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Wind energy in Italy: mapping and environmental profile of the electricity production from Italian wind farms

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Abstract

The Intergovernmental Panel on Climate Change's sixth report noted the highest average annual emissions of greenhouse gases of the period 2010-2019. Consequently, ambitious targets and pledges must be set to reach the goal of limiting global warming well below 2°C (Paris Agreement target). The European Union (EU) exemplifies this commitment by setting the goal, within the European Green Deal strategy, of reaching climate neutrality by 2050. This implies a change in many sectors, especially the energy one. The increasing share of renewable energy in recent years represents a pivotal aspect requiring sustained emphasis. The thesis presented herein is developed in accordance with this aspect. A mapping of the Italian wind farms with a total installed capacity higher than 200 kW is performed. A top-level estimate of farms' electricity production is modelled through a new technique proposed by the author. Based on the model outputs, the climate profile of wind electricity is assessed using the process-based Life Cycle Assessment method. The inventory was derived from ecoinvent 3.9.1 background databases and scaled up into five rated power (600, 850, 2000, 3000 and 4200 kW). According to regional position, rated power and average wind speed, an updated emission factors database of Italian wind electricity is obtained. An interactive map is created by the author with all the findings of the work.
According to the thesis' assumption and model, the range of climate profile goes from 13.62 to 44.58 gCO_2eq/kWh_{el}. This is aligned with the literature and the ecoinvent database. Moreover, hydrogen production with alkaline water electrolysis was analysed. In all cases, if supplied with Italian wind electricity, the emissions embodied are lower than the EU taxonomy limit.

Keywords: wind energy, life cycle assessment, climate change, wind farms mapping

Abstract in lingua italiana

Il sesto rapporto del Gruppo intergovernativo sul cambiamento climatico ha rilevato le più alte emissioni medie annue di gas serra del periodo 2010-2019. Di conseguenza, è necessario fissare obiettivi e impegni ambiziosi per raggiungere l'obiettivo di limitare il riscaldamento globale ben al di sotto dei 2°C (obiettivo dell'Accordo di Parigi). L'Unione Europea (UE) esemplifica questo impegno fissando l'obiettivo, tramite la strategia Europe Green Deal, di raggiungere la neutralità climatica entro il 2050. Ciò implica un cambiamento in molti settori, soprattutto in quello energetico. L'aumento della quota di energia rinnovabile negli ultimi anni rappresenta un aspetto cruciale che richiede un impegno costante. La tesi qui presentata si sviluppa in funzione di questo aspetto. Viene eseguita una mappatura dei parchi eolici italiani con una capacità installata totale superiore a 200 kW. Una stima di primo livello della produzione di energia elettrica dei parchi viene modellata attraverso una nuova tecnica proposta dall'autore. Sulla base dei risultati del modello, il profilo climatico dell'elettricità eolica viene valutato utilizzando il metodo di analisi del ciclo di vita. L'inventario è stato ricavato dai database di base di ecoinvent 3.9.1 e scalato per cinque potenze nominali (600, 850, 2000, 3000 e 4200 kW). In base alla posizione regionale, alla potenza nominale e alla velocità media del vento, è stato ottenuto un database aggiornato dei fattori di emissione dell'elettricità eolica italiana. L'autore ha creato una mappa interattiva con tutti i risultati del lavoro.

Secondo le ipotesi e il modello della tesi, il range del profilo climatico va da 13.62 a 44.58 gCO_2eq/kWh_{el}. I valori sono in linea con la letteratura e con il database ecoinvent. Inoltre, è stata analizzata la produzione di idrogeno con elettrolisi di acqua alcalina. In tutti i casi, se alimentata con energia eolica italiana, le emissioni generate sono inferiori al limite della tassonomia europea.

Parole chiave: energia eolica, analisi del ciclo di vita, cambiamento climatico, mappatura dei parchi eolici

Contents

1 | Introduction

Greenhouse gasses (GHG) have the crucial role of absorbing infrared radiation from the earth's surface and efficiently insulating this from the cold space [1]. Nevertheless, the increasing atmospheric concentration has resulted in an energy imbalance of the Earth's climate system with the consequential increase in the global average temperature [2]. It is stated by several scientific publications and organizations.
The sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) reported the highest average annual greenhouse gasses emission of the period 2010-2019 [3]. According to this report, around 60 $GtCO_2eq$ were released into the atmosphere in 2019, lowering the carbon budget left for temperature targets. At the current rate, the total carbon budget would be over within the next 10-15 years. Therefore, several decisions and agreements have been made to challenge climate change. The Paris Agreement of 2015, during COP21 (conference of the parties), was the most important one. It strongly relies on the fifth report of the IPCC. In this agreement, for the first time, the goal of limiting warming well below 2°C and pursuing efforts to stay very low 1.5°C was stated. Indeed, over 180 countries submitted the nationally determined contributions (NDCs) [4]. Nevertheless, these targets were not aligned with the reduction goal of 1.5°C. In the AR6, this is stated and summarised by the figure reported below, Figure 1.1. Projected global GHG emissions from NDCs announced prior to COP26 "would make it likely that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C" [3]. As can be noted by Subplot (a) of the figure, different modelled pathways are studied and projected with the associated probabilistic bars. The dark blue one considers the implementation of the NDCs until 2030. In Subplot (b), a focus on the GHG emissions of this pathway is reported according to different policy assessments. It is worth highlighting the difference between the green and light-blue trends without going into the details. The projected emission outcomes from near-term policy assessments for 2030 are not aligned even with the limiting 2°C scenario. It means a higher reduction rate is needed in the following years to reach the goal. It would make the decarbonization process even harder. Indeed, more ambitious pledges must be submitted.

All the targets and pledges call for changes in every aspect of society because every sector

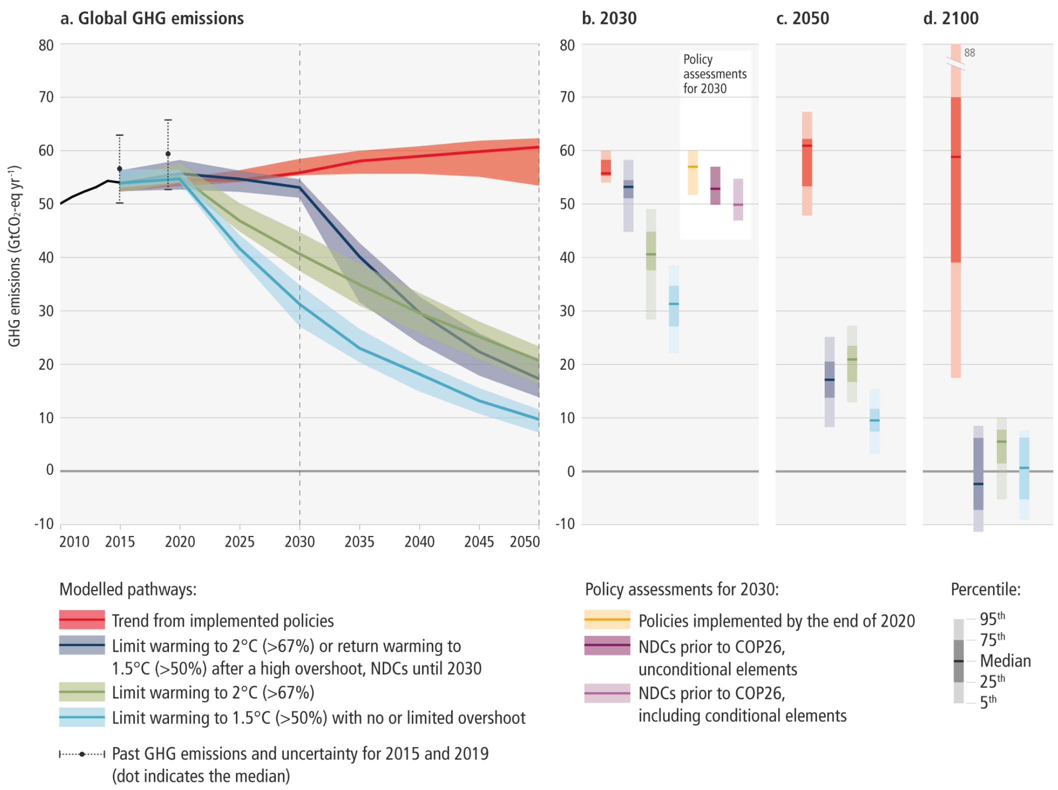

Figure 1.1: Global GHG emissions of modelled pathways [3]

has an impact. Figure 1.2 reports the GHG emissions per sector found in the very last report of the World Resources Institute [5]. The energy sector, which accounts for more than 36% of global GHG emissions, has a key role. In reality, this influence could be even greater if one considers that energy use plays an important role in other sectors, such as transportation, industry, and buildings. Indeed, the percentage could reach around 75% as the "Our World In Data" outcome dated 2016 [6].
All that matters is the huge role of the energy sector in global GHG emissions. Consequently, there are many difficulties, but at the same time, opportunities are present in this area. Indeed, it is around this sector that the work presented in this thesis is structured.

Focusing on the European Union (EU), a number of policy actions to increase ambitions for 2030 and 2050 were launched under the European Green Deal strategy. With the aim of making the European Union's economy sustainable, the goal of achieving climate neutrality in 2050 has been set [7]. This commitment is biding by the EU Climate Law and helped by a series of legislations and packages set by the European Commission (EC). Above all, the "Fit for 55" legislative package was tabled in 2021 "to respond to the requirements in the EU Climate Law to reduce Europe's net greenhouse gas emissions by at least 55% by 2030" [8]. This is aligned with the goals of becoming the first climate-natural

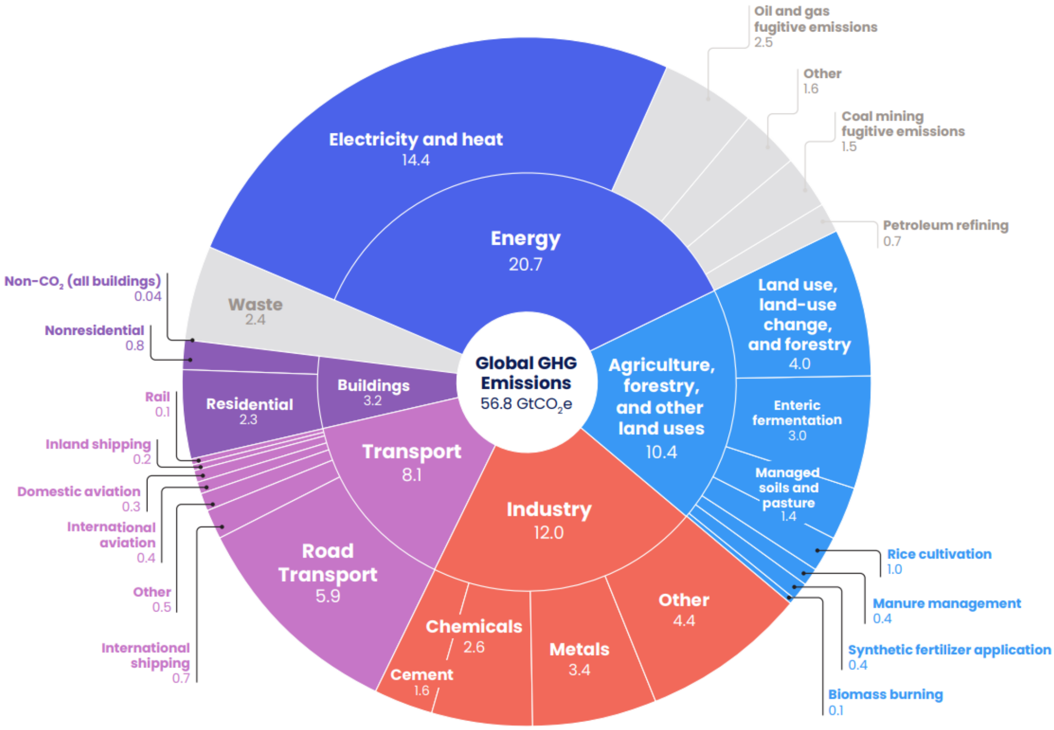

Figure 1.2: Global net anthropogenic GHG emissions by sector in 2021 [5]

continent by 2050 of the EU Green Deal. Another important plan set in the sector of Europe's energy system is the REPowerEU. These measures were set to respond to Russia's invasion of Ukraine with the goal of reducing dependence on fossil fuels and fast forward the green transaction [9].
Another important tool implemented by the EC in this sector is worth mentioning: the EU taxonomy for sustainable activities. This classification "helps direct investments to the economic activities most needed for the transition, in line with the European Green Deal objectives" [10]. More practically, it determines the conditions to qualify as environmentally sustainable economic activity.

Under the large energy sector umbrella, the electricity area is among the first to be considered for transition. The shift from conventional energy sources to more sustainable ones is essential to achieve the reduction target. Indeed, the higher the share of renewables in the market, the faster the EU's goal of 45% renewable electricity by 2030 is met [11]. Besides this, key roles would be played by efficiency enhancement and reduction of the energy demand too. In the context of renewables, a huge discussion arises around the availability of these carbon-neutral sources. Several studies, for example for solar energy, highlight the problem of the so-called "duck curve": the solar power production and the peak demand over a day are shifted [12]. This time imbalance could result either in an overloaded electricity grid or lower generation system efficiency. A similar intermittent problem can be found in another growing renewable source, the wind. In this case, rather than the daily trend, the randomness of the wind itself is a huge obstacle. Indeed, this aleatory of wind turbine production makes this solution unsuitable for the base load, i.e., the minimum amount of electricity always required by the grid. Over the years, more and more emphasis has been placed on coupling these renewable energy systems with storage systems to overcome this hurdle. Batteries or hydrogen are two examples. In the first case, the electricity is stored as it is, for being rejected in the grid or in another system later on. In the other way, the electricity can be used to power an electrolyser. The production of low-emission hydrogen through this technology has grown in the past few years and could be a breakthrough in the energy transition. 550GW of this technology are required to reach Net Zero Emissions by 2050 Scenario of the International Energy Agency (IEA), hence huge efforts and investments are needed [13].

Hydrogen as an energy carrier has immeasurable value and can be considered, at the status quo, one of the most promising carriers to replace fossil fuels. Nowadays, according to the International Renewable Energy Agency (IRENA), only 4% of global hydrogen production comes from electrolysers while almost half, 47%, of the production is from natural gas [14]. This difference leads to a classification of H_2 based on the production process. By convention, a colour is associated with each category. In Figure 1.3 a comprehensive classification is reported with a short description [15].

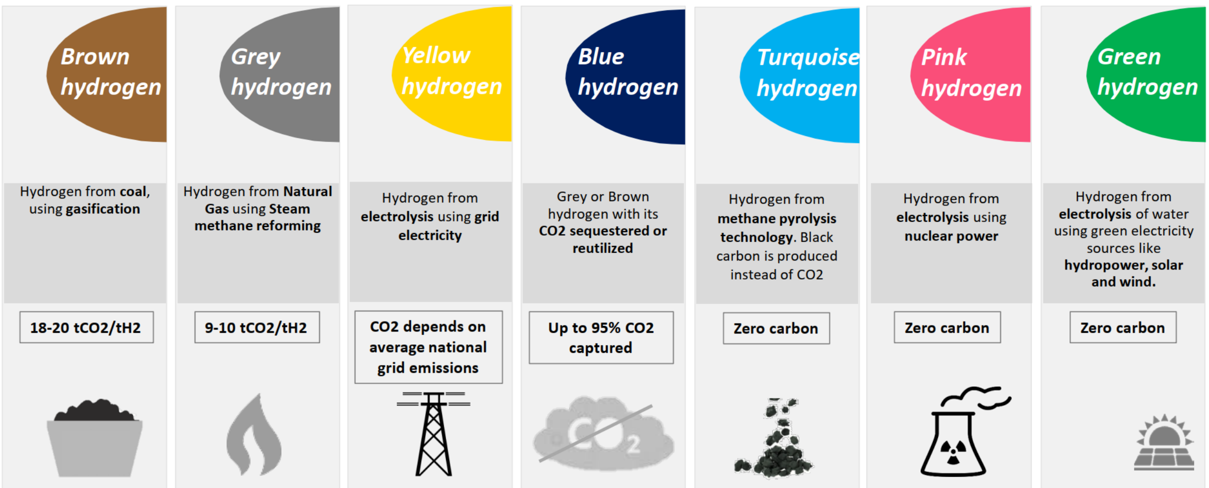

Figure 1.3: Hydrogen classification [15]

Most of the hydrogen produced by steam methane reforming falls under the grey colour, with an average impact of 9-10 tCO_2/tH_2. More harmful to the environment is the brown hydrogen which comes from coal through gasification. Both these typologies can become low-carbon if the process is coupled with a carbon capture and storage system (CCS), aiming to reduce up to 95% of the emissions. This is the so-called blue hydrogen, as noted in the figure above. The cleanest and most ambitious way to produce this energy vector is the green one. Split water into hydrogen and oxygen through electrolysis powered by renewable energy such as solar, wind or hydropower. This method is the preferred one because it would increase the share of renewable while producing an energy carrier with a key role in hard-to-abate sectors; where other alternatives, like electrification, are unfeasible or more expensive, hydrogen-based solutions are the major players. Indeed, this solution is considered by the European Community "the technology of choice" for its energy transition strategy [15]. Nevertheless, hydrogen production needs to deliver GHG emissions savings of 70% compared to fossil fuels to respect the EU taxonomy legislation. As a result, a threshold value of 3.38 tCO_2eq/tH_2 is set [16]. For water electrolysis technologies, different solutions are present in the market such as alkaline water electrolysis (AEL), proton exchange membrane water electrolysis (PEM) or solid oxide electrolysis cell (SOEC). The first solution, which is the most established and mature one, is considered the most favourable solution for low-carbon hydrogen production [17]. Generally, the total carbon dioxide emissions from H_2 production by water electrolysers are mainly due to the electrical energy supply [17]. This leads to the key role of electricity's emission factor (EF). It is in this direction that the presented thesis is addressed. In particular, the topic of the work is the coupling of renewable electricity from wind turbines and electrolysers in Italy. The focus is on the renewable power generation side and the revision of Italian wind electricity emission factors. To contextualize, in 2022, the share of electricity production from wind turbines was slightly less than 7%, corresponding to around 20 TWh of the total Italian production [18]. With an off-shore installed capacity of 0 GW by 2021, the Ministry of Ecologic Transition has received increasing interest in offshore wind projects [19]. An example is the project in Molise: between January 2028 and December 2033, 70 offshore wind turbines of 15 MW each are projected to be installed, for a total capacity of 1.05 GW [20]. The target by 2030 is a total installed capacity, including offshore, of 19.3 GW with an on-shore value by 2021 that was around 11.8 GW [19, 21].

