Askov, South Jutland.

In the 20^{th} century, rapid growths and as much fast declines of wind turbines market took turns through years. In Denmark, after the successful experiment of Poul la Cour, 72 wind-driven electric generators were in operation by 1908, most of them designed with four blades and a peak power of 25 kW. In 1927 the Jacobs brothers opened a factory in Minneapolis, Minnesota, which produced small wind turbines for farm use. In 30 years, they sell around thirty thousand wind generators, mainly in Africa. In 1931, the Darrieus wind turbine was invented, with a vertical axis which allowed to harvest energy from all wind directions, and the further advantage of leaving on the ground the heavy equipment, instead of atop of a tower. The large widespread of small wind generators in the rustic U.S. stopped when the government decided to start the rural electrification in 1936, since with a given investment the supply of electricity to a farm was steadier and safer.

The first example of a utility scale wind turbine was the WIME D-30, operated in Balaklava, URSS, from 1931 to 1942. It was characterised by a three blades rotor diameter of 30 m, mounted on a steel lattice tower of 30 m, capable to generate a peak power equal to 100 kW with an annual load capacity factor near 32% [7]. The first wind turbine with a nominal power higher than 1 MW was built in Castleton, Vermont, in 1941, which was characterised by a power capacity equal to 1,25 MW. It remained operative for 1100 hours, until a blade failure occurred [7]. No comparable size turbines were constructed for 40 years.

After some years of decline, the wind turbine technology was back in vogue after 1973, more precisely during the first oil crisis, following an oil embargo proclaimed by Organization of Arab Petroleum Exporting Countries. Considering the increase of the oil price, mainly in the U.S., a renewed attention towards wind technology began. NASA, with funds from National Science Foundation and United States Department of Energy, started to develop several wind turbine designs, which set many records for diameter dimensions and power output. These turbines featured some technologies used in contemporary industry, such as steel tube towers and variable speed generators. None of these generators were put in mass production, and when the oil price returned to decrease many firms left the market.

On the contrary, in Denmark the wind technology experimented a significant growth from 1970s, which led to an increment of power output and efficiency thanks to an extensive serial production. The consequence was that all commercial wind turbines followed the Danish model, so that a light weight three blades upwind design.

Arriving to last years, at the beginning of 21st century, the concerns about global warming, fossil fuels depletion, and energy security, led to an expansion of interest in renewable energy. The grid parity was reached in these years, while the cumulative capacity in the world continued to grow, achieving a global nominal power equal to 732 GW in 2020 [8], and an electricity generation of 1.412 TWh/year [8] (equal to 5,6% of global electric consumption).

2.2.3. Wind turbine technology

In order to exploit the power in the wind, a turbine is necessary. The energy contained in the wind is only kinetic, and it depends on the air speed *U*, air mass (i.e., density *ρ*), and area swept by turbine rotor *A*. It is possible to calculate the power *P* using the following formula [9]:

$$P = 0{,}5\rho A U^3 \tag{2.1}$$

The extractable power by a turbine is minor than the one calculated by *Equation 1* because of the power coefficient C_p, which multiplies the second term of *Equation 1*. The power coefficient depends mainly on the air velocity through the rotor, and it varies for each turbine. However, it has an upper limit equal to 16/27, which is called Betz limit (from the physicist who developed its formulation) [9]. The reason why the power coefficient must be smaller than Betz limit is an effect called wake rotation. Indeed, the air passing through the rotor of a wind turbine starts to rotate, and this reduces the mechanical extractable energy. The power coefficient can be correlated with a factor called tip speed ratio λ, defined as the fraction between the tangential velocity at rotor tip and the wind velocity. Higher tip speed ratio implies higher power coefficient, which tends to Betz limit. In *Figure 6* [10] below is shown a graph which summarises the performances of several types of wind turbine.

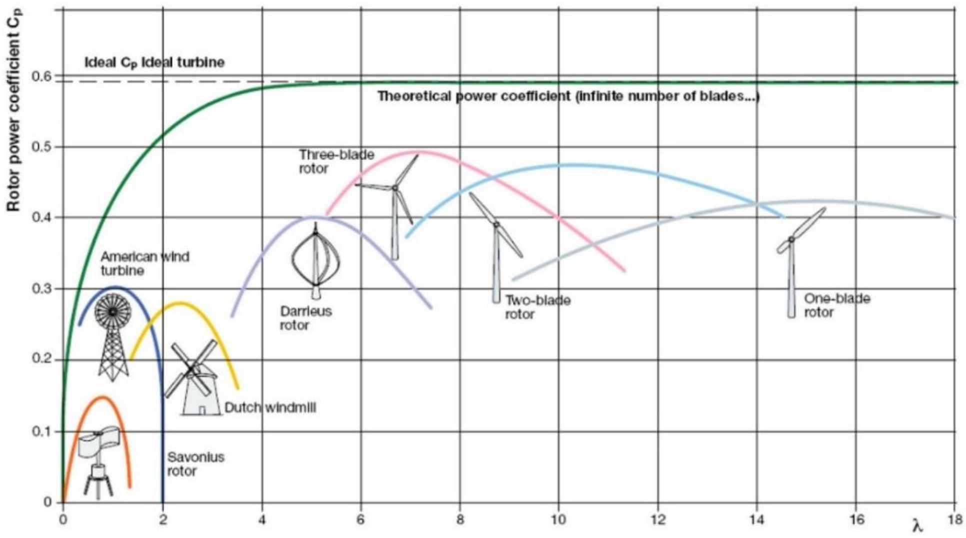


Figure 6 - Performances of wind turbines

There are two types of wind turbine: horizontal and vertical axis. The horizontal axis wind turbine (HAWT) is the most deployed and best-performing technology. The main components of a HAWT are shown in *Figure 7*.

The rotor is almost always upwind, so that it is not sheltered by the tower and the efficiency is higher. The yaw control, which allows the nacelle to rotate on the horizontal plane, must be active to put the rotor in upwind direction. In case the wind is too strong, the rotor is moved from upwind direction to reduce the load on the blades. Furthermore, a pitch control is also present in a modern wind turbine. The pitch angle is defined as the angle between the plane of blade rotation and chord line (which links the edges of the blade). Hence, changing the pitch angle allows to regulate the power output of the turbine since the aerodynamic force on the blade varies too. In *Figure 8* the pitch adjustment is shown. Additionally, the mechanical brake can be activated to diminish the rotor speed, to not overload the generator. The gearbox is necessary to link the rotor (low speed) to the generator (higher efficiency at high speed). The direct current generated is permutated by the transformer in alternating current, and then delivered to the electricity network. The modern wind turbine does not feature the gearbox in favour of a direct drive, which is lighter and more efficient than the previous solution, but more expensive.

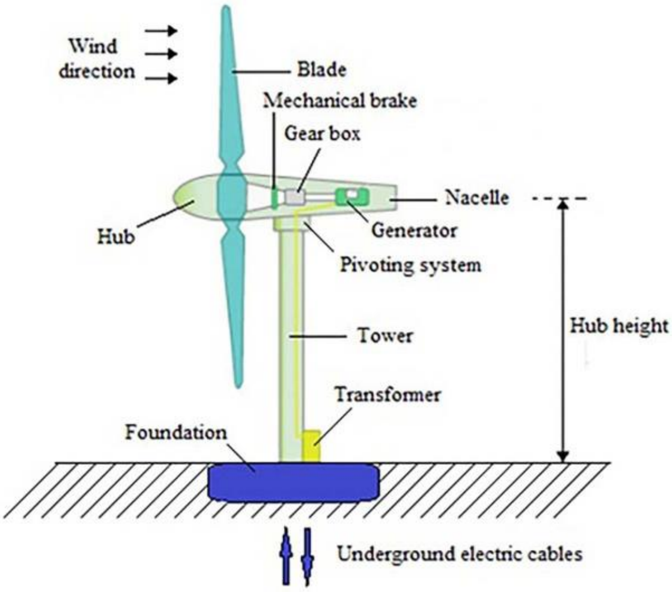


Figure 7 - Components of HAWT

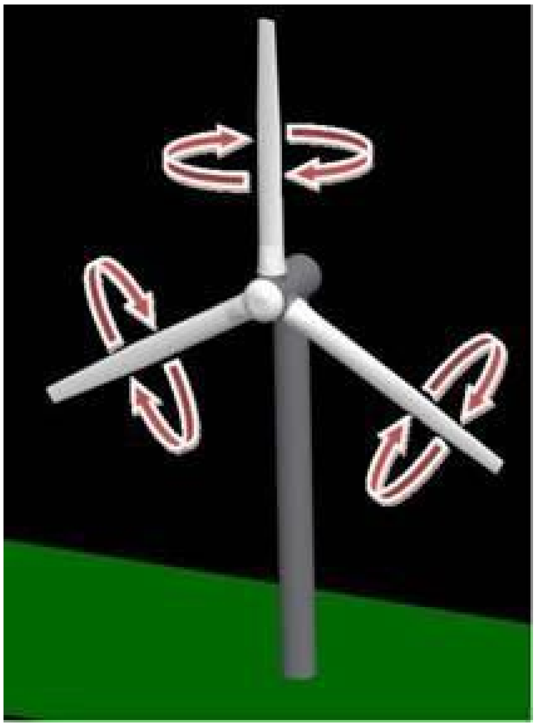


Figure 8 - Pitch adjustment

Each HAWT is characterised by a graph called power curve (*Figure 9*). This curve puts in relationship the wind speed with the power output of the turbine, and it shows some important technical details of the turbine itself. In the horizontal axis there is the wind speed, and the curve starts at a certain velocity called cut-in speed. Then there is an increment of the power output while also the wind speed increases, until it becomes constant and equal to rated power (at rated wind speed). After this point, the power does not change even if the speed growths, until it becomes null when the velocity reaches the cut-out speed. Beyond this speed value, the turbine is blocked (by means of the strategies above-mentioned) for safety reasons.

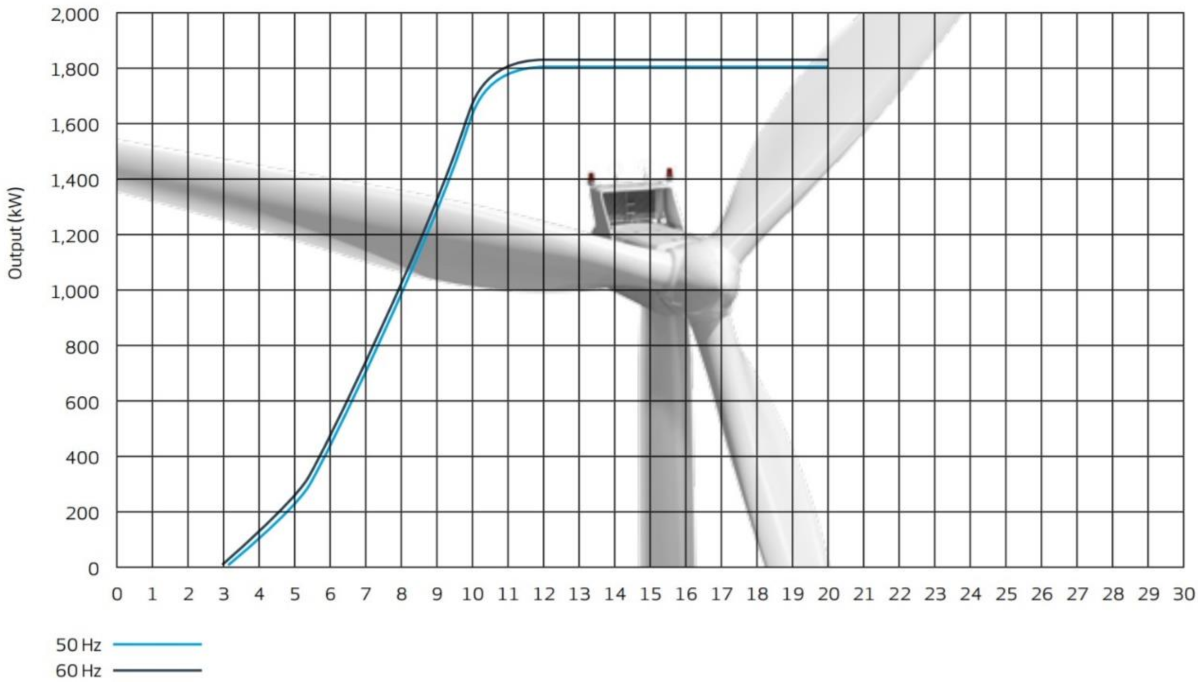


Figure 9 - Power curve for Vestas V100; on x-axis the wind speed is indicated [m/s] [11]

Depending on the three technical wind speed described above, each turbine is divided into different classes (*Table 1*) [12]. If the wind velocity increases, smaller rotor is employed in order to lower the stress on the structure.

Wind turbine class			I	II	III
V_{ave}		(m/s)	10	8,5	7,5
V_{ref}	(m/s)		50	42,5	37,5
	Tropical (m/s) $V_{ref,T}$		57	57	57

Table 1 - Wind turbine classes [12]

V_{ave} is the average wind speed in a year, V_{ref} is the is the reference wind speed average over 10 min (more precisely, a turbine designed for a wind turbine class with a reference wind speed V_{ref} is designed to withstand climates for which the extreme 10 min average wind speed with a return period of 50 years at turbine hub height is lower than or equal to V_{ref} [12]), while $V_{ref,T}$ is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones.

Eventually, a control strategy must be implemented in order to keep the turbine safe while extracting the maximum available power (*Figure 10*). There are distinct types of control strategies, based on which parameter (or parameters) can be varied during operation. The best solution is the variable speed – variable pitch [13] (VS-VP): below the rated wind speed, variable speed and fixed pitch allow to maximise energy capture and power quality; above the rated wind speed, fixed speed and variable pitch permit efficient power regulation at nominal power. This is the only control strategy that theoretically achieves the ideal power curve shown in *Figure 9*.

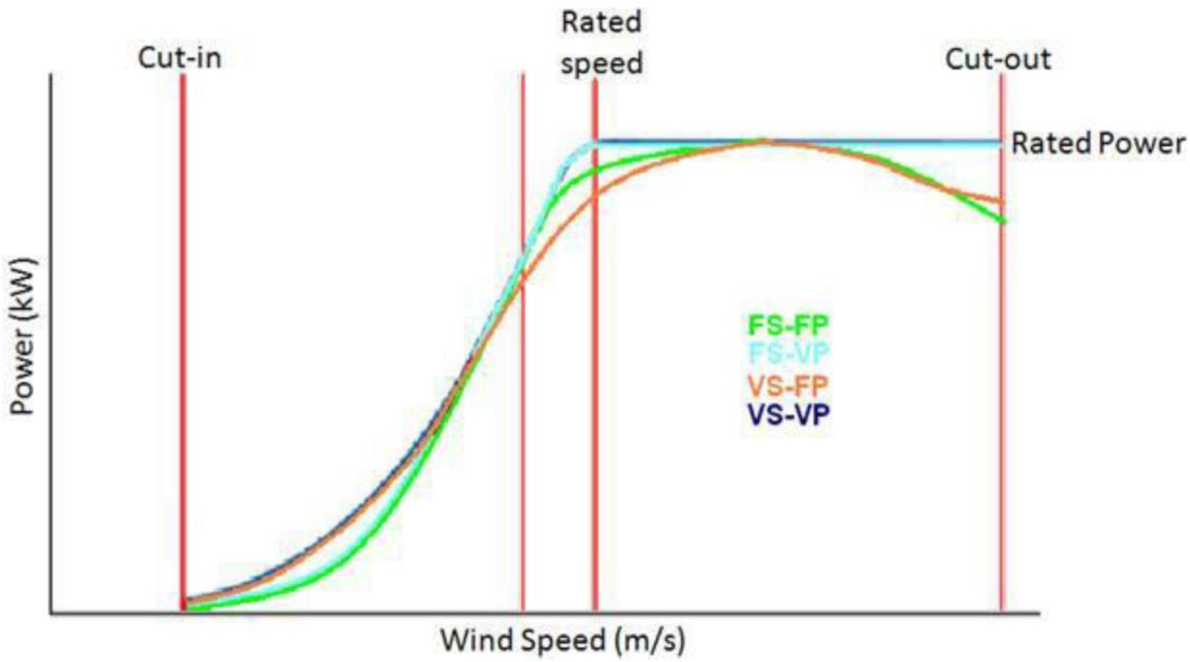


Figure 10 - Power curves for different control strategies [13]

The second technology of wind generator is vertical axis wind turbine (VAWT). They are classified in two groups: drag-type and lift-type. The drag-type VAWT is also called Savonius turbine, and it is quite simple: the wind hits the blades which start to rotate, driving a generator. This mechanism implies that the efficiency is limited, therefore they are proposed only for low power application. However, it has the advantage to do not need yaw mechanism. The lift-type VAWT is also called Darrieus turbine, and it works with lift effect. In this case, as well, the yaw mechanism is not necessary, and the construction is simple and cheap. The main drawbacks are the low efficiency and the costs to build a very high turbine. Moreover, they require a starting mechanism. These two kinds of turbine can also be merged to reduce the cut-in speed.

2.2.4. Advantages and disadvantages

Having briefly discussed the main aspects about the wind turbine technology, it can be debated the major benefits and drawbacks about it. The principal advantage is that the wind is a renewable source, so the electricity generation is completely fossil free. Moreover, also the carbon footprint is quite low, and the trend is further descending. Indeed, the biggest contributors to carbon emission are the production of the tower, the foundation and the blades, and the total amount of carbon dioxide equivalent produced is equal to 11 g/kWh of electricity generated [14], far less than fossil sources. Another advantage is the cost of the electricity, comparable to the less expensive gas combined plant (*Figure 11)* [15].

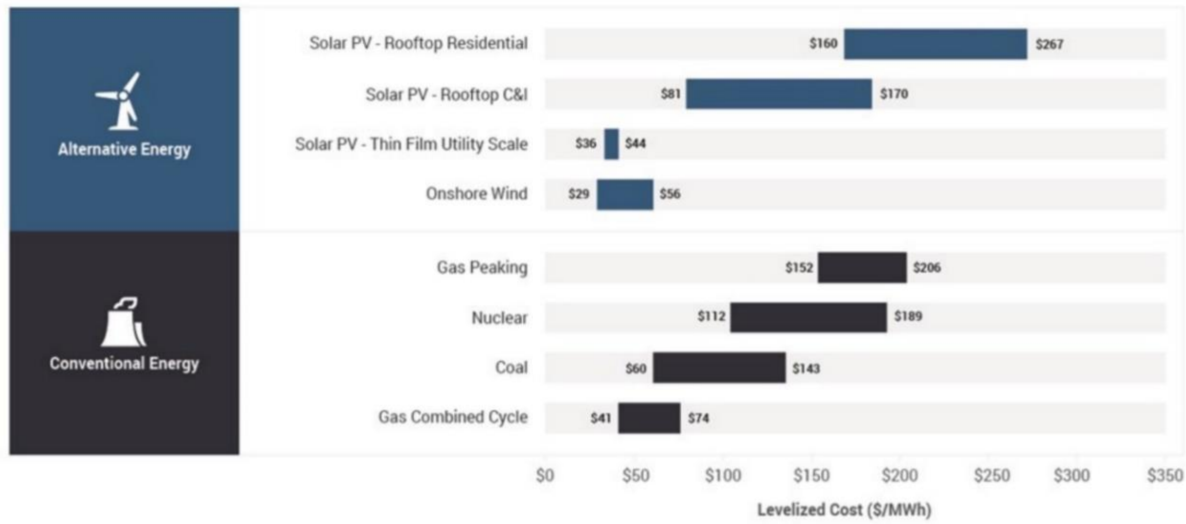


Figure 11 - LCOE for diverse sources [15]

Other benefits are the cost regularity of electricity generated during operating period and the fact that it is self-suppliant, so it is not necessary to use any type of fuel for the production. They are also usable in remote areas without a connection to electricity network.

The main drawback [16] is, being the wind an intermittent renewable source, also the production can fluctuate during a year or a single day. This also affects the stability of the network, reducing its resilience. Furthermore, the energy produced is difficult to store since some storage technologies are not efficient and others not economically feasible yet. For human beings, the major disadvantage regards the noise which is produced by the turbine. Indeed, near the tower the noise is very high (*Figure 12* [17]*)*, and a safe distance from buildings must be enforced. Another social inconvenience concerns the visual impact on the landscape; hence some correct layouts should be considered before installing a wind farm. The worst repercussion on fauna is the impact that a wind turbine can have on migrating birds. In any case, the number of birds killed by wind turbines (between 140.000 and 500.000 each year in the U.S. [18]) is very lower than other threats, such as cats or buildings [18] (*Figure 13*).

Figure 12 - Noise by wind turbine [17]

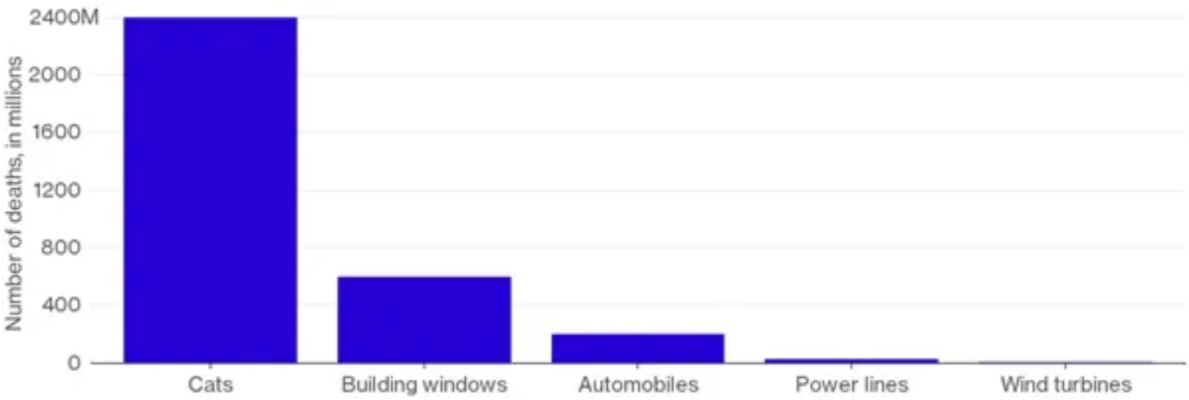


Figure 13 - Causes of birds deaths [18]

2.3. Wind energy in Italy and Sardinia

2.3.1. Wind energy deployment

The wind turbines are one of the most promising technologies to reduce the use of fossil fuels in the various energy sectors. Several projects have been developed and approved in Italy for installing wind farms, and some policies have been implemented to regulate a quite recent completely new market. The value of investments in RES in Italy are shown in *Figure 14* [19] for the most recent years. As it is possible to observe, the investment in wind projects were slightly higher than the ones in PV projects, before a dramatic fall in 2020.

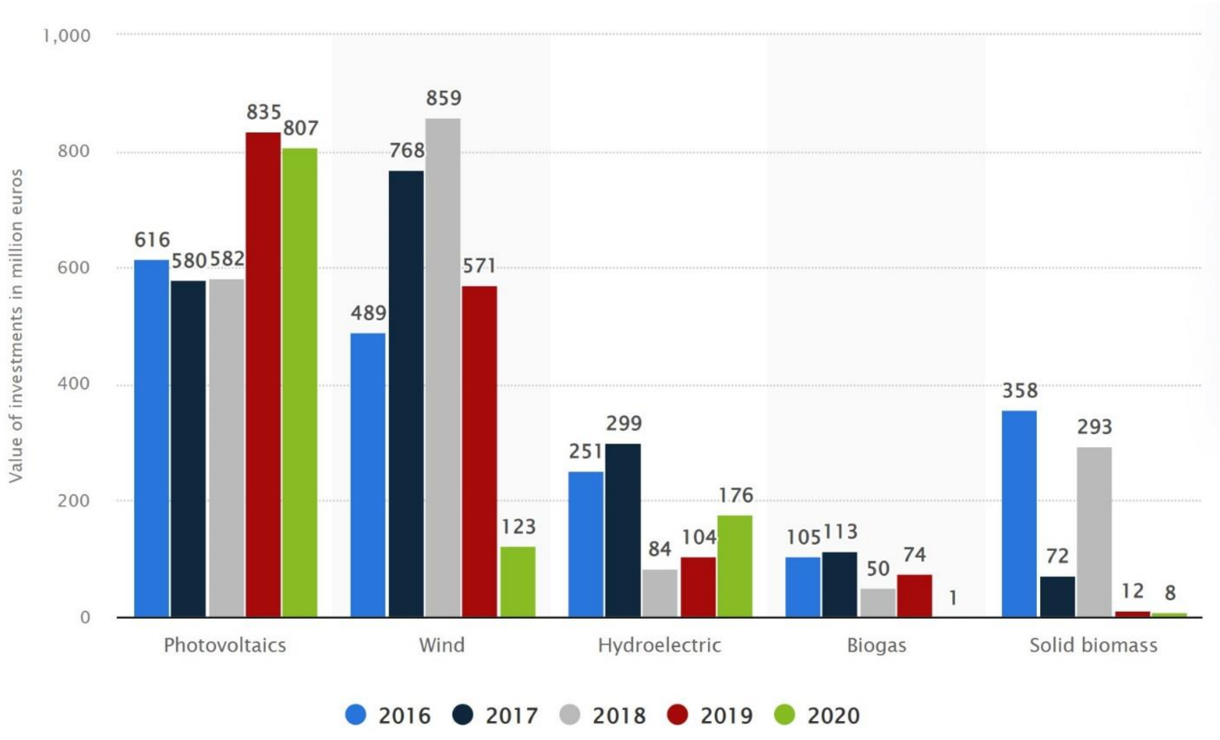


Figure 14 - Investments in RES in Italy

The Italian transmission system operator, Terna, publishes each year a report where it is summarised the electricity generation in Italy, and the related sources [20]. At the end of 2020, the gross installed power capacity is nearly equal to 120 GW, of whom 11 GW represented by wind generation. In Sardinia, the gross installed capacity is nearly 5 GW, of which 1 GW constituted by wind turbines. The installed wind power trend in Italy is depicted in *Figure 15*.

For what concerns the electric production, the gross total generation in Italy in 2020 is approximately 280 TWh/year, of whom around 19 TWh/year deriving from wind turbines. In Sardinia, the gross generation is around 13 TWh/year, of which 1,7 TWh/year coming from the 594 wind plants.

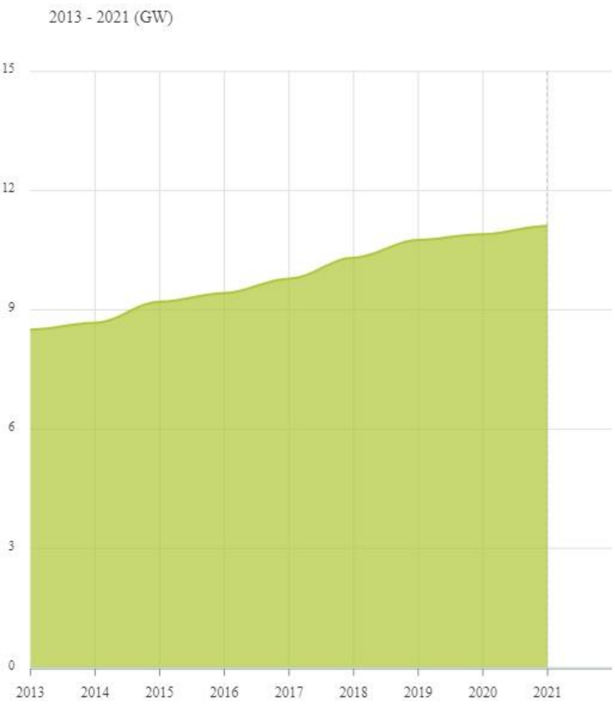


Figure 15 - Installed wind capacity in Italy [21]

The authorization procedure to obtain before installing a renewable energy source (RES) plant in Italy has been simplified to allow a faster approval of the project. This has been done introducing a measure called Autorizzazione Unica (AU) [22], which represents a formal consent to build and operate a renewable plant with an installed capacity greater than a threshold. This document is released by the ensemble of all local authorities (regions or delegated provinces) involved in the project, after the environmental impact evaluation (Valutazione di Impatto Ambientale VIA or Verifica di Assoggettabilità VA), necessary for wind plants with capacity higher than 1 MW. The AU must be approved or denied within 90 days of the proposal, plus the time required by VIA.

The growth of wind deployment in Italy, and the technological progress, has permitted to diminish the costs related to build and operate a plant. In *Figure 16* is shown the weighted-average LCOE trend for new commissioned onshore wind projects in Italy [23], while in *Figure 17* is represented the investment costs trend for the same category [23]. The LCOE is a quantity (€/MWh) which correlates the investment and annual costs of a wind turbine (more generally, of an electric generation plant) with the energy the same turbine is able to produce, in its entire lifetime. The decreasing of the construction cost of a wind turbine, coupled with an increasing of the efficiency (so that more electricity can be produced with respect to an older turbine, with the same external conditions), both derived by technology improvements, leads to a reduction of the costs and an increment of the electricity generated, lowering in turn the LCOE.