On the on-shore capacity, the author performed a mapping procedure and an environmental assessment to compute the GHG emissions embodied in electricity production. Indeed, renewable power plants do not emit direct emissions, but their environmental impact is greater than zero. The indirect emissions, from raw materials, transportation, disposal, and so on, are accounted for in a life cycle assessment analysis. Among the life cycle approach methodologies (such as environmental extended input-output analysis, material flow analysis etc) the process-based Life Cycle Assessment (LCA) is considered the leader worldwide for evaluating the environmental impact of complex systems. It is

widely used in projects and in the European Commission (EC) programs. Hence, through these assessments, there is the capability to derive information and data used for strategy and decision-making [22].
This assessment is needed for a fair comparison with other sources, both conventional and low-emissions ones. Furthermore, by considering the average energy consumption of water electrolysis technologies, the resulting value can be compared with the threshold of 3.38 tCO_2eq/tH_2 set by the EC.

1.1. Previous works on the topic

Even though wind energy is considered much cleaner than conventional energy from burning fossil fuels, the environmental impact through its whole life cycle is not zero. The direct emissions are effectively null because the operational phase is burden-free. But upstream and downstream emissions are present, i.e. related to the supply chain of all the raw materials and to the disposal at the end of life. Through the application of the LCA method, these aspects are considered and accounted for. This allows to have a realistic overview of wind turbine technologies and holistic comparisons can be done.
Therefore, a review of the literature is carried out in this section. Several LCA studies on electricity produced by wind turbines, focusing on the onshore ones, were found. The goal was to obtain a rough estimation of the range of value of equivalent carbon dioxide (CO_2eq) per electric kilowatt-hour (kWh_{el}). To do so, rather than a paper on a single case study on a specific wind park, it was looking for research that grouped several wind parks. In fact, some papers were found critically analysing other lifecycle studies of wind energy. Besides this, another aim of the literature review, was to gain the state-of-the-art of the LCA method applied to wind turbines. In this case, papers on a single onshore and offshore case study were more relevant.
If these first two aspects were found in the literature, no studies related to the estimation of the production of huge amounts of wind parks, followed by the environmental impact assessments were found. This is the gap filled by this paper for the Italian market.

As stated, there was widespread literature on LCA for wind turbines. Especially for onshore wind turbines, which currently cover more than 90% of the wind capacity [23]. In particular, Lenzen and Munksgaard [24] and Nugent and Sovacool [25] reported an extended review of multiple articles. In the first one, 72 articles reported energy and CO_2eq analyses of wind turbines have been investigated. As a result, a range of CO_2eq emissions intensity between 7.9 and 123.7 gCO_2eq/kWh_{el} was found for unit powers from 0.3 to 3000 kW. Nugent and Sovacool screen 153 lifecycle studies covering not only wind turbines but

also photovoltaic (PV) technologies. From the whole dataset, the two authors detected 41 "best" articles that were effectively considered for the result. In the end, an average of 49.9 gCO_2eq/kWh_{el} is found for the GHG emissions for PV and 34.1 gCO_2eq/kWh_{el} for wind energy. For this latter, its range falls from 0.4 to 364.8 gCO_2eq/kWh_{el}. The author analysed the original papers to gain a better insight into these two extreme cases. The upper limit comes from an off-grid system composed of four wind turbines of 400 W [26]. It is a very extreme case because of the small size of the turbine and the presence of a battery bank. On the other hand, the lower extreme comes from Songling et al. [27]. They compared the environmental impact of 1 kWh_{el} produced by a 600 MW coal-fired thermal power and a 2 MW wind turbine. The adoption of this latter would lead, in the specific case study of Fuzhou, to economic and environmental savings.
As carried out by these two reviews, "results from existing life-cycle assessments of their energy and CO_2eq intensity show considerable variations" [24]. Multiple factors can cause this. From differences in methodology and scope to discrepancies in lifetime, technology, and more. Nevertheless, the competitiveness of this technology is assessed with no doubt with respect to conventional energy sources. Both the scattering of the emissions intensity and the overall low environmental impact of wind turbines are also stated by Van de Vate [28], even with a smaller sample of six studies.
For the offshore solution, Brussa et al. [29] perform an LCA assuming a cradle-to-gate approach on a large wind farm on the coasts of Sicily. The case study was the project of an installation site with a power capacity equal to 3 GW, which would be higher than the total onshore wind power installed nowadays in Italy. It consisted of 190 floating wind turbines with 14.7 MW of rated power. The final result of 31 gCO_2eq/kWh_{el}, caused mainly by steel for aerogenerators and floaters, confirmed the competitiveness with other low-emission electricity generation technologies.
In the comparison among the works, the quality of the results strongly depends on the input parameters. This aspect is handled by Ardente at al. [30] in an assessment of an Italian wind farm: 11 turbines of 660 kW each located in Sicily. The climate profile of 1 kWh_{el} of electricity production is computed and the resulting global warming potential (GWP) is 14.8 gCO_2eq/kWh_{el}. A One-At-a-Time Sensitivity Analysis (OAT-SA) was performed. Especially, the emission factor varies from 8.8 to 18.5 gCO_2eq/kWh_{el} by considering a range of yearly electricity production of -13% and +35%. This result is quite significant for its non-linear trend. Indeed, an increase of 35% in production results in a reduction of around 40% (6 grams) of the emission factor, while, on the other hand, a reduction of only 13% in electricity increase of around 20% (4 grams). This asymmetry highlights the bigger impact of reduction rather than increase in production.
The influence of energy production by a variety of parameters is highlighted by Messineo

et al. [31]. In this paper, small turbines on the Italian market have been analyzed. The wind condition and the type of terrain have resulted in key factors for the choice of turbine. This is an important topic because in a more general work, like the one presented in this paper, these local phenomena, related to the orography of the area, come to pass. Even though they are essential for a new wind farm proposal, it is impossible to keep track of them in such analyses.
Bonou et al. [32] assess the environmental impact of four representative power plants onshore and offshore with 2015 state-of-the-art technology. The 7 gCO_2eq/kWh_{el} results and 11 gCO_2eq/kWh_{el} for onshore and offshore respectively, highlight the bigger impact for these latter. This is mainly due to larger high-impact material requirements for capital infrastructure. Indeed, this stage resulted in the most impactful one: extraction and production of the materials account for 70% of the climate change impact on the onshore wind turbine. After treatment and recycling at the end of life (EoL) is consequently important due to environmental saving. Furthermore, the author performed a system's sensitivity to major assumptions by considering one of the four parks. As a result, the technical specifications were the most influential: wind speed, efficiency of conversion, and lifetime. Indeed, the value of 7 gCO_2eq/kWh_{el} was obtained with a wind speed of 8.5 m/s.

To the best author's knowledge, there is no paper in the literature that evaluates the production of a large series of wind parks and computes their environmental impact. This is done only at a small scale for a specific case study. Increasing the scale, for example, at a regional or national level, would give a clear overview of the state of the art of wind energy production in that area. It would be known where the parks are placed, how many turbines and of which type they are composed, but most importantly, how much electricity they produce and with which emission factor. In addition, once the procedure is validated, this could be used to evaluate the productivity and environmental impact of parks with no real data access or hypothetical parks. It could also be scaled up or implemented in other circumstances. Even the resulting emissions factors would be more specific with respect to, for example, the national one from the background life cycle inventory database ecoinvent [33].
This work aims to fill this gap in the Italian market with a first degree of approximation. Around 80% of the total Italian wind capacity is evaluated, and the environmental impact is computed for a representative sample. The LCA is performed for three clusters of wind turbines depending on the rated power and the average wind speed. This helps to have a comprehensive overview of the Italian wind farms: from their location and characteristics to their expected lifetime, productivity, and climate profile. According to the size and the

position, an average value of the gCO_2eq per kWh_{el} emitted is provided. In the end, a range of climate profiles in Italy is obtained according to the assumption and model used. All these outcomes could be used in countless situations. For example, in the aforementioned coupled system of electrolysers powered by electricity from renewable sources. The use of updated and specific values could be useful for the evaluation of the entire system. Both in terms of production and environmental impact. Thanks to the comprehensive knowledge of Italian wind electricity production, a reliable preliminary analysis can be conducted.

In a nutshell, the novelty of the research is the application of the LCA method with a holistic database of wind farms in Italy. A modelling technique for wind electricity production is proposed by the author, and the outcomes are validated with primary data. For the life cycle inventory, the data were derived from the ecoinvent 3.9.1 background database. The emissions of carbon dioxide equivalent were assessed using the Environmental Footprint (EF) 3.1 characterization method with a 100-year time horizon. Another aspect proposed in this thesis, not present yet in the literature, is the application of Monte Carlo (MC) analysis to the results. This is a step further with respect to a sensitivity analysis of the results like the one presented by Ardente et al.[30]. In this work, the uncertainty embodied in the LCA method and the one of wind production are considered simultaneously.

Lastly, the validation results are implemented with the climate profiles obtained. Indeed, a range of climate change emission factors is obtained. These wind electricity values are compared with literature results and the ecoinvent 3.9.1 background dataset.

1.2. Focus and aim of the research

The main focus and goal of the thesis can be summarised as follows:

- Top-level estimate of farms electricity production considering around 80% of the total Italian wind onshore installed capacity;
- Environmental profile (focus on climate profile) of 1 kWh_{el} depending on farm's region, location average wind speed and wind turbine rated power;
- Provide a climate change EF range for onshore wind turbines in Italy more detailed with respect to the LCA background database (ecoinvent 3.9.1);
- Verifying if, according to the uncertainty obtained, hydrogen production with water electrolysis technologies respects the EU taxonomy limit.

All the results and conclusions obtained in this thesis, are strictly related to the assumption and the input sources used. It is, in fact, a first degree of approximation but it is still validated with literature and ecoinvent dataset. Nevertheless, for more strong statements, the use of primary data is necessary.

2 | Materials and methods

In this section, the methodologies used in the research, as well as the materials, are analyzed. The structure of the chapter is the following: firstly, the wind turbine model is carried out (i). This latter is used to determine the yearly productivity of the Italian farms. Subsequently, all aspects of the LCA are reviewed (ii); product system, system boundaries, functional unit, and impact categories are covered separately. Lastly, the methodology used for the validation is explained (iii), followed by a short overview of the Monte Carlo (MC) analysis is implemented (iv).

At the end of the chapter, the workflow followed during the thesis is reported. It can be referred to for a better understanding of all the linking between the processes or for having an overview. Figure 2.4 refers to the data collection and wind turbine model implementation, while Figure 2.5 summarises the steps implemented in the second part of the LCA analysis.

2.1. Wind turbine electricity production model

The goal of this first part was to analyse and identify a smart way to approximate the electricity production of wind turbines. The goal of the research is, in fact, to estimate the production of several wind farms in Italy with a first degree of approximation. Therefore, it was necessary to find a method that could be applied in all cases, regardless of the specific characteristics of the turbine, providing an estimation of the electricity yield. Due to the importance of electricity production in the LCA, a technique easily to scale up with sufficient accuracy from an engineering point of view was sought. For this goal, several ways were presented in the literature and reviewed in order to find the best fit for this work.
The implementation of the different techniques was performed through Python codes [34]. In the Appendix A, more details on the coding part can be found.

Caduff et al. [35] provided a procedure for calculating the maximum power captured by the wind turbine. The electric power (P_{el}), which is the value of interest, was computed from the maximum captured power ($P_{captured,max}$) net of losses as shown in eq 2.1. In the paper, a generator efficiency of 94% was assessed [36], and another 5% of the power was considered lost due to rotor blade soiling (1-2%), wind hysteresis (1%), and losses for the grid connection [37].

$$P_{elec} = \eta_{generator}\eta_{losses}P_{captured,max} \tag{2.1}$$

The maximum captured power was computed according to Betz's law, which indicates the maximum power that can be extracted from the wind [38]. As shown in eq 2.2, Betz's limit was multiplied by the kinetic power ($P_{kinetic}$). This latter is basically the energy, over time, that the turbine receives and transforms into mechanical or electrical forms. It is the energy available in the wind, strictly connected to the kinetic energy of a large mass of air moving [39].
The kinetic power was computed according to the equation 2.3. The air density (ρ_{air}) was approximated to 1.2 kg/m^3 by Caduff et al., while the rotor area (A_{rotor}) was computed with the rotor diameter in the circle's area formula.

$$P_{captured,max} = \frac{16}{27}P_{kinetic} \tag{2.2}$$

$$P_{kinetic} = \frac{1}{2}\rho_{air}A_{rotor}v_{hub}^3 \tag{2.3}$$

The wind speed at the hub height (v_{hub}) was a key part of the model. To compute this value, the formula 2.4 was implemented according to Caduff et al. By this equation, it is possible to project the wind velocity at different heights. Indeed, this power law represents the wind gradient. The subscripts 1 and 2 characterise two different points in space. In particular, they indicate two points related to the wind turbine but at different heights. By knowing the wind velocity at a certain height, hence knowing v_1 and H_1, it is possible to project the velocity at a different height H_2. The exponent a, known as Hellman exponent or wind shear, stands for the typology of surrounded terrain and air. A value of 1/7 was chosen, which was at the lower range of wind shear for onshore regions [35]. For Caduff et. al point No. 1 was characterised by an annual wind speed of 5 m/s at 10 m height. With this selection, a unique power value was computed, according to the hub height selected. H_2 was substituted with the hub height; consequently, v_2 was the wind speed at the hub.
This aspect was changed in this work, as an hourly-based outcome was desired. Nevertheless, the same formula was used, with the same wind shear, but a different approach for the wind speed value was chosen. Indeed, 8760 wind speed values were used, resulting

in an hourly value of power production. More details on the procedure applied by the author to have wind speed on an hourly basis were reported in section 2.1.1.

$$v_2 = v_1 \cdot \left(\frac{H_2}{H_1}\right)^a \tag{2.4}$$

The procedure exposed by Caduff et al. was not suitable for the goal of the project because many key aspects were left out; as stated, it was possible only to compute a maximum production value with respect to the average wind speed. Indeed, a more precise method was needed. From the literature, another way to estimate the production of these kinds of systems was found: by approximating the power curve function of the wind turbine.
The power curve, reported in Figure 2.1, represents the relationship between the wind speed and the output power of a specific wind turbine. Usually obtained by the manufacturers from field measurements of wind speed and power [40], it could be characterized by different parameters and regions. As explained by Sohoni et al. [41], four regions can be detected. Region 1 is before the threshold of the cut-in speed, $v_{cut,in}$, where the production is null because the rotor is not moving. Once this threshold is overcome, the power increases with the increase of wind speed following a complex nonlinear relationship. This complicated link needs to be approximated in the best way possible to get a precise and reliable model. The rated wind speed, v_{rated}, indicates the speed from which the wind turbine production is the rated one, hence the maximum. This stands up until the cut-off speed when the rotor is stopped mainly for safety reasons (region 4).
The power curve is unique for the model considered. Therefore, to approximate the generic function of region 2 with simpler functions, it required the knowledge of some of the parameters just mentioned This information could be collected from different sources, as explained in the next section 2.1.1. Depending on the analytic expressions, different information was required, but some assumptions were needed in case of a lack of data. Critical overviews of the different techniques were present in the literature and were analysed hereinafter.

Sohoni et al. [41] provide an excellent summary of the most common modelling techniques. For this case study, the focus was on the polynomial one in the spectrum of parametric power curve models. Among these, several were tested in this paper and reported below, with pros and cons. In choosing the best technique, it looked for a trade-off between the challenge of getting the parameters needed for the approximation and the accuracy of the power curve obtained.
Firstly, a modelling method based on Weibull parameters was considered [42]. It gives quite a satisfactory response for higher annual average wind speed; however, it should

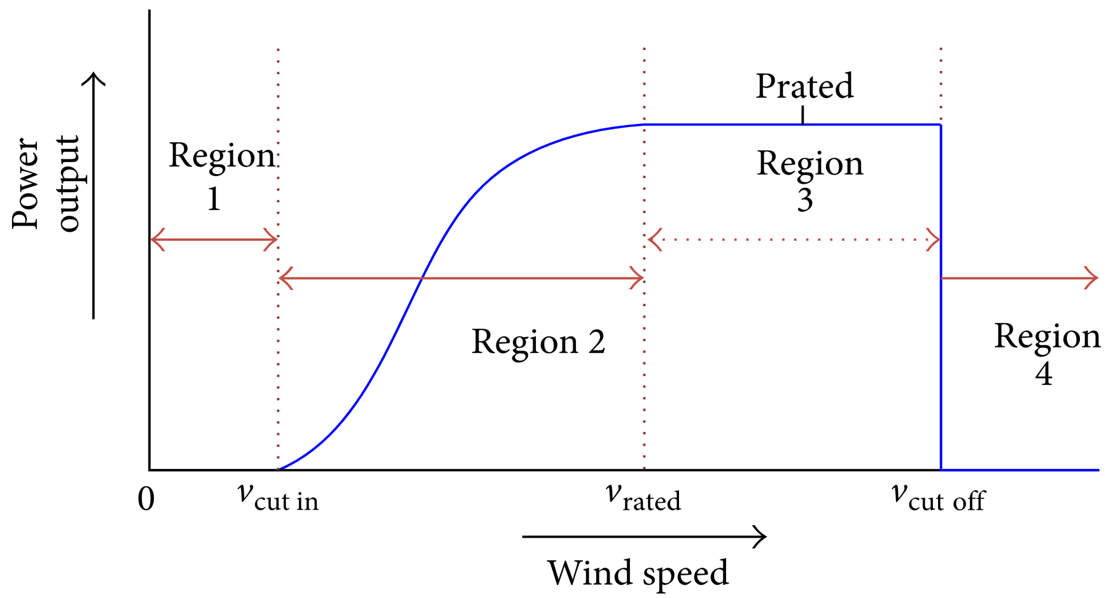

Figure 2.1: Typical power curve [40]

not be employed where accurate analysis is required [43]. Nevertheless, this technique was still used in the beginning. From the power curve, the parameters needed were only the three velocities, i.e., cut-in, cut-off, and rated velocity. The analytic expressions used were reported in system 2.5 where Pr stands for the rated power. The Weibull parameters a_1 and b_1 were calculated according to the velocities and the shape parameter k, as shown in equations 2.6. This latter was set equal to 2, which gave sufficient accuracy in analysing the wind power system [44]. An array of 8760 values was obtained with the hourly wind data. The yearly electricity production was achieved by summing the values and multiplying for a general coefficient of loss of 0.9. This value is a rounding up of the one used by Caduff et al. [35].

$$\begin{cases} P = 0; for\, v < v_{cut,in} \\ P = a_1 + b_1 \cdot v^3; for\, v_{cut,in} < v < v_{rated} \\ P = Pr; for\, v_{rated} < v < v_{cut,off} \\ P = 0; for\, v > v_{cut,off} \end{cases} \tag{2.5}$$

$$\begin{cases} a_1 = Pr \cdot v^k_{cut,in} / (v^k_{cut,in} - v^k_{rated}) \\ b_1 = \dfrac{Pr}{(v^k_{rated} - v^k_{cut,in})} \end{cases} \tag{2.6}$$

On the other hand, cubic approximation gives an acceptable value of goodness of fit making this approximation very attractive due to its simplicity [40]. Therefore, this technique was implemented as reported in the system 2.7 [45, 46]. In this case, the specific power (P_{spec}) was used, i.e. the rated power divided by the rotor area. The additional equations for the methodology were carried out in the system 2.8. With the same steps as in the previous case, productivity was obtained.

$$\begin{cases} P = 0; for\, v < v_{cut,in} \\ P = a \cdot v^3 - b \cdot P_{spec}; for\, v_{cut,in} < v < v_{rated} \\ P = P_{spec}; for\, v_{rated} < v < v_{cut,off} \\ P = 0; for\, v > v_{cut,off} \end{cases} \tag{2.7}$$

$$\begin{cases} a = \dfrac{P_{spec}}{v_{rated}^3 - V_{cut,in}^3} \\ b = \dfrac{v_{cut,in}^3}{v_{rated}^3 - V_{cut,in}^3} \end{cases} \tag{2.8}$$

Nevertheless, the curvature of the power curve was not followed by these two techniques [41], hence, the output was misleading in some cases. A more precise method was needed. Indeed, for Thapar et al.[43], a model based on cubic spline interpolation replicates the performance of the actual turbine almost exactly. In order to apply this procedure, all the power-speed couples of the curve were needed. Usually, from the manufacturer, a step of 0.5 m/s for the wind speed is applied. Therefore, a spline cubic approximation was done at each step [47]. In the end, the resulting curve was practically overlapped with the real one. A practical example is reported in section 4.1.2, where the quality of the approximation from a quantitative point of view can be appreciated. Despite the goodness of this approach, the scalability was unfeasible. Adding manually a list of 20 or more couple of velocity and power for more than 500 farms was too demanding.

This paper proposed a new trade-off technique to overcome this scaling problem. It was observed that region 2 of the power curve presents an inflexion point, mostly in the middle of the range given by $v_{cut,in}$ and v_{rated}. Therefore, it was decided to split the spline interpolation in two, according to this inflexion point. The wind speed where the inflexion point was present was not known precisely. So, an approximate velocity was chosen for each specific power curve. This latter was in the middle of the range, where the inflexion point was roughly. Indeed, from now on, this velocity will be called middle velocity.
The two interpolations with the cubic spline were one from the cut-in velocity to this middle velocity, while the other from this latter point to the rated velocity. The result was an excellent approximation with far less data input with respect to the previous method.

Only a few percentage points of difference were observed with respect to the manufacturer's power curve. This was validated with three different models of wind turbines. The results of these verifications and a comparison between the different techniques were reported in more detail in section 4.1.2.
In conclusion, this method was considered the best trade-off possible. Adding just one piece of information, which did not require much more effort, greatly increased the quality of the approximation with respect to the first two methods. On the other hand, few percentages of difference were present with respect to a holistic cubic spline interpolation. It was considered more than acceptable for the sake of the analysis. Furthermore, the author selected the middle point roughly. It was enough to choose a point where, approximately, the inflexion was. It is another positive aspect of the procedure that does not require the exact position of the inflexion point.

In the end, this method is proposed as an empirical solution for power curve modelling techniques as one of the best trade-offs between data requirements and the accuracy of the outcome.

2.1.1. Data collection

An essential part of this work was the data collection. Few but key information on the farms was required:

- Position (elevation optional)
- Number of wind turbines
- Rated power of the turbine
- Rotor diameter of the turbine
- Hub height of the turbine
- Model of the turbine (owner/commissioner optional)

Unfortunately, to the best of the author's knowledge, no database with all these details was present at the national level, nor at the regional one (except for Basilicata [48]). Therefore, the integration of several sources was done to accomplish the data input of the model.
In the Italian atlas AEOLIAN (Atlante EOLico ItaliAno) [49], most existing wind turbines were reported divided into clusters depending on the rated power. However, other important aspects like the "technical limits" of the wind park, heights and diameters, or the model were not reported. Nevertheless, this website was the reference one for com-

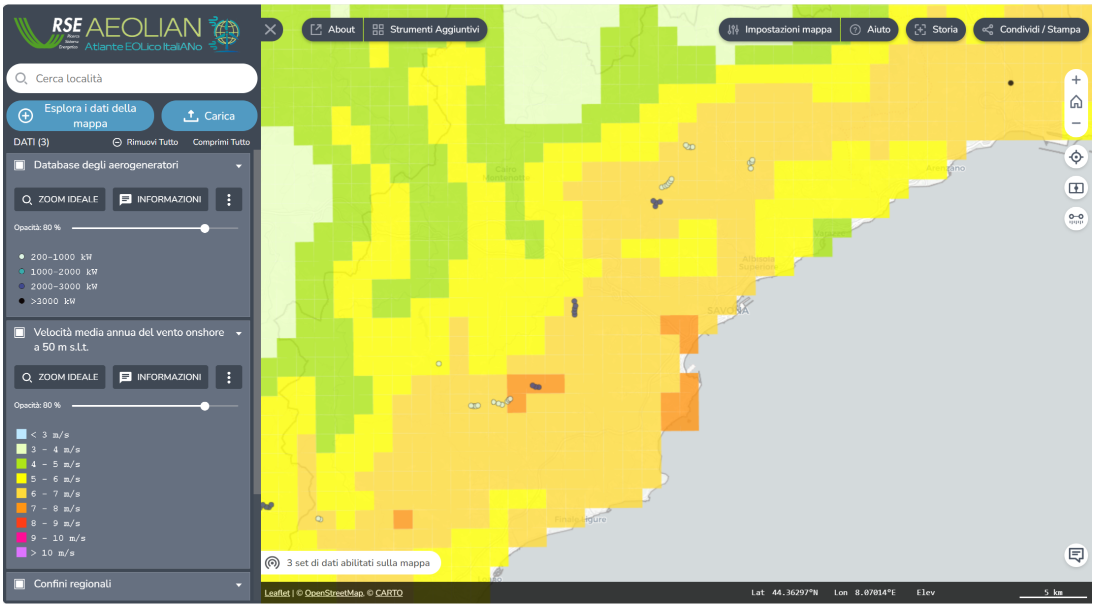

Figure 2.2: View of the Italian Atlas - zoom on Liguria

puting the wind speed. The information on the average wind speed at different heights above the ground (a.b.g.) was present. For the analysis, the value at 50 meters a.b.g. was used as explained later on. Figure 2.2 shows a view of the atlas. The points represent the wind turbines, coloured according to the legend on the left while the colormap refers to the wind speed at 50 meters above the ground.

A great and almost complete database was found in "The Wind Power" online access [50]. Information like the number of wind turbines, rotor diameter, and turbine model were often obtained from this website. The main issues of this database were the inaccuracies of some farms' locations and information. Double-counting parks were found, especially for the ones in different cities with wind turbines. In addition, some data were out of date as double-checked with other sources. Nevertheless, globally this free platform is considered very reliable and useful.

From the same website, the reference database for the wind turbine model was selected [51]. This choice was made for consistency because, contrary to other sources like the manufacturer's website, the power curves of almost every model analyzed were present. Therefore, when the wind turbine model was found, the power curve and its parameters were carried out from the above source. Cut-in, cut-off, and rated wind speeds were obtained, as well as the middle velocity of the curve. Besides these, the diameter of the rotor and a range of possible hub heights were also given.

Another institutional source used was the "GSE Atlaimpianti" [52]. The list of the national renewable plants was reported, and the wind turbine lists were tracked region by region. The limits of this website were essentially two. Firstly, the lists were incorrect

at times (out-of-date, wrong position), and secondly and most importantly, only the city where the park is installed and the total power was present. No additional and critical information needed for the holistic mapping was reported.
"Google Earth" [53] also had an important role in this research. It was used as a controller and a counting system, to check if the number of wind turbines was correct, the park's location, and even if it existed
In conclusion, plentiful work was put into trying to match all the information from these sources and to fill the gaps with countless research. For example, the parks were often grouped differently in the abovementioned sources. Therefore, further analyses were conducted to have the truest data input. Nevertheless, as stated, some assumptions were made in case of no data or conflicting ones. The main assumption was on the wind turbine's height, which was the most challenging information to get. Even on some operator websites, this value was missing. For the principle of being conservative, the minimum hub height from the range given in the model's database was selected [51]. With this choice, the wind profile at the hub was the lowest possible, resulting in the lowest electricity production and the higher environmental impact in the last

One last aspect of the data acquisition part was the meteorological file and the consequential wind speed values calculation. As mentioned in the previous section, hourly-based data for the wind velocity were chosen. This led to more accuracy in the final electricity production with respect to using an average value. However, the counterpart was the absence of data at a precise position.
Indeed, EnergyPlus Weather (epw) files were used. These kinds of files, developed by the United States Department of Energy (DoE), are the standard for energy simulation in buildings [54]. They were used in this work because, among the information given such as dry bulb temperature, relative humidity, direct normal radiation and more, the wind speed is part of it. On an hourly basis, the wind speed and its direction were reported. However, the second information was not used for the sake of the analysis.
This source of weather data was of two major classes: historical data and typical weather years (also known as typical meteorological year - TMY). While the first class was real data from a particular location, the "typical years are ersatz years assembled to match the long-term data from a particular location using a particular statistical measure" [55]. The resulting format is a mix of months from different years. For this reason and not only, this kind of format was chosen in this work. In particular, after some research and trials, a database with TMYs derived from the most recent 15 years (2007-2021) was found and chosen as the source of the project [56]. These files were preferred to others for different reasons. Firstly, the time span was considered appropriate for the scope of the project

and also in all the Italian territory, these specific databases were present. This was not true for example for the TMY considering value from 2004 to 2018 from the same data collection website.
Nevertheless, the position of these files, which are in correspondence with some anemometers, was not always the best one. On very few occasions, the location of the farms and the anemometer were closed. In the other case, the majority of the time, the closest anemometer to the park was chosen. In case more than one was suitable, the elevation was the decisive factor. The one closer to the park's elevation was selected. For the anemometer, it was one of the information given by the epw file, whereas, for the park, it was either found on some websites or taken directly from the atlas knowing the position.
The scaling procedure was implemented after a wind park was coupled with the reference anemometer. The mean wind speed from the epw file was calculated and a scale factor (SF) was computed as shown in equation 2.9. The numerator is simply the average wind speed calculated from the epw file, while the denominator was obtained by the Italian atlas [49].

$$SF = \frac{V_{mean,anenometer}}{V_{mean,atlas}} \tag{2.9}$$

Therefore, the hourly values of wind velocity of the epw file were scaled by this factor and, lastly, projected to the hub height according to Hellman, eq 2.4. In this case, v_1 was the average wind speed from the atlas at 50 meters. Therefore the denominator, H_1, was 50 while H_2 was the hub height of the specific case. As a result, the hourly wind profile was estimated at the wind turbine height. Thanks to this, the production hour by hour was computed. Only through these steps, it was possible to exploit at the best the modelling of the power curve implemented.
The position and the number of anemometers had an important role in the final production estimation. Unfortunately, they were not distributed equally in the Italian territory. In several regions, few anemometers were present hence the resulting wind profile at the hub height was less accurate. For example, in Umbria and Basilicata, only two anemometers were present. Oddly, in the South, where the presence of the parks was much higher, fewer epw files were available. The same problem was found in other meteorological sources [57, 58]. Indeed, another way to work around this aspect was not found. This was a consideration taken into account in the discussion of the results later on.
Afterwards, it was tested another wind hourly database: ERA5 hourly data on single levels from 1940 to present [59]. With this database, the park location can be directly used and an hourly wind profile is obtained. Indeed, the problem of anemometers' position is overcome. Nevertheless, the performance obtained was similar to one of the procedure used in this thesis. Further comments are reported in section 4.4.1.

In conclusion of this data collection, the park's productivity was estimated using the abovementioned method. To visualize all this information, an interactive map was created. To do so, a code was written based on the Folium library: an open-source Python package for data visualization and manipulation [60]. For each farm, the city where is located, the number of wind turbines, the turbine's model (with its rated power), the total power installed, the estimated productivity and the equivalent hours were reported. Furthermore, the position of the anemometers was also implemented. Thanks to this, the asymmetry between the presence of wind parks and epw files can be appreciated. In section 4.1.3 several views were carried out with a short description of how to use the map. The gap in the literature mentioned at the beginning of the section was filled with this database.

2.2. Life cycle assessment

In this study, the LCA method was preferred to others for its leadership role in Europe for environmental metrics [22]. A generic framework of the LCA methodology is reported in Figure 2.3.

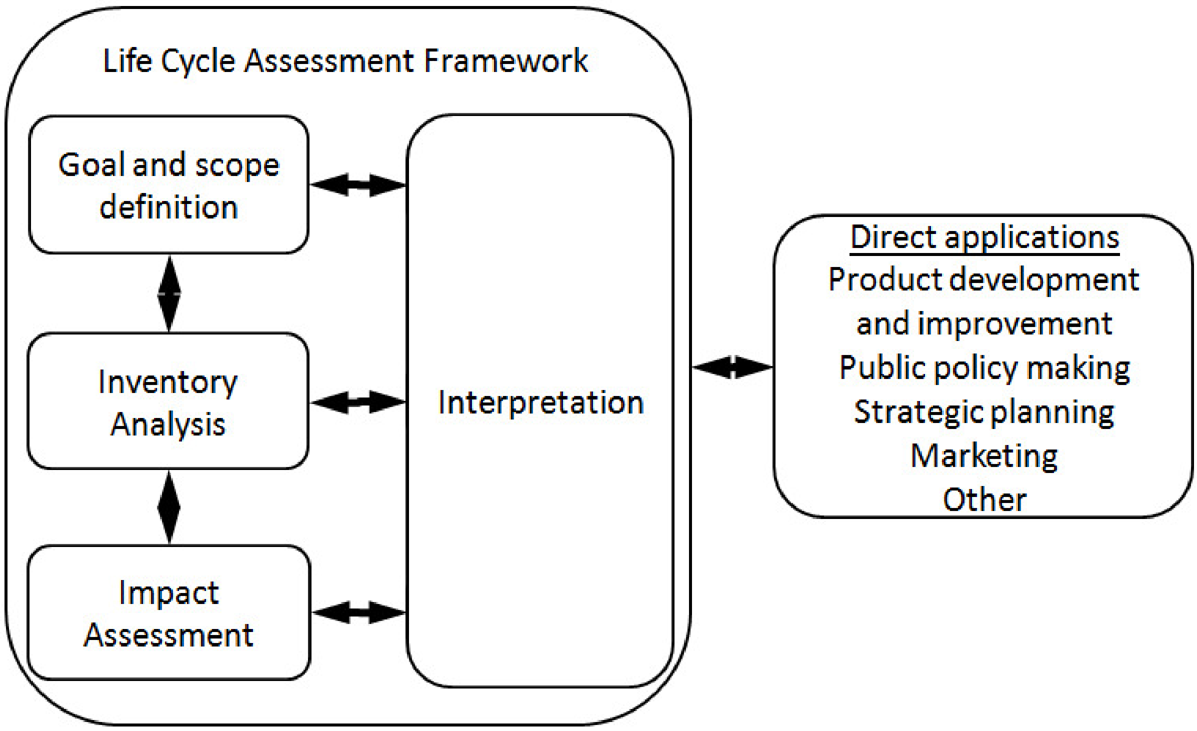

Figure 2.3: Schematic Life Cycle Assessments framework [61]

As stated, this thesis aims to assess the environmental impact of electricity production of onshore wind turbines in Italy. Therefore, all the life phases of the turbines are accounted for to span their emissions on the whole electricity production during their lifetime. The phases are composed of different activities and processes that are the core of the inventory analysis. In this stage, the amount of raw materials used, the energy and water consumption, the transport done and many others are analysed and a numerical value is associated with each activity. In the end, every action has an impact on the world, which can be assessed with different impact categories. As the flow chart notes, the interpretation and critical review of the results are essential through all these steps. Only with these latter the LCA outcomes can be used for countless applications

In this section, all the aforementioned steps are carried out in more detail. Indeed, the methodology is analysed in all the aspects: product system (i), system boundaries (ii), the functional unit (iii) and lastly the general method with the MC implementation (iv). The outcomes were obtained using Brightway2, an open-source software developed by Chris Mutel [62].

2.2.1. Product system

The analyses were performed applying the "cradle-to-grave" approach. Indeed, the following phases were considered:

- Resources (land occupation and transformation);
- Materials/fuels (aluminium, cast iron, lubricating oil, fuel for transport, etc.);
- Electricity/heat (medium voltage electricity for additional material processing);
- Waste to Treatment (electronic scrap, waste glass, scrap copper, etc.).

Each phase is associated with different activities and processes, called exchange activities in this work. Indeed, they have a crucial role because, strictly related to the system boundaries, they define what is included in the study and what is not. Each activity is then associated with a value, called exchange input or exchange amount, which is the exchange flow with the world: for example, for raw materials, this value is simply the amount of raw materials needed for the turbines. Indeed, the exchange amount is associated with a certain impact on the environment.
The activity processes and the related exchange amount were retrieved from a study of the Paul Scherrer Institute (PSI), by Burger and Bauer [63]. Three datasets were reported, specifically for three wind turbines of different rated power. In Chapter 3, the list of the activity processes considered is reported.

The consequence of the presence of three different databases, specific to a wind turbine model, was the creation of clusters related to these latter. These were created as follows. The specific turbine used by Burger and Bauer is on the left-hand side and the corresponding subset is after the arrow.

- Nordex N50/800 ⟶ rated power lower than 1 MW
- Vestas V80/2000 ⟶ rated power from 1MW up to 3MW
- Enercon E112/4500 ⟶ rated power higher than 3MW

The model of the wind turbine was reported in a unique way throughout the report. The construction company's name is followed by its acronym, usually the initial letter, and the diameter of the rotor; the last number is the power expressed in kilowatts.