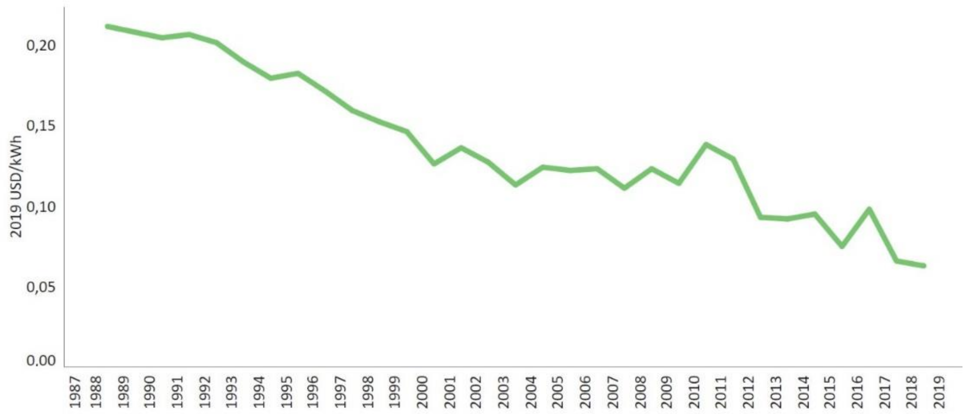


Figure 16 - LCOE for wind plants in Italy [23]

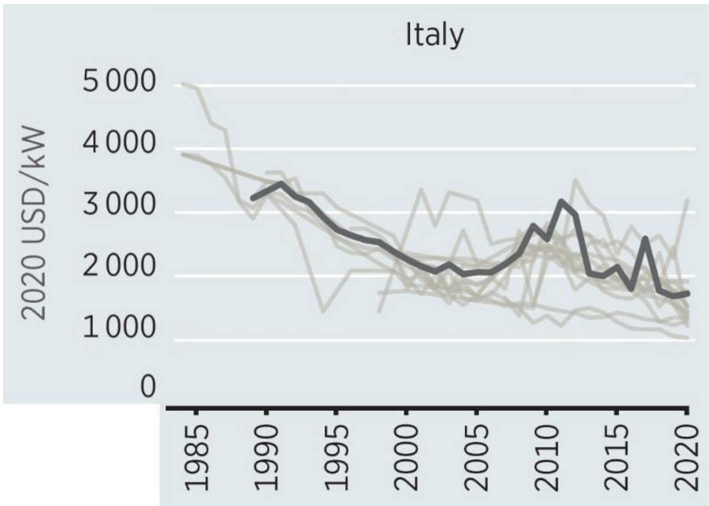


Figure 17 - Investment costs for wind turbine installation [23]

2.3.2. Near and long-term goals

The most important document for the achievement of sustainable goals promoted by UN and EU in Italy is the Piano Nazionale Integrato per l'Energia e il Clima (PNIEC) [24], which has been proposed according to Regulation (EU) 2018/1999 [25]. It has been definitely approved at the end of 2019 by the Government and sent to European Commission. It establishes new national objectives within 2030 and 2040 for increasing energetic efficiency, favouring RES, decreasing CO_2 emissions, increasing energetic safety, incrementing energetic independence, developing interconnected energy networks, alongside the measures to activate. The main purposes are a reduction of greenhouse gases emissions for various sectors (transport, residential, agriculture, wastes, tertiary, non-energetic industries) by 33% at 2030 with respect to values at 2005 (reaching a total amount of GHG emissions, for all sectors, equal to 328 million tons of CO_2 equivalent in 2030); a reduction of consumption for primary energy and final energy by 43% and 39,7%, respectively, with respect to values at 2007; share of RES in the gross final consumption at 2030 equal to 30%, following a trajectory well defined. For what concerns the last point, the predicted RES penetration for different energy sectors should be: 55% for electric sector; 33,9% for thermal sector; 22% for transport sector. In order to fulfil these tasks, the renewable plants power capacity must increment according to *Table 2*. In the last two columns, the relative increment of the power capacity at 2025 and 2030 with respect to the values at 2017 are indicated.

Source	2017 [MW]	2025	2030	ΔP (2025-2017)	ΔP (2030-2017)
Hydro	18.863	19.140	19.200	1,47%	1,79%
Geothermal	813	920	950	13,16%	16,85%
Wind	9.766	15.950	19.300	63,32%	97,62%
of whom offshore	0	300	900	-	-
Bio energies	4.135	3.570	3.760	13,66%	9,07%
Solar	19.862	28.550	52.000	43,74%	161,81%
of whom CSP	0	250	880	-	-
Total	53.259	68.130	95.210	27,92%	78,77%

Table 2- RES capacity increment [24]

Considering the goals for Sardinia, the document of reference, together with PNIEC, is the Piano Energetico ed Ambientale della Regione Sardegna (PEARS) [26], approved definitely in 2016 with a regional deliberation (n. 45/40 02/08/2016). The unique objective is the abatement of CO_2 emissions by 50% at 2030 with respect to the data in 1990. In order to achieve it, three scenarios have been proposed for each energy sectors. Regarding the electric sector, the major proposals are an increment of self-consumption from RES production, with the hypothesis of constant consumption with respect to 2014. This approach aims to reduce as much as possible the electricity delivered to the network, to guarantee the stability of it, also taking into account that the regional production is remarkably larger than the consumption (*Figure 18* [27]).

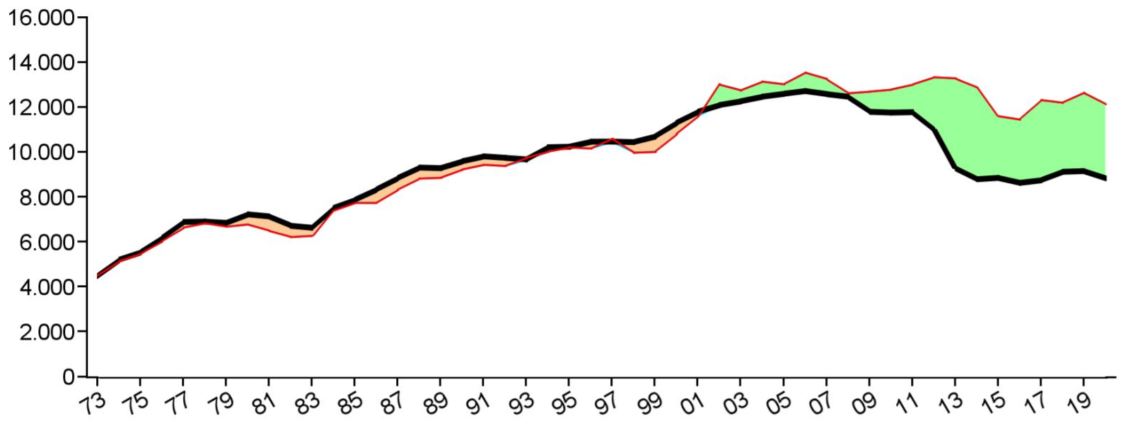


Figure 18 - Production vs consumption Sardinia. In vertical axis the values are in GWh; black curve is consumption; red curve is production; green area is surplus; orange area is deficit [27]

Moreover, the PNIEC has been declined for each Region by a study developed by Ricerca Sistema Energetico (RSE), a company owned by Gestore dei Servizi Energetici (GSE, which is entirely shared by Economic and Finance Ministry, MEF, and it is in charge to promote advancement of RES and energy efficiency, and also to manage the incentives for RES plants), considering availability of the land and indicators of land consume [28]. For Sardinia, it has been hypothesised a wind capacity of 2,08 GW and a photovoltaic capacity of 2,2 GW in 2030.

Most recently, the new European Green Deal [29] [30] changes the goal of GHG emissions reduction by 2030, increasing it from -40% to -55% with respect to value in 1990 [31]. A pack of law proposals have been presented at European Parliament called "Fit for 55" in order to accomplish the new objective for EU. Therefore, also the goals declined in PNIEC should be varied to fulfil the new targets. To do so, the Ecologic Transition Ministry has proposed a document called Piano per la Transizione Ecologica (PTE) [32], which provides the new objectives for the Country, integrating the policies already defined by Piano Nazionale di Ripresa e Resilienza (PNRR [33], which outlines the measures to adopt to enhance the green transition, together with other relevant missions, using community funds constrained to a well-defined schedule). The updated goals are:

- Total GHG emissions equal to 256 million tons of CO_2 equivalent in 2030.
- Primary energy reduction equal to 45% at 2030 with respect to 2007.
- Phase out of coal generation by 2025.
- RES penetration in electricity generation equal to 72% at 2030 (reaching 95-100% at 2050).
- Installation of new RES power capacity of around 75 GW within 2030.
- An electrochemical storage capacity of around 30-40 GW for long-term strategy.

In order to satisfy these purposes, the PTE highlights the two biggest obstacles to overcome: the difficulties related to authorizations of the projects, which lessens the growth of the sector (despite the AU procedure described in *Section 2.3.1*); the slow progression of renewable capacity, directly correlated to the previous point. To give an insight about this problem, in 2020 1,88 GW of photovoltaic capacity was put up for auction by GSE but only 0,47 GW were allocated, while in the same period in Spain the entire capacity was sold (3,03 GW), with offers which exceeded 9 GW [32].

2.4. Literature review

Several scientific papers have studied and assessed the wind potential in different regions of the world, considering location aspects and optimisation. Usually, two different purposes are pursued: the quantification of the extension of the area available for wind turbines installation, and in some cases the classification of each portion of territory according to the suitability for wind exploitation; the evaluation of the proper wind potential, so a quantity which expresses how much electricity can be produced with wind turbines in a certain area. Even if these two aims are directly connected, since the second one is a consequence of the first, often in the literature only one of them is evaluated. More precisely, if the classification of the available area is assessed, only the wind power capacity is estimated, using an empirical power density based on real or model turbines. The power capacity varies with respect to wind potential because of the capacity factor, which rarely it is evaluated in this type of study, but it is considered as an average for real operating wind farms in similar external conditions.

When a wind potential is properly calculated, the most used approach is to consider a power curve of a model or real turbine and the probability distribution of the wind speed in a certain area (which correlates a wind velocity with the percentage of its occurrence in a year). The power production of a turbine is obtained by the multiplication of these two curves, for a given location, while the energy yield (which is the annual energy generation) is calculated as the multiplication of the power production with the availability factor and the hours in a year. Then, the energy yields for each available area are summed to obtain the final wind potential for the study region. According to various papers, the wind potential lays in a range between 96 to 580 PWh globally and 0,4 – 77 PWh in Europe [35].

When evaluating both previous cases, mainly in recent years, some geographical constraints are used to limit or rank the available area for wind turbine installation. These constraints are evaluated using a GIS software. Furthermore, the wind data can be considered in two separate ways [35]: a static assessment, which requires a wind atlas with wind speeds (approach used in this thesis); a dynamic assessment, which estimates real-time renewable generation using data from wind masts or meteorological analysis.

The constraints considered in the literature can be very different, but most of them are common. Several reviews in the literature analyse and summarise which constraints are used in some relevant papers. For instance, Shao et al. [36] discovered that the majority of the papers studied consider urban areas (with buffer), water bodies, slope, roads, and airports as exclusion constraints, so zones where it is forbidden to construct wind turbines. Average wind speed is implemented in almost all papers as technical criterion, while distances from transmission network and roads are usual economic criteria. The same study analyses also the weighting method for the criteria, resulting that more than half of the studies considered use the analytical hierarchy process (AHP) to define the importance of the criteria. This method consists of two main steps: a pairwise comparison to weight the criteria (ranking the criteria basing on their importance according to researcher's judgement); a weighted linear combination to evaluate the alternatives. However, right after AHP, the second most common method is to not consider a weighting process, as it has been done in this thesis.

Another review about the criteria used to assess the wind potential has been conducted by McKenna et al. [35]. They found that many papers consider settlements buffer, airports, railways, and protected areas as exclusion criteria. Additionally, the study also analyses the various definitions of wind potentials provided in the literature and compares them to the original distinction made by Hoogwijk et al. [37]. It also provides an insight to the economy related to a wind turbine, considering installation and operation, providing some parameters to evaluate the profitability of a wind project. However, the study also points out that only few papers estimate the generation costs linked with the wind potential, and the methodologies widely vary, hence the results must be understood considering the proper context.

Together with previous reviews, other papers have been considered while developing the method for this thesis. For example, Baseer et al. [38] studied the wind farm development in Saudi Arabia using some evaluation constraints (wind speed, buffers from settlements, proximity to electric grid, etc.), ranking them with an AHP method to obtain the most suitable locations to install the turbines. The main result is that only 1,86% of study area is rated as most suitable, with another 14,65% as highly suitable.

The same procedure has been followed by Saraswat et al. [39] while assessing the solar and wind potentials in India. Thirteen evaluation factors are ranked using AHP method, and the results show that only 0,91% (~30.000 km^2) of study area can be classified as highly suitable, with a theoretical wind power capacity varying from around 120 to 210 GW.

A similar approach has been used by Höfer et al. [40], which evaluated the suitability areas in Städteregion Aachen region, Germany, applying some exclusion criteria to the available area and implementing an AHP method to rank the remaining sites according to other evaluation criteria. The major outcomes are that no area receives the maximum score, while 1,74% of the available area has a high suitability index.

Another procedure has been followed by Latinopoulos & Kechagia [41], who rated the suitability of the site locations in the Regional Unit of Kozani, Greece, using some evaluation criteria (slope, wind speed, current land uses, distance from roads, distance from natural areas, distance from relevant sites) set as fuzzy sets. A value for each factor is provided for all cells in the grid, varying from 0 (not suitable) to 1 (highly suitable). Together with evaluation criteria, also exclusion constraints are implemented. The main result is that 12% of study area has a suitability index higher than 0,5.

Two tables summarising the criteria considered in the literature and established by local legislations, together with the assumptions done for this work, are reported in the next section. The papers taken as reference for this thesis have been choses using two main limitations:

- Only articles and reviews published on certain periodicals are considered.
- Only articles and reviews published after 2010 are considered

The criterion to select the magazines is the relevance of them. In order to evaluate it, a website called SCImago is utilised [42], which ranks each periodical basing on several indicators (e.g., the number of citations). The chosen magazines are the following: “Renewable and Sustainable Energy Reviews”, “Renewable Energy”, “Energy”, “Applied Energy”, “Energy Policy”, “Energy Economics”. The selected articles are obtained on a website called Scopus [43].

2.4.1. Description of constraints in the literature

2.4.1.1. Economic aspect

The constraints that affect the economic aspect are mainly the ones which could increase the investment cost of the project (e.g., costs for installation) or decrease the profitability of it (e.g., low electricity production).

2.4.1.1.1. Wind speed

The first constraint to consider is the average wind speed. Indeed, if the mean velocity is too low, the turbine production is small too. Considering that the costs for a turbine (CAPEX and OPEX) are independent by its productivity, a scarce electricity production implies that the revenues are meagre, and the investment could not be recovered. For these reasons, a lower threshold for the average wind speed is considered.

The regional and national legislations do not enforce this constraint, but several papers in the literature do. Several values are proposed, depending also on where the study has been carried out. The lower edge of the range is 3 m/s, while the higher is 6 m/s (at 135 m above the ground).

2.4.1.1.2. Slope of terrain

Another factor which can influence the economic viability of the project is the slope of the terrain. This is true for two varied reasons: the first it is the difficulty to install a turbine in a very steep location (due to the large foundation); the second is the complication to reach a similar area with heavy machinery. To avoid these problems, a higher threshold for terrain slope has to be considered.

Also in this case, the legislation does not establish any limits, while in the literature the values lie in a range between 7% and 30%.

2.4.1.1.3. Elevation

The elevation factor affects the economic feasibility of wind turbine installation for the same argumentations discussed in the last point. A superior threshold is implemented, with a value of 900 m MSL (mean sea level) imposed by Sardinia laws.

2.4.1.1.4. Distance from transmission network

The distance from transmission (high voltage) network impacts on the economic aspect for two motives: higher space between a wind turbine and the electricity network implies larger investment costs for the connection (e.g., cables) and more relevant losses during operation, so that the revenues diminish. Therefore, a superior threshold is considered to comply with these requirements. However, for sake of safety, also an inferior limit should be implemented, to reduce the risk of damages to network in case of turbine failure.

In Italy, the upper limit is equal to 10 km (given as an advice of good practice), and it is also considered in many other scientific papers. Moreover, local regulations do not establish a lower limit, while a common value in the literature is 200 m.

2.4.1.1.5. Distance from roads, railways, and highways

As last factor related to economic profitability of a wind turbine installation, it can be considered the distance from the main routes of transport. The same reasons described for the previous point are valid also in this case. Therefore, an upper and lower threshold should be implemented.

According to Sardinia legislation, only the inferior limit must be respected, obtained with a formula: the sum of hub height and rotor radius, increased by another 10%. In the literature, the less boundary varies from 100 m to 500 m, while the higher is commonly equal to 10 km. In some papers, the minimum distance from highways is different with respect to minimum distance from roads.

In the next table (*Table 3*) all the values for the constraints related to economic aspect, imposed by laws, or considered in the literature, are summarised. The greater (less) sign indicates that it is possible to install a wind turbine if the value of that parameter, in the area under investigation, is larger (smaller) than the one represented in the table. If a paper does not consider a factor, the abbreviation n.c. (not considered) is used.

Table 3 - Values for economic constraints

STUDY	WIND SPEED [m/s]	SLOPE [%]	ELEVATION [m MSL]	DISTANCE FROM HV NETWORK [km]	DISTANCE FROM ROADS/RAILWAYS [km]	DISTANCE FROM HIGHWAYS [km]
Onshore wind farms GIS-Assisted suitability analysis using PROMETHEE II [44]	>4	<30%	n.c.	>0,2 & <10	>0,2 & <10	>0,5
Wind farm siting using a spatial Analytic Hierarchy Process approach: A case study of the Städteregion Aachen [40]	>6 (at 135 m)	<30%	n.c.	>0,1	>0,1	>0,02 (from rotor tip)
GIS-based site suitability analysis for wind farm development in Saudi Arabia [38]	>5	n.c.	n.c.	<10	<10	<10
A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece [41]	>4,5	<25%	n.c.	n.c.	>0,15	n.c.
GIS based site suitability assessment for wind and solar farms in Songkhla, Thailand [45]	>4	<15%	n.c.	<10	<10	<10

MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India [39]	>3 (at 100 m)	<15%	<2000	<10	<10	n.c.
GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State [46]	n.c.	<10%	n.c.	n.c.	>0,5	n.c.
GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey [47]	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia [48]	>3,5	<7%	n.c.	>0,2	>0,2	n.c.
Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany [49]	n.c.	n.c.	n.c.	n.c.	>0,2	>0,2
Sardinia/Italy legislation	n.c.	n.c.	<900	<10	>([hub_height+rotor_radius]*1,1)	>([hub_height+rotor_radius]*1,1)

2.4.1.2. Social aspect

In this section are discussed those factors which could have an influence on the social aspects and people. Indeed, a wind turbine can disturb the living of population nearby, due to noise or safety reasons.

2.4.1.2.1. Urban areas buffer

The first element that can be considered is the distance from urban areas. A buffer is implemented because a wind farm is very noisy, and not immune to failures (with all correlated risks). So, wind turbine should be installed only at a safe distance to urban areas, and dwellings more in general.

In Italy, the minimum distance to respect between a wind turbine and a single building is 200 m, while in Sardinia an additional buffer is implemented around an urban area, equal to 500 m. In the literature, the buffer around a city varies according to the extension of region considered and its population density, starting from 500 m [38] and arriving to the extreme case of 10 km [39].

2.4.1.2.2. Productive areas buffer

Another constraint related to the social aspect is the minimum distance from productive areas. This definition includes all productive activities present on a territory, for each economic sector (e.g., agriculture, manufacturing, mining). A buffer is implemented to protect the human activities in these areas, although often these zones are preferable to install wind farms due to their pre-existing anthropogenic degradation.

In Sardinia, only the areas containing the production facilities are prohibited to construct wind turbines. However, it is advised that abandoned production zones should be preferentially exploited to install a wind farm. These places are called brownfield areas [50]. In the literature, this type of constraint is not quite common, and only a paper considers a buffer of 500 m [44], while another excludes only the productive area itself.

2.4.1.3. Environmental aspect

In this part the constraints related to the environmental aspect are discussed. First of all, in some areas it is forbidden to construct anything due to their relevance for flora and fauna (e.g., natural parks). Then, other zones are not buildable in order to not ruin the landscape or to reduce the contamination of the territories.

2.4.1.3.1. Natural areas buffer

In the definition of natural areas are included all legally instituted parks and territories, both regional and national. In these zones it is prohibited to build, to preserve the beauty and purity of natural ecosystems. For this reason, a buffer should be implemented, also for not disturbing too much the local fauna. Moreover, the trees present in a park could affect the productivity of a wind turbine acting as an obstacle and creating turbulence.

The Regional legislation excludes from construction only the exact extension of the natural areas, which include important bird areas (IBA), regional and nation parks, wetlands (as defined by Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat [51]), volcanos, and more generally forests. In the literature, a proper buffer is applied, with a value between 1 km [44] and 10 km [39].

2.4.1.3.2. Distance from seashore

Another factor to consider is the distance from seashore, for two main reasons: first, the presence of a wind farm near the sea can spoil the landscape and reduce the tourism in the area; second, a wind farm might disturb fauna living near the shores (e.g., seagulls).

In Sardinia, the minimum distance to install a wind turbine from the seashores is set equal to 300 m, while in the literature this constraint is not very considered.

2.4.1.3.3. Distance from water bodies

To conclude the discussion about environmental aspects, it should be considered to implement a buffer around water bodies: lakes and rivers. A minimum distance is often applied because the installation of a wind turbine (i.e., transportation of components, construction of the foundation, etc.) could be quite polluting, so a buffer reduces the probability of water contamination. Additionally, many animal species rely on lakes and rivers to survive, therefore the proximity to a wind turbine may disturb their natural habitat.

According to Sardinia legislation, minimum distances from lakes and rivers must be respected, respectively equal to 300 m and 150 m. In the literature, an enormous range of values are considered, starting from 50 m [40] and arriving to 7 km [39].

2.4.1.4. Safety aspect

As last category of constraints it is possible to consider the safety aspect. These limitations are necessary to guarantee safe conditions for human beings in the zones involved, and also to reduce the risks for the infrastructures.

2.4.1.4.1. Airports buffer

As first constraint it is considered a buffer around the airports, both civil and military. A minimum distance must be applied to permit the take-off and landing in safe conditions. Indeed, a wind turbine near the airstrip might produce a consistent wake effect which can cause troubles to pilots during operations.

In Italy, the airspace where it is forbidden to build correspond to the Aerodrome Traffic Zone (ATZ), which includes a circular area of five nautical miles (about 9.26 km) around the Aerodrome Reference Point (ARP) [52]. However, the Ente Nazionale per l'Aviazione Civile (ENAC, which is the national aviation authority in Italy) can modify this distance (e.g., for Cagliari's airport the buffer is reduced to 4 NM ~ 7,41 km [53]). In the literature, smaller values for the buffer are considered, in a range from 500 m [44] to 7 km [39].

2.4.1.4.2. Distance from natural gas and telecommunication networks

The last constraint that could be applied refers to the minimum distance to respect around the natural gas and telecommunication networks. This is done to reduce the risks of accident near important and at the same time delicate infrastructure. Although a limitation could be implemented, only few papers in the literature take into account these constraints, and even the legislation does not establish a safe buffer. Therefore, also considering the scarce development of NG network in Sardinia (and the difficulties to obtain reliable maps about it and telecommunication network) it has been chosen to not apply the restrictions in this thesis, which are however reported to complete the discussion.

For the constraints debated in *section 2.4.1.2*, *2.4.1.3* and *2.4.1.4*, the following *Table 4* summarises all the values considered in the literature and in the legislation.

Table 4- Values for social, environmental, and safety constraints

STUDY	URBAN AREAS [m]	PRODUCTIVE AREAS [m]	NATURAL AREAS [km]	SEASHORE [km]	WATER BODIES [m]	NG NETWORK [m]	TC NETWORK [m]	AIRPORTS [km]
Onshore wind farms GIS-Assisted suitability analysis using PROMETHEE II	>1000	>500	>1	>1,5	>150	>300	>250	>0,5
Wind farm siting using a spatial Analytic Hierarchy Process approach: A case study of the Städteregion Aachen	>550	n.c.	0	n.c.	>50	n.c.	n.c.	n.c.
GIS-based site suitability analysis for wind farm development in Saudi Arabia	>500	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	>2,5
A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece	>500 (pop[1]<2000) >1000 (pop>2000)	0	>1	n.c.	n.c.	n.c.	n.c.	>3
GIS based site suitability assessment for wind and solar farms in Songkhla, Thailand	>1000	n.c.	>1,5	n.c.	>400	n.c.	n.c.	>3

[1] pop means population

MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India	>10000	n.c.	>10	>10	>7000	n.c.	n.c.	>7
GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State	>1000 (towns) >2000 (cities)	n.c.	n.c.	n.c.	>3000	n.c.	n.c.	n.c.
GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey	>1000 (towns) >2000 (cities)	n.c.	>1	n.c.	>400	n.c.	n.c.	>2,5
Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia	>500	n.c.	>2	n.c.	n.c.	n.c.	>250	>3
Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany	>800	>300	>1	n.c.	n.c.	n.c.	n.c.	>1
Sardinia/Italy legislation	>500	0	0	>0,3	>150 (rivers) >300 (lakes)	n.c.	n.c.	>9,26

3. Methodology

3.1. Data and study area

As discussed in *section 2.1*, the area under assessment is Sardinia, which is the second biggest island in Mediterranean Sea [54]. The region has been instituted in 1948 [55], and it is divided in four provinces and one metropolitan city, Cagliari, which is also the county seat. It has a surface of around 24.000 km^2, that makes the region the third largest in Italy, but only about 1,6 million of inhabitants [56]. The low value of population density (third to last in Italy) makes the region very suitable for RES plants installation, considering that most of the territory in uninhabited.

Beside the electrical interconnection between the northern and southern part, the island is also connected with two undersea direct current cables to the peninsula. One is called Sa.Pe.I., which connects the island with Lazio, a region in central Italy, and it is able to transfer a power of 1000 MW with a voltage of 500 kV [57] (direct current). The second one is called Sa.Co.I., which connects Sardinia, Corsica, and Tuscany, and it is capable of transferring 300 MW with a voltage of 200 kV [58] (direct current). The last project is under dismantlement, and it will be substituted by an updated version, with the same operating voltage but with the possibility to transfer 400 MW [58]. The transmission network of Sardinia is presented in *Figure 19*.

Figure 19 - Transmission network of Sardinia [59]

Red lines indicate aerial lines of 380 kV AC; green lines indicate aerial lines of 220 kV AC; blue lines indicate aerial lines of 150 kV AC; yellow lines indicate aerial lines of 70 kV AC; pink lines indicate aerial lines of 200 kV DC, while pink dashed lines indicate cable lines of 200 kV DC (Sa.Co.I.); purple dashed lines indicate cable lines of 500 kV DC (Sa.Pe.I.).

In order to evaluate the wind potential in Sardinia, some constraints must be considered. These restrictions are imposed by two main laws, directly linked between them. The first one is a Ministerial Decree promulgated by Economic Development Ministry (D.M. 10/09/2010 [60]) which provides some guidelines for the installation of wind turbines in Italy. These principles regard all scopes related to wind turbine, including authorisation to construction, operation of the plant, and technical guidelines. The Decree also establishes that each Region must identify the non-suitable areas for turbine installation, proposing the exclusion criteria depending on the peculiarity of the territory, the typology of RES plant, and the power installed. The Region adopted these regulations with the promulgation of a Regional Council Deliberation dated 27 November 2020 [61], in which all constraints are listed together with the proper reference theme.

The areas which correspond to these constraints are obtained from a web database run by the Region, named Sardegna Geoportale [62]. On this website it is possible to obtain the data and the areas related to different items, such as buildings or regional parks. These maps are downloaded in the form of ESRI shapefiles, which are quite easy to work with.

For what concerns the wind data, they are obtained by a website called Global Wind Atlas (GWA) [4], where it is possible to download the average wind speed map at a certain height for a given area, together with other meteorological information (e.g., mean temperature and mean pressure). This wind climate information is included in a file called generalised wind climate, an ASCII file, which is fully compatible with WAsP software, as it acts as meteorological data source [63]. The values of roughness and orography, necessary to assess the productivity of a wind turbine, are got from a software called WAsP Map Editor. This software requires as input the geographic coordinates of the area's centre, together with the longitude and latitude extensions. Alternatively, it is possible to define the coordinates of two opposite vertices of the square. The terrain roughness and the orography are evaluated separately and then joined in a vector map.

3.2. Wind energy resource calculation

3.2.1. Overview of WAsP software

The software used in this paper to assess the annual energy productivity (AEP) of a wind turbine is called WAsP [64]. It has been developed by Danmarks Tekniske Universitet (DTU), near Copenhagen. Along the productivity, it is possible to evaluate other parameters for a certain area, such as the average wind speed, the capacity factor, or the power density. The area of interest must be divided into a grid to obtain these data, and the spatial resolution affects the precision and the computational time of the simulation. This resource grid is useful to determine the best spot to place a wind turbine, considering the cell with the highest AEP or power density. It is also possible to compute the performance of a wind farm, taking into account the wake effect.

First of all, a vector map which contains the data about elevation and terrain roughness must be created. To do so, a software included in the WAsP suite, called WAsP Map Editor, is used. These data are imported in the software using a web database managed by GWA. In order to obtain the maps with the information searched, the coordinates of the centre must be defined, equal to the coordinates used on GWA to download the meteorological data. The necessary coordinates that must be used are obtained with a simple method: basing on the region shapefile, a grid of points is created, each of them distanced 20 km, and the coordinates are measured. This information represents the coordinates of centres of the sectors (which are squares) in which the surface of Sardinia is divided, in order to reduce the computational burden on WAsP Map Editor. Then, it is necessary to establish the map extension, and the screenshot of the procedure is shown in *Appendix* section[2], with the explanations of the field that must be defined. It has been decided to divide the entire region into squares of twenty kilometres per side, so that more precise data can be utilised for each simulation. Eventually, the two files containing the maps of the elevation and terrain roughness are merged together to obtain the vector map.

Having downloaded the meteorological data and having obtained the information about the morphology of the area, it is possible to initiate the simulations on WAsP. Beside these files, also the turbine characteristics are uploaded in the workspace (from a database provided by the software itself). Then, two items are added to the project: a turbine site, which is placed in an arbitrary location; a resource grid. More specifically, this last step is particularly important since the resource grid allows to estimate the turbine productivity for each node in which it is divided[2]. The spatial resolution of this grid must be set before its creation, and its value affects the precision of the simulation: a higher resolution reduces the number of cells in the grid, diminishing the accuracy and the computational time; a smaller resolution increases the number of cells in the grid, raising the precision of the output and the

[2] See Appendix A

computational burden. For this thesis, a spatial resolution equal to 500 m has been choice, taking into account the minimum distance that must be respected between two turbines.

Eventually, the simulations are performed for each turbine. The possible outputs are different quantities averaged for every node. For instance, the wind speed for a certain cell is taken as the mean wind velocity in that specific square, calculated considering the meteorological data provided by GWA.

3.2.2. Wind turbine choice

The WAsP software has a database which contains different wind turbines, for different classes, operating frequencies, and powers. Three types of wind turbines were chosen: V80-2 MW, V90-1,8 MW and V100-1,8 MW. All of them are produced by Vestas Wind Systems A/S, a Danish company which designs, manufactures, and installs wind turbine. Vestas has installed a total wind power capacity of around 145 GW in 85 countries [65]. The number in the turbine names indicates the rotor diameter in metres. These turbines are respectively class I, II and III, and are ones of the most installed by the company [65]. These three turbine classes are able to cover the entire range of average wind speed present in the region, therefore are the best choice to assess the wind potential. New versions of these wind turbines have been designed, with higher rated power, but the differences in AEP are quite restrained for the locations considered in this analysis, hence the previous wind generators have been chosen to reduce the investment costs (directly related to the nominal power). The technical specifications of the three wind turbines are reported in *Table 5*.

Turbine	Rotor diameter [m]	Rated power [MW]	Hub height [m]	Cut-in speed [m/s]	Cut-off speed [m/s]	Class
V80	80	2	67	4	25	I
V90	90	1.8	80	4	25	II
V100	100	1.8	80	3	20	III

Table 5 – Turbine's characteristics

3.2.3. Input and output data

In order to evaluate the AEP, several data are necessary as input. First of all, the meteorological information about the area under investigation. These parameters regard mainly the average wind speed, obtained by GWA (*section 3.1*). Along with the mean speed, also the wind roses are acquired by GWA, which are useful to consider the main direction of the wind for each square in which the regional surface is divided (*section 3.2.1*). These data are combined with the vector map discussed before (*section 3.1*). The presence of morphological obstacles influences the productivity of a wind generator based on the direction of the wind (hence the necessity of the wind rose). When these data are uploaded to WAsP, it is possible to create the resource grid (*section 3.2.1*) and launch the simulation for the three different turbines. As already pointed out, the position of the generator is irrelevant for the computation.

Once the calculations are done, it is possible to export the data of AEP and mean wind speed in the form of raster grids, more specifically ASCII grids. This type of file contains information about the coordinates of the lower left corner of the map (in this case, a square), the value of the cell size (500 m), the number of columns and rows (variable for different sectors), and the values of the parameter considered (i.e., AEP and mean speed). The output quantities are listed according to the position on the map (e.g., first value corresponds to highest left cell, last value corresponds to lowest right cell). These files are merged together to obtain a unique map for the entire region, and then it is converted in shapefile (which is a vector) with QGIS. The two shapefiles containing the AEP and the average speed are joined to have a single atlas with all information necessary for the study. The conversion is necessary since constraint maps are in shapefile form, so that successive operations upon them are simpler.

3.3. Constraints for wind energy exploitation

In this section the constraints considered in this assessment of the wind potential will be defined and discussed. The categorisation of each constraint according to which aspect it influences is the same reported in *section 2.4.1*. The description about why each criterion is important it has been done before, but not all of them are implemented in this thesis, for distinct reasons.

Starting from the economic constraints, the wind speed is surely a significant factor to consider while evaluating the wind potential. Taking into account the indications provided by the literature, and the wind resource in Sardinia (*Figure 5*), for this thesis a lower threshold equal to 3,5 m/s (at 80 m above the ground) is applied for the average wind speed. As described in *section 3.2.3*, the value of the mean speed is computed by WAsP for each cell of the grid, so if an element of the lattice (a square of 500 m per side) shows a smaller average wind velocity it is removed from the available area.

The second important economic criterion is the steepness of the terrain, which is applied in this thesis with an upper limit equal to 30%. This value, the highest among the ones considered in the literature, has been chosen evaluating the morphology of Sardinia. Indeed, the majority of the territory is constituted by flat terrain, so this percentage does not exclude a significant extension of the region, increasing the available area for turbines installation respecting the indications shown in the literature. Directly connected to this constraint, also an upper threshold for the elevation with respect to sea level is implemented in this assessment. Sardinia does not have high mountain chains, and the value defined for this criterion is equal to 1500 m MSL, which excludes a very limited portion of territory but allows to exploit the wind resource present at relevant altitude.

The last two economic criteria, the distance from ways of transport and the distance from electric transmission network, can be also considered as safety factors. Indeed, in this thesis a lower limit for these constraints is applied, equal to 200 m, while the upper threshold for the transmission network and the roads is imposed equal to 10 km. A superior boundary for railways is not considered since its extension on the territory is quite restrained, so it cannot be exploited to deliver turbine components to installation sites. Instead, a maximum distance from roads and high-voltage network is set for two distinct reasons: the components of a wind turbine are delivered using road transport, so the upper threshold for roads buffer allow to limit the costs (e.g., no necessity to build new routes, limited use of heavy machinery to move components); the losses through the wind turbine connection to the transmission network increases if the connection length augments, so less electricity can be sold and the revenues diminish (lowering also the LCOE).

Considering the social aspects, the most important constraint to impose is the buffer around urban areas. In this thesis, the value for this buffer is set equal to 500 m, in order to reduce the noise level produced by a wind turbine in the cities. At this distance, the noise generated by a turbine is lower than the noise produced by a refrigerator (*Figure 12*), while the available area remains relevant. For what concerns the productive areas, it has been chosen for this thesis to exclude only the territories occupied by production facilities, in order to reduce the risks for the workers and the machinery.

Regarding the environmental aspects, all criteria described before are applied in this thesis. The respect and protection of natural areas is ensured considering a buffer around them equal to 1 km. The regional and national parks and the wetlands are included in the natural areas constraint, while another buffer equal to 500 m is applied for forests in general. Moreover, also the territories indicated as IBA and important for the landscape (in according to the definition provided by the Region) are excluded from the available area, without a buffer. Another relevant constraint for Sardinia is the minimum distance to respect from seashore. A buffer equal to 500 m is implemented, to reduce the negative impacts of wind turbines (noise and landscape ruin) on the beaches and marine locations, since the economy of the Region relies consistently on summer tourism, mainly concentrated near the sea. To conclude the discussion about environmental aspects, a buffer around water bodies is considered in this thesis, equal to 150 m, in order to balance the necessity to protect rivers and lakes with the possibility to increase the available area.

Considering the safety aspects, having already discussed about the buffer around infrastructures, it is possible to define a buffer around the airports. Sardinia has three major airports (Cagliari, Olbia, Alghero), and a buffer equal to 3 km is applied around them. This value, much lower than the national indication, is chosen considering the values provided by the literature, and it allows to increase the territory available for turbines installation (with respect to indications by ENAC) having at the same time a limited impact on the airports operations. For what concerns the distance around natural gas and telecommunication networks, taking into account that in the literature it is rare that a similar constraint is implemented, it has been decided in this thesis to not apply it either. Moreover, the natural gas infrastructure is not very developed, and it is managed by different companies, so obtaining a precise map of its extension is quite impossible.

To summarise all values described above, the following *Table 6* is presented.

Wind speed	> 3,5 m/s	Natural areas buffer	> 1 km
Slope	< 30%	Forests buffer	> 500 m
Elevation	< 1500 m	IBA buffer	0
HV network buffer	> 200 m & < 10 km	Landscape assets buffer	0
Transports buffer	> 200 m & < 10 km > 200 m (railways)	Distance from seashore	> 500 m
Urban areas buffer	> 500 m	Water bodies buffer	> 150 m
Productive areas buffer	0	Airports buffer	> 3 km

Table 6 - Values for constraints applied in this thesis

3.3.1. Application of constraints to available area

Having discussed the restrictions that are applied in the calculation of the wind potentials, it is necessary to explain how these constraints are considered in this thesis.

As already debated, a GIS software (QGIS [34]) is used to obtain the suitable areas for the various potentials. One important parameter to define before operating with shapefiles is the reference system. In this study, it is set to WGS 84 (EPSG:4326), which divides Earth using degrees as measurement system. However, for some operations degrees are not highly effective, so another reference system, Monte Mario / Italy zone 1 (EPSG:3003), is used. This last system uses metres as measurement unit, so that it is simpler to do the calculations.

The procedure for available area computation is quite simple: starting from the entire surface of the Region, each map containing the extension of a constraint is subtracted using the "Difference" command present in the software. All operations are done with vector maps, so that ESRI shapefiles.

For some constraints, specifically those which establish a maximum distance as buffer, it has not to be used the "Difference" tool because the area included in the buffer corresponds already to the suitable area. Instead, the "Clip" command is utilised, which adds to the resultant layer only the portions of the polygons which are overlapped. Instead, for the constraints which impose a minimum and a maximum distance as buffer, the two commands are used subsequently: first, the buffer with the minimum distance is applied; then, the buffer with the maximum value is calculated; eventually, the first map is subtracted by the second one, obtaining the desired criterion, which in turn is clipped with the suitable areas map.

The majority of the limitations are already downloaded as shapefiles, while some other not. For instance, the digital elevation model (DEM) map, which is divided into a grid with a spatial resolution of ~900 m (30 arc-sec), is obtained as a raster file [66]. This DEM is called GTOPO30, and it was produced by U.S. Geological Survey considering several raster and vector sources of topographic information. A conversion is needed, and this is performed using the "Raster pixels to polygons" tool, which transforms each cell into square polygons with the same information and dimensions. The output data from WAsP are also converted with this method.

The map containing the slope data, instead, is obtained using the "Slope" tool, which considers two adjacent cells of DEM map to calculate the steepness of the terrain. For what concerns the buffers, they are done using the homonymous command, acting on maps with Monte Mario reference system (the buffer must be defined with the same measurement unit of the map; in case of Monte Mario, metres).

After applying all constraints considered, it is possible to join the suitable areas map with the one containing the data about the wind speeds and turbines productivity. This operation aims to maintain only the portions of maps which are overlapped, so that for each suitable area the AEP and average wind velocity is provided. This is achieved using the "Join attributes by location" tool.

Having the suitable areas and the productivity data, it is possible to create a grid with points corresponding to the turbines. Additionally, a 50 m buffer is applied to each point, which represents the biggest rotor radius among all turbines considered in the study (V100). This map is joined with the previous one (suitable areas with AEP data) in order to keep only the turbines (with their buffers) entirely enclosed in the constructable area. Furthermore, each point constituting the grid is distanced 500 m from another, in order to reduce the impacts among the turbines (wake effect). This distance takes into account also the 50 m buffer. With these simple operations, the map containing the possible locations of the turbines is obtained, together with the total productivity and the installed power.

3.4. Estimation of wind energy potential

Having discussed the various constraints taken into account in this thesis, in this section the types of wind potential are debated. Several potentials are considered in order to have a better understanding on how a constraint influences the final productivity. The following *Figure 20* reports a scheme of the procedure followed to compute the wind potential starting from the wind resource, while *Figure 21* shows a scheme of how the potentials are intercorrelated.

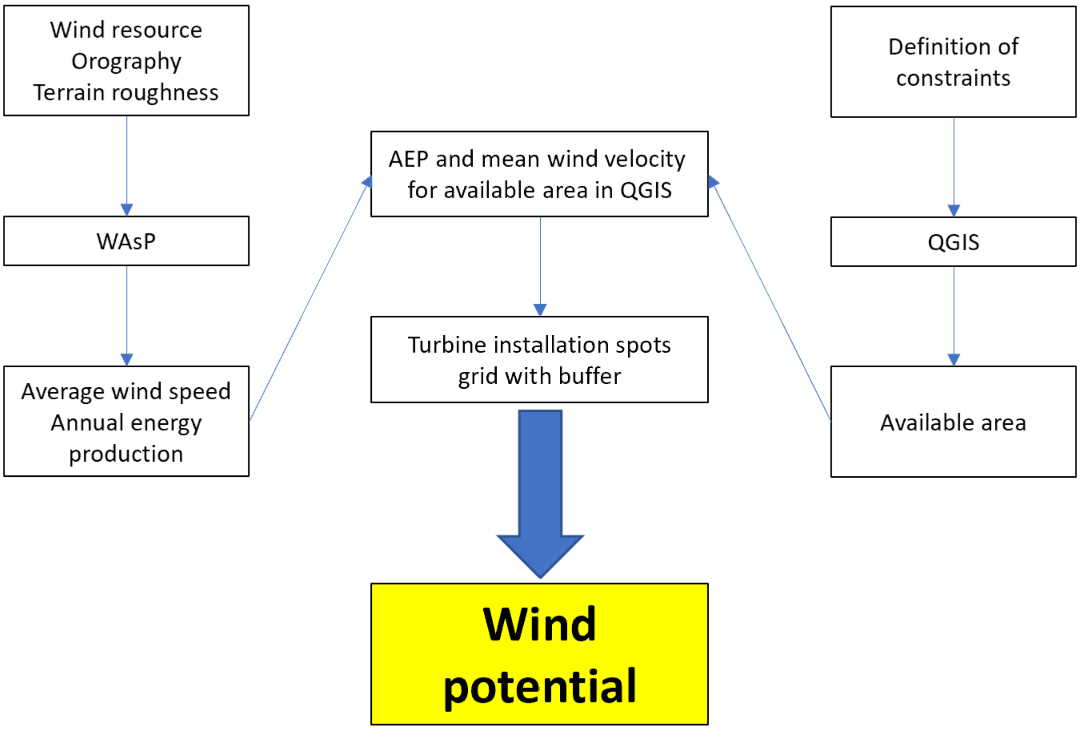


Figure 20 - Schematic procedure for wind potential assessment

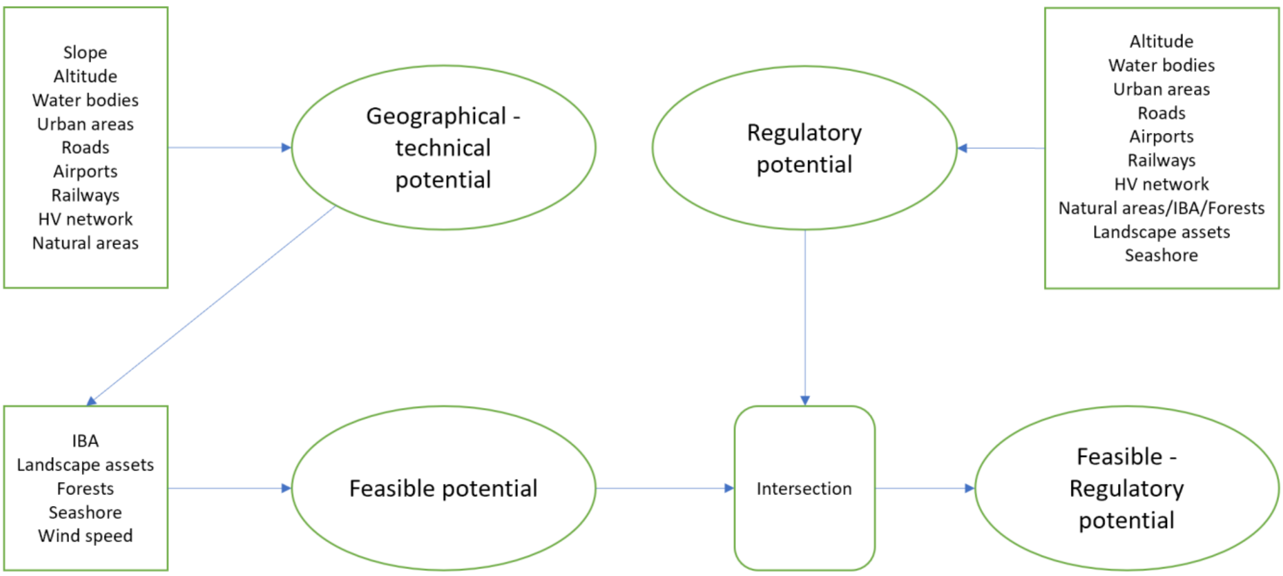


Figure 21 - Schematic definition and correlations of wind potentials

3.4.1. Geographical potential

The first potential to be considered is the geographical potential. This is defined as the amount of the available area for wind turbine installation accounting for dissimilar categories of constraints [35]. It is expressed in square kilometres. Apart from the theoretical potential, which refers to the total energy of the wind in a certain region (therefore it is not related to any constraints), this is the least strict potential possible. Indeed, only some of the limitations described in *section 2.4.1* are applied to evaluate this potential.

More precisely, it has been decided to implement the following constraints in the calculation of the geographical potential (*Table 7*).

Constraints	Geographic potential
Slope	< 30%
Altitude	< 1500 m MSL
Water bodies	> 150 m
Urban areas	> 500 m
Roads/Highways	> 200 m & < 10 km
Airports	> 3 km
Railways	> 200 m
HV network	> 200 m & < 10 km
Natural areas	> 1 km

Table 7 - Constraints for geographic potential

As it is possible to observe, several types of constraints are implemented, involving each category described before. The decision about which limitations include comes from a literature review. The procedure to apply these constraints is quite simple and straightforward: starting from the total area under investigation, each restriction is implemented singularly, reducing the available area for installation, up to arriving to the minimum surface possible, which is equal to the geographical potential.

The other constraints not listed above are considered in the feasible potential. The fact to separate the impact of the limitations is mainly arbitrary. Indeed, the constraints applied to the geographical potential are more common (and more important too), both in the literature and in the legislations, and the majority of the scientific papers applies this set of criteria. However, it is also possible to change the importance of each restriction, according to some externalities (e.g., area under investigation, country where the study is performed, opinions of inhabitants, etc.), and so also the geographical potential can be calculated with different constraints.

3.4.2. Technical potential

The geographical potential discussed above does not permit to obtain a value for turbines productivity, since it is only an area. To compute how much energy can be produced by wind turbines installed in the surface estimated in the previous step, the technical potential is necessary. It corresponds to the energy generated in a year within the geographical potential [35]. It is expressed as GWh/year.

Even for this potential some constraints must be considered, but they are not “physical” limitations, so related to geographic information, rather they are linked to wind turbine engineering. Indeed, to assess the technical potential the turbine characteristics, and the various sources of losses present in a wind farm (e.g., energy conversion), must be taken into account. So, the turbine technology is the crucial factor for the evaluation of the technical potential. Different wind turbines (either with various classes or various power curves) can perform better or worse in the same specific area (in this case, the geographical potential), hence the technical potential can vary too. For this reason, in this study three wind turbines are considered, and for each of them the annual productivity is calculated, in order to decide which should be installed. The WAsP software computes the annual production of a turbine also including the possible losses; therefore, no further actions are necessary to correctly evaluate the potential.

Together with the technical potential, also an economic potential can be evaluated. This is not considered in this thesis since many papers do not estimate this potential either, but a brief description should be provided to complete the current discussion. The economic potential is defined as the fraction of the technical potential that can be economically realised [35], and it depends on energy policies and market frameworks. It is expressed as kWh/year. The reason why it is not included in this analysis is the difficulty to compute the costs for a single wind farm (or turbine) when a region as big as Sardinia is investigated, where many turbines are installable. Furthermore, it can vary a lot in a fleeting period of time, accordingly to new policies or incentives, hence a long-term estimation is not possible.

3.4.3. Feasible potential

To conclude the analysis about the “common” wind potentials, it is considered the feasible potential, which expresses the electricity that can be produced in a year by wind turbines (GWh/year) starting from the technical potential and applying additionally constraints. Different definitions have been provided for this type of potential, but most of them relate it to the public acceptance of wind projects [35]. Practically, it includes constraints which are not directly linked to economic or technical aspects, rather to social and, to a lesser degree, environmental factors. Considering the variability of definitions, it is not possible to give a precise description of the feasible potential. Additionally, estimating the social acceptance of a wind farm can be a highly challenging task, even greater if the region under investigation is quite large. People's opinions can vary a lot from locations to locations and over time, also accordingly to technological improvements or climate change issues.

For the reasons abovementioned, in this thesis the feasible potential is computed applying the constraints not implemented in the geographical potential (*Table 8*). This potential is the strictest among all potentials (theoretical, geographical, technical, economical). The approach used here is not standard, but it allows to break up the effects of the constraints in two different potentials, in order to compare the results.

Constraints	Feasible potential
IBA	0
Landscape assets	0
Forests	> 500 m
Seashore	> 500 m
Wind speed	> 3,5 m/s

Table 8 - Constraints for feasible potential

3.4.4. "Regulatory" potential

The last potential considered in this study is called "regulatory" potential. This is not defined in the literature, and it refers to the potential only implementing the constraints established by national and regional legislations. It is expressed in kWh/year. Some constraints are equal to ones applied to previous potentials, but with different buffer values. Some restrictions are not considered at all, while new ones are implemented. The following *Table 9* summarises all constraints considered in the regulatory potential.

Constraints	Regulatory potential	Constraints	Regulatory potential
Altitude	< 900 m MSL	Railways	>([hub_height+rotor_radius]*1,1)
Water bodies	> 150/300 m	HV network	< 10 km
Urban areas	> 500 m	Natural areas/IBA/Forests	0
Roads/Highways	>([hub_height+rotor_radius]*1,1)	Landscape assets	variable
Airports	> 5 NM	Seashore	> 300 m
Buildings	> 200 m	Volcanos	0
Areas with geomorphological and hydrogeological sites	0	Areas with notable public interests	0
Archaeological sites	0	Burnt areas	0

Table 9 - Constraints for regulatory potential

3.5. Wind energy costs

After the discussion about the constraints and the potentials, in this section the costs related to wind turbine installations will be deepened. Various sources of data are considered, which present also significant variations.

3.5.1. Turbine costs

Starting from the costs related to the installation of a wind turbine, four different references are taken into account: the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), Lazard, and the National Renewable Energy Laboratory (NREL). The first two sources provide data specifically for Italy, while Lazard refers to global data and NREL to US plants. However, the wind costs are calculated considering all references, to give an insight about how much the source material can influence the preliminary economic profitability of a RES project (and also to do a sort of sensitivity analysis). The costs considered in the various reports are presented in *Table 10*.

Source	**Installation costs [€/kW] [3]**	**O&M costs [€/kW/y]**
IRENA Power Generation Costs 2020 [23]	~1200 global ~1600 Italy ~1335 Europe	~44 Germany ~38 Norway
IEA Projected Costs of Generating Electricity 2020 [67]	~1300 Italy	-
Lazard levelized cost of energy [68]	~900 - 1190	~22,5 – 31,7
Cost of Wind Energy Review 2019 – NREL [69]	~1250	~38

Table 10 - Costs according to sources

As it is possible to observe, data are quite dissimilar, and the costs referred to Italy are generally higher than the global and European average. However, the vast number of turbines installable according to the various potentials can lower the costs also for Italy. For what concerns the operation and maintenance costs, no data are provided for Italy, so the ones given for other European countries are utilised. The O&M costs are necessary to calculate the LCOE, which represents the expense required to produce 1 kWh of electricity, using the formula below:

[3] Exchange rate 1 USD = 0.8814 €

$$LCOE = \frac{I_0 \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \; [35] \tag{3.1}$$

where I_0 is the investment cost, n the lifetime of the plant, M_t is the annual cost in year t, r is the discount rate, E_t is the energy produced by plant in year t. In this study, the discount rate r is set equal to 4% (considering the minimal risk related to this type of investment) and the lifetime n is set equal to 25 years [67]. The annual costs are equal to the O&M costs, while the annual energy is equal to the technical, feasible, and regulatory potentials. The O&M costs are assessments about how much money each year is necessary to guarantee the correct operation of a wind turbine (e.g., to repair a failure). This quantity can vary a lot because of some externalities (e.g., environmental conditions) for different plants, so an estimation is more difficult with respect to the investment costs.

To provide an insight about how the investment cost for a turbine is divided into its components, the *Table 11* below is reported. The percentages are obtained from the breakdown present in [69], which is referred to a turbine model in US, and they are kept constant. The cost values are provided considering the CAPEX estimated by IRENA for Italy, as an example.

	Percentage	Cost [€/kW]
Rotor module	19,99%	319,78
Blades	12,81%	205,01
Pitch assembly	4,18%	66,85
Hub assembly	3,06%	49,03
Nacelle module	33,98%	543,73
Nacelle structural assembly	6,82%	109,19
Drivetrain assembly	13,37%	213,93
Nacelle electrical assembly	11,63%	186,07
Yaw assembly	2,23%	35,65
Towe module	14,97%	239,55
Turbine capital cost	**68,94%**	**1103,06**
Development cost	1,11%	17,83
Engineering and management	1,25%	20,06
Foundation	4,11%	65,74
Site access and staging	3,06%	49,03
Assembly and installation	3,06%	49,03
Electrical infrastructure	10,10%	161,56
Balance of system	**22,70%**	**363,23**
Construction financing cost	2,37%	37,88
Contingency fund	5,99%	95,82
Financial costs	**8,36%**	**133,70**
Total CAPEX	**100,00%**	**1600,00**

Table 11 - Cost breakdown for a turbine

3.5.2. Wind electricity market in Italy

As described in *section 2.3.2*, the incentives related to renewable plants are managed by GSE, which is the company owned by Economic and Finance Ministry designated to promote RES development. The incentives are regulated by a Ministerial Decree (04/07/2019, also called FER1 [70]) promulgated by Economic Development Ministry (MISE), which divides the plants into four groups according to typology and renewable source.

The plants with installed power greater than 1 MW participate to the auctions, through which the available capacity is assigned to projects which propose the largest cost reduction compared to reference tariffs. With equal proposals, other criteria of priority are applied. The reference tariff for each source is established by an appendix to the same Decree, and for wind plants with power capacity larger than 1 MW it is equal to 66,5 €/MWh[4]. After the auction, the plants can have access to incentives after they become commercially operative.

Since the definitive approval of the Decree, seven calls for bids have been proposed, the last one closed on 30th October 2021. The total power capacity offered for group A (wind and PV plants) through auctions was 5.500 MW. Excluding the last call (whose results have not been published yet), the offer was 3.900 MW, while the capacity allocated was less than 2.200 MW [71]. This is the quantification of the problem highlighted previously (*section 2.3.2*).

The incentives are calculated considering the net produced electricity delivered to the network, computed as the least value between net production and electricity measured by meter [71]. The Decree provides for three different tariffs:

- The reference tariff, provided by the Decree (66,5 €/MWh).
- The offered tariff is calculated applying to the reference tariff the reductions asked by the owner of the plant, in order to gain a higher priority level.
- The final tariff, which is calculated applying to the offered tariff other reductions established by Decree for the plants admitted to incentives.

The final tariff is reduced by certain amounts in some specified negative cases, as for instance the if a plant uses regenerated components or it is not operative after 15 months of results publication [70].

For plants with power higher than 250 kW, the incentive is calculated as difference between the final tariff and hourly energy district price since the electricity remains to the plant operator.

The Decree also establishes a temporal limit for the starting of operation of the plant, equal to 31 months after the publication of the correspondent call results [72]. If a plant does not respect the technical requirements, or it is not connected to the electric network, the possibility to access the incentives forfeits, but the plant operator can participate to other auctions.

[4] See Appendix B

4. Results

Having discussed which constraints are applied in the calculation of the various potentials, in the current section the results related to wind productivity and cost are reported for each of them.

4.1. Wind potentials

The first important outcomes of this thesis are the data about the wind potentials. These results are divided according to the definitions presented in *section 3.4*.

4.1.1. Geographical potential

The geographical potential is the first and the least strict among all potentials considered in this thesis. It is obtained applying the procedure discussed in *section 3.4.1*, and it does not allow to calculate a wind productivity. Instead, it is useful to understand how much soil is available for wind installation considering some of the most used exclusion criteria. The map showing which are the suitable areas is presented below (*Figure 22*).

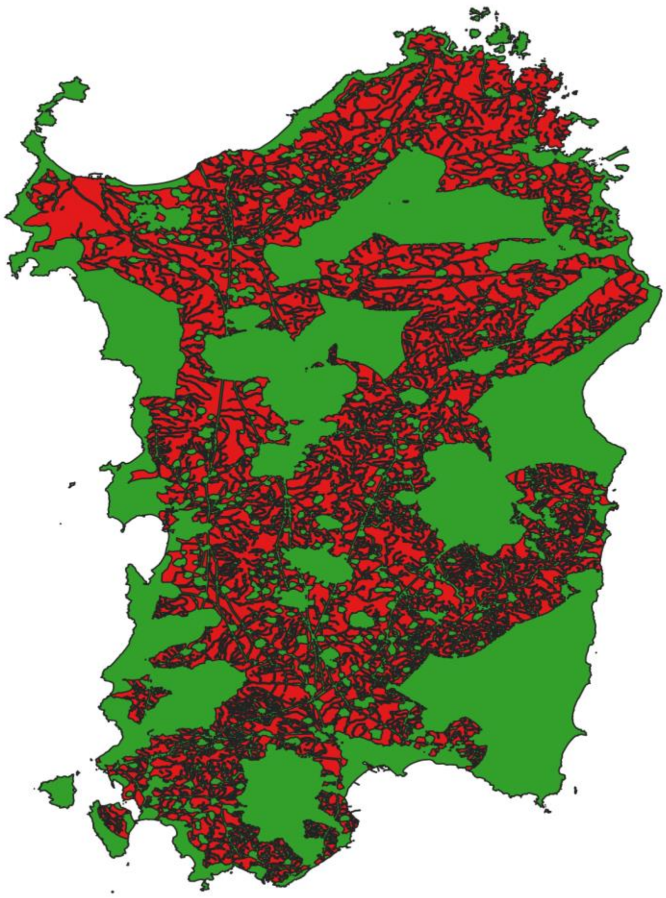


Figure 22 - Suitable areas map for geographic potential. In green the Region, in red the available area

As it is possible to observe, the suitable area is quite large with respect to the entire surface. This is confirmed also by data, which show that the available area is equal to 9.448 km^2, that represents the 39,22% of the Region extension. The division of the suitable area according to each province is presented in *Figure 23*. The values in the tags indicate the square kilometres of available area, while the percentages indicate how much surface of each province [73] is suitable for wind turbine installation. Oristano and Sassari have an available area around the half of their extensions, while the province of Cagliari displays an incredibly low percentage, mainly due to the small surface and the presence of quite large urban areas.