The amount of exchange given by the Swiss report was adjusted according to the specific wind turbine. A scaling procedure was applied, as carried out hereinafter.
Lastly, the activity processes and their related exchange input for the LCA process, were collected by the ecoinvent database, version 3.9.1 cut-off [33]. Indeed, the choice of the cluster was not casual but follows the division applied in the ecoinvent database.

In this thesis, it was implemented a procedure seldom applied to estimate the environmental impacts of wind energy [35]: the scaling of the exchange amount of the activity data. As stated, the databases were provided for three specific wind turbine models. Therefore, for the holistic analysis of this work, it was necessary to find a way to transpose this data set to other models. These scaling laws are provided by Caduff et al. [35] who were able to associate a proportional relation linked to some turbine characteristics at each parameter. In Table 2.1 the scaling relationships used in this analysis were reported. D is the rotor diameter, while the symbol h indicates the height of the hub.

Table 2.1: Engineering-Based Size Scaling Laws [35]

Parameter	Proportional to
Power, p	$\propto D^2 h^{3/7}$
M_{rotor}	$\propto D^3$
$M_{nacelle}$	$\propto D^3$
M_{tower}	$\propto D^2 h$
$M_{foundation}$	$\propto D^3$
$M_{electronics\&cables}$	$\propto h$

In this work, these relationships were assigned manually to the different activity processes. This was done according to the principle of similarity and relevance. For each item, the most likeness scaling factor was implemented and the resulting LCA inventory was obtained. In the case where more than one law was relevant, a mean value was calculated and used. For example, for the 4.5MW Enercon turbine, the *Alkyd paint* activity process was used for the tower, nacelle and the three blades. Therefore, the exchange amount was adjusted according to all three proportionalities.

2.2.2. System boundaries

As stated in previous sections, the work was concentrated on the Italian wind farms; therefore, the geographical boundaries were the Italian ones. The sea areas are not considered in these boundaries because the focus is on onshore wind turbines. As for the temporal boundaries, the lifespan of the turbines was set to 20 years. A further assumption was made because all the parks were considered brand-new. The year of construction was not considered: it was another challenging parameter to take trace and not considered an essential one. Therefore, all the parks were assumed to last for at least 20 years. Nevertheless, this assumption was supported by the hourly-based wind speed data, which showed an average among different years. The outcome of CO_2 impact is shared during the lifetime, independently of the starting year at even wind data.
Lastly, a technical threshold of 1% for the activity processes was considered for the Life cycle inventories (LCIs). The cut-off rule was set at 1% in terms of environmental impact, meaning no output and input below this level were considered in the LCA model.

2.2.3. Functional unit

The analysis's functional unit (FU) was set to 1 kWh of electricity produced by the wind turbine. This is in accordance with all the literature related to the environmental impact of these kinds of systems [25, 64, 65].
Furthermore, for the sake of the analysis the lifespan of all the parks was set to 20 years [35]. The assumption used to consider an even production through these years; the yearly electricity output from the wind turbine model was replicated during the lifetime.

2.2.4. Life Cycle impact assessment method

Usually, the environmental profile of a system is composed of different impact categories [29, 66]. For the sake of the report, 28 impact categories following the Environmental Footprint (EF) method 3.1 were computed [67]. Nevertheless, only the Climate Change (CC) category was considered in the results; the emissions metric used was the global warming potential with a time horizon of 100 years. This impact category is the most relevant and the most common, too. Furthermore, the Monte Carlo process was only performed upon the CC category for computational reasons.

2.2.5. Analysis of the results with water electrolysis technologies

The resulting emissions factors are commented on in relation to the energy consumption of water electrolysis technology. As stated, for these technologies, the total GHG emissions are from the electrical energy supply, and the EU taxonomy limit is set to 3.38 tCO_2eq/tH_2.
Considering the state-of-the-art AEL, PEM and SOEC technology, the energy consumption ranges from 3.6 kWh/Nm^3H_2 to 6.5 kWh/Nm^3H_2 [15, 17]. For the Alkaline water electrolysis, which is the most common one, the range of interest is between 5.0 kWh/Nm^3H_2 and 5.9 kWh/Nm^3H_2 [17]. The relation for the conversion in kilograms is expressed in the equation 2.10. With this relation, the energy consumption can be expressed in kWh/kgH_2, and the results are reported in Table 2.2. Then by multiplying the last row for the emission factor, a value can be obtained to compare it with the EU taxonomy limit. This procedure is repeated two times: for the deterministic outcome in section 4.2.1, and for the stochastic one in section 4.4.2.

$$1\,Nm^3H_2 = 0.08988\,kgH_2 \tag{2.10}$$

Table 2.2: Energy consumption of the state-of-the-art water electrolysis [15, 17]

Water electrolysis technology	AEL		General range	
	min	max	min	max
[kWh/Nm^3H_2]	5	5.9	3.6	6.5
[kWh/kgH_2]	55.6	65.6	40.1	72.3

2.3. Validation of the wind turbine model

A reference source not mentioned in section 2.1.1 was Terna, an Italian company operating the electricity transmission networks [68]. From this, the totality of the Italian wind park was given in terms of numbers and capacity installed [21]. Divided by region and into six clusters based on the park's total power, the database is reported in Table 2.3. The total electricity production by region was also reported, with data updated to 2021. These data were considered the most correct due to Terna's position in the Italian market; therefore,

the objective was to replicate this dataset in the best possible way.
For the sake of the analysis, only the last three clusters were considered: from 200 kW to 1 MW, from 1 MW to 10 MW and higher than 10 MW. Hence, only farms with a total installed capacity higher than 200 kW. This decision was made for two main reasons. At first, for the goal of coupling wind farms with electrolysers, wind farms with low installed capacity are not of interest. It is likely that these kinds of systems are commonly for single users or even for domestic use. Therefore, the surplus would be minimal and not relevant to hydrogen production. Indeed, for this latter, more of interest are wind farms of several megawatts installed. The other motivation was the feasibility of getting the park's information. It was unfeasible to retrieve all the details of these parks and, moreover, not worth the effort. Indeed, with this reduction, only around 2% of the total capacity was dropped. For the same reasoning of data accessibility, in some regions, even the parks within the range of 200 kW and 1 MW were not considered. In Lazio, Campania, Apulia, Basilicata, Calabria, Sicily, and Sardinia only parks with installed capacity higher than $1MW$ were assessed. As a consequence, an additional 2% of the total power was excluded. As stated, not all the information about this capacity was collected and, in section 4.1.1, the resulting capacity review was carried out.

Table 2.3: Terna database [21]

Region	P < 12kW		12kW ⩽ P < 20kW		20kW ⩽ P < 200kW		200kW ⩽ P < 1MW		1MW ⩽ P < 10MW		P ⩾ 10MW		Total		Gross Production 2021
	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Energy [MWh]
Piedmont	7	0.03	3	0.06	6	0.23	0	0.00	1	6.00	1	17.50	18	23.82	28 000
Aosta Valley	3	0.01	0	0.00	1	0.03	0	0.00	1	2.55	0	0.00	5	2.58	4 200
Lombardy	11	0.05	1	0.01	0	0.00	0	0.00	0	0.00	0	0.00	12	0.06	0
Trentino-South Tyrol	7	0.02	0	0.00	2	0.06	1	0.30	0	0.00	0	0.00	10	0.38	0
Veneto	14	0.06	1	0.02	0	0.00	0	0.00	3	13.35	0	0.00	18	13.43	22 600
Friuli-Venezia Giulia	5	0.01	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	5	0.01	0
Liguria	10	0.04	0	0.00	5	0.15	3	2.40	19	70.45	2	45.20	39	118.24	154 300
Emilia Romagna	30	0.12	2	0.03	32	1.43	4	1.90	3	8.80	2	32.60	73	44.88	83 200
Tuscany	50	0.22	4	0.06	51	2.44	6	1.20	5	32.25	6	106.80	122	142.97	287 000
Umbria	18	0.08	2	0.03	2	0.07	3	1.30	1	1.50	0	0.00	26	2.99	2 400
Marche	30	0.15	0	0.00	15	0.66	2	0.40	1	8.00	1	10.00	49	19.21	37 800
Lazio	28	0.14	2	0.04	34	2.01	7	3.50	4	17.00	2	52.00	77	74.69	151 600
Abruzzo	14	0.05	0	0.00	10	0.59	8	5.85	6	32.65	7	232.35	45	271.49	482 900
Molise	10	0.05	2	0.02	47	2.61	4	2.39	7	28.65	16	371.90	86	405.63	718 400
Campania	42	0.23	0	0.00	447	26.96	60	44.99	30	104.41	59	1 665.90	638	1 842.49	3 557 100
Apulia	118	0.68	17	0.29	874	51.04	178	129.08	41	126.71	113	2 688.24	1 341	2 996.04	5 387 100
Basilicata	31	0.21	3	0.05	1 216	83.30	150	68.78	9	29.26	48	1 293.67	1 457	1 475.27	2 651 800
Calabria	40	0.25	3	0.06	319	17.58	40	18.25	8	44.10	28	1 098.20	438	1 178.44	2 204 100
Sicily	190	1.42	32	0.58	604	29.93	8	7.44	14	98.91	65	1 984.34	913	2 122.63	3 393 900
Sardinia	102	0.53	11	0.21	455	27.19	18	5.15	5	25.56	22	1 054.50	613	1 113.15	1 760 500
Total	760	4.35	83	1.48	4 120	246.29	492	292.93	158	650.15	372	10 653.20	5 985	11 848.40	20 926 900

Anyway, the concept driving the validation phase was rather straightforward and intuitive. From the Terna database, the 2021 productivity was linearly scaled according to the total capacity of wind power documented in this paper. Consequentially, a comparison was made between the two values, the real one and the approximated one. The model was validated quantitatively, and critical results reviews were implemented.
This, in reality, was the second validation process employed for analysing the wind turbine model's output. Initially, a more specific analysis was conducted on select farms. The sample was chosen based on the availability of the park's estimated production data. In certain instances, this latter was found on the operational or commissioning company website or on some other sources. The validation cluster, therefore, was composed of all the parks where this data was available. In conclusion, the model's output for this subset was compared with the one found in the above sources. An additional quantitative way to assess the model's quality was obtained. To visualize the subset and the results, please refer to section 4.3.

2.4. Monte Carlo implementation

Lastly, error propagation using MC was performed on the results. The parks' subset of the second-mentioned validation procedure was used.
The MC was performed, as described in Famiglietti et al. [66], considering the level of uncertainty on electricity production (related to the implementation of the model itself) and the inherent uncertainty on the activity processes collected from ecoinvent 3.9.1. The exchange amount was not deprived of uncertainty due to the inherent variability of the natural world [66]. Two separate Monte Carlo analyses were performed: one with only the uncertainty related to the ecoinvent database, and the other aggregating this last with the confidence level on the subset of wind parks. More details on the creation of the inventory, hence the uncertainty and the distribution, were reported in section 3.2.
The procedure to write the code for running the Monte Carlo followed the instructions given in a Brigthway seminar [69]. The executions were fixed at 1000 for both cases with dependent sampling. The outcomes were later statistically analysed and some indicators were carried out to review the assessments. In the end, with the same procedure used for the deterministic outcome, the resulting emission factors are commented on together with the energy consumption of water electrolysis technologies.

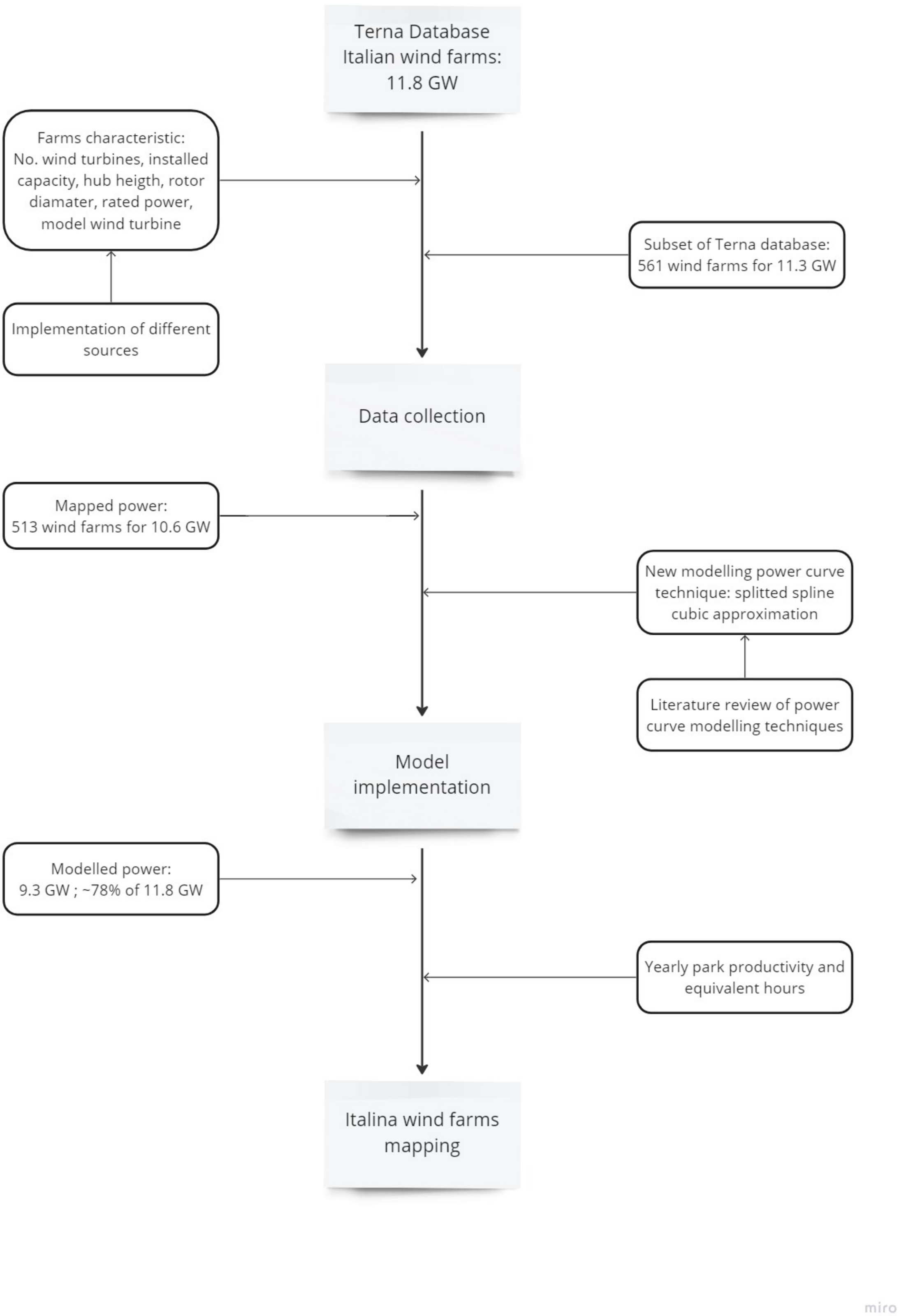

Figure 2.4: Workflow of the mapping procedure and productivity modelling

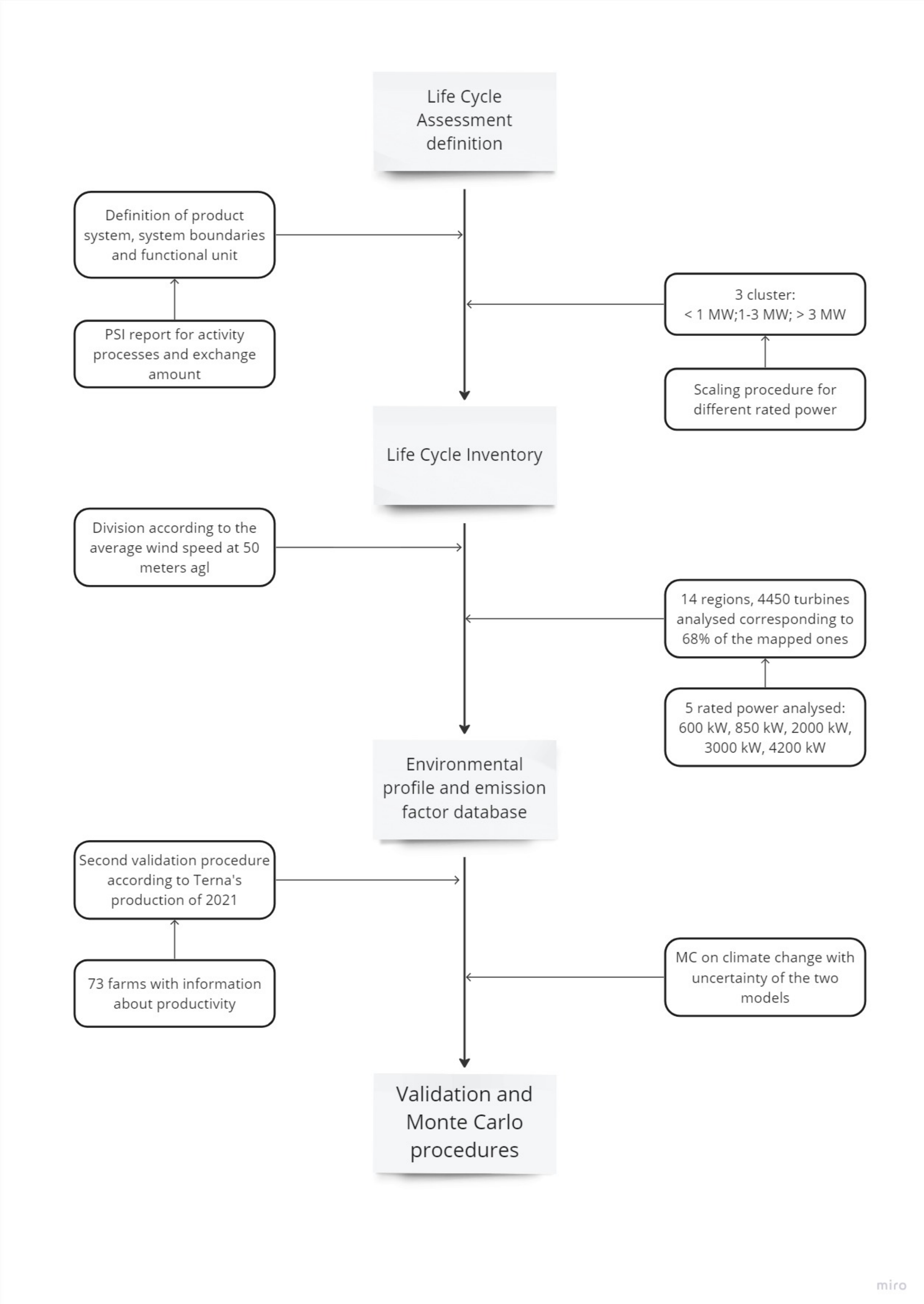

Figure 2.5: Workflow of the life cycle assessments and the validation procedure

3 | Life cycle inventory analysis

In this section, a more in-depth sight was done to the inventory of the environmental impact analysis. As stated, the latter's quality is then reflected in the quality of the results. The structure of the section consists of the examination of the inventory (i) for the deterministic results and then (ii) for the stochastic one, hence for the MC. A synthetic summary of the practical steps was reported as well in each subsection. This gives an overview of the whole procedure. Nevertheless, all these analyses were carried out here from a qualitative point of view; all the quantitative results were reported in the next chapter 4.