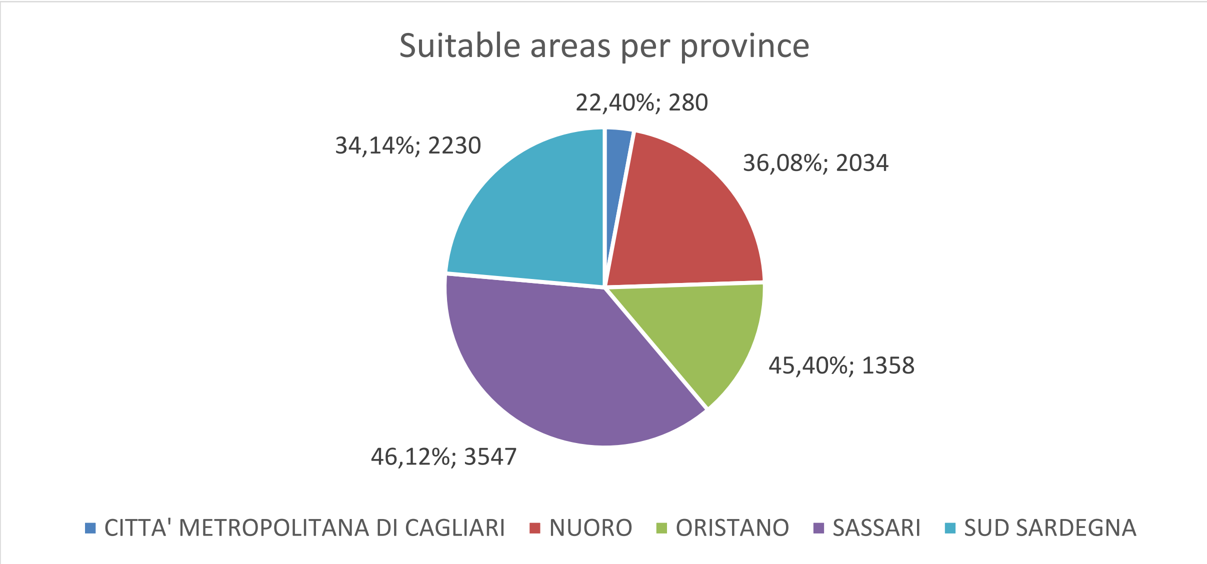


Figure 23 - Suitable areas breakdown per province

The suitable area calculated applying the methods discussed in *section 3.3.1* is further manipulated in order to separate each "island". An island is a portion of the suitable area which is completely isolated (i.e., no points of contact) from the rest of the map. This breakdown is performed with a simple procedure: first of all, the data of the suitable areas map are merged in one single item, so that the shapefile contains only one element corresponding to the entire surface, using the "Dissolve" command present in QGIS; then, the "Multipart to single parts" tool is utilised on the dissolved map, in order to obtain a number of elements in the shapefile equal to the number of islands present in the map; eventually, the area of each island is computed with the "Field calculator", that allows to add data for every element in the shapefile according to a specific mathematical or logical expression.

In order to deal with the small islands, two possibilities can be considered [49] depending on the size of the polygons involved. The first effect concerns the areas (assumed to be of circular shape) too small to erect a wind turbine. The threshold to consider a polygon too small is variable and it depends on which turbines are employed in the study. However, it is possible to set a value of 0,01 km^2 as maximum edge. The areas of islands lower than this threshold are summed up, and the result is multiplied with the turbine density (calculated as the division between the nominal power and the required space for a wind turbine, which depends on the minimum distances to respect) in order to obtain the additional turbine power capacity for the potential considered. The second effect regards the circular polygons with an area between 0,01 and 1 km^2. In this case, it would be possible to install a wind turbine, but multiplying the area with the turbine density the power capacity would be lower than the one provided by the single turbine. Hence, the first effect leads to an overestimation of the capacity installable, while the second effect underestimates the potential.

In this thesis, the problem of small islands is solved with another method. Indeed, the productivity is calculated considering of installing a turbine only if the entire cone representing the wind generator is contained in the suitable area (*section 3.3.1*). Therefore, if an island is too small, it is excluded by the potential computation since no turbine is present. Furthermore, the turbine density is not used, since the WAsP software already provides the data about the annual energy productivity.

4.1.2. Technical potential

The technical potential is directly related to the geographical potential. The suitable area is the same, and in this potential the wind productivity is computed for each turbine considered in this thesis.

The procedure to obtain which turbine performs the best in a certain zone has been already discussed. The grid representing the turbines contain the annual energy production for the three turbines. A simple logical expression is defined in the "Field calculator" in order to extract the maximum AEP among the three calculated, together with the corresponding turbine.

Having the productivity and the best turbine for each spot, it is possible to calculate the capacity factor and the equivalent hours. For the technical potential, the total annual productivity is equal to 133.619 GWh, while the installed capacity is 58,46 GW. Dividing these two quantities, the equivalent hours are equal to 2285 h/year, and the capacity factor is 26,09%. The capacity factor is computed using *Equation 3* below:

$$CF = \frac{equivalent\ hours}{total\ hours\ in\ a\ year} * 100 \qquad (4.1)$$

This result is coherent with the average capacity factor obtained in other studies (e.g., [49]). Moreover, it is also consistent with the average European onshore wind capacity factor, that it is around 25% for all operating wind plants, while it is estimated around 30-35% for new installations [74].

The number of turbines installable according to the technical potential is 32.473, while the most used generator is the V100 (31.426 turbines, 96,8%). The V90 is second with 1001 installations, while the V80 has been resulted the best only for 46 spots. The breakdown of the turbines according to the province of installation is reported in *Figure 24*.

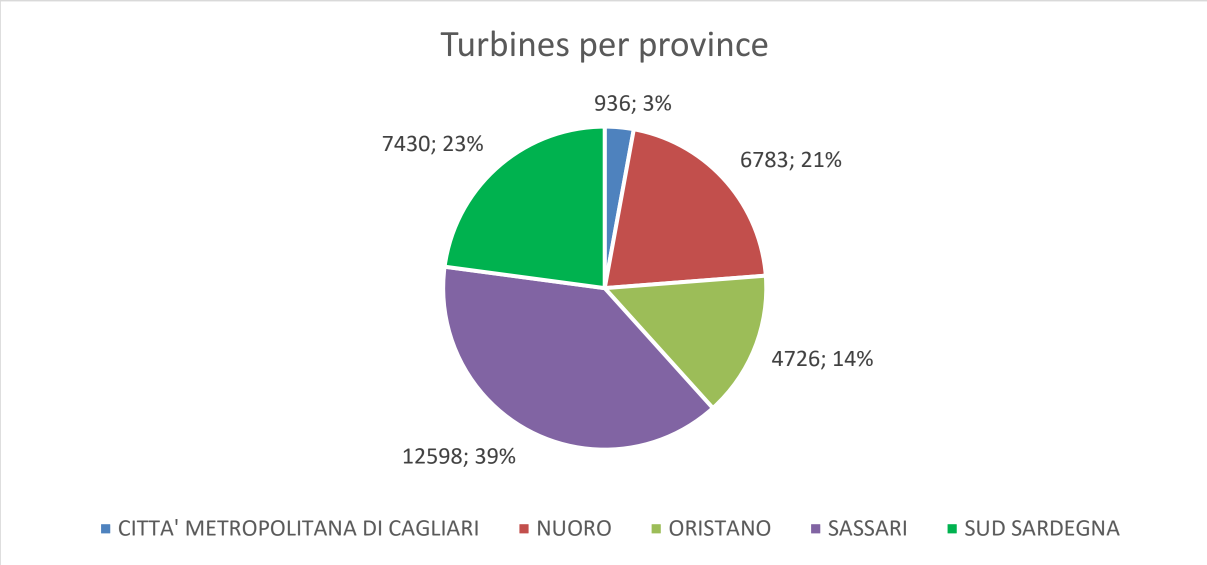


Figure 24 - Turbines breakdown per province

The province of Sassari is the one with the highest share of turbines installation, since it has the biggest extension but an extremely low population density [73]. On the contrary, Cagliari has the lowest number of turbines installation, since it is the smallest province. Moreover, most of the territory consist of urban areas, which is one of the exclusion criteria considered in this potential. In the following figures (*Figure 25*, *Figure 26*) are presented the breakdowns of the productivity and the capacity for each province.

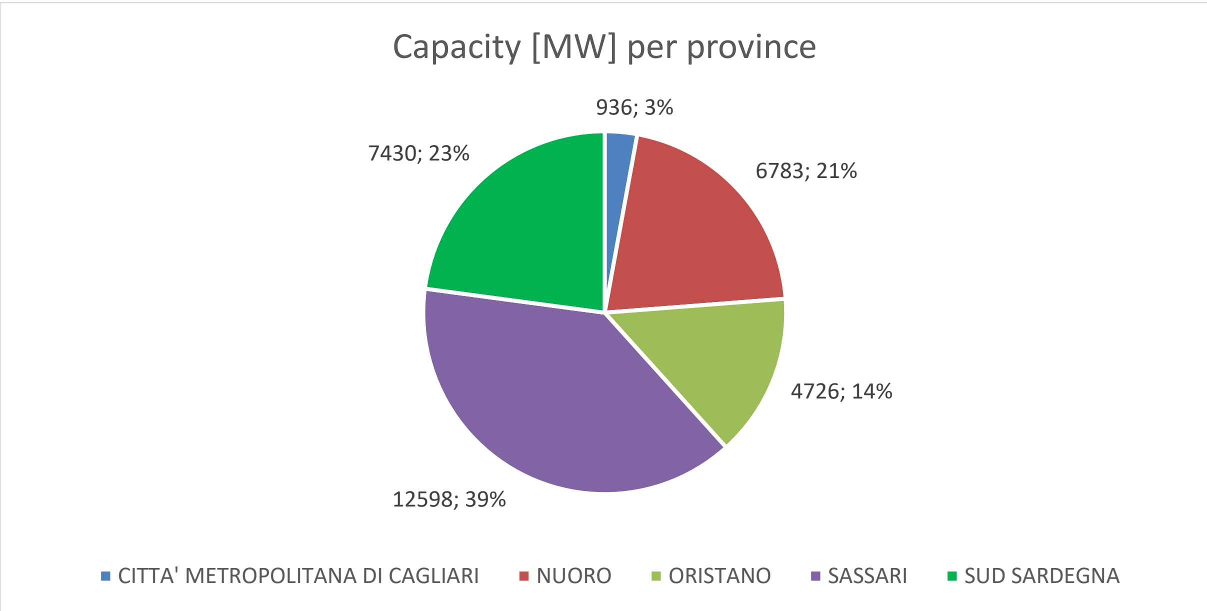


Figure 25 – Wind installed capacity breakdown per province

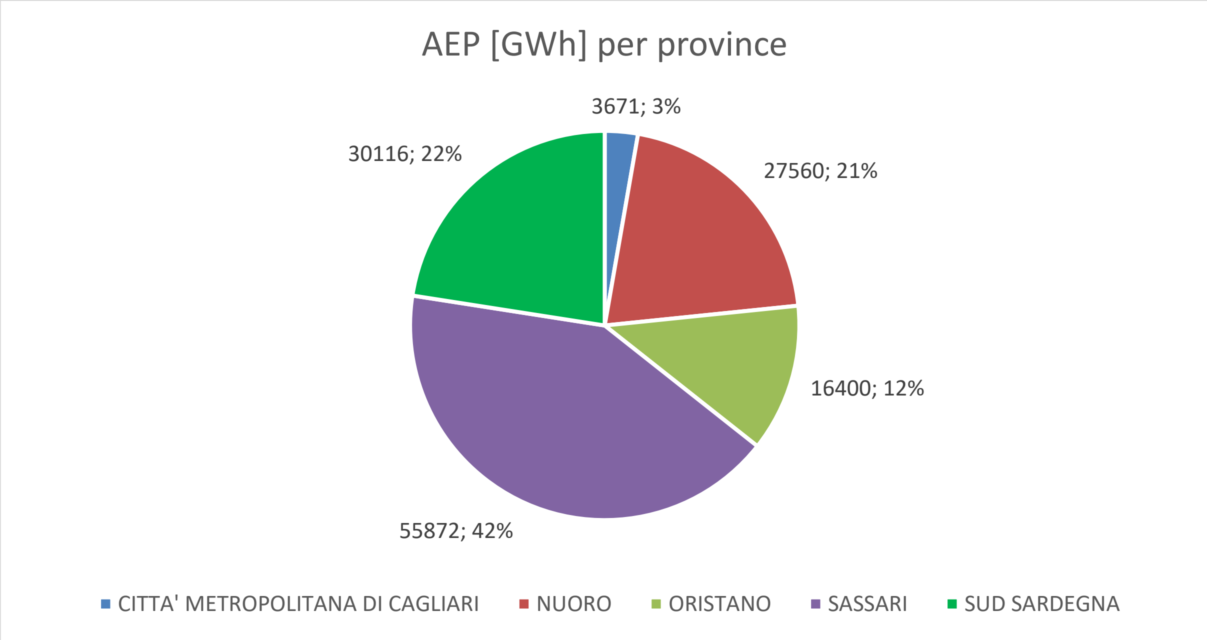


Figure 26 - AEP breakdown per province

Even for these parameters the best province is Sassari, which almost reaches half of the total turbine production. Instead, Oristano has an AEP share lower than the capacity share, so that it shows a small capacity factor. This is also confirmed by wind data (*Figure 5*), that display a lower average wind speed in this territory compared to the rest of the Region, mainly due to a particular morphological shape that passes from plains to mountain chains, hence a great variability in terrain roughness is present.

The following *Table 12* summarises all the information discussed above.

	Turbines	Capacity [MW]	AEP [GWh]	CF	V80	V90	V100	Suitable area [km^2]	Percentage
Cagliari	936	1.685	3.671	24,87%	0	25	911	280	22,4%
Nuoro	6.783	12.211	27.560	25,77%	6	310	6.467	2.034	36,08%
Oristano	4.726	8.514	16.400	21,99%	36	113	4.577	1.358	45,4%
Sassari	12.598	22.676	55.872	28,13%	0	479	12.119	3.547	46,12%
Sud Sardegna	7.430	13.375	30.116	25,70%	4	74	7.352	2.230	34,14%
Sardinia	32.473	58.461	133.619	26,09%	46	1001	31.426	9.448	39,22%

Table 12 - Regional data for technical potential

The province of Oristano has the lowest capacity factor and the highest share of class I turbine (V80, almost 80% of the total installations of this turbine). The wind resource is mainly concentrated near the coastline, while it is quite scarce in the inner zone, but only a little portion of the province is excluded by the technical potential, hence many turbines are located where the productivity cannot be high due to low wind speed. However, near the shoreline the wind resource is stronger than in the remaining province, and so the installation of V80 turbines becomes feasible and convenient (even if the number is much lower than the installations of V90 and V100 turbines).

In conclusion, in the following figure (*Figure 27*) the location of turbines identified following the application of technical potential criteria in each province are shown, in order to give an overview on where they are located most.

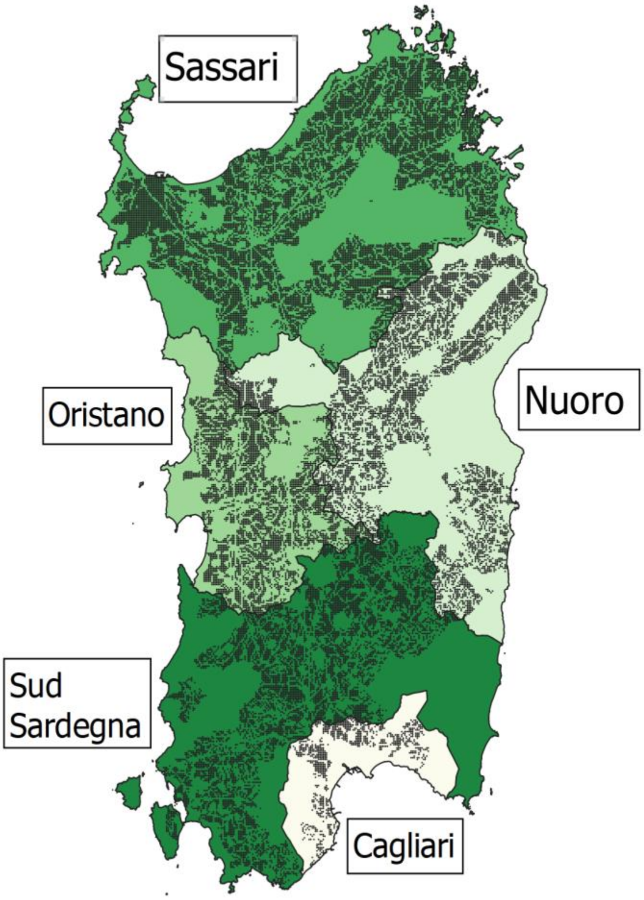


Figure 27 - Turbines locations for technical potential

4.1.3. Feasible potential

The feasible potential represents a further restriction in the available area with respect to the technical potential. The same procedure explained for the previous potential is applied for the feasible potential. The exclusion criteria are implemented starting from the suitable areas obtained before. The productivity is computed for each turbine, and these data are joined with the grid representing the turbine spots in order to establish the best performing generator.

The suitable area is much lower than the one obtained by the geographical potential, and it is shown in *Figure 28*. The available area is very widespread, and many small islands are present. The total suitable area is around 3.160 km^2, that is equal to 13,12% of the Region extension. The reduction with respect to the geographical potential is around 66,5%, mainly due to the forests buffer. The separation of the extension of suitable areas depending on the province is shown in *Figure 29*.

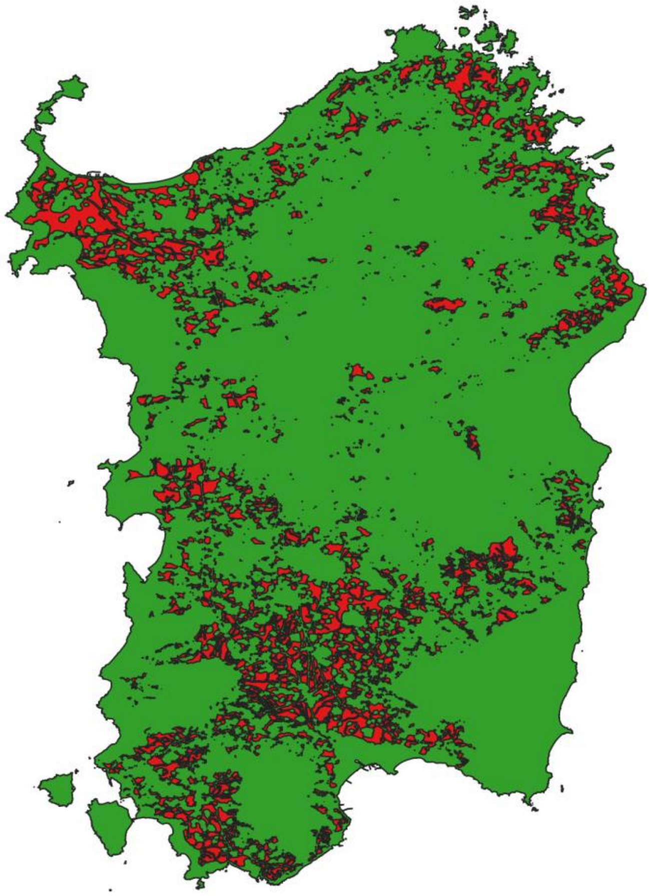


Figure 28 - Suitable areas map for feasible potential. In green the Region, in red the available area

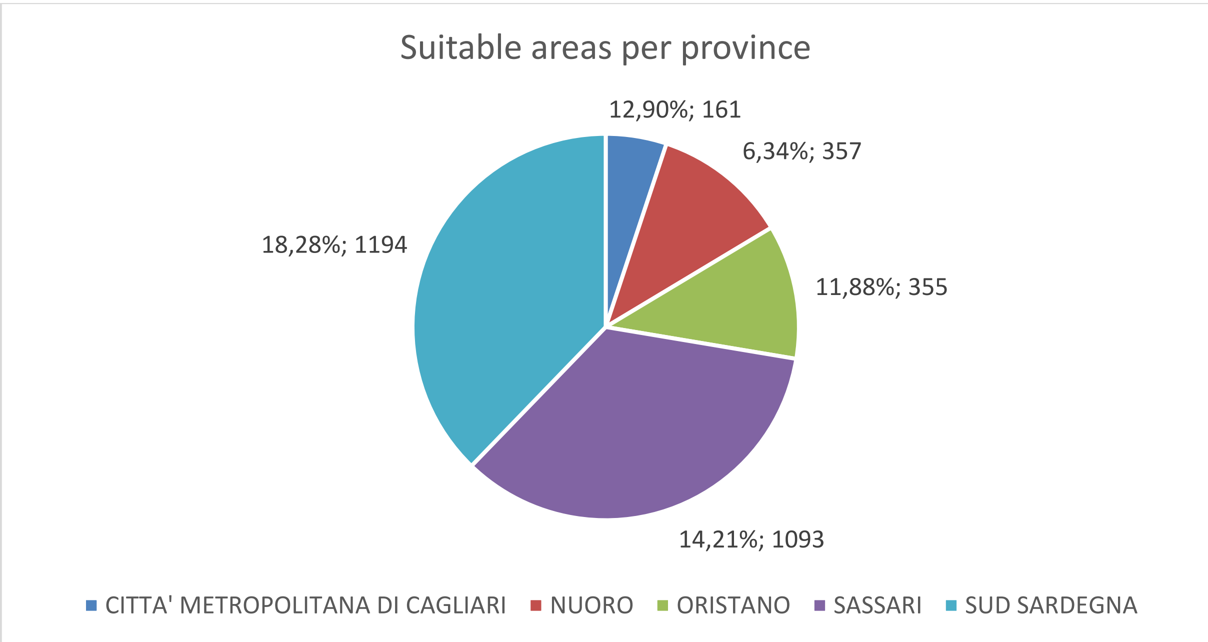


Figure 29 - Suitable areas breakdown per province

This significant difference in the available area is reflected also in the turbine production and power capacity installable, which are equal respectively to 42.725 GWh/year (diminution of 68%) and 18,35 GW (diminution of 69%). However, having implemented additional constraints in order to obtain more performing locations (e.g., buffer around forests diminishes the wake effect, a lower threshold for wind speed allows to exclude all sites with exceptionally low wind resource), the capacity factor slightly increases, arriving to 26,58%, equal to 2328 full load hours.

The number of turbines installable decreases substantially with respect to the technical potential, now equal to 10.193 possible locations (reduction of 68,5%, consistent with the reduction of the capacity since all turbines have similar nominal power). The most used turbine is again the class III V100, with a number of installable spots equal to 9.896 (share of 97,1%, marginally higher with respect to technical potential). The second most common turbine is the V90, with 273 possible installations, while the V80 turbine performs the best only in 24 locations. The possible locations breakdown according to the province of installation is presented in *Figure 30*.

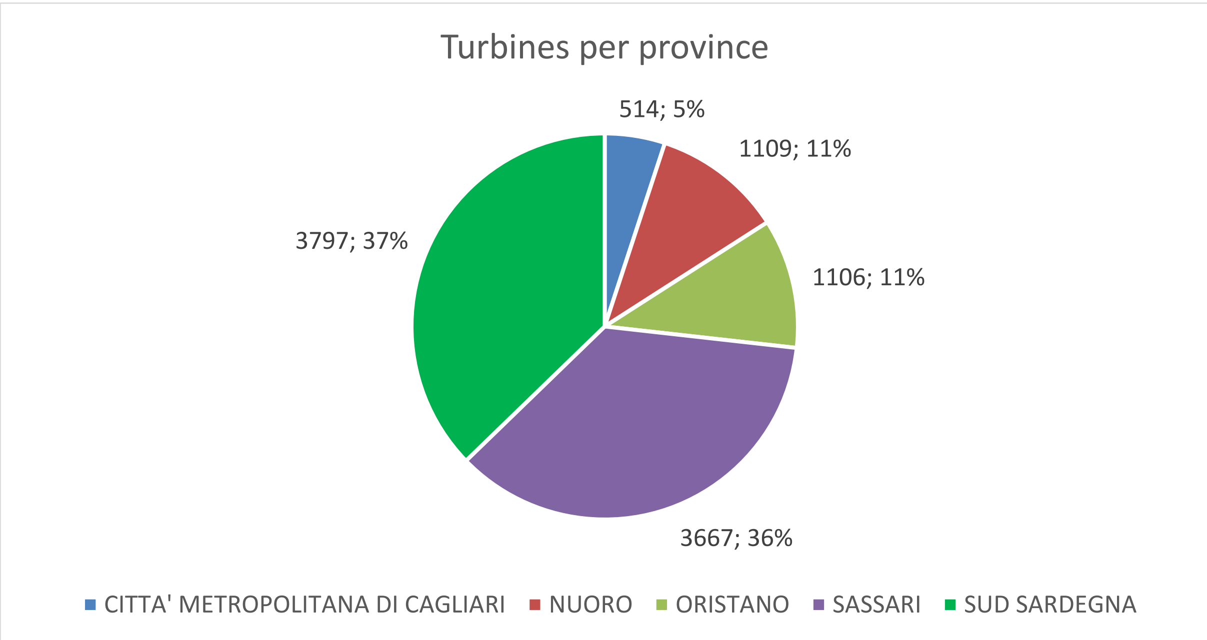


Figure 30 - Turbines breakdown per province

For the feasible potential, the most exploited province is no more Sassari but Sud Sardegna. Both of them have similar extension, but the province of Sassari is more covered by forests and woods with respect to Sud Sardegna, so the available area has been greatly reduced with respect to the geographical potential.

In the next two figures (*Figure 31*, *Figure 32*) are presented the division of the power capacity and annual energy production for each province.

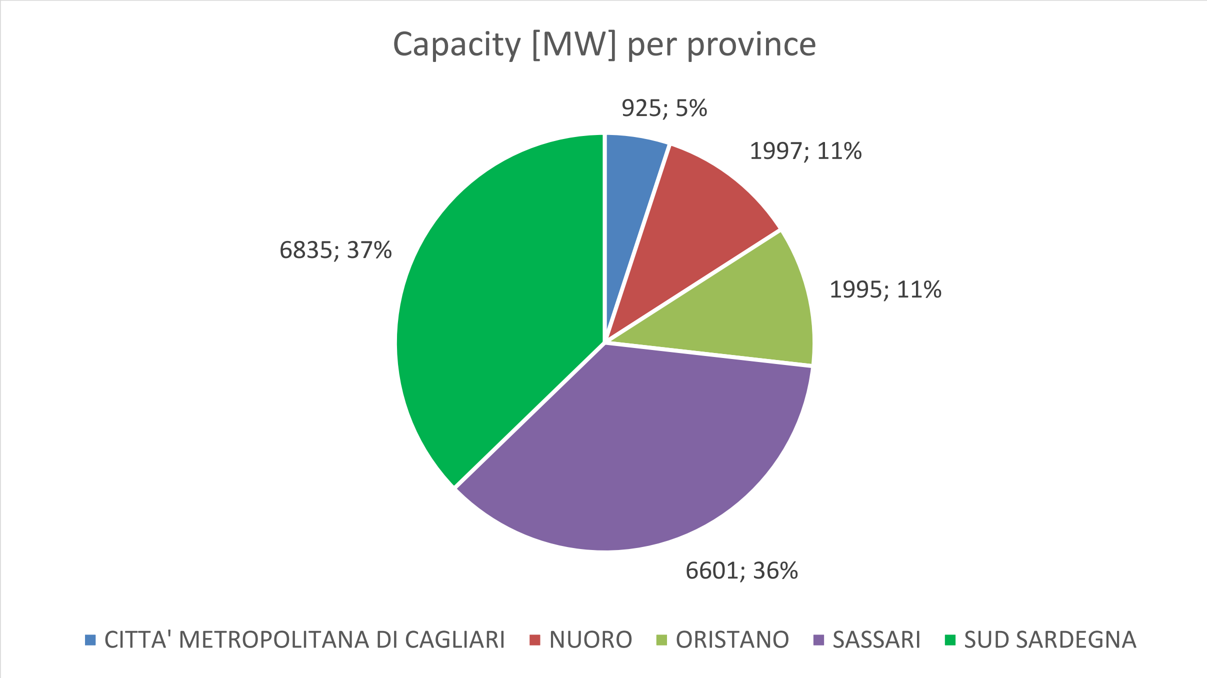


Figure 31 - Capacity breakdown per province

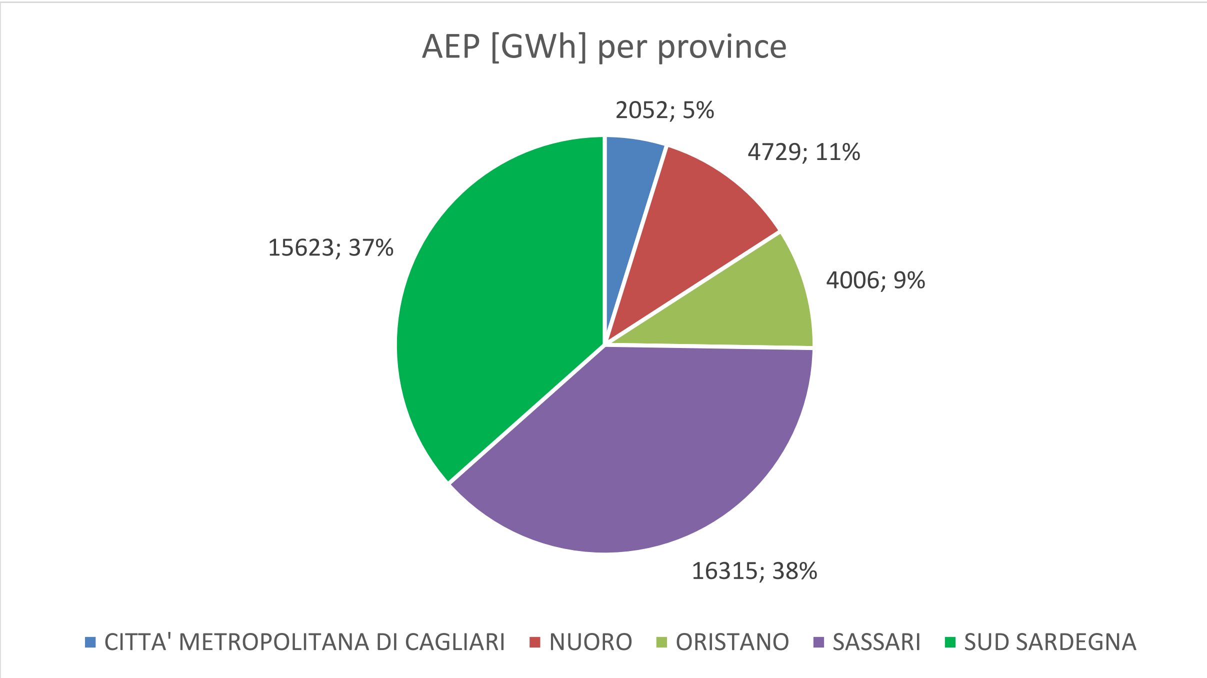


Figure 32 - AEP breakdown per province

Once again, the province of Oristano has an AEP share lower than the share of the capacity, hence the capacity factor is the least among all provinces. Despite a higher capacity, Sud Sardegna shows a lower productivity with respect to Sassari, mostly due to the fact that the main directions from where the strongest wind blows are west and north-west [75] (respectively, Ponente and Mistral), which directly hit the province of Sassari, and only to a lesser degree the province of Sud Sardegna. However, Sud Sardegna has become the second most productive province of the Region, with an AEP nearly equal to the one obtained for Sassari, while for the technical potential its contribution is much more restrained. A plausible reason why this improvement happened can lay in choice of the constraints, since Sud Sardegna is less covered by forests with respect to the other provinces.

A summary about all data discussed for the feasible potential is provided in *Table 13*.