But first, the lists of activity processes used in the LCI are reported hereinafter. In Table 3.1 and Table 3.2, all the activities considered in this life cycle assessments are reported. Divided by the life phases, all the processes present in all three inventories are listed. Besides the activity name is also reported the geography. In fact, a different part of the word leads to different emissions embodied in the activity. The easiest example is electricity production; the national grid is quite different for the European Member States and even more varied around the world. As can be noted from the table below, in general, a global value was chosen to be more conservative by Burger and Bauer.

The legend for the geography acronymous is reported in Table 3.3 for the ones of interest. This list comes from the complete one provided by Mutel [70].

As can be observed, the operational and management part was not considered because of the lack of precise data and the impact of this stage can be considered negligible [32]. This is in accordance with the finding of an LCA performed by Vestas itself on one of the wind turbines. "The operation of the turbine does not directly contribute in a significant way to overall environmental impacts, except that electricity production and turbine lifetime are significant factors when assessing the impacts per kWh of electricity produced " [71]. Furthermore, there is no activity such as electricity production in the tables. Indeed, this is present and is the primary activity on which all the assessment is made; IT is not reported because of its particular role. The electricity production of the wind farms is reported as well and the other exchange amounts are modified by consequence.

Table 3.1: Activities and processes in LCI - Materials/Fuels phase

Activity name/ Reference product name	Geography	Life cycle phase
Alkyd paint, white, without water, in 60% solution state	RER,RoW	
Aluminium scrap, new	GLO	
Aluminium scrap, post-consumer	GLO	
Aluminium, cast alloy	GLO	
Aluminium, wrought alloy	GLO	
Cast iron	GLO	
Concrete, normal	GLO	
Copper, cathode	GLO	
Electronics, for control units	GLO	
Epoxy resin, liquid	RER, RoW	
Excavation, hydraulic digger	GLO	
Glass fibre reinforced plastic, polyamide, injection moulded	GLO	
Iron scrap, unsorted	GLO	
Lead	GLO	
Lubricating oil	RER, RoW	
Polyethylene, high density, granulate	GLO	
Polypropylene, granulate	GLO	
Polyvinylchloride, bulk polymerised	GLO	
Polyvinylchloride, emulsion polymerised	GLO	Materials/Fuels
Polyvinylchloride, suspension polymerised	GLO	
Reinforcing steel	GLO	
Road	GLO	
Section bar rolling, steel	GLO	
Sheet rolling, aluminium	GLO	
Sheet rolling, chromium steel	GLO	
Sheet rolling, steel	GLO	
Steel, chromium steel 18/8	GLO	
Steel, chromium steel 18/8, hot rolled	GLO	
Steel, low-alloyed	GLO	
Steel, low-alloyed, hot rolled	GLO	
Synthetic rubber	GLO	
Tin	GLO	
Transport, freight, lorry 7.5-16 metric ton, euro3	RER	
Welding, arc, steel	GLO	
Wire drawing, copper	GLO	
Zinc	GLO	
Zinc coat, pieces	GLO	

Table 3.2: Activities and processes in LCI - other phases

Activity name/ Reference product name	Geography	Life cycle phase
Occupation, industrial area	-	Resources
Occupation, traffic area, road network	-	
Transformation, from pasture, man-made	-	
Transformation, to industrial area	-	
Transformation, to traffic area, road network	-	
Diesel, burned in building machine	GLO	Electricity/heat
Electricity, medium voltage	GLO	
Wind power plant, 800kW, fixed parts	GLO	
Wind power plant, 800kW, moving parts	GLO	
Wind turbine network connection, 2MW, onshore	GLO	
Wind turbine network connection, 4.5MW, onshore	GLO	
Wind turbine, 2MW, onshore	GLO	
Wind turbine, 4.5MW, onshore	GLO	
Electronics scrap from control units	GLO	Waste to treatment
Scrap copper	CH, Europe without Switzerland, RoW	
Scrap steel	CH, Europe without Switzerland, RoW	
Waste glass	BR, CO, CY, IN, PE, RER, RoW, ZA	
Waste mineral oil	CH, Europe without Switzerland, RoW	
Waste paint on metal	CH, RoW	
Waste paint on wall	GLO	
Waste plastic, mixture	BR, CO, CY, IN, PE, RER, RoW, ZA	
Waste polyethylene	BR, CO, CY, IN, PE, RER, RoW, ZA	
Waste polyethylene/polypropylene product	CH, Europe without Switzerland, RoW	
Waste polypropylene	BR, CO, CY, IN, PE, RER, RoW, ZA	
Waste polyvinylchloride	BR, CO, CY, IN, PE, RER, RoW, ZA	
Waste reinforced concrete	CH, Europe without Switzerland, RoW	
Waste rubber, unspecified	CH, Europe without Switzerland, RoW	

Table 3.3: Geography name legend

Shortname / acronymus	Name
GLO	Global
RER	Europe
RoW	Rest of Word
BR	Brazil
CO	Colombia
CH	Switzerland
CY	Cyprous
IN	India
PE	Peru
ZA	South Africa

3.1. Life cycle inventory for deterministic results

After the mapping of the Italian farms, the selection of a meaningful sample for the LCA was determined. In order to accomplish this, several reasons were made, and the decision was again driven by an effort-reward trade-off.
From the large database, some key aspects were evaluated and considered more important for the results. Besides the regional discrepancy that was considered from the beginning, the wind speed and rated power of the single wind turbine were chosen as parameters of distinction. Indeed, the parks were subdivided according to these latter characterizations. A comprehensive Table was created in which, for each region, each column was allocated for different rated powers. For each region and for each rated power, the parks were further subdivided according to the wind speed. A range with a step of 0.5 m/s was chosen, starting from 5 m/s to 7 m/s. Naturally, the other two ranges were beyond the extremists. These groups were chosen according to the most common values found after data collection. It was observed that the majority of the wind farms were characterized by an average wind speed between 5 m/s and 7 m/s. The step of 0.5 m/s was chosen as a trade-off and was considered sufficiently accurate. Indeed, the range of velocity was verified from the Italian atlas as well. As noted later in Figure 4.8, the typical velocity at 50 meters above ground level in correspondence with the parks is inside the aforementioned range. Lastly, in cases where more than one park was inside the specific cluster of velocities, the one with more wind turbines, hence more total power, was chosen. With this arrangement, major importance was reserved for the most influential park.
This table is reported in the results section 4.2 (Table 4.4). From this latter the number of total wind turbines for rated power was available. According to this amount, the selection of which cluster of power to analyse was chosen. For each of the three macro clusters detected by the databases, i.e. the ones reported in section 2.2.1, the rated powers with a higher number were preferred. For the first cluster, wind turbines with rated power of 600 kW and 850 kW were chosen; for the middle cluster with 2000 kW and 3000 kW; for the last cluster, the LCA was assessed for wind turbines of 4200 kW. In conclusion, of the 6754 wind turbines modelled, these five categories cover 67%. Thus, 4550 wind turbines were accounted for in this study for the LCA.
For each park, the amount of electricity produced from the model multiplied by the lifespan. This total was the exchange amount of the primary activity data, hence the electricity production. After this, the life cycle assessment was performed through a code written in Brightway. This code takes as input the life cycle inventories and, then, each exchange amount is scaled according to its relationship with respect to the reference turbine (Table 2.1). For example, if the park was composed of wind turbines 850kW,

the reference turbine was Nordex N50/800 (see section 2.2.1). Indeed, the diameter and the hub height were compared with the reference one and the exchange value was scaled according to the law assigned.
Subsequently, the impact categories were computed and saved. The Table mentioned before was therefore updated with the value of the climate change category, i.e., the grams of CO_2e per kWh_{el}. The resulting Table was reported later on in Chapter 4.

3.2. Life cycle inventory for stochastic results

The last steps mentioned in the previous section 3.1, were the same adopted for the stochastic approach. What changed was the first part, hence the creation of the inventory. As stated, a subset of parks was used for the validation of the wind turbine model. Therefore, this analysis was done with this inventory. Around 70 parks were embodied in this subset and divided according to the three macro clusters. Unfortunately, the number of samples was not the same for the three classes. The bigger one was the middle class, from 1 MW to 3 MW with around 40 parks, followed by the lowest range, with half of the farms. Lastly, the remaining range was composed of only 6 parks. This asymmetry was explained by the narrow presence of wind turbines with high-rated power (higher than 4000 kW) in Italian territory. It could be considered a problem from a statistical point of view. In most cases, the bigger the sample is, the better because the outcomes would be based on wider examples. Unfortunately, there was nothing to overcome this imbalance. Later, the average of different parameters was taken to create the virtual wind turbine to assess the stochasticity of the results. Three Tables were created with the virtual turbine's characterizations to use in the environmental assessment.
The creation of the database necessary for the LCA was crucial. A unique database was created in order to maintain the same error propagation. The three singular ones, used for the deterministic outcomes, were merged together one after the other. With this precaution, the outcomes were more reliable from a statistical point of view.
As commented, a lognormal distribution was considered for the kilowatt-hours produced. The mean of the distribution was the natural logarithm of the electricity amount, while the dispersion of the parameter was the natural logarithm of the geometric standard deviation. This latter was computed on the absolute relative difference between the model and the "real" output of the parks. After inserting this information, the exchange amount of the other activity processes was scaled according to the reference turbine of the belonging class. In the end, a unique database with the electricity production, its distribution, and the scaled amounts was obtained.
Furthermore, a Brightway code was run considering this uncertainty. The code read the

unique database created and the Monte Carlo method was applied. 1,000 iterations were done, and for each one, the outcome was the climate change impact category value for the three virtual wind turbines. Thanks to the singular database, at each execution the uncertainty on the activity processes that were common in the three clusters, was the same. This can be considered a valid approach from a stochastic point of view because the same error propagation was maintained for the three different outcomes.

In the end, the same code was run but considering only the inherent uncertainty in the activity processes of ecoinvent. The values of electricity production were considered exact, with no uncertainty. Again 1,000 execution was performed and the mean, the lower and upper standard deviation were computed. These statistics indicators were also computed for the previous MC assessments. Therefore, in the result section 4.4, these key parameters of the two distributions were reported and commented on.

4 | Results and discussion

In this chapter, all the main and relevant results are carried out. Mainly reported through the interactive map, every outcome is critically reviewed. Firstly, (i) the wind turbine data collection and modelling are examined. Later, (ii) the deterministic LCA outcomes are carried and (iii) a short a short section regarding the validation of the wind turbine model is reported. After, (iv) the stochastic results are listed and the last section (v) reports the final range of CC emission factors considering the validation outcomes.

4.1. Wind turbine electricity production model

Due to the great amount of outcomes and information provided in this section, further subsections were created. This allows for a better focus on the topic and to clearly understand the conclusion.
At first, (i) the data collection outcomes are reported. The total installed capacity in Italy is compared with the one actually examined in the paper. After, (ii) the result of the different modelling techniques is carried out through some examples. Lastly, (iii) the interactive map is introduced. A first overview of the results implemented in the map is reported.

4.1.1. Collection data outcome

As stated, not all the parks were considered from the Terna database reported in Table 2.3. Indeed, in Table 4.1 the ranges selected for this study are listed. The first three clusters were not considered at all; the whole subset of parks below 200 kW as total installed capacity has a weight of only 2.13% of the total. Therefore, with this assumption, only a few parts of the almost 12 GW of Italian wind power installed were neglected. Furthermore, for some regions, even parks within the range of 200 kW-1MW were ignored due to the challenge of getting the information required and their little significance on the total. For example, the over 170 parks in Apulia within this range have a total power installed of 129.1MW, which accounts for less than 5% of the total of the region. The work needed to account for these parks was not worth it. The same was done for other

Table 4.1: Subset of Terna database

Region	200kW ⩽ P < 1MW		1MW ⩽ P < 10MW		P ⩾10MW		Total	
	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]
Piedmont	0	0.00	1	6.00	1	12.50	2	18.50
Aosta Valley	0	0.00	1	2.55	0	0.00	1	2.55
Lombardy	0	0.00	0	0.00	0	0.00	0	0.00
Trentino-South Tyrol	1	0.30	0	0.00	0	0.00	1	0.30
Veneto	0	0.00	3	13.35	0	0.00	3	13.35
Friuli-Venezia Giulia	0	0.00	0	0.00	0	0.00	0	0.00
Liguria	3	2.40	19	70.45	2	45.20	24	118.05
Emilia Romagna	4	1.90	3	8.80	2	32.60	9	43.30
Tuscany	6	1.20	5	32.25	6	106.80	17	140.25
Umbria	3	1.30	1	1.50	0	0.00	4	2.80
Marche	2	0.40	1	8.00	1	10.00	4	18.40
Lazio	-	-	4	17.00	2	52.00	6	69.00
Abruzzo	8	5.85	6	32.65	7	232.35	21	270.85
Molise	4	2.39	7	28.65	16	371.90	27	402.94
Campania	-	-	30	104.41	59	1 665.90	89	1 770.31
Apulia	-	-	41	126.71	113	2 688.24	154	2 814.95
Basilicata	-	-	9	29.26	48	1 293.67	57	1 322.93
Calabria	-	-	8	44.10	28	1 098.20	36	1 142.30
Sicily	-	-	14	98.91	65	1 984.34	79	2 083.26
Sardinia	-	-	5	25.56	22	1 054.50	27	1 080.06
Total	31	15.74	158	650.15	372	10 648.20	561	11 314.10

regions as can be seen in the table below, where empty cells ("-") are present in the first range of rated power.

As a result of this first skimming, a total of 11 314.1 MW was obtained corresponding to 561 parks. This corresponds to roughly 95% of the total Italian capacity. Therefore, the goal of collecting data was referred to as this amount.

Unfortunately, as already pointed out, not all the 561 parks were mapped. In this work, two additional reductions are present and are reported hereinafter. Firstly, finding the information for all the capacities considered was challenging. Indeed, in Table 4.2 the list of parks where some information was found is reported. With the same layout of the previous Table 4.1, the difference for each region and each power range can be appreciated. The clusters where some discrepancies are presented are reported within the bald text to better visualise the comparison between the two tables. To the best of the author's knowledge, these mismatches were not possible to overcome.

Different scenarios are present. For example, all 19 parks with power between 200 kW and 1 MW are mapped in Liguria. Nevertheless, the total installed capacity is lower with respect to the Terna value. In the sources of these wind parks, this means asymmetries were found about the total power installed for the park. Even if Terna's data are considered completely correct, it is decided to account for a total power of 62.10 MW (Table 4.2 instead of 70.45 MW (Table 4.1) anyway; no other way to overcome this issue was found. In the South, the trend is more or less the same. Most of the parks are in this area, so

Table 4.2: Mapped parks of the subset

Region	200kW ⩽ P < 1MW		1MW ⩽ P < 10MW		P ⩾10MW		Total	
	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]	Number	Power [MW]
Piedmont	0	0.00	1	6.00	2	12.50	3	18.50
Aosta Valley	0	0.00	1	2.55	0	0.00	1	2.55
Lombardy	0	0.00	0	0.00	0	0.00	0	0.00
Trentino-South Tyrol	1	0.30	0	0.00	0	0.00	1	0.30
Veneto	0	0.00	3	13.35	0	0.00	3	13.35
Friuli-Venezia Giulia	0	0.00	0	0.00	0	0.00	0	0.00
Liguria	3	2.40	19	**62.10**	2	45.20	24	109.70
Emilia Romagna	4	1.90	3	8.80	2	32.60	9	43.30
Tuscany	6	1.20	5	32.25	6	106.80	17	140.25
Umbria	3	1.30	1	1.50	0	0.00	4	2.80
Marche	2	0.40	1	8.00	1	10.00	4	18.40
Lazio	-	-	**3**	**18.80**	2	52.00	5	70.80
Abruzzo	8	5.85	**7**	**39.78**	**11**	**214.15**	26	259.78
Molise	4	2.39	7	28.65	16	**372.20**	27	403.24
Campania	-	-	**19**	**90.69**	**64**	**1 682.05**	83	1 772.74
Apulia	-	-	**19**	**90.01**	**84**	**2 301.44**	103	2 391.45
Basilicata	-	-	**5**	**25.18**	**47**	**1 216.34**	52	1 241.52
Calabria	-	-	**8**	**39.66**	**29**	**1 081.05**	37	1 120.71
Sicily	-	-	**18**	**103.41**	**67**	**1 825.84**	85	1 929.25
Sardinia	-	-	**4**	**20.43**	**25**	**1 034.00**	29	1 054.43
Total	31	15.74	124	591.16	358	9 986.17	513	10 593.07

mapping was even harder. As a result, the numbers of parks or the power installed are often different with respect to the Terna database.

It was challenging to collect correct data from nearby wind parks. Commonly, the information was different between the different sources and it was hard to replicate the division expressed in Table 4.1. In other cases, such as in Calabria, 8 parks were found between 1 MW and 10 MW but the total installed power has proven lower. As a rule of thumb, the goal during the collection was to try to replicate the Terna division as much as possible, but higher importance was given to the total power. The closer the total mapped power was to the real one, the better, regardless of the exact subdivision of the number of parks in the rated power ranges. As a result of this data collection, the total wind capacity mapped is 10593.07 MW corresponding to 93.6% of the total reported in Table 4.1, 11314.10 MW. Furthermore, the number of parks passed from 561 to 513.

Unfortunately, the electricity production was not estimated for all these 513 parks. This was mainly due to missing the key information of the turbine model. No assumptions were made on this factor because it would result in misleading the results. The power curve is the cornerstone of the modelling techniques. Hence, without this information, it is not possible to compute the yearly production. As a result, a lower number of megawatts is assessed on the whole.

In Table 4.3 a summary of these different downsizing methods is reported. It can be appreciated, divided per region, the total capacity in the different steps. The first column

is the grand total of the whole Italian wind park. In the column "Subset Power", the capacity reported are the ones considered for the sake of the analysis. It is the "Total" column of table 4.1, hence the power considered for data collection. Of this total, a lower amount was mapped by the author and is reported in the third column. In the last column, only the parks for which the electricity production was estimated are considered. Therefore, the last column is most interesting because it reports the installed capacity evaluated in this work.
The last row reports the percentage difference between the different totals. As can be noted, the major loss comes from the last step. Around 12% of the total power is lost, and this is a huge topic that comes from the report. Insufficient information on the mapped parks was the main source of incompleteness.

It can be stated that, of the total power considered in the subset, 82.3% was successfully mapped and modelled. Overall, the outcomes of this report concern 78.6% of the 11.8 GW of Italian wind capacity. 513 wind parks, with a total installed power of 9.3 GW, are evaluated.

Region	Italian Power [MW]	Subset Power [MW]	Mapped Power [MW]	Modelled Power [MW]
Piedmont	23.82	18.50	18.50	18.50
Aosta Valley	2.58	2.55	2.55	2.55
Lombardy	0.06	0.00	0.00	0.00
Trentino-South Tyrol	0.38	0.30	0.30	0.00
Veneto	13.43	13.35	13.35	13.35
Friuli-Venezia Giulia	0.01	0.00	0.00	0.00
Liguria	118.24	118.05	109.70	102.80
Emilia Romagna	44.88	43.30	43.30	43.30
Tuscany	142.97	140.25	140.25	139.85
Umbria	2.99	2.80	2.80	2.40
Marche	19.21	18.40	18.40	10.40
Lazio	74.69	69.00	70.80	69.00
Abruzzo	271.49	270.85	259.78	243.45
Molise	405.63	402.94	403.24	402.84
Campania	1 842.49	1 770.31	1 772.74	1 436.12
Apulia	2 996.04	2 814.95	2 391.45	2 118.17
Basilicata	1 475.27	1 322.93	1 241.52	993.06
Calabria	1 178.44	1 142.30	1 120.71	1 039.55
Sicily	2 122.63	2 083.26	1 929.25	1 834.65
Sardinia	1 113.15	1 080.06	1 054.43	841.02
Total	11 848.40	11 314.10	10 593.07	9 311.01
Difference	-	4.51%	6.37%	12.10%

Table 4.3: Comparison of the total installed capacity in the different steps

4.1.2. Power curve approximation

As carried out in section 2.1, four different techniques were tested and reviewed in this thesis. Three come from the literature, while the fourth one, the one applied in the end, is a novelty proposed by the author. Three turbine models were tested, and the results are carried out hereinafter to verify the quality of the approximation.
The models analysed were chosen according to the most common. In the beginning, after mapping some regions, it was noted that some models were present more than others. Therefore they were used for this test. After the majority of the regions were mapped, another model was added for completeness. Finally, the three models listed below 95 parks are considered; their power curves are reported in Figure 4.1, 4.2 and 4.3. For coherence with the results, the power curves were not taken from the manufacturers but from the reference online database [51].
The three models are:

- Vestas V52/850
- Enercon E82/2000
- Vestas V90/2000

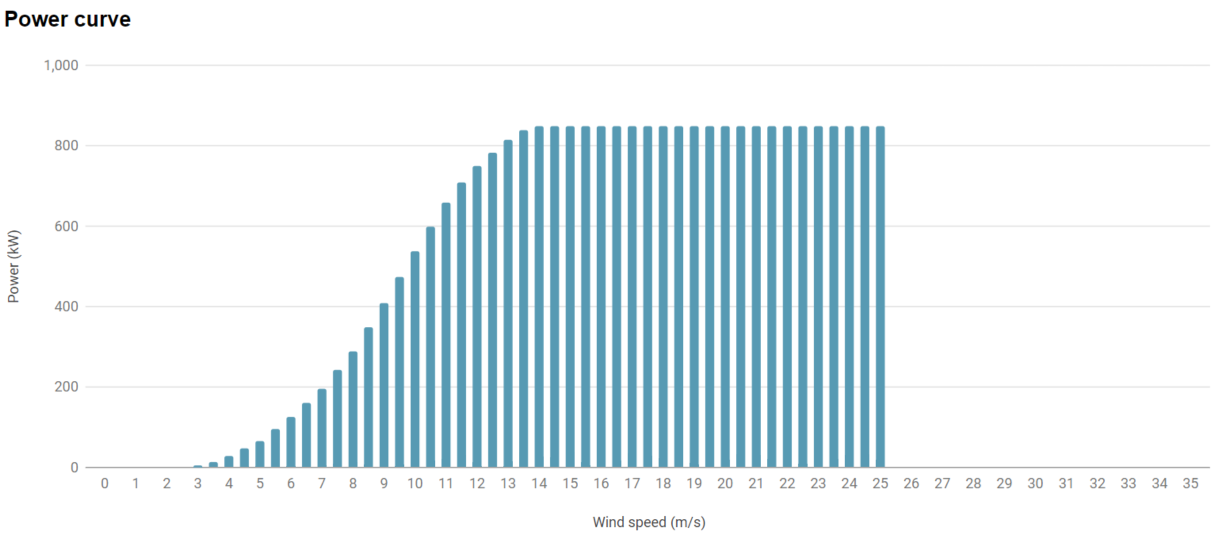

Figure 4.1: Vestas V52/850 - Power Curve

With a step of 0.5 m/s, the speed-power couple were collected and implemented in the Python code. Through this latter, the different techniques were compared and later the production was estimated. For the sake of the analysis, the spline cubic approximation with all the speed-power couples is used as a reference. As stated in the literature, this approach replicates almost exactly the actual performance of the wind turbine [43]. There-

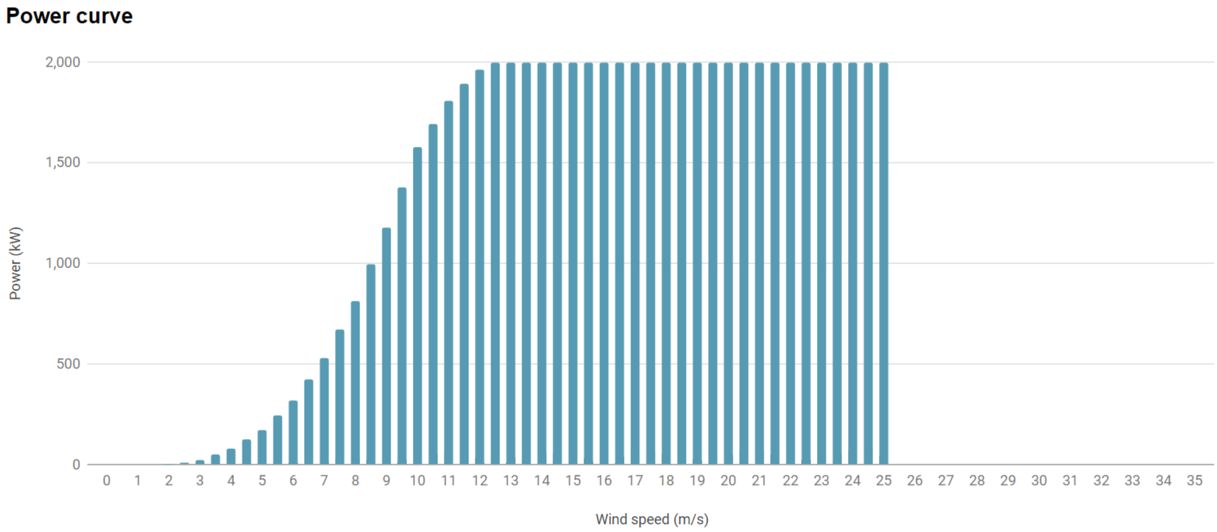

Figure 4.2: Enercon E82/2000 - Power Curve

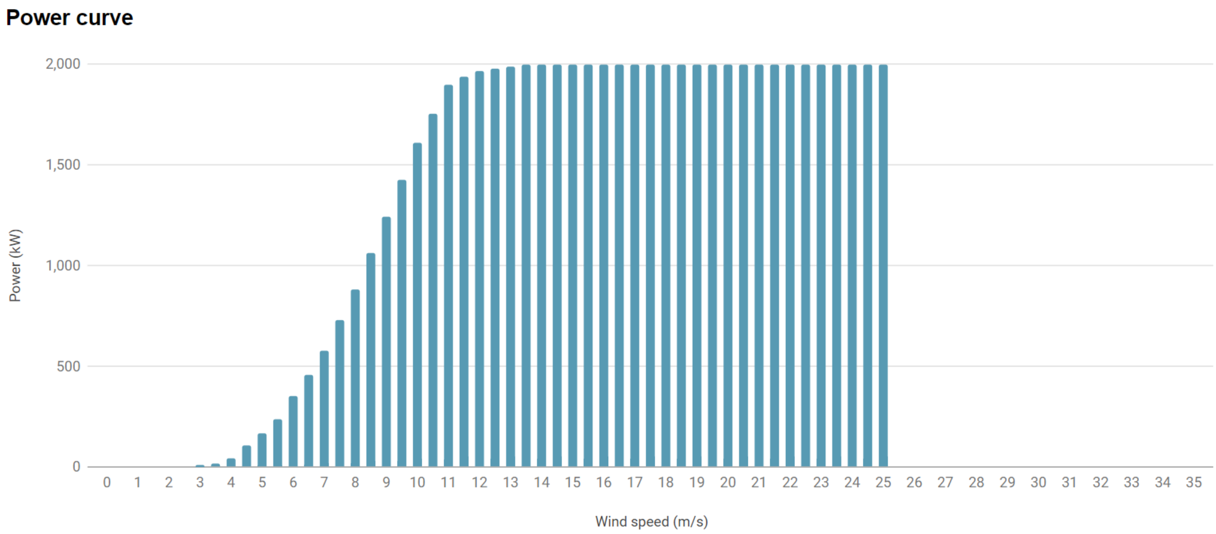

Figure 4.3: Vestas V90/2000 - Power Curve

fore, the Weibull and cubic approximation are compared with this reference modelling technique; in the left-hand side of Figure 4.4, 4.5 and 4.6 the comprehensive comparison is reported. On the other side, in Subfigure 4.4b, 4.5b, 4.6b, the comparison between the holistic spline cubic and the one proposed in this paper is reported.
The red points are the couples of values coming from the power curve characterization; as noted, the dotted blue line, i.e., the spline cubic technique, can be considered the actual power curve. In the case of Weibull and Cubic techniques, the difference can be detected graphically. The concavity of the yellow and the green curves does not change with these approximations like in the real case. Therefore, an appreciable difference in the result can be noted. For all the models, the magnitude of the discrepancy seems to be more or less the same. Indeed, an underestimation of the power produced would happen for every wind speed. Only for the Enercon E82/2000, Figure 4.6a, does the yellow curve for wind speed near the cut-it value have a greater production than the actual one.
For all the parks mapped, in case these three models were present, the electricity production difference was computed. A percentage difference was computed considering the output of the spline approximation as the correct one. Despite the power curve being the same for the specific model, the resulting difference strongly depends on the wind speed values. According to the figures, the more the wind speed is in the lower part of the curve, the better it is. Indeed, the difference is less marked in this area of the chart.
The cubic approximation technique results in the worst one, as can be noted also by the charts. The average difference in electricity production is around 32%. The Weibull techniques' performance is much better, which differentiates the outcomes of around 13%. Nevertheless, the performances obtained are not considered sufficient for the scope of the paper. The electricity production is the key input for the LCA, hence the better the approximation the better the quality of the climate profile. Indeed, another technique is needed and proposed by the author.
As it can be pointed out by looking at the right-hand side figures, the difference in this case is far less. For the smaller turbine, Figure 4.4b, the two lines seem to overlap for all the range of interest. Also, the difference is not visually appreciable in the case of Enercon E82/2000. On the contrary, in Figure 4.5b, a slight discrepancy can be noted for wind speed in the 10-13 m/s range. Nevertheless, this dissimilarity is not comparable with the Weibull or cubic one.
The beige star stands for the middle point chosen by the power curve data. In the end, on the 95 parks evaluated, the percentage difference is around 2.4%. A quite remarkable achievement which was more than acceptable for the study.

(a) Weibull and cubic approximation (b) Author's proposing approximation

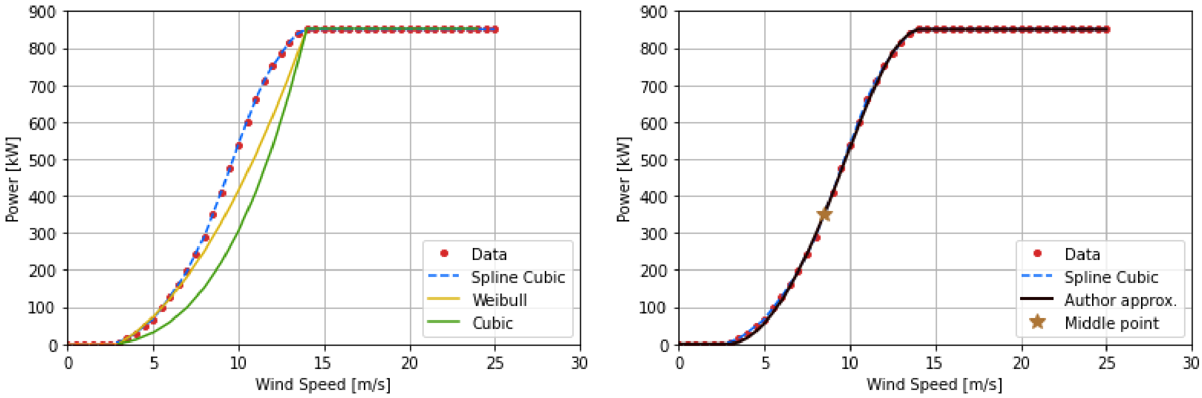

Figure 4.4: Comparison of modelling techniques - Vestas V52/850

(a) Weibull and cubic approximation (b) Author's proposing approximation

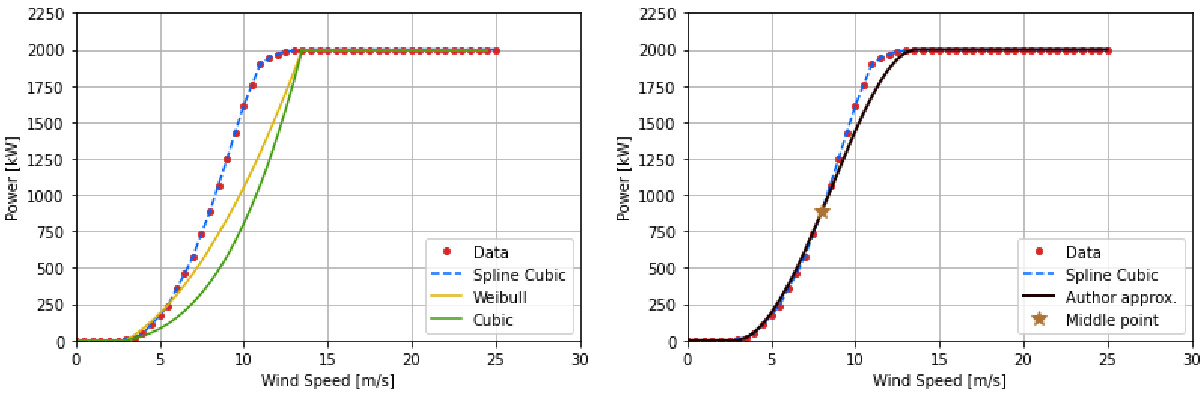

Figure 4.5: Comparison of modelling techniques - Vestas V90/2000

(a) Weibull and cubic approximation (b) Author's proposing approximation

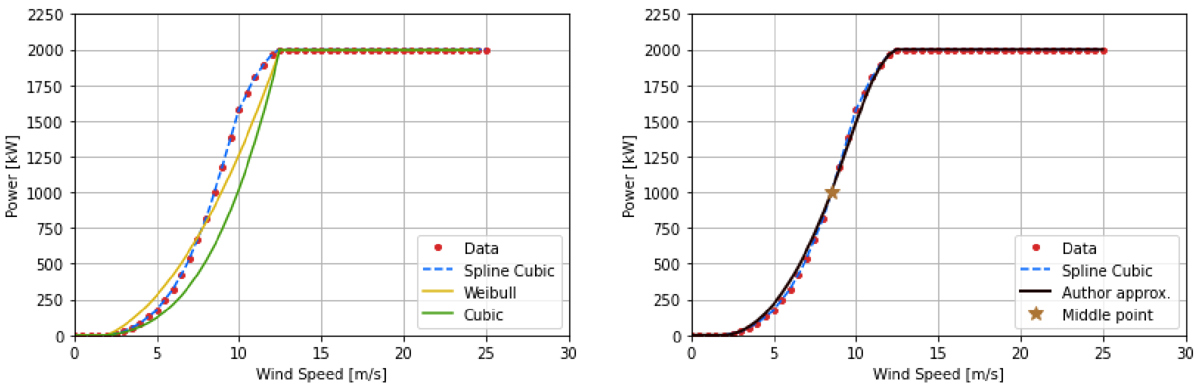

Figure 4.6: Comparison of modelling techniques - Enercon E82/2000

As already pointed out in the report, this last method is proposed as an excellent solution for power curve models. The additional information required, i.e., the curve's middle point, leads to a difference in the order of 2% with the real electricity production. This accuracy is more than acceptable for mostly of engineering research.

4.1.3. Farms map

After this first part of the project, the database for the further life cycle assessments was created. For all the parks modelled, a value of yearly electricity production of one turbine was estimated. By multiplying this amount by the number of wind turbines in the park, the total production of the park was obtained.
The author's idea was to create a better way to visualize these outcomes; a compact but exhaustive solution to allow the users to benefit from the database created. Taking as inspiration the different sources used in data collection, an interactive map was created. In the end, a satisfactory and personalized map was created, which could always be improved.

In this section, a first overview of the map is carried out, with a focus on the data collection and wind turbine modelling outcomes. Later, in section 4.2.2, the focus is shifted to the results of the environmental assessments.
Figure 4.7 reports the map at the first opening. The blue icons highlight all the mapped parks, and their distributions throughout the Italian territory can be instantly visualized. At first, this can be compared with Figure 4.8, which reports the average wind velocity at 50 meters above ground level coming from the Italian atlas AEOLIOAN (the figure was modified for best suitability). As stated previously, all the park information required was missing in the Italian atlas but still, it was used for the average wind speed at the park location.
From the comparison between Figure 4.7 and 4.8, it can be appreciated how the maps' distribution of the parks generally follows the average speed trend. In the South, where the wind speed is higher, the density is higher as well. The same can be stated for the islands.
Obviously, this consideration is not the only one. There are many other reasons, also behind the engineering world, that influence the position and the installation of wind farms that are not covered in this thesis.