	Turbines	**Capacity [MW]**	**AEP [GWh]**	**CF**	**V80**	**V90**	**V100**	**Suitable area [km^2]**	**Percentage**
Cagliari	514	925	2.052	25,32%	0	12	502	161	12,9%
Nuoro	1.109	1.997	4.729	27,03%	3	51	1.055	357	6,34%
Oristano	1.106	1.995	4.006	22,93%	19	30	1.057	355	11,88%
Sassari	3.667	6.601	16.315	28,22%	0	154	3.513	1.093	14,21%
Sud Sardegna	3.797	6.835	15.623	26,09%	2	26	3.769	1.194	18,28%
Sardinia	10.193	18.352	42.725	26,58%	24	273	9.896	3.160	13,12%

Table 13 - Regional data for feasible potential

Some of the comments done for the technical potential are valid also for the feasible potential. In particular, Sassari shows the highest capacity factor, larger than the regional average, and the greatest production. On the contrary, Oristano has the lowest full load hours, and at the same time the biggest share of V80 installations (again almost 80%). To conclude the discussion about the feasible potential, *Figure 33* is provided with all possible turbine locations.

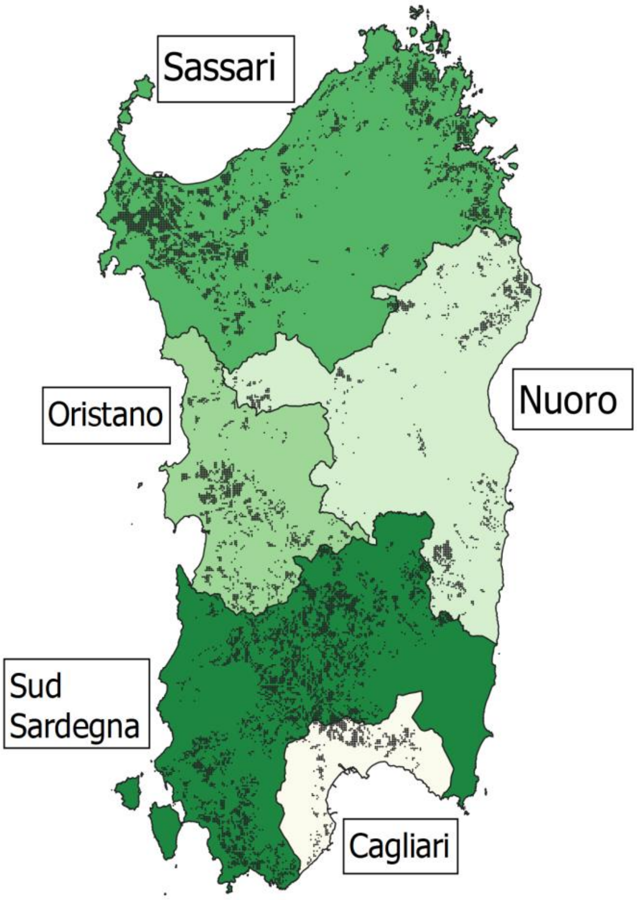


Figure 33 - Turbines locations for feasible potential

4.1.4. "Regulatory" potential

Having discussed the potentials with exclusion criteria coming from the literature, it is necessary to also evaluate the wind potential according to the actual legislative constraints. To do so, the "regulatory" potential has been defined. In this case, all criteria established by Regional or national laws have been implemented in the calculation in order to obtain a wind potential as much as possible consistent with the real situation. The procedure is always the same, but some of the criteria considered have different buffer values, while others are completely new. All criteria are applied starting from the Region shapefile, and the suitable areas map obtained is shown in *Figure 34*.

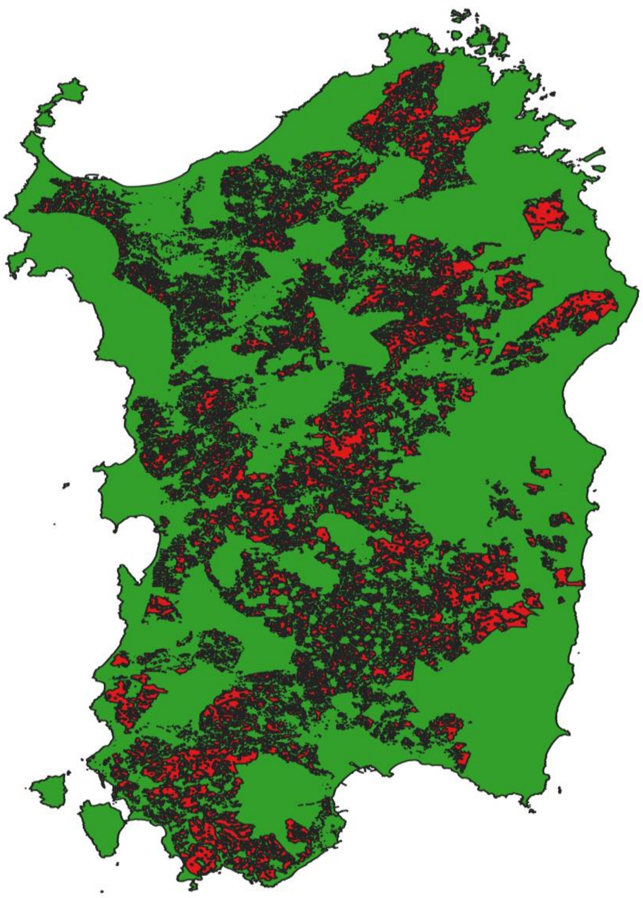


Figure 34 - Suitable areas map for regulatory potential. In green the Region, in red the available area

The available areas are more concentrated than the ones obtained for the feasible potential, and a quantitative analysis reveals that they are equal to 4.526 km^2, around 19% of the Region extension. This result shows that the regulatory potential is less strict with respect to the feasible potential as defined in this thesis. Hence, two possibilities can be equally true: either the exclusion criteria applied in this thesis are too restricting (even if they are in line with the constraints considered in the literature) or the limits imposed by laws are too weak (compared to scientific studies). In any case, this result is quite surprising. The division of the suitable areas with respect to the provinces is reported in *Figure 35*, where the numbers refer to extension of the available area in the province correlated, while the percentages display how much provincial extension can be occupied by wind turbines.

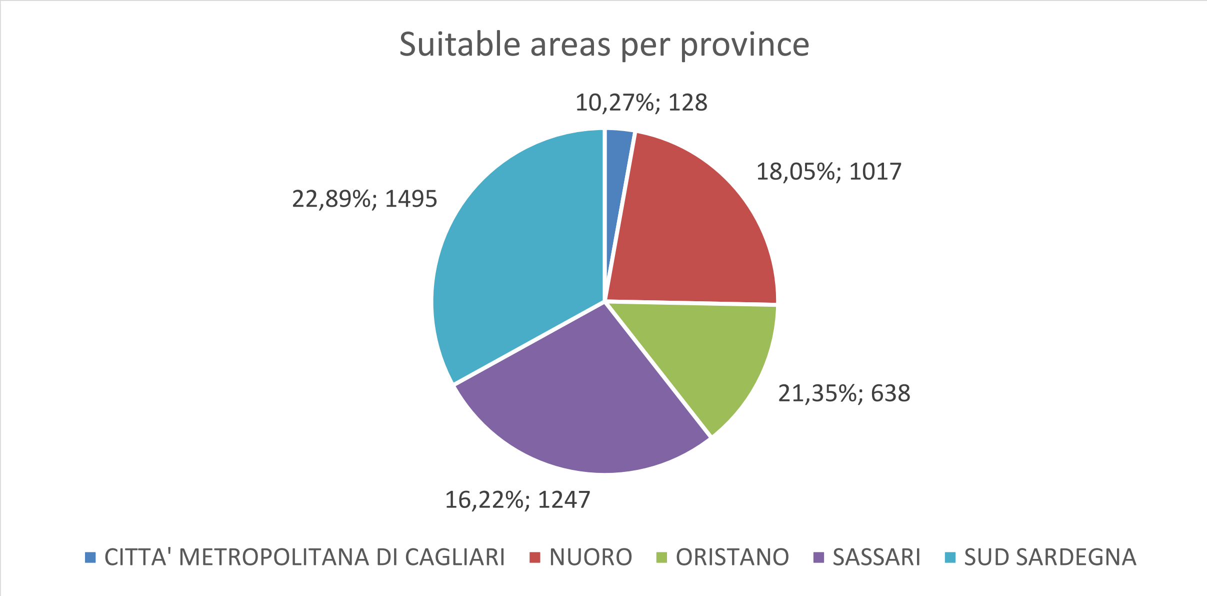


Figure 35 - Suitable areas breakdown per province

Applying these exclusion criteria, the power capacity installable in Sardinia is equal to 23,39 GW, with a possible annual energy production equal to 52.499 GWh. These two quantities lead to a capacity factor of 25,63%, or 2245 full load hours. As it was easily predictable, the AEP is greater than the feasible potential, but the capacity factor is lower of about 1% compared to the previous potential, and it is also smaller than the one calculated for the technical potential.

The number of turbines that can be constructed according to this potential follows the trend of the power capacity, increasing with respect to the feasible potential. Applying these exclusion criteria, it is possible to install 12.988 turbines, of which 12.608 are V100, with a share of 97,1%, remained constant with respect to the previous two potentials. The V90 and V80 turbines are the best solution in 342 and 38 locations, respectively. The categorisation of all turbines locations according to the province of installation is provided in *Figure 36*.

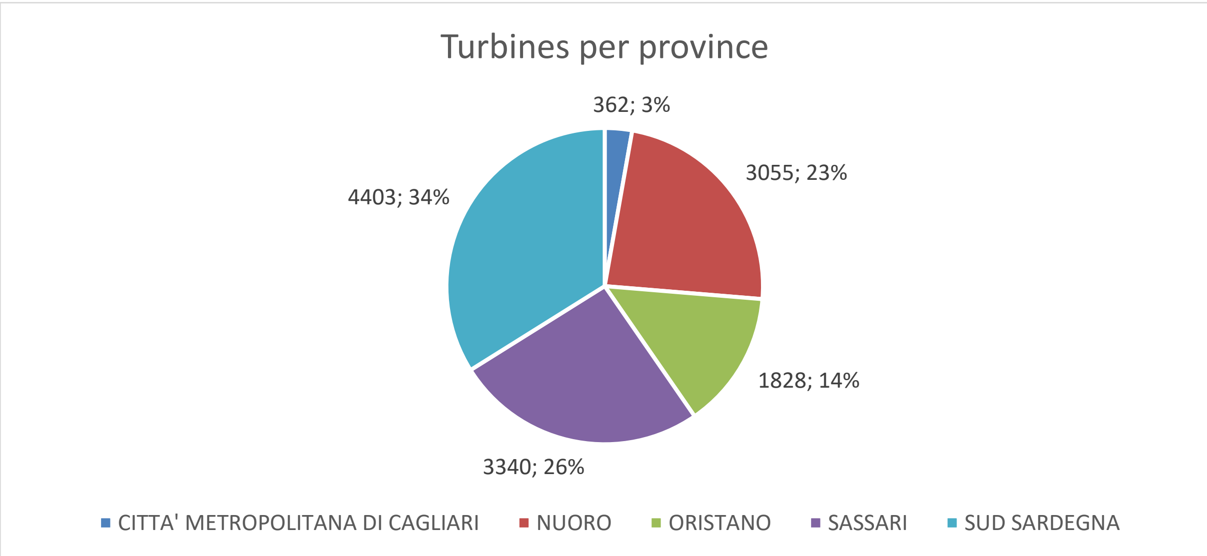


Figure 36 - Turbines breakdown per province

The above figure shows that Sassari is no more the leading province in wind generation, in fact it has a number of turbines similar to the province of Nuoro, and much lower with respect to the province of Sud Sardegna. The main reason is that the province of Sassari has a relevant portion of territory where a geomorphological risk is present. This is a constraint introduced by the regulatory potential, and it affects mostly the province of Sassari and, to a lesser extent, the province of Nuoro. For what concerns the other provinces, Cagliari has the least exploited territory, with a number of installations even lower than the one calculated in the feasible potential.

In the following figures (*Figure 37*, *Figure 38*) are displayed the division of the power capacity and energy production for each province.

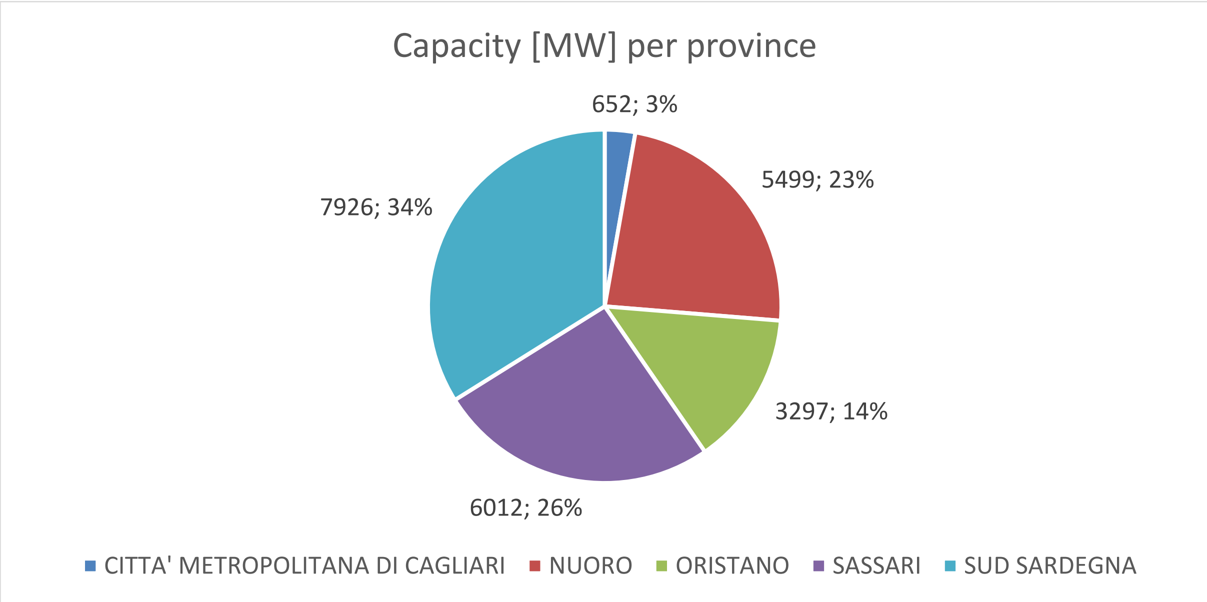


Figure 37 - Capacity breakdown per province

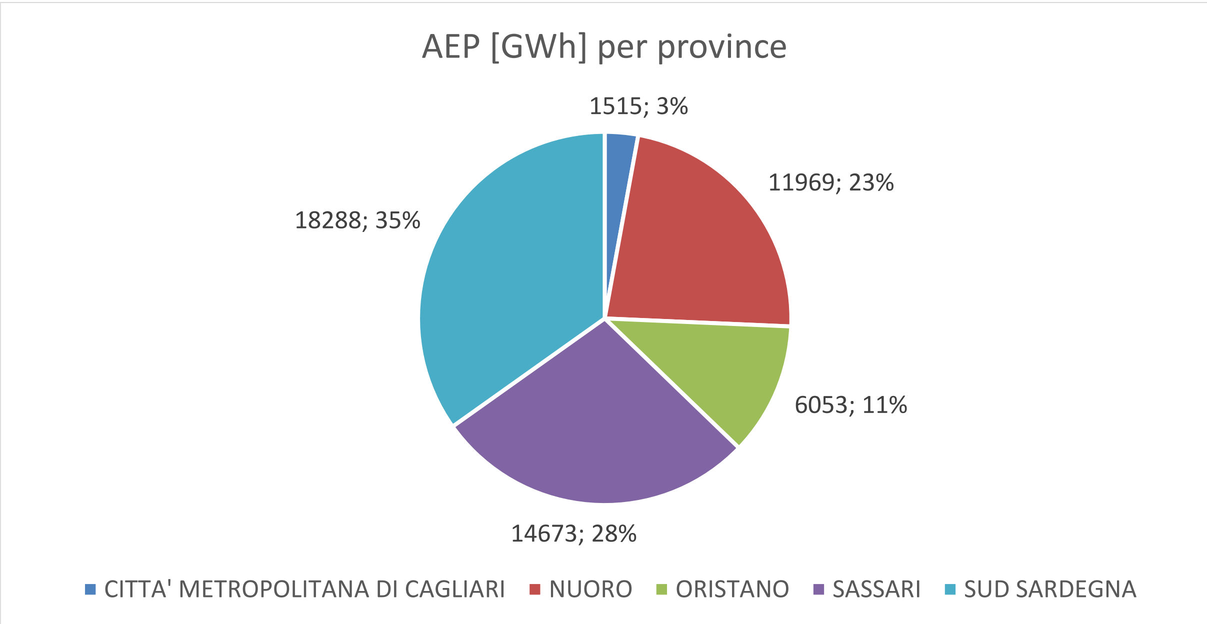


Figure 38 - AEP breakdown per province

Even for this potential the province of Sassari performs quite well, having an AEP share greater than the capacity share. This is true also for the province of Sud Sardegna, while on the contrary Oristano remains the worst province for wind exploitation. Sud Sardegna has become the most productive province because the constraints considered in this potential exclude a lower percentage of territory with respect to the other provinces. Indeed, it has the largest suitable areas among all provinces, and the gap with the second of the list (Sassari) has increased with respect to the feasible potential. Moreover, Sassari has another disadvantage with the regulatory potential: the north and north-west parts of the province, so the windiest portions of territory, are excluded by calculation because of geomorphological risks, important bird areas, and Nature 2000 areas. This exclusion affects greatly the turbine productivity, considering the direction of the predominant winds (discussed for the previous potential).

All the data evaluated above are summarised in *Table 14*.

	Turbine	**Capacity [MW]**	**AEP [GWh]**	**CF**	**V80**	**V90**	**V100**	**Suitable area [km^2]**	**Percentage**
Cagliari	362	652	1.515	26,54%	0	13	349	128	10,27%
Nuoro	3.055	5.499	11.969	24,85%	0	99	2.956	1.017	18,05%
Oristano	1.828	3.297	6.053	20,96%	34	25	1.769	638	21,35%
Sassari	3.340	6.012	14.673	27,86%	0	127	3.213	1.247	16,22%
Sud Sardegna	4.403	7.926	18.288	26,34%	4	78	4.321	1.495	22,89%
Sardinia	12.988	23.386	52.499	25,63%	38	342	12.608	4.526	18,79%

Table 14 - Regional data for regulatory potential

Despite the situation described above, Sassari remains the province with the highest capacity factor, while Sud Sardegna and Cagliari are above the Regional average. Instead, Nuoro and Oristano lose 2% in the capacity factor with respect to the feasible potential, below the Regional mean. Oristano remains the province with the highest share of V80 installations (nearly 90%), while Nuoro has increased the annual production by 153% compared to the feasible potential. This is mainly due to the removal from the constraints of the buffer around forests, which are very present in the province of Nuoro. The turbines locations are reported in *Figure 39*.

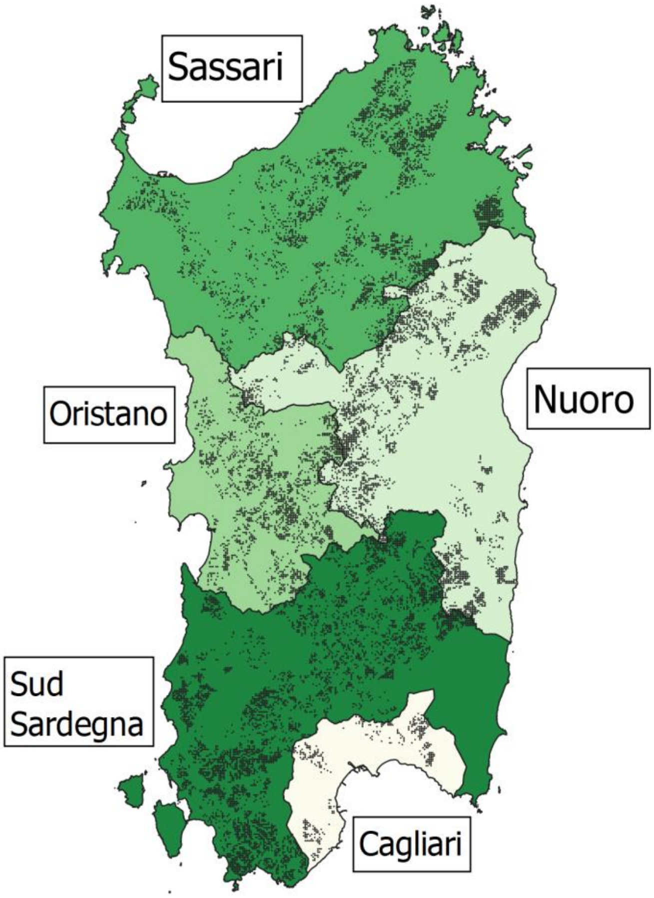


Figure 39 - Turbines locations for regulatory potential

4.1.5. Feasible – "regulatory" potential

All potentials discussed in *section 3.4* have been estimated and evaluated. In the following pages a new "potential" will be assessed, called feasible – regulatory potential. This is fictitious since does not add any information or constraints to the calculation, rather it is obtained intersecting the feasible and the regulatory potential. This operation is done using the "Intersection" tool in QGIS, which has as input layers the suitable areas obtained for the previous potentials. The "Intersection" command compares the two input layers and creates a new map which contains only the portions of polygons which are overlapped. The reason why a similar potential has been assessed is to define a situation as much strict as possible, in order to evaluate the worst case for wind turbines installation. Indeed, some available zones are exclusive for the feasible potential or the regulatory potential, hence removing these areas leads necessarily to the lowest potential among all the ones computed in this thesis. In other words, in this potential the strictest values for each constraint (listed in *Table 3* and *Table 4*) have been applied. This is confirmed by data, because only an area equal to 1023 km^2 is available for turbines installation, which corresponds to 4,3% of Region extension. This information is qualitatively provided in *Figure 40*.

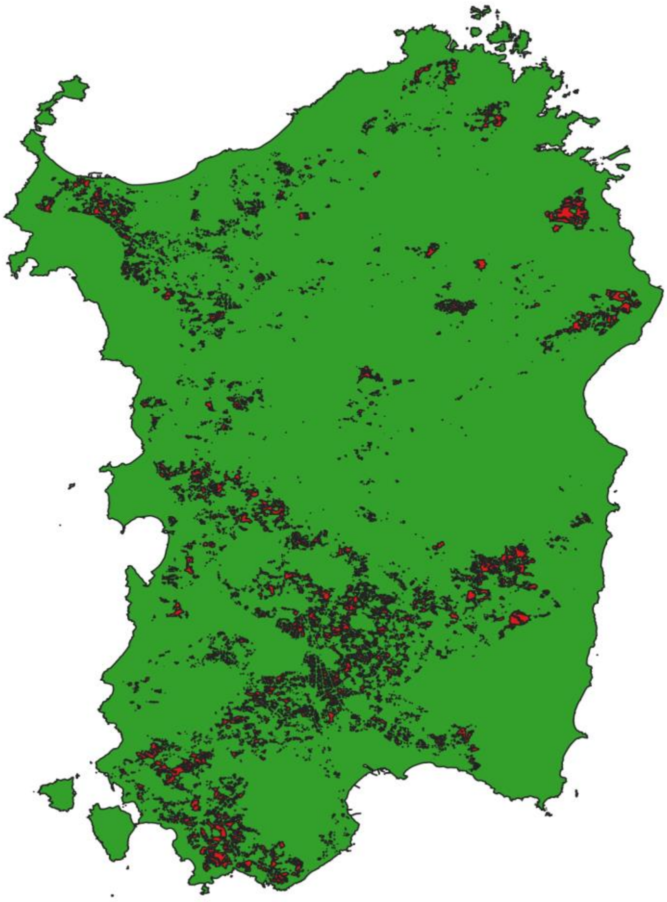


Figure 40 - Suitable areas map for feasible - regulatory potential. In green the Region, in red the available area

The available areas are very scarce, and mostly concentrated in the southern half of the island. The number of turbines installable is also much lower than the other potentials, with only 2.486 spots identified, of which 2.412 are represented by V100 turbine. V90 and V80 perform the best for 67 and 7 locations, respectively. The number of turbines is around the 25% of the suitable locations obtained with feasible potential, and around 20% of those obtained with regulatory potential. The share of the suitable areas for each province is reported in *Figure 41*.

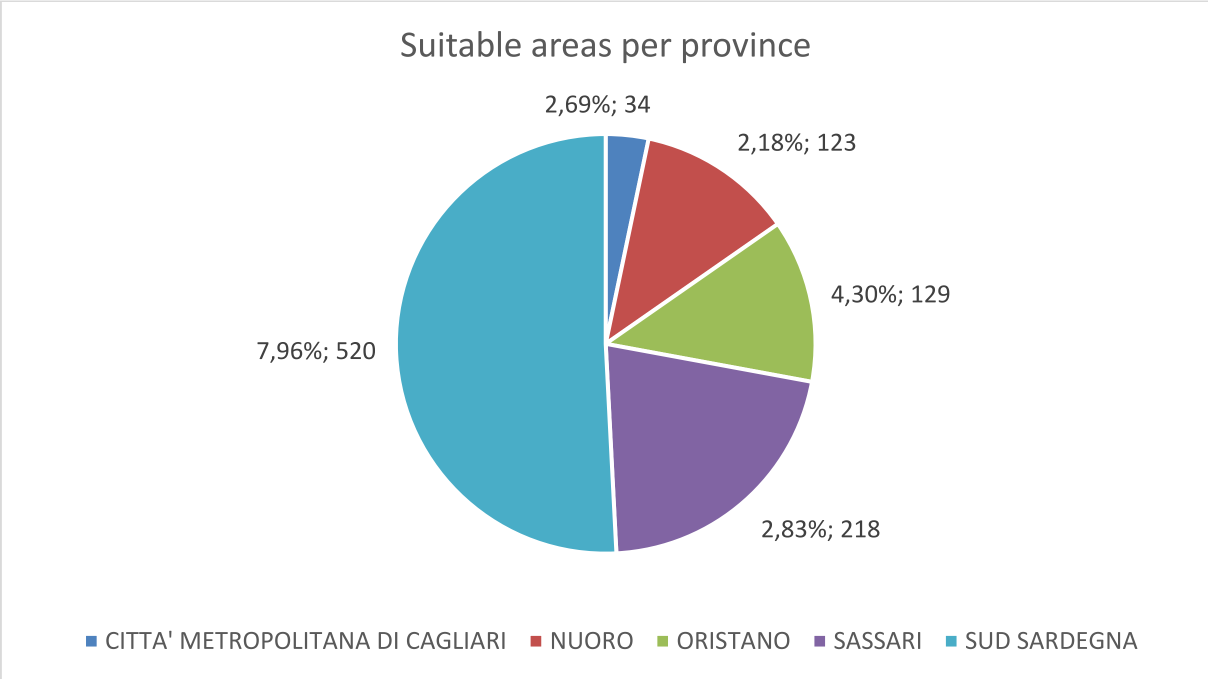


Figure 41 - Suitable area breakdown per province

The map of *Figure 40* already provided qualitatively the information presented in the previous figure, so that the suitable areas are mainly concentrated in the southern part of the Region (Sud Sardegna and Cagliari, which together account for more than half of the total available area). However, the percentages show that only a little fraction of each province surface is eligible for wind turbines installations. Indeed, the most exploitable province is Sud Sardegna, which has around 8% of its extension available for turbines construction. In the previous potentials, only Nuoro for the feasible potential had a percentage lower than 10%, while for this potential four out of five provinces have an available area smaller than 5% than their total extensions.

Considering these data, the productivity and power capacity are quite restrained too. For what concerns the annual production, the simulations provide a result equal to 10.549 GWh/year, which is the 25% of the AEP for the feasible potential. The power capacity is also much lower, with a result around 4 GW. However, having considered the strictest constraints possible, the operating time is the highest among all potentials with 2337 full load hours, which corresponds to a capacity factor of 26,67%. Despite an increment with respect to the feasible potential, the capacity factor is still quite far from the average results obtained by new wind plants [74].

Along with the relevant reduction of the power capacity, directly related to the suitable area extension, also the number of installable turbines undergoes a significant decrease. As already said, only 2.486 turbines are installable, and their division according to the province of operation is reported in *Figure 42*.

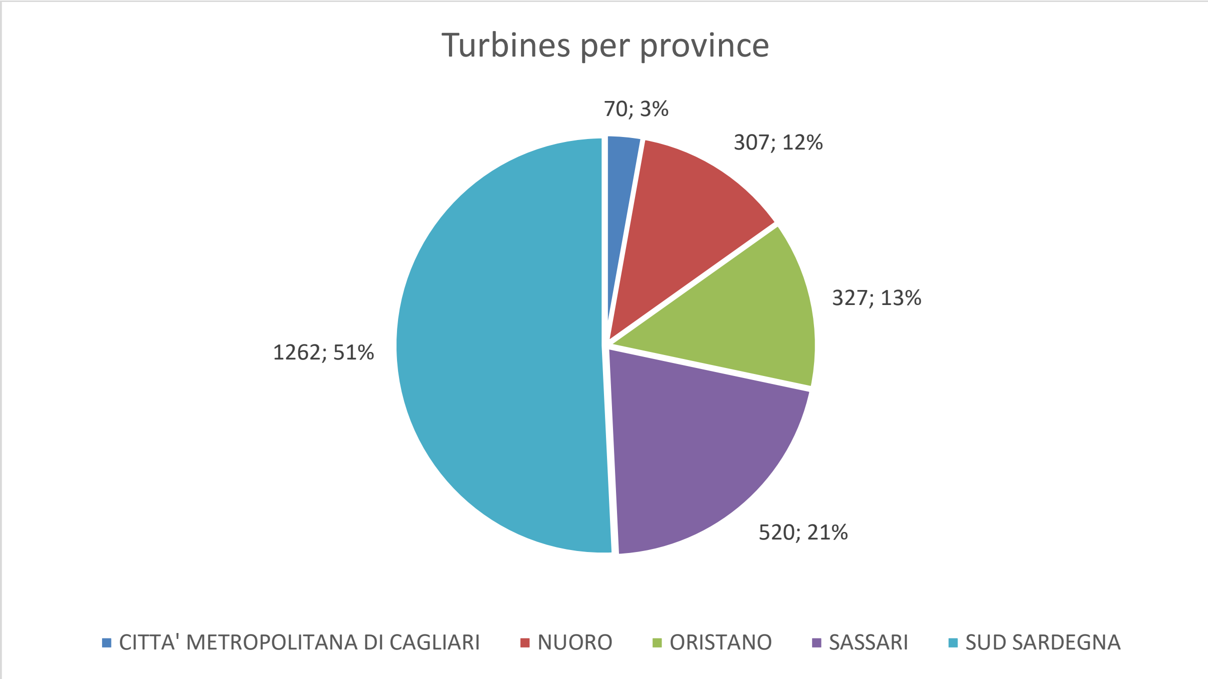


Figure 42 - Turbines locations breakdown per province

Consistently with the results about the suitable areas and power capacity, Sud Sardegna is the province with the highest share of turbines (more than half). Sud Sardegna and Sassari together account for almost three quarter of the total turbines number, but with absolute values well behind with respect to the results obtained by previous potentials. This figure also implies that the constraints considered in this thesis affect the province of Sud Sardegna less than the other provinces. Indeed, the share of installable turbines in this province grows while applying new constraints. More specifically, the turbines share passes from 23% with technical potential to 37% with feasible potential, remains nearly constant with regulatory potential, and arises to 51% when all exclusion criteria (with the higher buffer values) have been implemented. Of course, the absolute values changed a lot while varying the constraints, but the normalised values continue to increase.