Figure 4.7: Interactive map with wind parks

Figure 4.8: Italian atlas with average wind speed at 50 m a.g.l. [49]

Another key aspect that is reported in the map, is the asymmetry between the position of the parks and the anemometer from which the epw files were obtained. The anemometers can be visualised on the map with an interactive panel control. The result is reported in Figure 4.9 where it can be appreciated the distribution in the whole territory, highlighted with the orange icons. These anemometers are the ones present in the database used for this thesis [56]. As stated in section 2.1.1, few epw data were available in the South.

This is further highlighted with the focus reported in Figure 4.10. Unfortunately, few anemometer data were found where the highest concentration of parks is present. As a result, an acceptable but not very accurate wind profile for these parks is obtained.

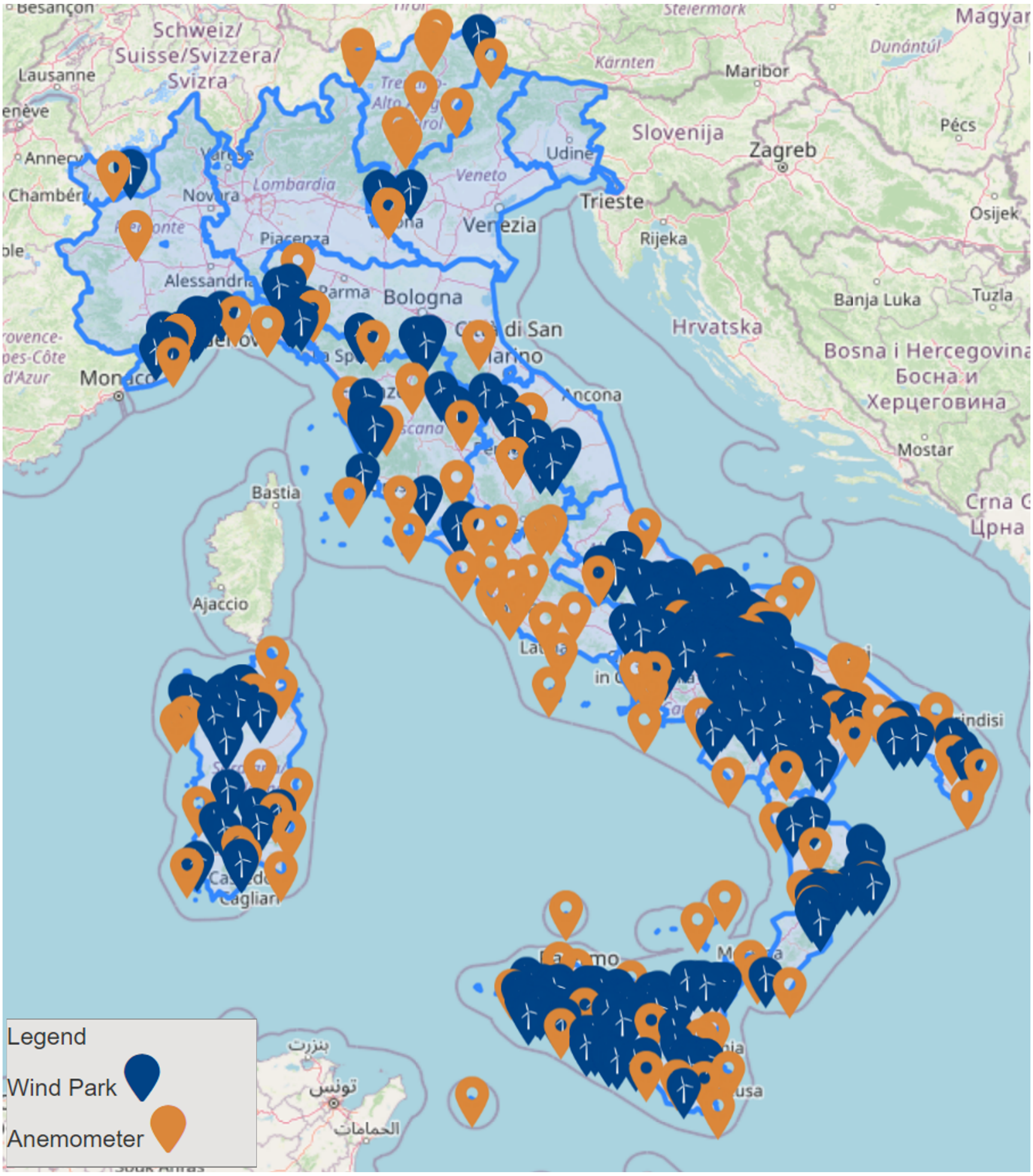

Figure 4.9: Interactive map with wind parks and anemometers

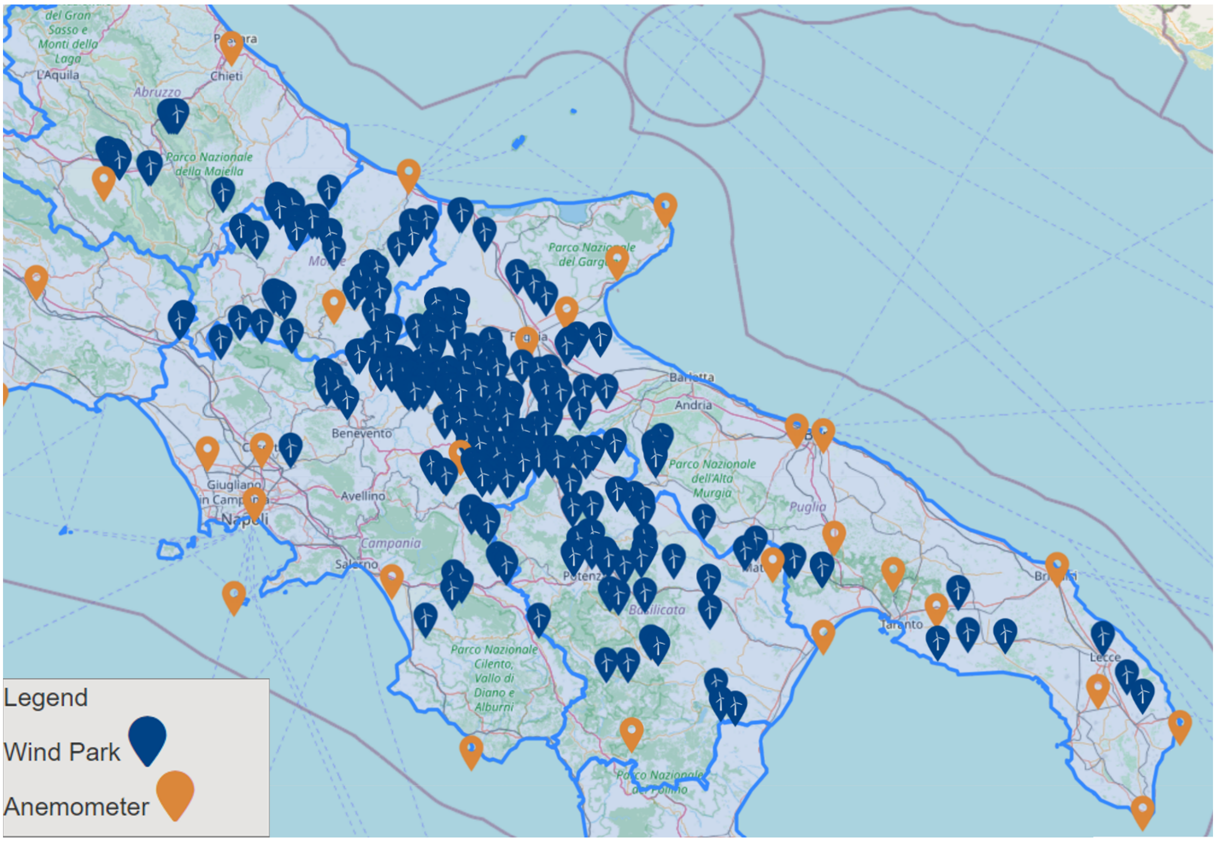

Figure 4.10: Focus on South region - wind parks and anemometers

Lastly, for each park, the most relevant information is reported. By clicking on a specific blue icon, a popup comes out with the following data:

- Location-city of the park
- Number of wind turbines
- Model of the wind turbine
- Total installed power
- Yearly productivity
- Equivalent hours

An example is reported in figure 4.11 for a generic wind park. The first three items are derived from the data collection while the yearly productivity and the equivalent hours are the result of the model applied.

In addition, other actions can be done on the map for a more user-friendly interface. For example, the regional borders can be hidden or changed with the provinces' or the municipalities' borders. Furthermore, it can be selected to show only the parks of specific regions through the panel control implemented. Lastly, the background map can be changed for a different visualization. An example of this customisation is reported in the previous figure 4.11 where the background map is different and the borders highlighted are the regional ones.

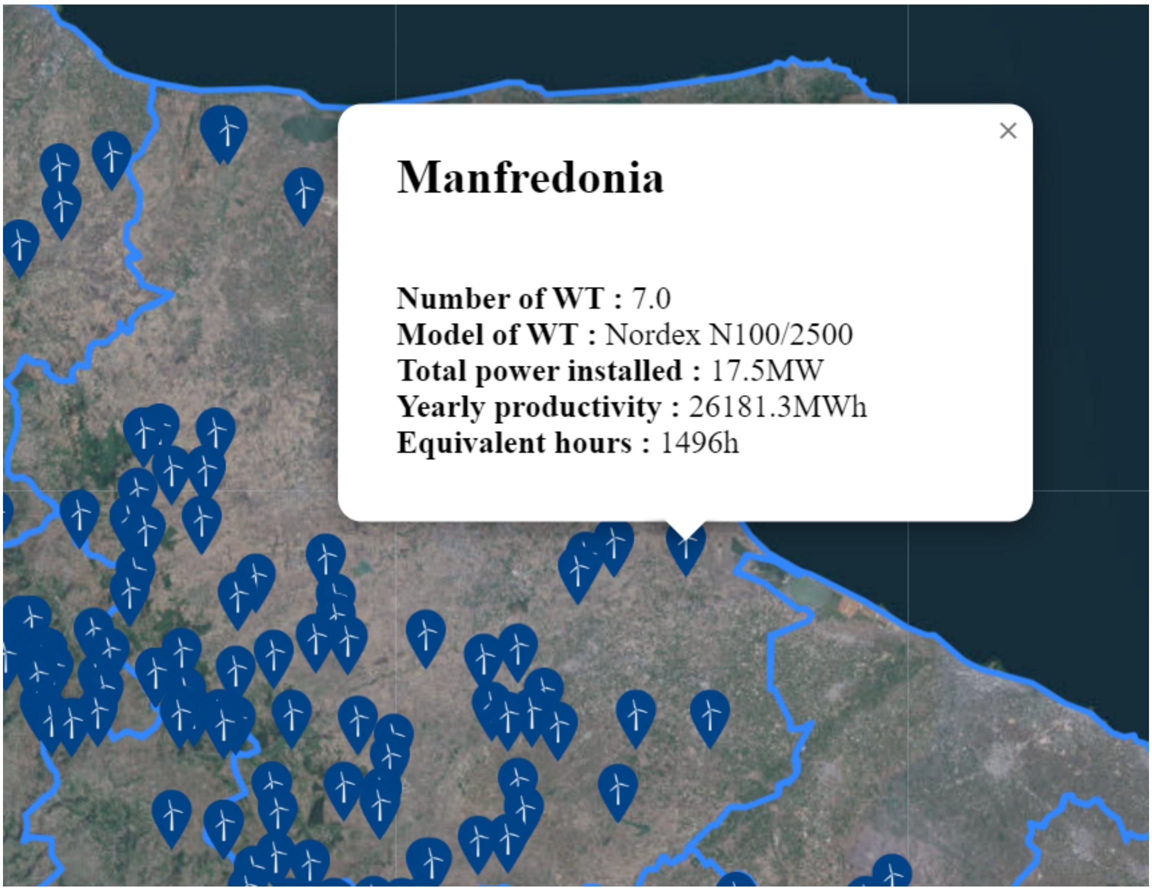

Figure 4.11: Example of information reported for each park

4.2. Life Cycle Assessments deterministic outcomes

As explained in section 3, the inventories for the life cycle assessments were created according to the results of the modelling part reported in Table4.3. 513 parks were mapped concerning a total number of 6754 wind turbines. As already pointed out, it was unfeasible to perform LCA for all these turbines, therefore, a selection was made. This was done according to each macro cluster's most common rated power. Indeed, for the range lower than 1 MW, the two rated power selected were 600 kW and 850 kW. In the middle range, from 1 MW to 3 MW, the most commonly rated power was 2000 kW and 3000 kW. Lastly, only the wind turbines with a rated power of 4200 were chosen for the

highest range.
These five selected powers interest a total of 4550 wind turbines, which correspond to around 68% of the ones mapped. With this choice, three regions are not considered, even if they have a modelled power higher than zero, as shown in Table 4.3. Piedmont, Veneto and Umbria have no wind turbines installed with one of these five rated powers. Therefore, in the following tables, these regions are not reported as well as the others with zero modelled power.

For each region and wind speed, the climate profile was computed according to the amount of electricity produced. In case more than one park was inside the same wind speed range, the electricity used was the one with the highest number of wind turbines. The climate change impact category outcome was saved and the Table 4.4 reports the final results. The total number of wind turbines, emission factor, and average wind speed are present for each rated power. From this table, divided in two for a better visual, all the LCA output can be appreciated. Indeed, state-of-the-art Italian wind farms have been obtained.
The wind speed value is the one coming from the atlas, hence the average wind speed at 50 m above ground level. It was decided to use this value instead of the resulting average wind speed at hub height, computed with the scaling procedure, in order to have a unique reference. In the first column from the right-hand side, the range of wind speed is reported for completeness.
The average emissions factor is highlighted in the last row, besides the total number of turbines for rated power. This value is a mathematical average of the emission factors in the central column of each rated power.
The majority of the wind turbines have a rated power of 850 kW (1748) or 2000 kW (1837). The average environmental impact of these two categories is 18.29 gCO_2eq/kWh_{el} and 17.93 gCO_2eq/kWh_{el} respectively.

Table 4.4: Climate Change emission factors outcome

Region	Rated power: 600 kW			Rated power: 850 kW			Rated power: 2000 kW			Rated power: 3000 kW			Rated power: 4200 kW			Wind speed
	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	range [m/s]
Aosta Valley				3	32.62	4.13										<5
																[5.50.5]
																[5.50-6]
																[6-6.50]
																[6.50-7]
																>7
Liguria																<5
																[5.50.5]
													6	91.58	5.74	[5.50-6]
				4	14.13	6.40	5	13.07	6.47							[6-6.50]
																[6.50-7]
				2	12.70	7.07										>7
Emilia Romagna	1	20.29	4.68													<5
				4	17.49	5.44										[5.50.5]
	6	12.71	5.90													[5.50-6]
	4	11.25	6.35													[6-6.50]
																[6.50-7]
																>7
Tuscany							4	22.57	4.53							<5
																[5.50.5]
				7	16.71	5.93	15	17.93	5.52							[5.50-6]
							10	16.78	6.14							[6-6.50]
	3	20.62	6.70													[6.50-7]
																>7
Marche																<5
																[5.50.5]
							5	16.08	5.72							[5.50-6]
							4	NO DATA	6.08							[6-6.50]
																[6.50-7]
																>7
Lazio																<5
	18	18.86	5.40													[5.50.5]
							30	16.72	5.99							[5.50-6]
																[6-6.50]
																[6.50-7]
																>7
Abruzzo				37	44.18	3.71	6	26.30	4.75							<5
	26	16.62	5.37				30	19.52	5.34							[5.50.5]
	56	14.95	5.76				4	18.02	5.63							[5.50-6]
																[6-6.50]
																[6.50-7]
																>7

Region	Rated power: 600 kW			Rated power: 850 kW			Rated power: 2000 kW			Rated power: 3000 kW			Rated power: 4200 kW			Wind speed
	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	N° [No.]	CC [kgCO2e/kWh]	Avg. speed [m/s]	range [m/s]
Molise							13	21.47	4.99							<5
							29	20.67	5.10							[5.50.5]
				15	16.90	5.54							7	116.52	5.86	[5.50-6]
				65	14.52	6.29	21	16.91	5.80							[6-6.50]
				45	13.29	6.98	17	14.32	6.06	8	12.44	6.59				[6.50-7]
																>7
Campania				10	26.63	4.50	19	21.81	4.78							<5
	4	30.29	5.32	34	19.32	5.19				12	15.34	5.46				[5.50.5]
	43	26.79	5.82				91	17.58	5.57	13	NO DATA	5.57				[5.50-6]
	125	16.25	6.23	49	15.31	6.23	35	13.24	6.37	67	12.37	6.51				[6-6.50]
	33	15.01	6.74	39	13.09	6.68										[6.50-7]
	21	12.78	7.22							35	17.43	7.89				>7
Apulia							246	22.93	4.88	37	28.32	4.72	2	110.20	4.62	<5
				17	20.28	5.20	84	20.36	5.17				6	NO DATA	5.28	[5.50.5]
				31	17.86	5.95	127	18.40	5.57	25	17.44	5.95				[5.50-6]
	48	16.74	6.16				76	15.71	6.12							[6-6.50]
	43	9.92	6.71													[6.50-7]
	196	8.72	7.22	6	11.47	7.11	23	8.48	7.09							>7
Basilicata				3	24.24	4.91	84	26.72	4.78	6	NO DATA	4.73				<5
							41	22.64	5.05	26	27.01	5.06				[5.50.5]
				11	23.20	5.98	66	24.19	5.63	8	20.48	5.79				[5.50-6]
							25	22.56	6.15	21	27.97	6.00				[6-6.50]
				28	18.18	6.65										[6.50-7]
																>7
Calabria							2	16.44	4.88							<5
							36	20.78	5.29							[5.50.5]
							142	17.50	5.66							[5.50-6]
				54	17.39	5.77	115	9.80	6.30							[6-6.50]
				22	11.10	6.96	10	14.48	6.52	5	10.34	6.84				[6.50-7]
				38	10.22	7.35										>7
Sicily				87	25.90	4.76							10	114.82	4.97	<5
				340	18.43	5.48	110	18.43	5.16	33	15.63	5.44				[5.50.5]
				195	18.09	5.77	82	15.87	5.76	11	15.34	5.50				[5.50-6]
				171	14.50	6.32	31	15.23	6.07							[6-6.50]
				228	13.28	6.62										[6.50-7]
																>7
Sardinia							35	21.94	4.71							<5
				23	20.70	5.13	10	16.23	5.29							[5.50.5]
				54	17.86	5.91	37	17.50	5.77							[5.50-6]
				115	14.30	6.36	48	13.12	6.51							[6-6.50]
				11	13.17	6.73										[6.50-7]
							69	9.16	7.09							>7
Total	627	16.35		1 748	18.29		1 837	17.93		307	18.34		31	108.28		

Table 4.5: Average climate change emission factor per region per rated power

Region	CC for 600 kW [gCO_2eq/kWh_{el}]	CC for 850 kW [gCO_2eq/kWh_{el}]	CC for 2000 kW [gCO_2eq/kWh_{el}]	CC for 3000 kW [gCO_2eq/kWh_{el}]	CC for 4200 kW [gCO_2eq/kWh_{el}]
Aosta Valley	-	32.62	-	-	-
Liguria	-	13.66	13.07	-	33.43
Emilia Romagna	12.28	17.49	-	-	-
Tuscany	20.62	16.71	18.17	-	-
Marche	-	-	8.94	-	-
Lazio	18.86	-	16.72	-	-
Abruzzo	15.48	44.18	20.39		-
Molise	-	14.36	18.46	12.44	38.55
Campania	18.00	16.54	17.08	14.24	
Apulia	10.24	17.91	19.92	23.93	35.07
Basilicata	-	19.93	24.69	23.83	-
Calabria	-	13.78	14.88	10.34	-
Sicily	-	17.19	17.04	15.56	41.35
Sardinia	-	15.91	14.27	-	-
Total	15.91	20.02	16.97	16.72	37.10

Table 4.5 reports the same results as the previous table but with another compact form. Indeed, a weighted average is computed for each region and for each rated power. There is no more distinction according to the average wind speed of the parks. The number of wind turbines inside the ranges of wind speed was used to obtain the weighted average reported in the cells of this table. For example, in Abruzzo, the emission factor for 2000 kW is very similar to the one obtained in Table 4.4 for a wind speed within the 5-5.5 m/s range. This is in accordance with the highest number of wind turbines in this range, 36, with respect to the other (6 and 4).