This reasoning is also applicable when the productivity and capacity breakdowns are considered (*Figure 43*, *Figure 44*). The results show that more than half of the power installed, and electricity produced, are located in Sud Sardegna, which becomes for all intents and purposes the driving province in wind energy exploitation. The same trends observed in the previous potentials for Sassari and Oristano are valid also in this case. Indeed, Sassari shows a higher share of AEP with respect to the share of capacity, while exactly the opposite can be said for Oristano. The main reasons explained above can be considered in this potential too: the province of Oristano has a particular and variable morphological shape which affects the turbines operation; the province of Sassari is located in the best positions to exploit intense winds. Since these tendencies have been noticed for all potentials, the constraints do not have a significant impact on how the production is divided among the provinces.

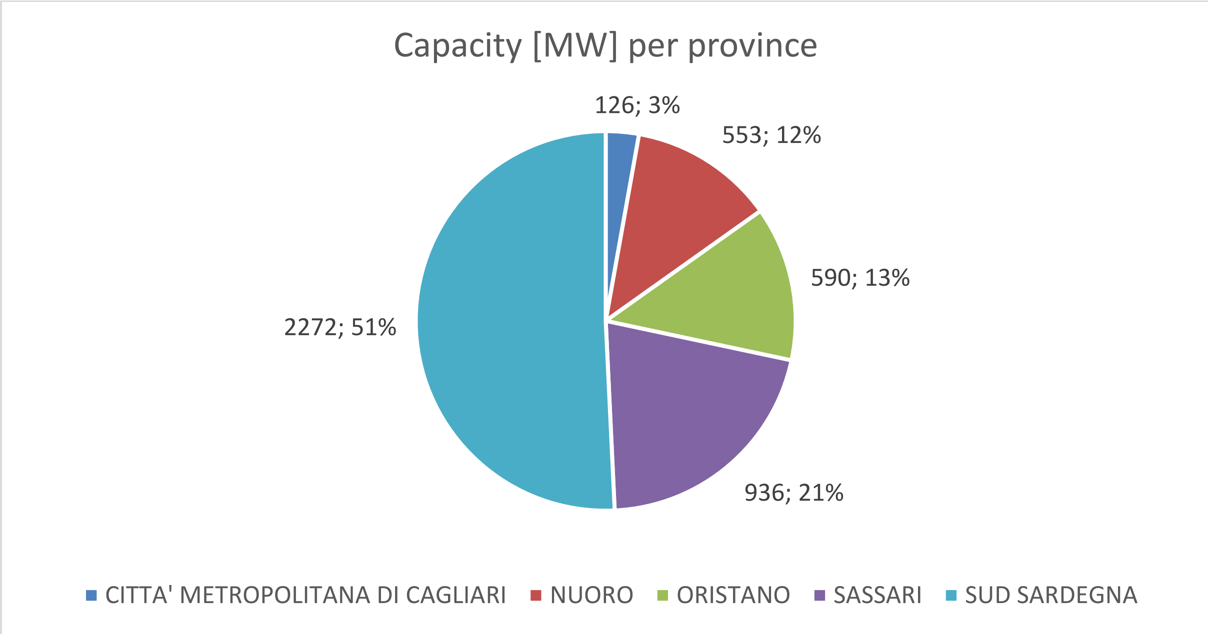


Figure 43 - Capacity breakdown per province

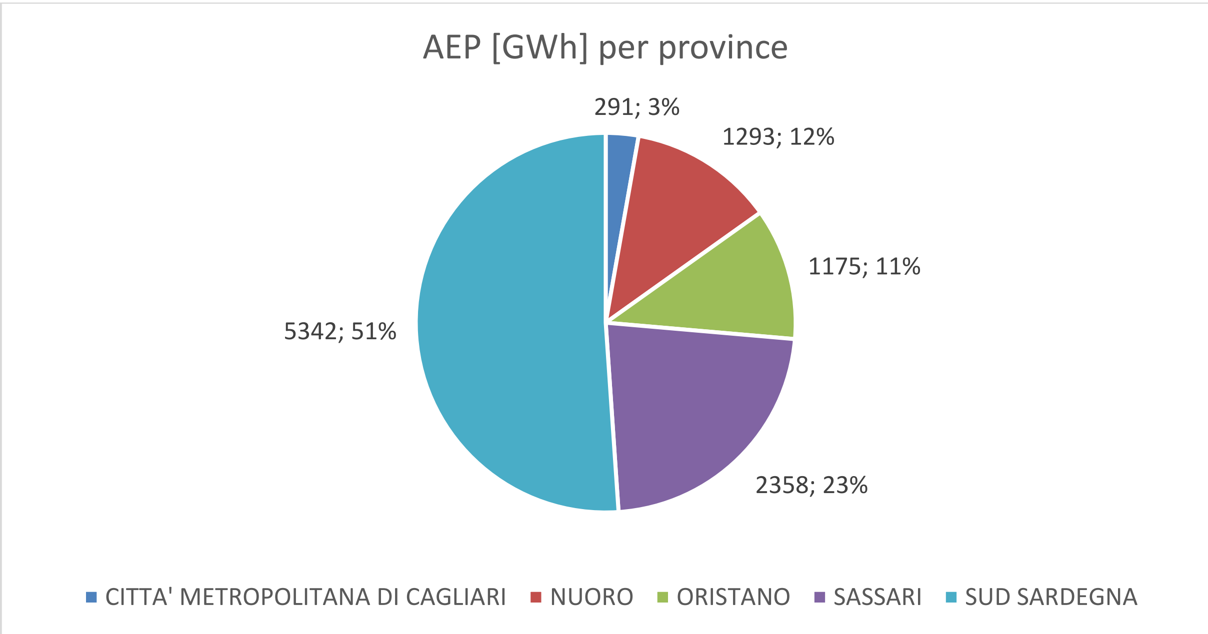


Figure 44 - AEP breakdown per province

All the data considered in this potential are reported in *Table 15*. As it is possible to observe, the province of Oristano has a capacity factor so low to significantly reduces the regional average, since it is well below it. Cagliari, Nuoro and Sud Sardegna have a capacity factor similar to the total mean, while Sassari remains the province with the highest full load hours. The V80 turbines are almost exclusively for Oristano, and if this province were not considered, the capacity factor of the Region would increase of around 0,5%, arriving to 27,27%.

	Turbine	Capacity [MW]	AEP [GWh]	CF	V80	V90	V100	Suitable area [km^2]	Percentage
Cagliari	70	126	291	26,35%	0	2	68	34	2,69%
Nuoro	307	553	1.293	26,71%	0	5	302	123	2,18%
Oristano	327	590	1.175	22,75%	6	5	316	129	4,30%
Sassari	520	936	2.358	28,75%	0	32	488	218	2,83%
Sud Sardegna	1.262	2.272	5.342	26,84%	1	23	1.238	520	7,96%
Sardinia	2.486	4.476	10.459	26,67%	7	67	2.412	1.023	4,25%

Table 15 - Regional data for feasible - regulatory potential

Eventually, *Figure 45* is provided with all turbines locations considered in the feasible – regulatory potential.

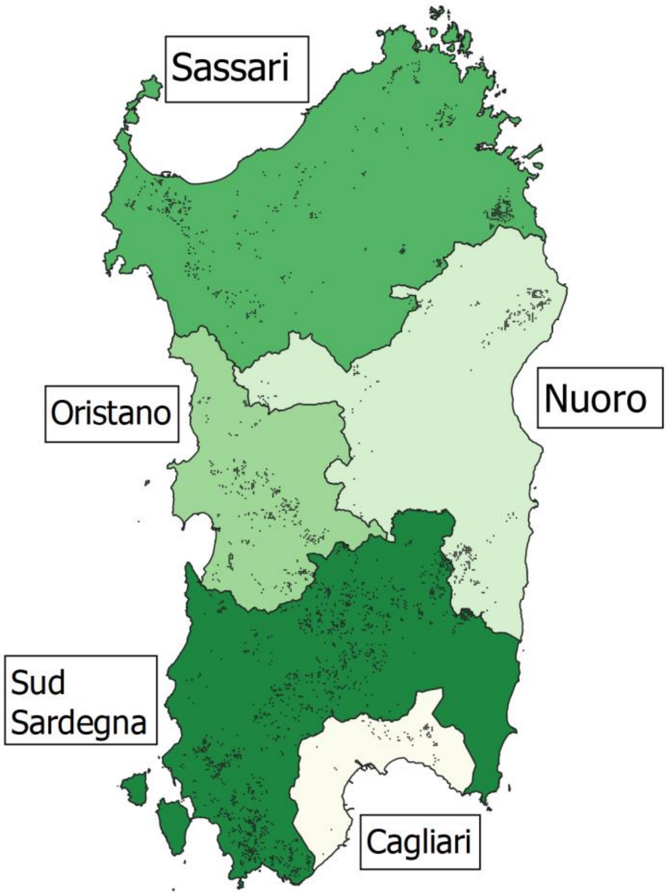


Figure 45 - Turbines locations for feasible - regulatory potential

Having discussed the results obtained for all potentials, the following figures are provided in order to summarise the main outcomes. *Figure 46* reports the results for the AEP, the power capacity and number of turbines for all potentials. *Figure 47* shows the operative conditions obtained for each potential, together with the associated LCOEs.

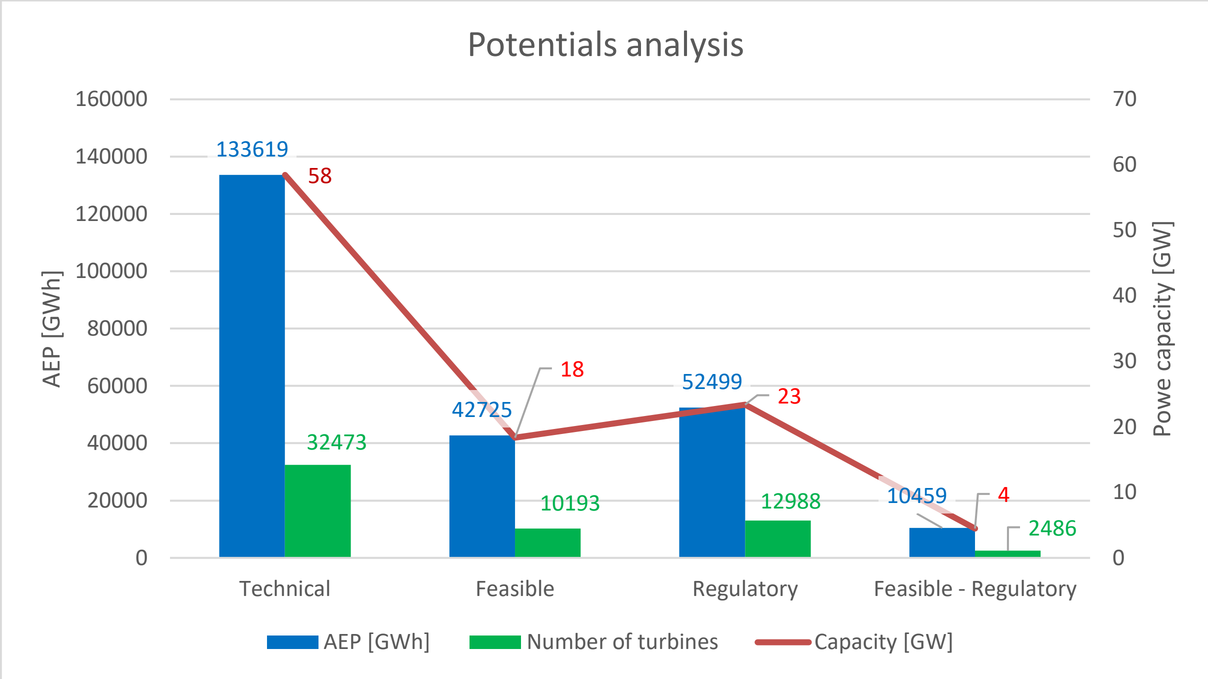


Figure 46 - Technical analysis of potentials

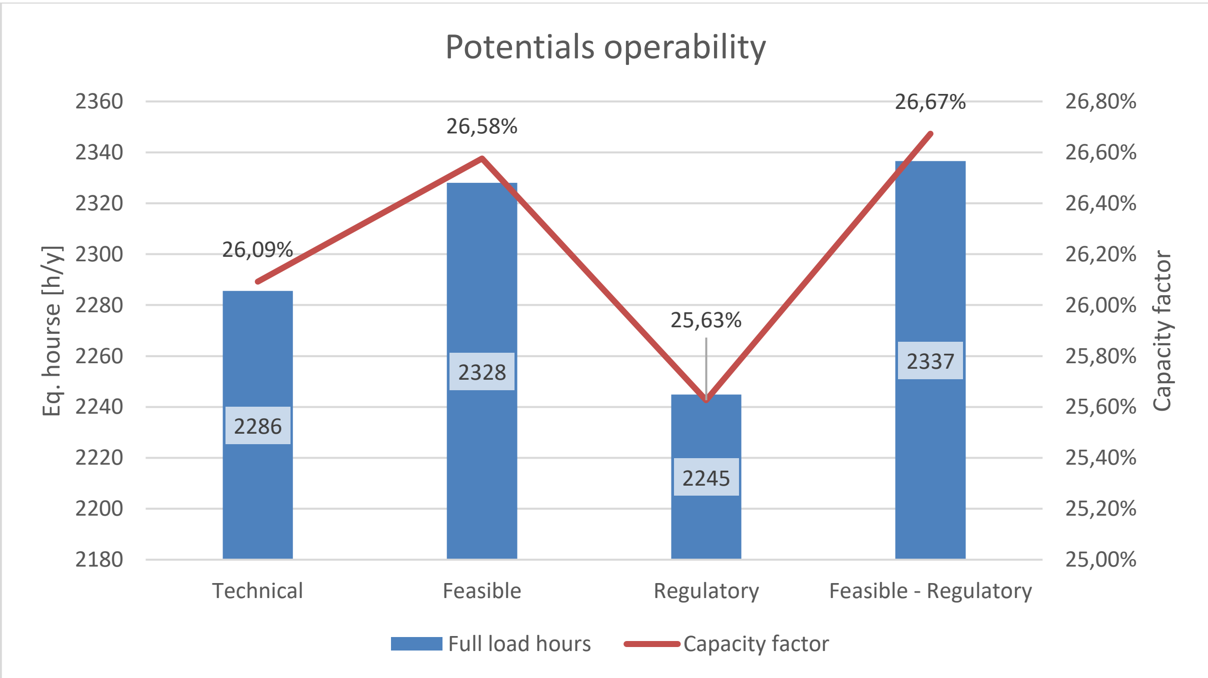


Figure 47 - Operative analysis of potentials

4.2. Investment costs and LCOEs

In this section of the thesis the costs related to wind turbines installation are evaluated. The investment costs of a wind turbine have been discussed in *section 3.5*, and they are directly correlated to the nominal power of the wind farm. Even the operating costs are proportional to the power installed and affect the levelized cost of electricity (LCOE) according to *Equation 2*.

The method to calculate the investment costs is very simple: the power capacity calculated for each potential is multiplied by the specific costs (reported in *Table 10*). The NREL data are not utilised in this computation since they are specifically referred to U.S. wind farms, while the other sources provide national or global average data. Having already set a plant lifetime equal to 25 years, the annual costs are calculated according to the numerator of *Equation 2*. These costs decrease each year since the investment depreciates with time. The annual energy is computed with the denominator of *Equation 2*, and also in this case it decreases with time because of the wear of the turbine. After the computation of annual cost and energy for each year, the LCOE can be calculated utilising the data provided by IRENA, IEA, and Lazard. The results are converted in €[5] in order to compare them with actual operating plants in Italy.

The following table (*Table 16*) contains the data about investment costs (in billions of euros) and O&M costs (in millions of euros) for all potentials, according to the various sources considered.

	IRENA		**IEA**		**LAZARD**	
Potential	**Investment costs [G€]**	**O&M costs [M€/y]**	**Investment costs [G€]**	**O&M costs [M€/y]**	**Investment costs [G€]**	**O&M costs [M€/y]**
Technical	93	2.576	74	2.576	62	1.546
Feasible	29	809	23	809	19	485
Regulatory	37	1.031	29	1.031	25	618
Feasible - Regulatory	7	197	6	197	5	118

Table 16 - Costs for each potential

Except for the feasible – regulatory potential, all other potentials have prohibitive investment costs, even considering the data from Lazard. However, the installed capacity is very huge for the first three potentials, much higher than the actual RES power present in the Region. On the contrary, the results for the last potential can be considered economically feasible with some dedicated public funds. Moreover, with some proper electric connections

[5] Exchange rate 1 USD = 0.8814 €

to the mainland, the production surplus could be transferred to the entire peninsula, in order to exploit appropriately the wind resource.

Having computed the investment and O&M costs, it is possible to calculate the LCOEs for each potential and each source, in order to compare correctly the results reported in *Table 17* and *Figure 48*.

LCOE	IRENA [€/MWh]	IEA [€/MWh]	LAZARD [€/MWh]
Technical	63,71	54,56	41,19
Feasible	62,55	53,56	40,44
Regulatory	64,87	55,55	41,94
Feasible - Regulatory	62,32	53,37	40,29

Table 17 - LCOEs for the various potentials

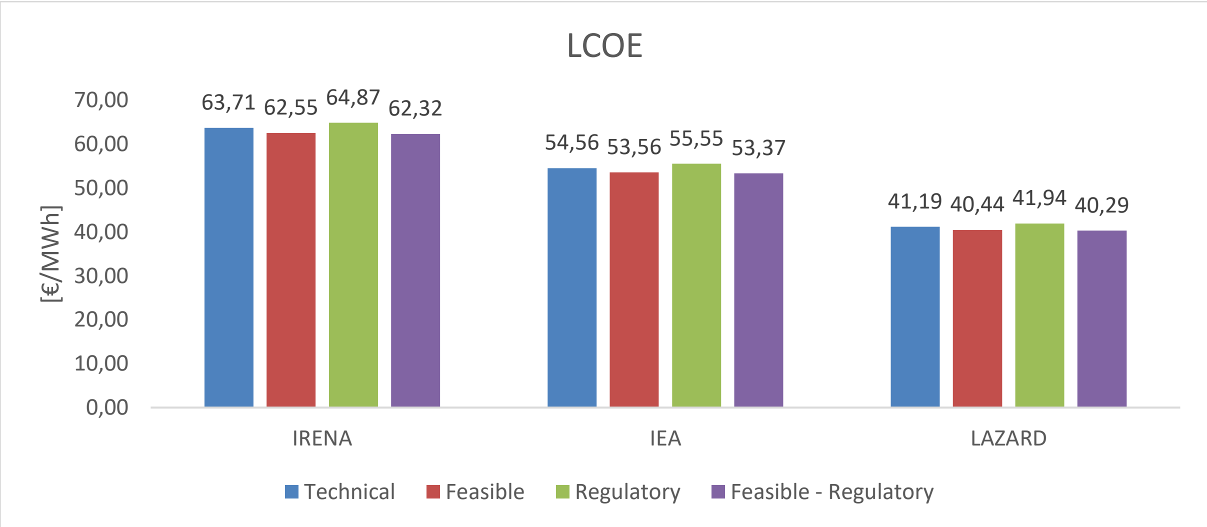


Figure 48 - LCOEs for the various potentials

Consistently with the investment and O&M costs, the LCOEs calculated with IRENA data are significantly higher than the other results, while with Lazard data the LCOEs are much lower and competitive with the weighted average LCOE of commissioned onshore wind farms in Italy [23] [67]. However, Lazard data are referred to average global wind plants, while IRENA and IEA provide statistics specifically for Italy (for 2020), hence they can be considered more "correct" while assessing the economy related to wind potentials. With this perspective, the results according to IEA can be taken as reference, even if they are much larger than the results from Lazard, and also slightly higher than the proposals in actual market.

Together with the various sources, also the different potentials show some interesting outcomes. First of all, the regulatory potential has the highest LCOE of all potentials. This is quite surprising since many constraints are considered in the calculation of this potential, but, apparently, they are not able to remove the worst areas for wind generation. Indeed, the lack of a threshold for the wind speed allows to build turbines where the average wind velocity is very low. Since the power capacity remains the same (and with it the investment and O&M costs), a lower capacity factor leads to a smaller annual production, and in turn to a higher LCOE.

However, this reasoning could be theoretically considered valid also for the technical potential, but in this case the final electricity cost is lower than the one discussed before. The difference for the capacity factors between these two potentials (*Figure 47*) implies that the constraints imposed by laws are stricter than the ones considered for the technical potential, but not better since the operability and economic feasibility of the regulatory potential are the lowest among all potentials.

A reason why the regulatory potential is the costliest could be the fact that some of the windiest spots are removed by the AEP computation applying the exclusion criteria. In order to provide an insight about this possibility, the turbines locations with an average wind speed higher than 6 m/s and lower than 3,5 m/s have been considered. In the entire island there are 5.517 cells with a wind velocity higher than 6 m/s (obtained from the WAsP output grids, *section 3.2.3*) and 3.408 with a wind speed lower than 3,5 m/s. For the technical potential, 4.853 turbines are located in the windiest cells (15% of the turbines installed), while 989 in the scarcest cells (3%). For the regulatory potential, 1.811 generators are placed in the best cells (14%), while 618 in the worst (4,8%). These percentages show that a higher share of turbines for technical potential is located in favourable spots than the share for regulatory potential, while exactly the opposite occurs when the worst situations are considered. Considering that between the two thresholds the turbine distribution for each speed is almost identical for both potentials, the differences highlighted above are the main causes for the higher LCOE (and lower capacity factor) of the regulatory potential compared to other potentials.

For the feasible and feasible – regulatory potential the argument is different. Both potentials establish a lower threshold for the wind speed, hence the LCOEs are lower with respect to the others. These two potentials have very similar LCOEs, but the least expensive is the feasible – regulatory potential for some cents. The reasoning in this case is completely the opposite than the one made before, so that the stricter potential has the best operating features. This result was predictable considering the capacity factors.

5. Discussion

5.1. Wind potentials in contemporary market

The annual energy production of the wind potentials in Sardinia have been computed and reported in the previous section. The main results are that the AEP lays in a range between 130 TWh and 10 TWh, with a capacity installed that varies between 58 and 4 GW. Comparing these data with the electricity statistics of Italy and Sardinia it is easy to understand that all potentials are not technically and economically practicable, except for the feasible – regulatory potential.

Starting from the geographical/technical potential, an AEP equal to ~134.000 GWh corresponds to 47,1% of the total electric consumption of Italy (~284.000 GWh/year [27]), while an installed capacity of 58,46 GW is equal to 49,1% of the gross efficient power capacity of Italy (~119 GW [20]). Furthermore, the goal for 2030 outlined by PNIEC is to have an onshore wind capacity of 18,4 GW in the entire country, while the target defined by PTE is to achieve a RES penetration in electricity production equal to 72% by 2030. With this potential, the power capacity installed is four times the target of PNIEC, while the AEP is higher than the gross renewable production of Italy (~117.000 GWh/year [76]) of all sources. Summing the actual and the estimated production, an electric renewable generation equal to 74% of the estimated electric consumption in 2030 (339,5 TWh/year [24]) is obtained. Considering the economic feasibility, an investment cost of 73,6 billion of euros (IEA data) is equal to 124% of the funds destinated to ecologic transition (59,3 billion of euros [32]) by PNRR. Focusing on Sardinia only, the AEP calculated for the technical potential is almost 17 times the electric consumption of the entire Region (~8.000 GWh/year [27]), while the capacity is around 12 times the gross efficient power actually installed (~5.000 MW) (22 times if only RES capacity is considered, 2.642 MW [20]).

Considering all these data and percentages, it is possible to state that a potential with similar characteristics (number of turbines, annual production, economic investment) is not suitable for a single region in Italy, least of all in Sardinia which has a limited internal electric consumption and a limited possibility for transferring this energy to the transmission network on the mainland. The results provided by this potential demonstrate that the constraints considered in *Table 7* are too little strict while assessing a wind potential. A possible solution could be to implement a further procedure to rank the available areas according to their suitability, as described in *section 2.4*, so that only the best locations are considered in the wind potential computation.

Furthermore, the share of turbine V100 (class III) installed in the technical potential is explanatory of how limited the wind resource in Sardinia is. Indeed, this turbine class performs the best when the average wind speed is below 7,5 m/s (*Table 1*), and in Sardinia 121.199 cells out of 122.896 (98,6% of the total area) present an average wind velocity lower than this value. Consistently with the previous data, the share of V100 is around 96,8% of the total number of installations, very similar to the percentage of cells below 7,5 m/s.

The constraints which reduce the most the suitable area of the geographical (and in turn technical) potential are the buffer around the high voltage network and the buffer around the rivers. More specifically, the buffer around transmission network identifies as suitable an area around 19.000 km^2, while the buffer around rivers determines an available area of around 18.000 km^2, hence it is the strictest criterion of the geographical potential. The other criteria have a lower impact on the technical potential, for several reasons. For instance, the buffer around the roads contains almost the entire extension of the Region, while the exclusion zones around urban areas are quite restrained since few municipalities are present in Sardinia.

In the *Results* section it has been highlighted that Oristano has the lowest capacity factor among all provinces. The main reasons have been already discussed (i.e., morphological shape, low exclusion area where wind is weak) but their impact on the productivity is very significant, mostly due to the installations of V80 turbines. Even if their number is not comparable to the other two turbines, it affects the capacity factor since class I turbine has the “worst” technical features (i.e., the power curve) for a study area like Sardinia. Nevertheless, they produce the maximum amount of electricity in 46 locations (0,14% of the total installations). Substituting the V80 turbines with the second most productive turbine in the province of Oristano, the capacity factor slightly increases. However, this difference is not very consistent (because the scarce installations of V80), so the causes of the low production in Oristano are attributable to peculiar environmental conditions of the province and to low percentage of exclusion area, which allows to install wind turbines in spots with AEP below the regional average (4,11 GWh/year).

A further development of the technical potential is the feasible potential. Starting from the suitable areas of the previous potential, other constraints are applied in order to reduce the number of turbines installable (*Table 8*). The main results are a power capacity equal to 18,35 GW (15,4% of the gross capacity of Italy, 3,7 times the gross power of Sardinia); an AEP equal to ~43.000 GWh (15,1% of Italian consumption, 36,5% of Italian RES production, 5,4 times the Sardinian consumption); an investment cost equal to 23,1 billion of euros (IEA statistics) (39% of PNRR funds). With respect to the technical potential, these data are much more practicable, even if still not achievable in a single Region. The power capacity matches perfectly with the target imposed by PNIEC for onshore wind development, while the AEP, combined with the actual RES production, would be equal to 47% of the estimated electric consumption in 2030, below the targets established by PNIEC and PTE.

In this potential, the strictest criterion is by far the buffer around forests. A qualitative analysis of this statement is provided in *Figure 49*, which shows the extension of this constraint with respect to the total surface of the Region. The quantitative analysis demonstrates that the suitable area decreases from 9.448 km^2 of the geographical potential to 3.360 km^2 only applying this constraint (the final available area for the feasible potential is 3.160 km^2). More than half of the island extension (24.090 km^2) is excluded by this constraint (15.654 km^2).

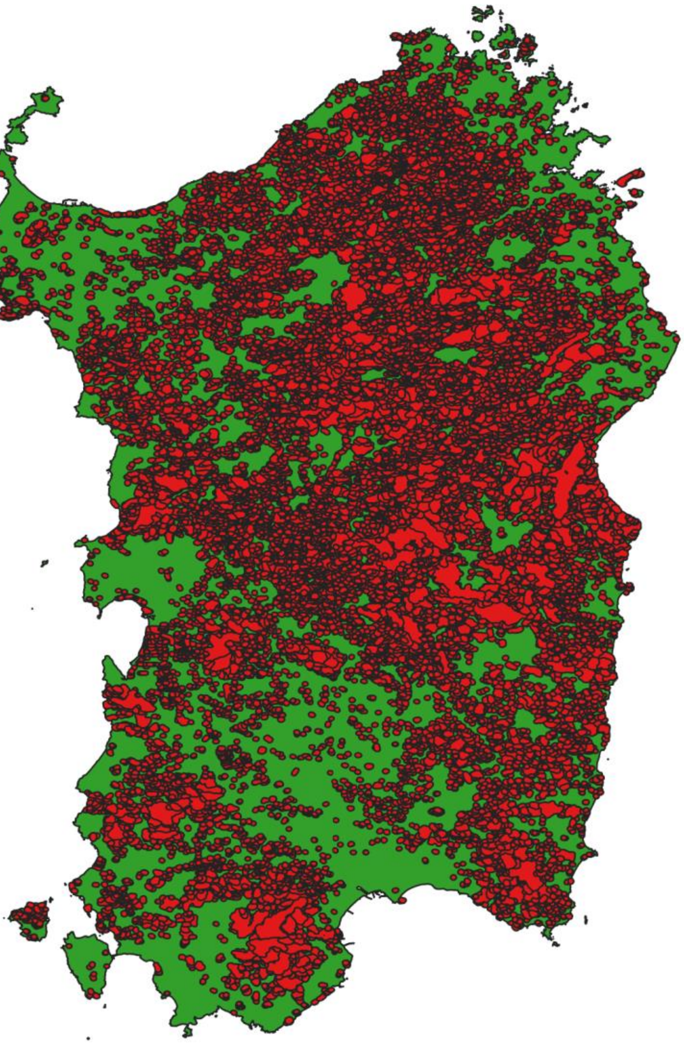


Figure 49 - Forests buffer for feasible potential

This result is not very surprising since Sardinia is very covered by woods, mainly broadleaved forests (both evergreen and not). The discussion made for the technical potential is valid also for the feasible potential, since Oristano is still the worst operative province while Sassari has the best productive features. Overall, the feasible potential has a capacity factor higher than the previous potential, hence some of the constraints introduced in this calculation are able to remove portions of the Region where the wind resource is not strong. The V100 turbines are again the most used generator in the island, with a share of about 97%, while the majority of class I turbines are located in the province of Oristano. The province with the highest increment of capacity factor with respect to the technical potential is Nuoro (1,27%), followed by the Oristano. On the contrary, Sassari has the lowest difference in the capacity factor between the two potentials, therefore exclusion criteria defined by the technical potential were quite good to identify the best locations. Furthermore, for both potentials no V80 has been installed in Sassari, despite it is the province where the predominant winds blow more frequently. This means that the average wind speed is not as high as in Oristano, where 1,7% of the installations consists of V80 turbines.

A conceptually different wind potential is the regulatory potential. This is not defined by literature but is calculated applying the exclusion criteria imposed by national and regional laws. This potential can be compared with the other two computed before in order to understand if the actual legislation needs to be improved or not. The annual productivity of this potential is equal to ~52.000 GWh (18,5% of Italian gross consumption, 6,6 times the Sardinian consumption, 45% of Italian RES production) with an installed capacity of 23,4 GW (19,6% of Italian gross power, 4,8 times Sardinian power). The investment cost is around 29,5 billion of euros (IEA), which is about the 50% of PNRR funds. The installed capacity is higher than the target established by PNIEC, while the sum between the estimated AEP and the actual RES production is equal to 50% of the foreseen Italian electric consumption in 2030.

As it is easily observable, these data are larger than the ones obtained by the feasible potential. However, the capacity factor of the regulatory potential is considerably lower with respect to the previous potential, with a decrement or around 1%, equal to 83 full load hours. The reasons why this decrease occurs are several, but mainly because of the absence of the lower threshold for the average wind speed. Indeed, considering the same criteria with the addition of the constraint that excludes the areas where the mean wind speed is below 3,5 m/s, the capacity factor increases from 25,6% to 26,2%. This last value is slightly higher than the capacity factor obtained for the technical potential, with the significant difference that a lower limit for the average wind speed was not defined in that case either. Hence, the causes of the small capacity factor for the regulatory potential cannot be attributed only to the lack of a constraint regarding the wind speed.

Considering the number of criteria applied in the calculation of the regulatory potential, and the fact that some of them overlap, it is quite impossible to identify which constraints are responsible for the poor turbines performance in this potential. Furthermore, some of the constraints which are applied, as for instance the exclusion of areas with hydraulic and morphological risks (for sake of safety) or the removal of the burnt areas (to reduce profit-making arsons), must be considered while computing the regulatory potential. In both situations the prohibition to build is valid for all types of constructions, not only for turbines installation. These kinds of limits are not considered in the literature, so they are not implemented in the geographical and feasible potentials, but their application in a regulatory potential must be taken into account.

More specifically, the capacity factor decreases (with respect to the feasible potential) in all provinces except for Cagliari, where it increases of 1,2%. Instead, the largest decrements occur in Oristano (-2%) and Nuoro (-2,2%), while the differences in Sud Sardegna and Sassari are nearly equal to zero. Comparing the capacity factors with the ones obtained for the technical potential, the increment for Cagliari is 1,7%, while the reductions for Nuoro and Oristano are 0,9% and 1% respectively. Sassari remains nearly constant, while in Sud Sardegna it also increases of about 0,6%.

In this potential several constraints have been implemented, and each of them correspond to specific exclusion areas, which in some zones are overlapping. In order to investigate which are the strictest, *Table 18* is provided.

Constraint	Area [km2]	Constraint	Area [km2]
Altitude above 900m	1044	Buffer around lakes	332
Archaeological sites	6	Mining zones	1848
Reclamation zones	194	Natural monuments	5
Marine protected zones	675	Important naturalistic areas	8
Restricted zones	4066	Parks	6253
Important botanical zones	180	Geomorphological risks	4140
Buffer around seashore	448	Hydraulic risks	313
Important faunistic zones	204	Saltworks	16
Buffer around rivers	3258	Site of Community Importance	5262
Landslide risks	2824	Special Areas of Conservation	3580
Flood risks	428	Volcanos	212
IBA	6007	Wetlands	130
Burnt areas	2029	Forests	10772
Airports	1234	Buffer around roads/railways	2545
Urban areas	1954	Transmission network	1106
Buffer around buildings	9306		

Table 18 - Exclusion areas for regulatory constraints

Consistently with the results obtained for the feasible potential, the forests correspond to the strictest constraint (singularly), while considering all criteria related to protected environment (IBA, SCI, SAC, parks, marine areas) are by far the group which exclude the largest territory of the Region. Even the buffers around buildings and transport routes are quite large. The union of all these exclusion criteria lead to a suitable area of 4.526 km^2, therefore many constraints remove the same portions of territory.

As last potential calculated in this thesis there is the feasible – regulatory potential, that is the intersection of the suitable areas of the two previous potentials. In this case the available area is for sure the lowest possible, since all constraints are applied, with the largest values for buffer if both potentials consider the same criterion.

The results confirm that this potential is more achievable than the others. Indeed, the annual production is equal to ~10.500 GWh (3,7% of Italian gross consumption, 1,3 times the Sardinian consumption, 8,9% of Italian RES production) with an installed capacity of 4,5 GW (3,8% of Italian gross power, 91,6% of Sardinian power) and an investment cost equal to 5,6 billion of euros (9,4% of PNRR funds). These outcomes are much more restrained than the ones obtained for the other potentials. The AEP, summed with the actual RES generation in Italy, leads to an estimated production in 2030 equal to ~127.000 GWh/year, equal to 37,5% of foreseen electric consumption in the same year.

This potential shows the best solution possible for a large spread of wind turbines in Sardinia. Indeed, with a limited number of turbines (2.486), the annual generation overcomes the actual Regional electric consumption and matches the foreseen consumption in 2030 [59]. With a proper development of other renewable plants and storage systems, Sardinia has the possibility to become electrically independent in few years, in line with the target defined by PEARS [26].

Another point in favour for this potential is the capacity factor. Indeed, it is the highest among all potentials computed, arriving to 26,7%. Considering the substantial number of exclusion criteria applied in the calculation of this potential, it is impossible to determine which criterion is responsible of the capacity factor increment. However, some of the trends observed before are valid in this case too. In fact, Oristano remain the province with least full load hours of the Region, even lower than the ones computed in the feasible potential. Even Nuoro has a decrement in the capacity factor, while Cagliari is the territory with the largest increase (1%), followed by Sud Sardegna and Sassari. If Oristano is excluded by calculation, the regional capacity factor increases of 0,6%, up to 27,3%. This province is the worst in the island for wind generation, but however the third for turbines installation. So, despite the application of the main criteria coming from scientific literature and all constraints imposed by laws, the low-productivity sites in Oristano are not removed by the potential calculation, affecting in a significant manner the final results.

In order to quantify how the production differs in the Region, it has been analysed the average AEP for each province and for one turbine, first considering the entire territory (without any constraints, so the whole extension of the province is included in the calculation) and then only evaluating the results for the suitable areas obtained in the feasible – regulatory potential. The outcomes are presented in *Table 19*.

	Cagliari	Nuoro	Oristano	Sassari	Sud Sardegna
Province (no constraints) [GWh]	4,09	4,15	3,43	4,43	4,13
Suitable areas [GWh]	3,94	4,08	3,55	4,30	4,11

Table 19 - Average AEP in each province

The scarce performances in Oristano are verified by the low average AEP in the province, the only one below 4 GWh/year. These results have been obtained cutting out the shapefile with the data about AEP and wind speed (WAsP outputs) with the shapefiles containing the provinces territories, using the “Clip” command. The second row reports the results calculated with the same method but substituting the entire territories with only the suitable areas in each province. Oristano is the only territory that has an average AEP in the suitable areas higher than the one computed for the entire province. However, the difference with the rest of the Region remains significant.

Having discussed the main technical results about the wind potentials computed in this thesis, the LCOEs can be further analysed. The results are summarised in *Table 17*, where it is evident that the capacity factor and the LCOE are directly correlated, since with equal nominal power (and so investment and O&M costs) a turbine with higher generation (i.e., full load hours) has lower costs of production, because more electricity can be sold to the market. Hence, the feasible and the feasible – regulatory potentials have very similar LCOEs, relevantly lower than the ones calculated for the other potentials. In particular, the LCOE computed for the regulatory potential is higher than the LCOE calculated for the feasible – regulatory potential of about 3,9%, having a capacity factor lower of around 4,1%.

In order to compare the economic profitability of the potentials, the LCOEs are compared with the costs of actual plants which participate to the last auction announced by GSE[6] [77]. The best onshore wind project proposed a reduction with respect to the reference tariff equal to 2,06%. As explained in *section 3.5.*2, the reference tariff is equal to 66,5 €/MWh, hence the previous reduction leads to an offered tariff of 65,13 €/MWh. All LCOEs calculated in this thesis are below this cost, even for the regulatory potential and IRENA statistics, therefore the profitability of these potentials is guaranteed. Furthermore, the data about wind plants estimated by Lazard seem to be not applicable in Italy, considering the significant difference of costs with real operating plants.

Eventually, in order to provide a brief sensitivity analysis, other minimum distances between the turbines are considered in the computation of the feasible – regulatory potential. The locations of the generators, which correspond to the points in the grid, are distanced 700 m in vertical direction and 700 m in horizontal direction. With this hypothesis, the procedure is the same applied before, and the primary results are an AEP equal to 4.374 GWh, a capacity of 1,9 GW, a capacity factor around 26,7%, and a number of turbines installed equal to 1040. The higher gap among the turbines do not lead to a larger capacity factor, nor to a lower LCOE (53,39 €/MWh with IEA data). Therefore, the wake effect in this territory is not very strong, and lower spaces can be enforced in order to increase the number of installations and, in turn, the annual production.

[6] See Appendix C

5.2. Power transferred in transmission network

Until now, the results obtained in the various potentials have been presented and discussed without considering a crucial factor for RES development in Sardinia: the electric infrastructure. Indeed, the fact that Sardinia is an island complicates the renewable growth in the Region, since together with the plants also the electric connections to the mainland should be guaranteed. If the transmission network in the island is well developed (only 1100 km^2 are farther than 10 km from the high-voltage network), the same is not true for the connections to the peninsula, or better is not true if the wind development reaches the levels defined by the potentials.

Actually, two links are present between the island and the mainland, with the possibility to transfer a total power of 1300 MW, as described in *section 3.1*. Considering the results obtained for the feasible – regulatory potential, which is the easiest achievable, around 2.500 GWh/year of the produced electricity is in surplus with respect to the actual consumption, not taking into account the actual renewable production of the island. Moreover, Sardinia is a net exporter of electricity since the closure of aluminium industry, with 393 GWh/year delivered abroad and 2.900 GWh/year delivered to other Italian regions [27]. The surplus produced by the feasible – regulatory potential can be transferred to the peninsula without a relevant improvement of the connections, since the actual relocation of electricity is even higher. Furthermore, summing the actual renewable production and the estimated potential production, the total generation is around 14 TWh/year, while the forecast consumption in 2030 is 10,5 TWh/year, so a limited surplus is still present but manageable by the already constructed electric connection to the mainland.

A different discussion must be done considering the other potentials. More specifically, the regulatory potential is characterised by a large capacity and significant production. Indeed, an installed power around 23,4 GW can create a considerable stress on the electric network, in particular on the sea links. In this case, the surplus defined as the difference of estimated renewable production in 2030 and the electric consumption is around 45 TWh/year, too big to be transferred to the mainland with the actual links (without considering the thermoelectric generation). Hence, new proper connections should be designed in order to guarantee the stability of Sardinia network, and at the same time develop the renewable electric production in the entire country. To do so, the Italian TSO, Terna, has proposed two main projects for improve the electric connection of the island with the rest of Italy. The first one is the strengthening of the actual Sa.Co.I, which should pass from 300 MW to 400 MW, utilising the same cables already placed. The second has been proposed in 2018, it is called Tyrrhenian Link and provides for two distinct connections: a west tract, between Sardinia and Sicily; an east tract, between Sicily and the mainland (Campania) [78]. Both tracts ensure a power transfer of 1000 MW each, so that the renewable production in the islands can be delivered to the peninsula. The project should become operative at the end of 2025, and the map of the connections is presented in *Figure 50*.

Figure 50 - Scheme of the Tyrrhenian Link

However, also considering these additional connections, the electricity surplus obtained by the regulatory potential is still too huge to be transferred with undersea links. The same is true for the feasible potential, since the difference in AEP is quite restrained, while for sure the results obtained by the technical potential imply that a similar development cannot be achieve.

For what concerns the feasible – regulatory potential, another analysis has been conducted. Having considered the electric connections with the mainland, it is possible to evaluate also the power transferred in the transmission network inside the island. The network is composed of four different high-voltage levels: 70 kV, 150 kV, 220 kV, 380 kV. These lines are mapped in *Figure 19*, and their data have been obtained by Open Street Map. The lengths breakdown of each voltage level in the Region is shown in *Figure 51*.

The network at 150 kV is the most common, while only few portions of the transmission network are operated at 70 kV. In order to determine how much power is delivered to each voltage level, the centroids for every tract of the transmission network have been considered. To do so, the "Centroids" command in QGIS has been used on the shapefile containing the data about the electric network, from which the low and medium voltages lines have been removed. Then, the minimum distances between the turbines in the grid and the centroids have been calculated, utilising the "Distance to nearest hub (points)" tool, which determines which electric line (i.e., centroid) is the nearest to every turbine and measures the gap. The use of centroids instead of the electric lines is necessary to ensure a correct calculation of the distances, otherwise the software generates wrong results if the spaces between points (i.e., turbines spots) and lines (i.e., electric network) are computed. Eventually, the power of all turbines connected to the same centroid are summed together using a MATLAB code, in order to calculate which are the most stressed lines in the network. The results are shown in *Figure 52*.

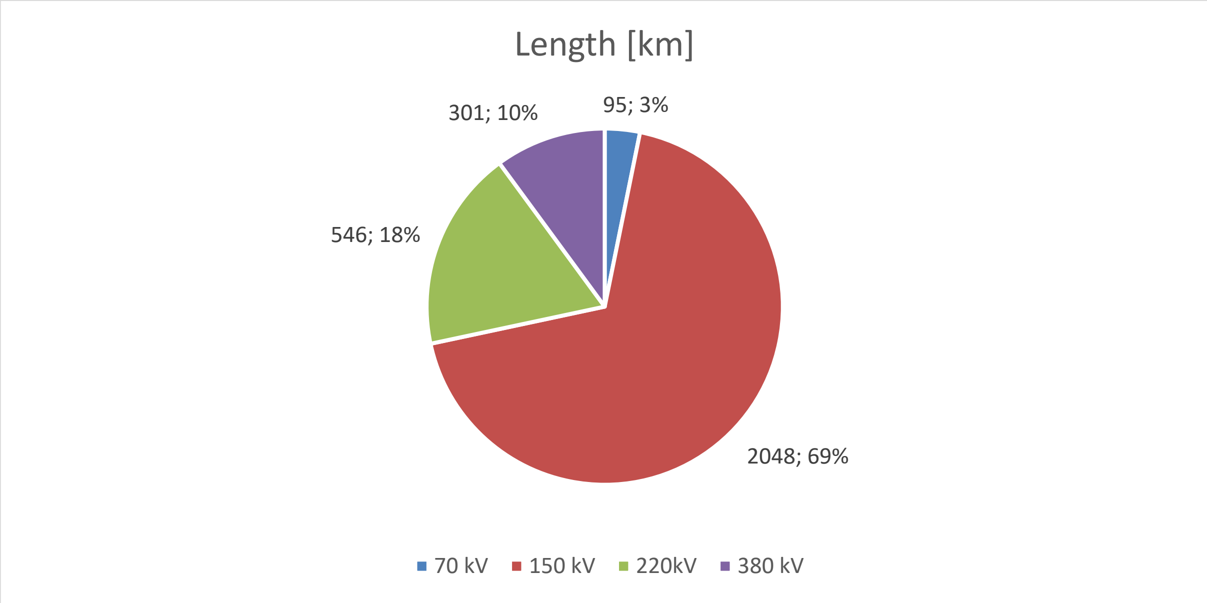


Figure 51 - Lengths of voltage levels

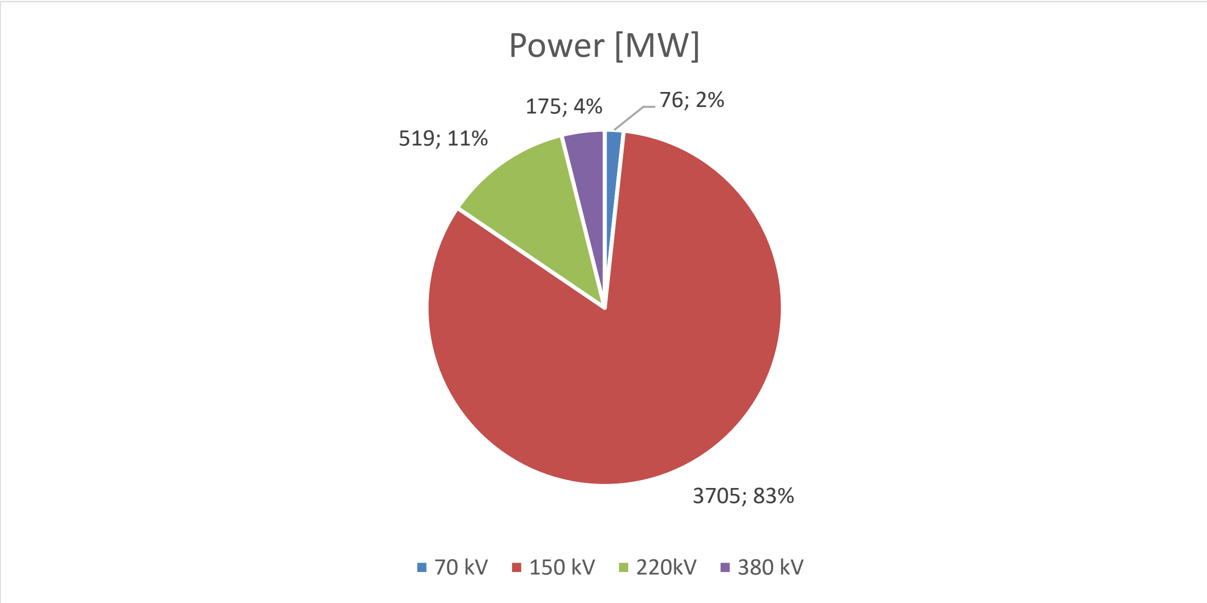


Figure 52 - Power delivered to each voltage level

The network at 150 kV constitutes the 69% of the total transmission network of Sardinia, but the 83% of the turbines power is delivered to this voltage level, equal to 3.705 MW. In particular, the maximum amount of power delivered to a single line at 150 kV is 326 MW, which is also the largest value among all voltage levels. The breakdown of the number of turbines according to the voltage at which they are connected is reported in *Figure 53*.

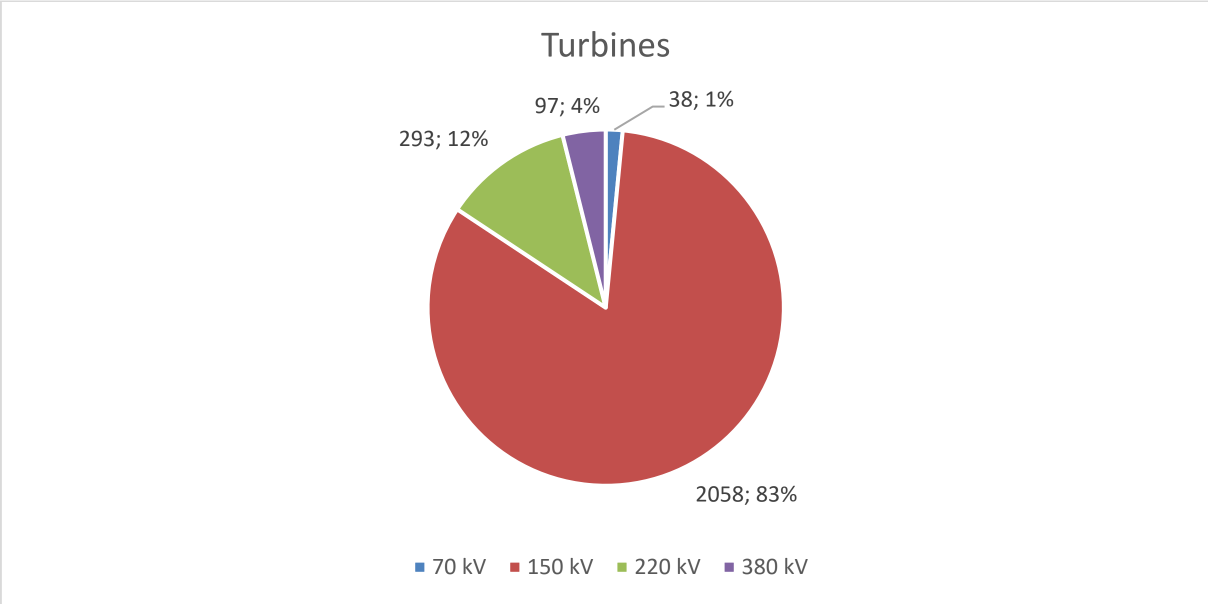


Figure 53 - Turbines connected to each voltage level

According to Terna, some criteria must be respected for connecting a production plant to the transmission network [79]. Indeed, a generation utility delivers the electricity to a different level of the high-voltage network depending on its power capacity[7]. The connection to the network at 150 kV is possible up to a power equal to 250 MW, while for larger capacity the connection must be done to higher voltage levels.

Considering the result presented before, the maximum power connected to a single line at 150 kV is larger than this threshold. This occurs for a cluster of 181 turbines in the south-west part of the Region (province of Sud Sardegna). The problem cannot be solved changing the voltage level to which these turbines are connected, since the nearest line at 220 kV is anyway farther than 10 km, which is the constraint buffer imposed around the transmission network. Hence, two solutions can be applied: 42 turbines are removed from the cluster, so that the capacity decreases below the threshold of 250 MW, with a reduction of the AEP around 150 GWh (if the least productive turbines are considered); a construction of a new line at 220 kV, with an approximated length of 20 km (calculated as the distance between the farthest turbine from the actual 220 kV network, reduced of the 10 km buffer established around the network itself). In the first case, the AEP and the power capacity of the feasible – regulatory potential become 10.305 GWh and 4,4 GW, respectively. The capacity factor remains nearly constant, and with it also the LCOE. Therefore, this resolution is much more reasonable than a construction of a new line only for serving a limited number of turbines.

Considering the storage development, in Italy 60.116 distributed storage systems are installed [80], with a total power equal to 315,3 MW and a total capacity of 529,3 MWh. Among these technologies, the lithium battery corresponds to 98,1% of the power installed,

[7] See Appendix D

and 97,4% of the capacity. However, only 20,3 MW of the installed power has a capacity higher than 100 kWh, which means that the large majority of the storage systems are used for low-power application, like for example coupled with domestic photovoltaic plants. The power installed for centralised hydro pumping is equal to 7.394 MW, while for electrochemical centralised storage is only 2 MW. Comparing the actual situation with the targets imposed by the PNIEC, it results that 600 MW of pumping power are necessary to fulfil the goal for 2023, while for 2030 the deficit is 3 GW. For what concerns the electrochemical centralised storage, 398 MW is the deficit with respect to the objective for 2023, and 3 GW lack for 2030. In Sardinia, the hydroelectric pumping power is equal to 240 MW, with an estimated storage time of eight equivalent hours. Moreover, to provide an ultra-fast regulation of the electric frequency in the network, Terna has developed a project called “Fast Reserve” [81] with which it has assigned, through an auction, the power of the electrochemical batteries requested for the service, equal to 30 MW for Sardinia.

6. Conclusions

The objective of this thesis is to compute and analyse the wind potential in Sardinia, in terms of how much electricity can be produced by wind generators, and the corresponding required power. To do so, some of the regional territory has been removed from the calculation for distinct reasons, which are safety, economic, environmental, and social. Within these four main categories, several exclusion constraints have been considered, each of them with a proper buffer and relevant references. The criteria applied in the exclusion procedure come from a literature review of scientific papers which carried out the same analysis, and from the laws which regulate the wind plant construction in Italy and in Sardinia. Together with the technical results of the simulations, also some economic parameters have been evaluated: the investment costs and the LCOEs. Diverse sources have been investigated to obtain the data about the turbine costs, in order to provide a complete overview of the actual market situation in Italy, and also a sort of sensitivity analysis since the statistics are quite dissimilar. Eventually, the economic results, especially the levelized cost of electricity, have been compared to some operating wind plants to determine is the potential calculated is economic profitable or not.

The exclusion constraints have been implemented in the calculation of the wind potentials utilising a geographic information system software, called QGIS. The maps corresponding to each criterion have been downloaded by a portal managed by the Region Sardinia, which collects the data and their extension for several items, as for instance the urban areas or the forests. Applying, if necessary, a buffer around each element of the map, the layers have been subtracted by the regional surface, until the suitable areas for wind turbines installation have been obtained. Then, a grid which simulates the positions of the generators in the available area has been created, and for each location the annual productivity and wind speed have been estimated using a software called WAsP, which is able to assess the turbine productivity in a certain area using meteorological and morphological (i.e., elevation and terrain roughness) data.

In order to provide a better understanding of how the wind potential can vary considering different constraints, four assessments have been done, with distinct initial hypotheses. First of all, three potentials show unattainable wind development in a single Italian region (considering the AEP, the power capacity, and the investment cost of the project), but the last one, which corresponds to the strictest potential possible, presents some interesting outcomes which can be achieved from both the economic and technical perspectives. This potential has been named feasible – regulatory because it is computed starting from the suitable area obtained intersecting the feasible and the regulatory potential. This operation allows to keep only the portions of the available areas which overlap, so that all exclusion criteria (with the strictest buffers) are applied.

The results of this potential can be considered achievable if proper funds are allocated to support the wind development in Sardinia. Moreover, a reform of the authorisation procedure is necessary to increase the interest of investors in wind farm construction. According to ANEV (Associazione Nazionale Energia del Vento, an association which includes several Italian companies related to wind technologies) president, Simone Togni, the average time for a wind plant approval is higher than 5 years [82]. Moreover, he also stated that the wind sector in Italy requires a stabilisation of the energy price rather than incentives, since the wind technology has reached a mature development [82].

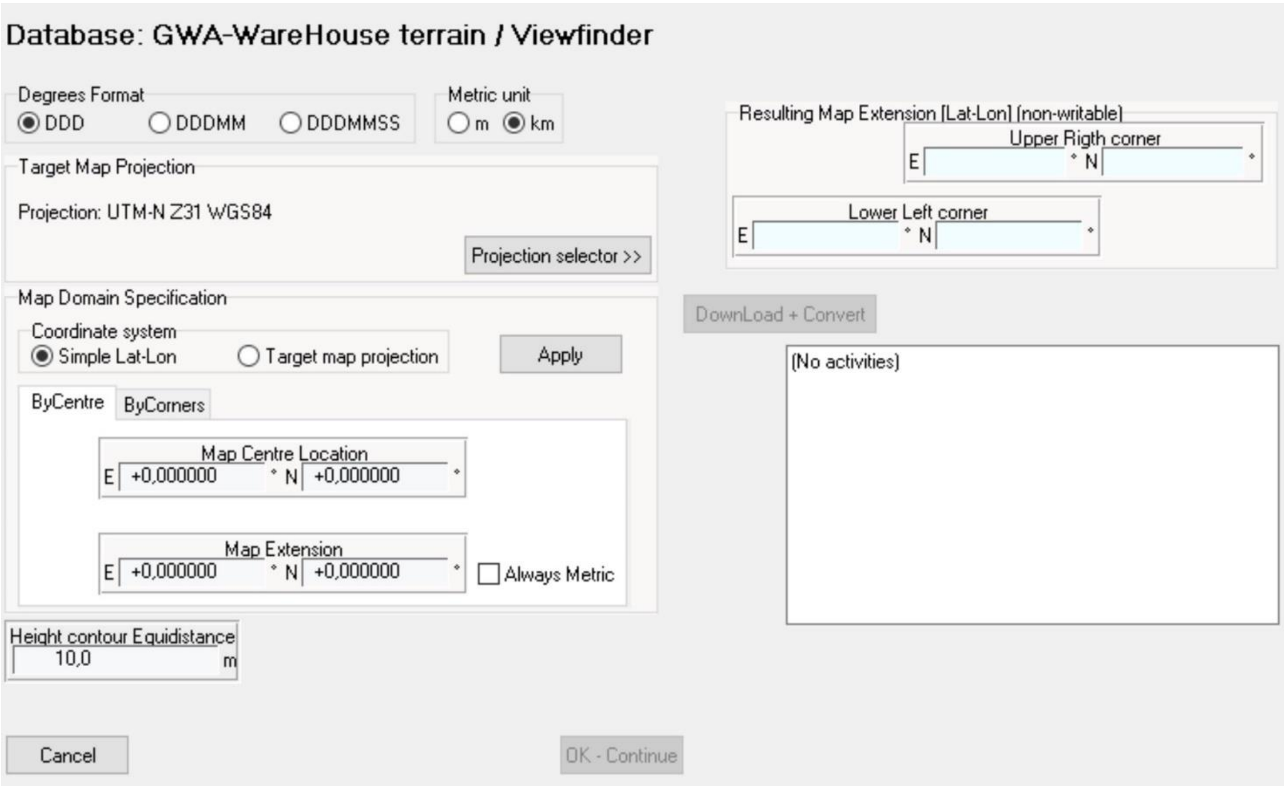
The feasible – regulatory potential is characterised by an installed power capacity of 4.476 MW, which is able to produce 10,5 TWh/year of electricity. The investment costs lay in a range between 7,1 and 4,7 billion of euros, and the LCOEs vary between 62,32 €/MWh and 40,29 €/MW, according to the various sources. With respect to the feasible – regulatory potential, the other potentials have similar LCOEs, but the power capacities are considerably higher, from 4,1 to 13,1 times the installed power. In turn, also the annual productions are much larger, from 4,1 to 12,8 times the AEP of the previous potential. Considering the absolute terms of these quantities, it is clear that the corresponding potentials cannot be taken into account while assessing the wind development in Sardinia, for two main reasons: the investment costs, too large even for the Recovery Fund approved by the European Union for helping the economic recovery; the electric infrastructure, which is unable to transfer a huge surplus of electricity to the mainland. Indeed, for three potentials the excess of renewable production of electricity in the island (considering the sum of the actual and the estimated generation) with respect to the actual electric consumption is higher than 38.000 GWh/year in the best case, and 129.000 GWh/year in the worst. With the possibility of transferring a power of 1300 MW to the peninsula (it should increase to 2400 MW before 2030), it is unthinkable to deliver this energy excess abroad or to other Italian regions. Furthermore, the forecast regional electric consumption in 2030 should increment to 10,5 TWh/year, hence the surpluses of electricity might vary from 35 TWh/year to 126 TWh/year, still larger than the energy transferrable outside the Region.

Considering these arguments, it is clear that the feasible – regulatory potential is the right compromise between the will of enlarging the RES share in the electricity production and the necessity to limit the costs and the space required. The surplus of generation can be delivered to the peninsula even without any new connections, and an excess is still present also considering the consumption in 2030. Moreover, the PNIEC provides for the coal phase-out within 2025, while for Sardinia the date is postponed to 2028 [83] in order to guarantee a satisfactory electricity supply until the activation of the Tyrrhenian Link. Two coal plants are present in the island, with a total capacity of 1190 MW [84] [85], which produce around 4.400 GWh in a year. To avoid the dismantlement, the coal plant of Fiume Santo (Sassari) could be converted in a plant which uses natural gas and biomass, but no applications have been done [86]. For what concerns the other coal plant (Portovesme, Sud Sardegna), it should be dismantled and converted to a production and storage site of renewable energy [86].

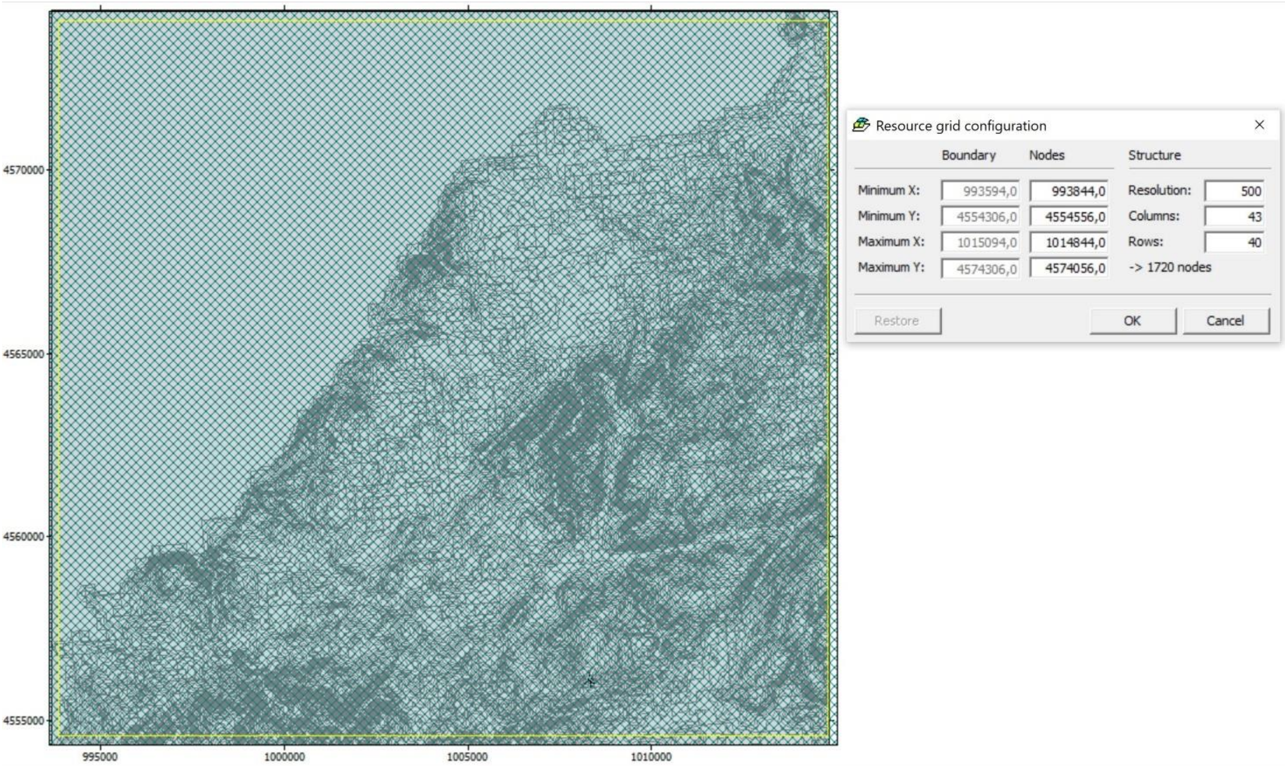
In conclusion, the feasible – regulatory potential results show that wind technology (under the hypotheses defined in the previous sections) can be considered a valid alternative of the fossil (especially coal) production. A significant development of the storage capacity in the island should support the renewable expansion, in order to limit the disadvantages related to the intermittence of the generation. Furthermore, the storage systems would increase the independence of the electricity supply of Sardinia, guaranteeing a completely green production within the target defined by the Region.

7. Appendix

A. Screenshots of WAsP software



This is the screen of the WAsP Map Editor, in particular the menu in which the elevation data are imported. As it is possible to see, several options must be set: the degrees format, which influences how the coordinates must be indicated in the map domain specification (both considering the centre or the corners); the target map projection, which updates automatically when the coordinates are set; the map extension (in metres or kilometres) in the vertical and horizontal directions, which establish how large the output map will be. When all information has been provided, the "Apply" button upload them in the software, the map is obtained by clicking "Download + Convert". After that, the file can be saved returning on the main screen of WAsP Map Editor. When two maps containing the elevation and the terrain roughness are saved, they can be joined to create a vector map. It is very important to set the same values in the map domain specification for both simulations, otherwise some data will be missed in the vector map.



In the above figure it is shown the screen for the spatial view of the resource grid in WAsP. Next to the map considered there is a table, in which one editable field is the resolution. The number of columns and rows are obtained when the grid is defined (in blue in the figure). It is possible to create manually the grid with the area of interest, or the columns and rows can be previously set and then the corresponding grid shifted where the simulations have to be performed. Depending on the structure fields the number of nodes (or cells) varies automatically. To the left in the table the coordinates of the grid are provided, which correspond to the coordinates indicated in the output ASCII grid.

B. Attachment of Ministerial Decree 04/07/2019

ALLEGATO *1*

Vita utile convenzionale, tariffe incentivanti e incentivi per i nuovi impianti

Fonte rinnovabile	**Tipologia**	**Potenza**	**VITA UTILE degli IMPIANTI**	**TARIFFA**
		kW	**anni**	**€/MWh**
Eolica	On-shore	1<P≤100	20	150
		100<P<1000	20	90
		P≥1000	20	70
Idraulica	ad acqua fluente (compresi gli impianti in acquedotto)	1<P≤400	20	155
		400<P<1000	25	110
		P≥1000	30	80
	a bacino o a serbatoio	1<P<1000	25	90
		P≥1000	30	80
Gas residuati dai processi di depurazione		1<P≤100	20	110
		100<P<1000	20	100
		P≥1000	20	80
Solare fotovoltaico		20<P≤100	20	105
		100<P<1000	20	90
		P≥1000	20	70

Tabella 1.1

I valori della tabella 1.1 sono ridotti, a decorrere dal 1° Gennaio 2021, del 2% per le tipologie di impianti di cui al gruppo B e del 5% per le tipologie di impianti di cui al gruppo A. Il GSE pubblica sul proprio sito internet la tabella aggiornata. Per le finalità del presente decreto, il GSE effettua una ricognizione annuale dei costi di produzione delle tipologie di impianti ammissibili agli incentivi, in particolare di potenza inferiore a 1 MW.

C. Results of the last auction for incentivised renewable production [70]

Numero Posizione	Codice di richiesta FER	Codice Aggregato	Codice Censimp	Ragione Sociale	P.Iva	Regione	Provincia	Comune	Fonte / Tecnologia	L'impianto/intervento ricadente nel perimetro di applicazione dell'articolo 56, comma 3 del D.L. 76/2020, ammissibile agli incentivi nel solo limite della potenza non assegnata agli impianti diversi da quelli di cui allo stesso comma 3, a sensi del comma 4 dello stesso articolo 56	Offerta di riduzione percentuale sulla tariffa di riferimento
1	FER202569		IM_0890553	ESNA S.R.L.	03394620920	SARDEGNA	SUD SARDEGNA	DOMUSNOVAS	Eolica onshore		2,06%
2	FER302356		IM_1235337	VEI GREENFIELD 1 S.R.L.	10638970961	PIEMONTE	VERCELLI	LIVORNO FERRARIS	Fotovoltaica		2,03%
3	FER302438		IM_1236517	BIOENERGY CASEI GEROLA SRL	06267660964	LOMBARDIA	PAVIA	CASEI GEROLA	Fotovoltaica		2,02%
4	FER302123		IM_1228344	BLUSOLAR SESTO CAMPANO 1	02276580681	MOLISE	ISERNIA	SESTO CAMPANO	Fotovoltaica		2,02%
5	FER302577		IM_1239268	NB5 S.R.L.	02940680347	EMILIA ROMAGNA	REGGIO NELL'EMILIA	MONTECCHIO EMILIA	Fotovoltaica		2,01%
6	FER302579		IM_1239483	NB5 S.R.L.	02940680347	EMILIA ROMAGNA	REGGIO NELL'EMILIA	MONTECCHIO EMILIA	Fotovoltaica		2,01%
7	FER302580		IM_1239490	NB5 S.R.L.	02940680347	EMILIA ROMAGNA	REGGIO NELL'EMILIA	MONTECCHIO EMILIA	Fotovoltaica		2,01%
8	FER202624		IM_1225911	WOOD EOLICO ITALIA S.R.L.	10778310960	SICILIA	TRAPANI	SALEMI	Eolica onshore		2,01%
9	FER202632		IM_1235677	VGE 01 SRL	02527920223	SICILIA	TRAPANI	MARSALA	Eolica onshore		2,01%
10	FER302260		IM_1230048	SEVEN SEAS S.R.L.	05712760825	FRIULI VENEZIA GIULIA	UDINE	PREMARIACCO	Fotovoltaica		2,01%
11	FER302293		IM_1234128	SEVEN SEAS S.R.L.	05712760825	FRIULI VENEZIA GIULIA	UDINE	PREMARIACCO	Fotovoltaica		2,01%
12	FER302481		IM_1236804	METKA EGN SARDINIA S.R.L.	15002941001	SARDEGNA	SASSARI	SASSARI	Fotovoltaica		2,01%
13	FER302395		IM_1233871	EEC SOLAR S.R.L.	02814020422	SARDEGNA	CAGLIARI	UTA	Fotovoltaica		2,01%
14	FER302530		IM_1238634	BLUSOLAR AUGUSTA 1 S.R.L.	02264190683	SICILIA	SIRACUSA	AUGUSTA	Fotovoltaica		2,01%
15	FER302498		IM_1233507	PARCO SOLARE FRIULANO 3 SRL	02993590302	FRIULI VENEZIA GIULIA	UDINE	MANZANO	Fotovoltaica		2,01%

16	FER302492		IM_1236314	PARCO SOLARE FRIULANO 3 SRL	02993590302	FRIULI VENEZIA GIULIA	UDINE	MANZANO	Fotovoltaica		2,01%
17	FER202578		IM_1201454	RWE RENEWABLES ITALIA S.R.L.	06400370968	SICILIA	TRAPANI	PARTANNA	Eolica onshore		2,00%
18	FER202644		IM_1224408	LUCKY WIND S.P.A.	02116900719	PUGLIA	FOGGIA	POGGIO IMPERIALE	Eolica onshore		2,00%
19	FER302259		IM_1226046	SIRIO1 S.R.L.	02986020309	FRIULI VENEZIA GIULIA	UDINE	SAN GIORGIO DI NOGARO	Fotovoltaica		2,00%
20	FER302125		IM_1197897	VRE.1	11702100964	EMILIA ROMAGNA	PARMA	SISSA TRECASALI	Fotovoltaica		2,00%
21	FER202583		IM_0845660	SOLARWIND 2 S.R.L.	02341870398	SICILIA	CALTANISSETTA	MAZZARINO	Eolica onshore		2,00%
22	FER302120		IM_1216005	ENGIE RINNOVABILI SARDEGNA SRL	10629620963	SARDEGNA	NUORO	MACOMER	Fotovoltaica		2,00%
23	FER302199		IM_1218789	MAG ABRUZZO S.R.L.	01618560708	ABRUZZO	L'AQUILA	TAGLIACOZZO	Fotovoltaica		2,00%
24	FER202640		IM_1205216	AMUNI S.R.L.	09724450961	SICILIA	TRAPANI	BUSETO PALIZZOLO	Eolica onshore		2,00%
25	FER202639		IM_1205199	AMUNI S.R.L.	09724450961	SICILIA	TRAPANI	BUSETO PALIZZOLO	Eolica onshore		2,00%
26	FER202691		IM_1236055	ADELASIA	11413160968	LIGURIA	SAVONA	CAIRO MONTENOTTE	Eolica onshore		2,00%
27	FER302458		IM_1232001	VRD 25.5 S.R.L.	07776070968	LOMBARDIA	MANTOVA	BORGO MANTOVANO	Fotovoltaica		2,00%
28	FER302584		IM_1238664	SIRIO SRL	05128900288	LOMBARDIA	MANTOVA	CERESARA	Fotovoltaica		2,00%
29	FER302535		IM_1238746	SOLAR ITALY VII S.R.L.	10482250965	LAZIO	LATINA	PONTINIA	Fotovoltaica		2,00%
30	FER302536		IM_1238751	SOLAR ITALY VII S.R.L.	10482250965	LAZIO	LATINA	PONTINIA	Fotovoltaica		2,00%
31	FER302538		IM_1238754	SOLAR ITALY VII S.R.L.	10482250965	LAZIO	LATINA	PONTINIA	Fotovoltaica		2,00%
32	FER302539		IM_1238756	SOLAR ITALY VII S.R.L.	10482250965	LAZIO	LATINA	PONTINIA	Fotovoltaica		2,00%
33	FER202630		IM_S19PCRT	ERG WIND ENERGY S.R.L.	12062051003	SICILIA	PALERMO	PARTINICO	Eolica onshore	Y	2,00%
34	FER202636		IM_S19MCNL	ERG WIND ENERGY S.R.L.	12062051003	SICILIA	CATANIA	MINEO	Eolica onshore	Y	2,00%
35	FER202635		IM_V19MCNL	ERG WIND ENERGY S.R.L.	12062051003	SICILIA	CATANIA	VIZZINI	Eolica onshore	Y	2,00%

D. Standard solutions for connections users - HV network

	Taglia Utenza	Tensione nominale	SOLUZIONI STANDARD		
			antenna (*)	**entra – esce (#)**	
Produzione	6 - 10 MW	MT ÷ 150 kV	*Soluzione da concordare con il Distributore*		
	10 – 100 MW	120 - 150 kV	si	si	entra–esce in semplice sbarra
	100 – 250 MW	120 - 150 kV	si	no	-
	200 - 350 MW	220 - 380 kV	si	si	entra–esce in semplice sbarra + bypass
	200 - 350 MW frazionati su più gruppi di produzione	220 - 380 kV	si	si	entra–esce in doppia sbarra
	> 350 MW	380 kV	si	si	entra–esce in doppia sbarra
Consumo	< 10 MW	MT ÷ 150 kV	*Soluzione da concordare con il Distributore*		
	10 - 20 MW	60 ÷ 150 kV	si	si	entra–esce in semplice sbarra
	20 – 50 MW	120 ÷ 150 kV	si	si	entra–esce in semplice sbarra
	30 – 100 MW	120 ÷ 150 kV	si	si	entra–esce in semplice sbarra
	> 100 MW	220 - 380 kV	si	si	entra–esce in semplice sbarra + bypass
Sistema Produzione e Consumo	La soglia per la scelta del livello di tensione in funzione della taglia va riferita al valore di potenza più alto tra: - massimo valore di potenza in immissione nell'ipotesi di consumo interno minimo - massimo valore di potenza in prelievo nell'ipotesi che la produzione sia minima		La scelta della soluzione convenzionale da adottare va rispettivamente riferita a quelle di Produzione o Consumo tenendo conto del: - massimo valore di potenza in immissione nell'ipotesi di consumo interno minimo - massimo valore di potenza in prelievo nell'ipotesi che la produzione sia minima		

Bibliografia

[1] Wikipedia, «Atmospheric circulation,» [Online]. Available: https://en.wikipedia.org/wiki/Atmospheric_circulation.

[2] The Comet Program, «Comet,» [Online]. Available: https://www.comet.ucar.edu/.

[3] M. C. Brower, Wind Resource Assessment: A Practical Guide to Developing a Wind Project, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2012.

[4] Global Wind Atlas, «Global Wind Atlas,» [Online]. Available: https://globalwindatlas.info/.

[5] VelAvventura, «Storia della vela,» [Online]. Available: https://www.velavventura.com/storia-della-vela/#:~:text=Le%20prime%20tracce%20di%20imbarcazioni,e%20dominare%20le%20rotte%20dei.

[6] Surf Iran, «Asbads of Iran,» [Online]. Available: https://surfiran.com/still-working-windmills-iran/.

[7] Wikipedia, «History of wind power,» [Online]. Available: https://en.wikipedia.org/wiki/History_of_wind_power.

[8] Irena, «Wind energy,» [Online]. Available: https://www.irena.org/wind.

[9] Wikipedia, «Betz's law,» [Online]. Available: https://en.wikipedia.org/wiki/Betz%27s_law.

[10] M. Ebrahimpour, R. Shafaghat, R. Alamian e M. Safdari Shadloo, «Numerical Investigation of the Savonius Vertical Axis Wind Turbine and Evaluation of the Effect of the Overlap Parameter in Both Horizontal and Vertical Directions on Its Performance,» *Symmetry,* vol. 11, n. 6, 2019.

[11] Vestas. [Online]. Available: https://mountainlaurelestates.org/Wind/Vestas_V_100_brochure.pdf.

[12] «BS EN IEC 61400-1-2019 Wind turbine requirements,» [Online].

[13] National Instruments, «Wind Turbine Control Methods,» 2020 October 2020. [Online]. Available: https://www.ni.com/it-it/innovations/white-papers/08/wind-turbine-control-methods.html.

[14] C. Helman, «Forbes,» 28 April 2021. [Online]. Available: https://www.forbes.com/sites/christopherhelman/2021/04/28/how-green-is-wind-power-really-a-new-report-tallies-up-the-carbon-cost-of-renewables/.

[15] IEA, «Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology,» [Online]. Available: https://www.nrel.gov/docs/fy19osti/72437.pdf.

[16] Wikipedia, «Wind turbine,» [Online]. Available: https://en.wikipedia.org/wiki/Wind_turbine#Disadvantages.

[17] «General Electric,» [Online]. Available: https://www.ge.com/news/reports/how-loud-is-a-wind-turbine.

[18] S. Kazilbash, «REVE,» 1 October 2020. [Online]. Available: https://www.evwind.es/2020/10/01/the-realities-of-bird-and-bat-deaths-by-wind-turbines/77477.

[19] «Statista,» 8 September 2021. [Online]. Available: https://www.statista.com/statistics/856594/investments-value-in-renewable-technologies-by-type-in-italy/.

[20] Terna, «Impianti di generazione,» 2021. [Online]. Available: https://download.terna.it/terna/3-IMPIANTI%20DI%20GENERAZIONE_8d9cece9d7e2a7d.pdf.

[21] Terna, «Fonti rinnovabili,» [Online]. Available: https://www.terna.it/it/sistema-elettrico/dispacciamento/fonti-rinnovabili.

[22] «Gestore Servizi Energetici,» [Online]. Available: https://www.gse.it/normativa/autorizzazioni.

[23] Irena, Renewable Power Generation Costs 2020, 2021.

[24] Ministero dello Sviluppo Economico; Ministero dell’Ambiente e della Tutela del Territorio e del Mare; Ministero delle Infrastrutture e dei Trasporti, «PNIEC,» December 2019. [Online]. Available: https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf.

[25] European Parliament, «Governance of the Energy Union and Climate Action,» 11 December 2018. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0001.01.ENG.

[26] Regione Autonoma della Sardegna, «Piano Energetico Ambientale Regionale della Sardegna,» 02 August 2016. [Online]. Available: https://www.gse.it/normativa_site/GSE%20Documenti%20normativa/SARDEGNA_DGR_n45-40__02_08_2016.pdf.

[27] Terna, «L’elettricità nelle Regioni,» [Online]. Available: https://download.terna.it/terna/9-REGIONI_8d9ced0f766c801.pdf.

[28] E. Garofalo, E. Lembo e D. Airoldi, «Valutazioni sulla disponibilità di aree e indicatori di consumo di suolo per il parco di generazione fotovoltaica ed eolica ipotizzabile in scenari di policy al 2030,» RSE, 2018.

[29] European Commission, «Delivering the European Green Deal,» [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.

[30] European Commission, *The European Green Deal,* Brussels, 2019.

[31] European Commission, «European Commission,» [Online]. Available: https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en.

[32] Ministero della Transizione ecologica, «Piano per la transizione ecologica,» 02 August 2021. [Online]. Available: https://www.senato.it/service/PDF/PDFServer/BGT/1310524.pdf.

[33] Presidenza del Consiglio dei Ministri, *Piano Nazionale di Ripresa e Resilienza,* 2021.

[34] «QGIS,» [Online]. Available: https://www.qgis.org/it/site/.

[35] R. McKenna, S. Pfenninger, H. Heinrichs, J. Schmidt, I. Staffell, C. Bauer, K. Gruber, A. N. Hahmann, M. Jansen, M. Klingler, N. Landwehr, X. G. Larsén, J. Lilliestam, B. Pickering, M. Robinius, T. Tröndle, O. Turkovska, S. Wehrle, J. M. Weinand e J. Wohland, «High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs,» *Renewable Energy,* vol. 182, pp. 659-684, January 2022.

[36] M. Shao, Z. Han, J. Sun, C. Xiao, S. Zhang e Y. Zhao, «A review of multi-criteria decision making applications for renewable energy site selection,» *Renewable Energy,* vol. 157, pp. 377-403, 9 2020.

[37] M. Hoogwijk, B. de Vries e W. Turkenburg, «Assessment of the global and regional geographical, technical and economic potential of onshore wind energy,» *Energy Economics,* vol. 26, n. 5, pp. 889-919, 9 2004.

[38] M. A. Baseer, S. Rehman, J. P. Meyer e M. M. Alam, «GIS-based site suitability analysis for wind farm development in Saudi Arabia,» *Energy,* vol. 141, pp. 1166-1176, 12 2017.

[39] S. K. Saraswat, A. K. Digalwar, S. S. Yadav e G. Kumar, «MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India,» *Renewable Energy,* vol. 169, pp. 865-884, 5 2021.

[40] T. Höfer, Y. Sunak, H. Siddique e R. Madlener, «Wind farm siting using a spatial Analytic Hierarchy Process approach: A case study of the Städteregion Aachen,» *Applied Energy,* vol. 163, pp. 222-243, 2 2016.

[41] D. Latinopoulos e K. Kechagia, «A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece,» *Renewable Energy,* vol. 78, pp. 550-560, 2015.

[42] «SCImago,» [Online]. Available: https://www.scimagojr.com/.

[43] «Scopus,» [Online]. Available: https://www.scopus.com/.

[44] K. F. Sotiropoulou e A. P. Vavatsikos, «Onshore wind farms GIS-Assisted suitability analysis using PROMETHEE II,» *Energy Policy,* vol. 158, 11 2021.

[45] S. Ali, J. Taweekun, K. Techato, J. Waewsak e S. Gyawali, «GIS based site suitability assessment for wind and solar farms in Songkhla, Thailand,» *Renewable Energy,* vol. 132, pp. 1360-1372, 3 2019.

[46] R. Van Haaren e V. Fthenakis, «GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State,» *Renewable and Sustainable Energy Reviews,* vol. 15, n. 7, pp. 3332-3340, 2011.

[47] N. Y. Aydin, E. Kentel e S. Duzgun, «GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey,» *Renewable and Sustainable Energy Reviews,* vol. 14, n. 1, pp. 364-373, 1 2010.

[48] L. Gigović, D. Pamučar, D. Božanić e S. Ljubojević, «Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia,» *Renewable Energy,* vol. 103, pp. 501-521, 4 2017.

[49] R. McKenna, S. Hollnaicher e W. Fichtner, «Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany,» *Applied Energy,* vol. 115, pp. 103-115, 2 2014.

[50] Regione Autonoma della Sardegna, *Individuazione delle aree non idonee all'installazione di impianti energetici alimentati da fonti energetiche rinnovabili,* 2020.

[51] Wikipedia, «Wetland,» [Online]. Available: https://en.wikipedia.org/wiki/Wetland.

[52] Wikipedia, «Zona di traffico di aeroporto,» [Online]. Available: https://it.wikipedia.org/wiki/Zona_di_traffico_di_aeroporto.

[53] ENAC, «Relazione Tecnico Illustrativa Mappe di Vincolo,» [Online]. Available: https://drive.google.com/drive/folders/1_fm6xtwE3yzCJoe4TQjeHpwad9U6qVTh.

[54] Wikipedia, «List of islands in the Mediterranean,» [Online]. Available: https://en.wikipedia.org/wiki/List_of_islands_in_the_Mediterranean.

[55] Wikipedia, «Sardinia,» [Online]. Available: https://en.wikipedia.org/wiki/Sardinia.

[56] ISTAT, «Il censimento permanente della popolazione in Sardegna,» [Online]. Available: https://www.istat.it/it/archivio/253977.

[57] Terna, «Sa.Pe.I. Il cavo dei record,» [Online]. Available: https://www.terna.it/it/progetti-territorio/sapei.

[58] Terna, «Interconnesione Sardegna - Corsica - Italia,» [Online]. Available: https://www.terna.it/it/progetti-territorio/progetti-interesse-comune/interconnessione-sardegna-corsica-italia.

[59] Ricerca Sistema Energetico, «Approvigionamento energetico della Regione Sardegna (anni 2020-2040),» 2020.

[60] Ministero dello Sviluppo Economico; Ministero dell'Ambiente e della Tutela del Mare; Ministero per i Beni e Attività Culturali, *Decreto Ministeriale 10/09/2010.*

[61] Regione Autonoma della Sardegna, *Delibera della Giunta Regionale n. 59/90,* 2020.

[62] Regione Autonoma della Sardegna, «Sardegna Geoportale,» [Online]. Available: https://www.sardegnageoportale.it/accessoaidati/downloaddati/.

[63] Global Wind Atlas, «Frequently Asked Questions,» [Online]. Available: https://globalwindatlas.info/about/faq.

[64] Danmarks Tekniske Universitet, «WAsP,» [Online]. Available: https://www.wasp.dk/.

[65] Vestas, «Track record,» [Online]. Available: https://www.vestas.com/en/products/track-record.

[66] WebGIS, «Terrain Data - GTOPO30,» [Online]. Available: http://www.webgis.com/terr_world.html.

[67] IEA, «Projected Costs of Generating Electricity,» 2020.

[68] Lazard, «Lazard's Levelized Cost of Energy Analysis—Version 15.0,» 2021.

[69] T. Stehly, P. Beiter e P. Duffy, «Cost of Wind Energy Review,» NREL, 2019.

[70] Ministero dello Sviluppo Economico; Ministero dell'Ambiente e della Tutela del Territorio e del Mare, *Decreto Ministeriale 04/07/2019.*

[71] Gestore Servizi Energetici, «Accesso agli incentivi,» [Online]. Available: https://www.gse.it/servizi-per-te/fonti-rinnovabili/fer-elettriche/incentivi-dm-04-07-2019.

[72] Gestore Servizi Energetici, «Regolamento Operativo per l’accesso agli incentivi del DM 4 luglio 2019,» 31 January 2022. [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Servizi%20per%20te/FER%20ELETTRICHE/NORMATIVE/DM%20FER%202019%20Regolamento%20Operativo%20per%20l%20Accesso%20agli%20incentivi%20con%20Allegati.pdf.

[73] TuttItalia, «Le province della Sardegna,» [Online]. Available: https://www.tuttitalia.it/sardegna/97-province/.

[74] Wind Europe, «Wind energy in Europe,» 2021.

[75] Sardegna Arpa, «Il clima della Sardegna - Il vento,» [Online]. Available: http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/pag004.asp.

[76] Terna, «Produzione,» [Online]. Available: https://download.terna.it/terna/5-PRODUZIONE_8d9cecf70a531dd.pdf.

[77] Gestore Servizi Energetici, «Accesso agli incentivi - Graduatorie,» [Online]. Available: https://www.gse.it/servizi-per-te/fonti-rinnovabili/fer-elettriche/graduatorie.

[78] Terna, «Tyrrhenian link,» [Online]. Available: https://www.terna.it/it/progetti-territorio/progetti-incontri-territorio/Tyrrhenian-link.

[79] Terna, «Guida agli schemi di connessione,» [Online]. Available: https://download.terna.it/terna/0000/0105/19.pdf.

[80] ANIE Rinnovabili, «Sistemi di Accumulo,» 2021.

[81] Terna, «Flessibilità rete elettrica,» [Online]. Available: https://www.terna.it/it/media/comunicati-stampa/dettaglio/Terna--aggiudicati-250-Mw-di-batterie-per-la-flessibilita-della-rete-elettrica.

[82] M. Dell'Aguzzo, «Energia Oltre,» 25 March 2021. [Online]. Available: https://energiaoltre.it/eolico-italia-anev-2021/.

[83] D. Madeddu, «La decarbonizzazione della Sardegna slitta al 2028,» Il Sole 24 Ore, [Online]. Available: https://www.ilsole24ore.com/art/la-decarbonizzazione-sardegna-slitta-2028-AEVWwpw?refresh_ce=1.

[84] EP Produzione, «Scheda centrale di Fiume Santo».

[85] Enel, «Centrale Termoelettrica Sulcis - Rendimento elettrico,» 2021.

[86] Il Post, «Le centrali a carbone rimaste in Italia,» [Online]. Available: https://www.ilpost.it/2021/11/14/centrali-carbone-italia/.