From the "Total" row, reporting the average value per rated power, a range between 16-20 gCO_2eq/kWh_{el} can be assessed for all the cases except for the 4200 kW wind turbines. This latter has a slightly higher average value, 37.10 gCO_2eq/kWh_{el}. This value can be justified as follows.
The reference wind turbine for this cluster is the Enercon E112/4500 for which the scientific paper gives the exchange amounts. After scaling according to Table 2.1, the final databases for some parks are analysed more deeply. A comparison between the different clusters is performed and reported in Table 4.6.
The focus is on the amount of raw materials, given in kg in the database, per kWh. This is an index of the density of raw materials per electricity, which greatly influences the final LCA results. As stated in the literature, sourcing raw materials is one of the most relevant phases for the overall impact. Therefore, this amount in mg per kWh is reported in the last column of the table. The exchange activities reported in Table 3.1 for the raw materials are considered, except for the aluminium and iron scrap and the activity with

units different from kg like concrete, road, etc. It is obviously the first high-level analysis but still reliable to understand better the outcome of the life cycle assessments.
From the table, a trend can be noted with the higher density for the higher-rated power. This means the increase in electricity production does not compensate for the increase in materials needed, hence the final emission factor is influenced negatively. This can explain the generally higher environmental impact of wind turbines of 4200 kW.
It must be noted how this is not the only reason but just one aspect. There are many others to be considered in the materials category, but in the other phases too.

Table 4.6: Further analysis on the LCI

Wind farm	Rated power [kW]	Equivalent hours [h]	CC [gCO_2eq/kWh_{el}]	Relative index [mg/kWh_{el}]
Calice Ligure	850	2364	12.70	5827.91
Andretta	2000	2099	13.23	4887.62
San Floro	3000	2414	10.34	3921.61
Castelmauro	4200	2513	38.55	9265.94
Cairo Montenotte	4200	2684	33.43	8613.90

In the end, in this section, the cornerstone of the work is presented. Updated and more specific emission factors for the Italian territory are achieved. An overview of the climate profile per rated power, region, and average wind speed is now available. The competitiveness of this renewable source to power electrolysers can be affirmed; moreover, the environmental impact is consistent with the literature [24, 25].

4.2.1. Deterministic results and water electrolysis technologies

A first rough estimate of the total emissions embodied in the production of hydrogen can be obtained with the results presented. By considering the electricity consumption of water electrolysis technologies carried out in section 2.2.5, Table 4.7 is obtained.
In the second column, the emission factors of the Italian territory are calculated in Table 4.5. The average value of the whole country is considered in this case, but a more precise and specific emission factor can be used for further analysis. What is to be emphasised in this section are the average outcomes. As can be noted by the table, in all the cases the value is below the EU taxonomy threshold of 3.38 tCO_2/tH_2. For the first four power-rated categories the results are well below the limit value and even lower than 2 tonnes per kilogram of hydrogen production. As expected by the LCA outcomes, the values associated with the rated power of 4200 kW are the highest ones; in particular, for the energy consumption value of 6.5 kWh/Nm^3H_2, hence the maximum value of the

range considered, the total emissions embodied would be 2.68 tCO_2eq/tH_2, still below the threshold.

Table 4.7: Emissions embodied in hydrogen production

Rated Power [kW]	CC [gCO_2eq/kWh_{el}]	AEL [tCO_2eq/tH_2]		General technology [tCO_2eq/tH_2]	
		min. emissions	max. emissions	min. emissions	max. emissions
600	15.91	0.88	1.04	0.64	1.15
850	20.02	1.11	1.31	0.80	1.45
2000	16.97	0.94	1.11	0.68	1.23
3000	16.72	0.93	1.10	0.67	1.21
4200	37.10	2.06	2.44	1.49	2.68

4.2.2. Interactive map implementation

The results presented in Table 4.5 are reported in the interactive map. This section reports some views of the map and indications on how to visualize the environmental impacts.
At first, on the panel control implemented, the borders need to be hidden and unselected. Afterwards, each rated power's emission factor can be picked and displayed. Figure 4.12 shows the map with the values for wind parks of 850 kW. The black regions are the ones not interested in this specific LCA; it means no wind turbines of the chosen rated power are installed. In this case, according to Table 4.4, Molise and Lazio are not coloured. Besides these two, other regions are not considered at all for the LCA, i.e., Piedmont, Lombardy, Trentino-South Tyrol, Veneto, Friuli-Venezia Giulia and Umbria.
Almost all the regions are characterized by a light-yellow colour, meaning the value of gCO_2eq/kWh_{el} is in the lower part of the range reported in the top-right legend. Aosta Valley and Abruzzo, on the other hand, are shown with a darker colour due to the higher climate impact, as reported numerically in Table 4.5: 32.62 gCO_2eq/kWh_{el} and 44.18 gCO_2eq/kWh_{el} respectively.

The same view of the map is reported for wind turbines of 3000 kW in Figure 4.13. In this case, it can be easily appreciated how these kinds of turbines are present only in the Southern regions and have an environmental impact from 10 to 24 gCO_2eq/kWh_{el}. The highest impact is present in Apulia and Basilicata, while Molise and Calabria have the lowest emissions.

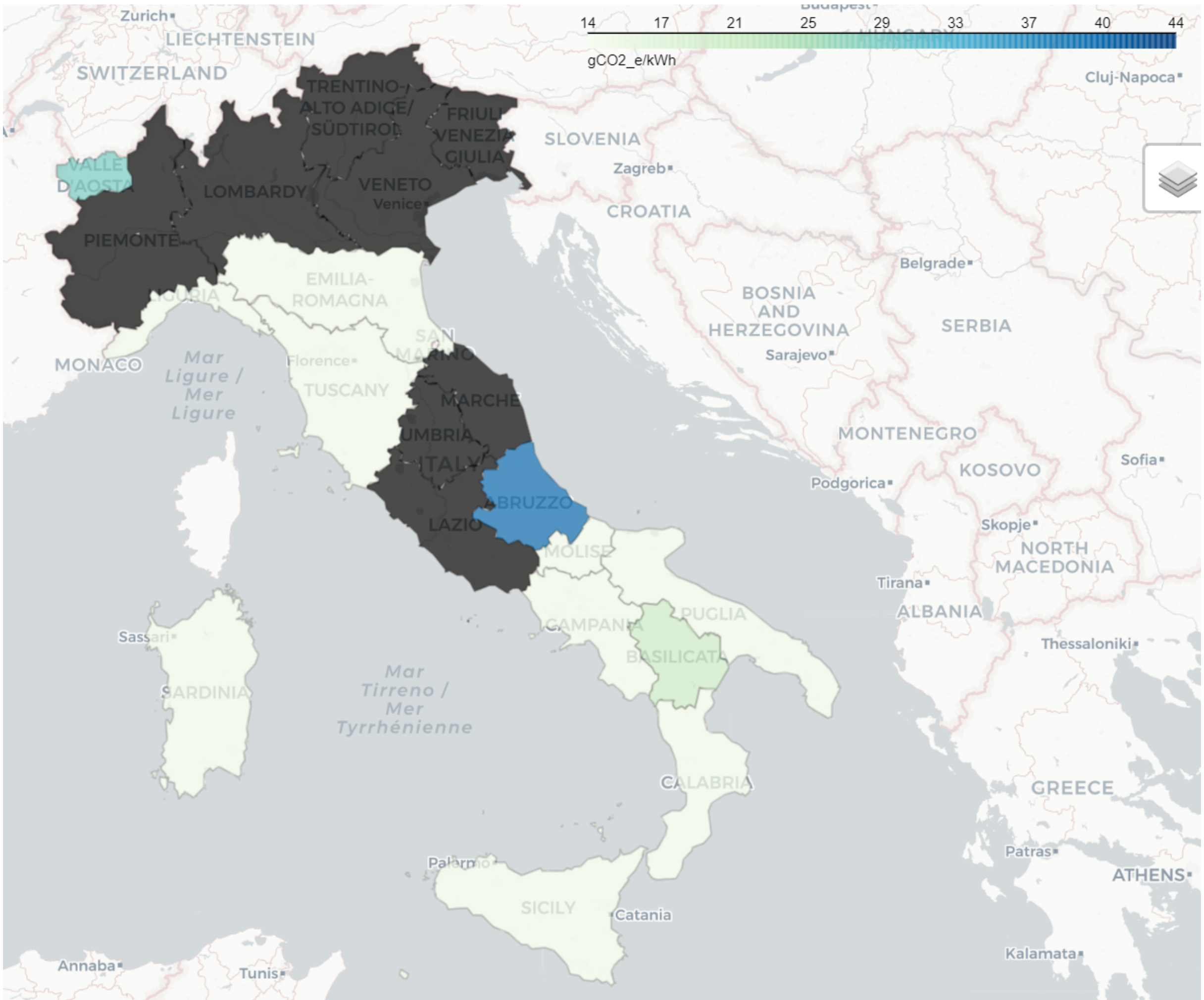

Figure 4.12: Emission factors for wind turbines of 850 kW

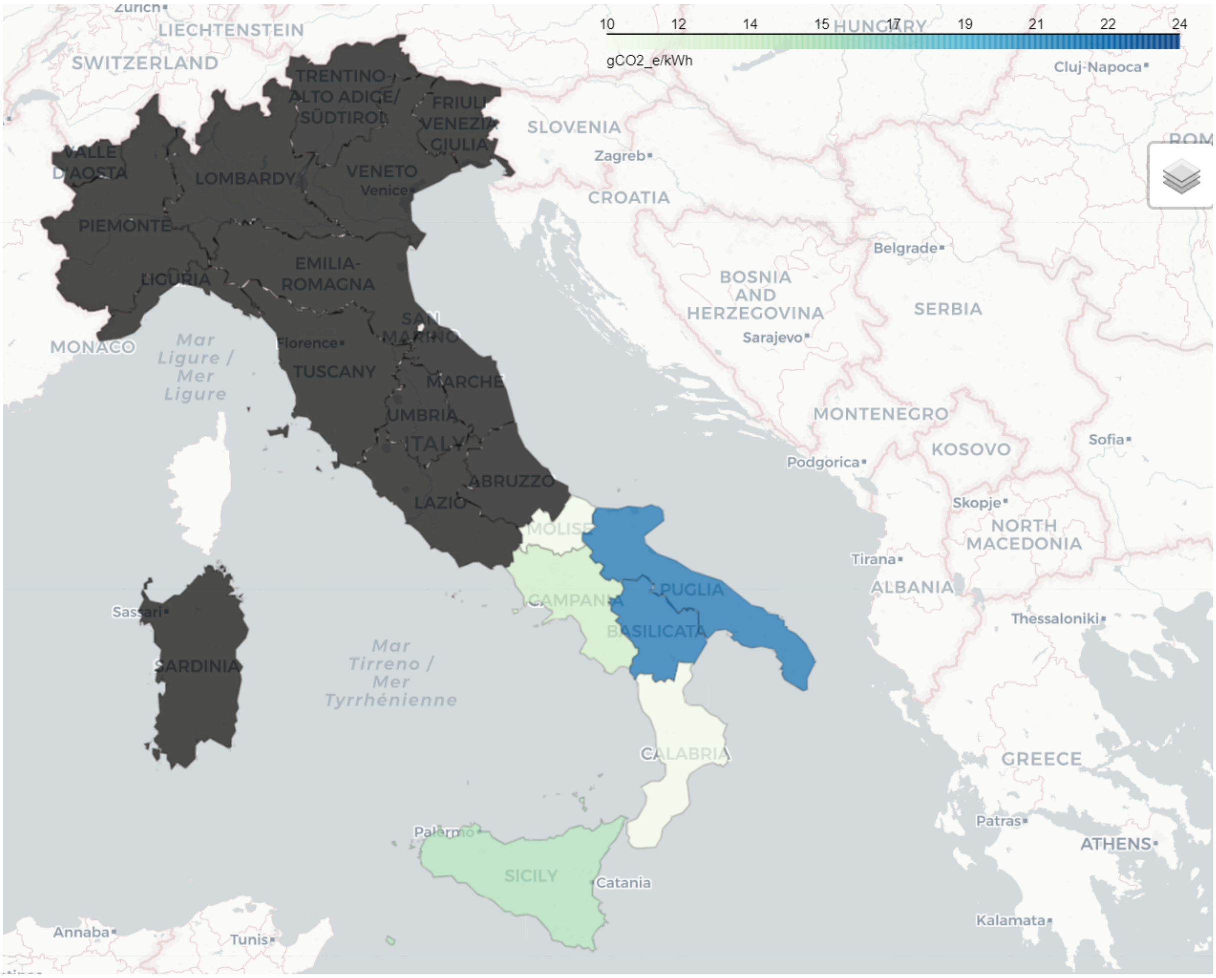

Figure 4.13: Emission factors for wind turbines of 3000 kW

In conclusion, the use of this interactive map and the tables above together give the database of the Italian wind farms in terms of environmental impact. The map can be used for the first qualitative assessments, while tables 4.5 and 4.4 can be used as a reference for better insights and quantitative values.

4.3. Validation of the wind turbine model

In this section, the results of the two validations explained in section 2.3 are reported. At first (i) the the validation according to the estimation of park productivity of the subset is reported. Later, (ii) the comparison with the gross productivity obtained by Terna, shown in Table 2.3, is commented.

4.3.1. 1^{st} validation

73 parks were considered in the subset mentioned in the previous section 3.2. These are the parks in which information about yearly productivity was found; hence it was possible to compare with the model output to assess the quality of this latter. This subset is reported, separated for each of the three macro-cluster, in tables 4.8, 4.9 and 4.10. The first six columns report the information about the park: region, location, number of wind turbines, the average wind speed at 50 m b.g.l and the capacity of the whole park and of the single turbine. Indeed, the columns most relevant for the validation procedure are the following three:

- Productivity [MWh]: this is the value of yearly park productivity found in the sources and used as a reference;
- Model productivity [MWh]: this is the value of yearly park productivity coming from the power curve model;
- Differences [%]; the percentage difference between the reference value and the modelled one.

A positive number in the "difference" column stands for an overestimation of the production by the model. On the other hand, if the model output is lower than the one found as a reference, the percentage difference is negative.
The last column reports the equivalent hours of parks computed according to the modelled electricity production value.

Table 4.8: Subset 1st validation: rated power lower 1 MW

Region	Location	N° of turbines [No.]	Avg speed at 50m agl [m/s]	Total capacity installed [MW]	Single turbine power [kW]	Productivity [MWh]	Model Productivity [MWh]	Differences [%]	Equivalent hour [h]
Emilia Romagna	Frassinoro	1	4.02	0.11	110	141.94	106.01	−25.31	963.71
Emilia Romagna	Frassinoro	1	4.02	0.20	200	258.06	192.74	−25.31	963.71
Tuscany	Talla	4	5.19	0.80	200	1 600.00	1 718.78	7.42	2148.48
Emilia Romagna	Farini	1	5.81	0.60	600	1 000.00	841.04	−15.90	1 401.73
Emilia Romagna	Albereto	4	6.35	2.40	600	4 000.00	4 510.94	12.77	1 879.56
Emilia Romagna	Tornolo	5	5.90	3.00	600	5 000.00	4 990.25	−0.20	1 663.42
Lazio	Vitivuso	15	5.40	9.00	600	14 000.00	15 700.37	12.15	1744.49
Sicily	Sclafani Bagni	11	5.88	7.26	660	9 235.90	15 008.07	62.50	2 067.23
Umbria	Fossato Di Vico	2	6.83	1.50	750	3 000.00	2 945.78	−1.81	1 963.86
Liguria	Rialto	3	7.00	2.40	800	5 304.00	6 757.82	27.41	2 815.76
Emilia Romagna	Monterenzio	16	5.25	12.80	800	25 000.00	24 242.72	−3.03	1 893.96
Tuscany	Firenzuola	17	5.82	13.60	800	25 256.09	29 677.62	17.51	2 182.18
Calabria	Olivadi	2	7.04	1.60	800	3 148.33	3 821.01	21.37	2 388.13
Calabria	Olivadi	10	7.04	8.00	800	15 741.67	19 105.07	21.37	2 388.13
Aosta Valley	Saint-Denis	3	4.13	2.55	850	4 000.00	2 479.47	−38.01	972.34
Emilia Romagna	San Benedetto Val Di Sambro	4	5.44	3.40	850	5 000.00	5 206.77	4.14	1 531.40
Tuscany	Chianni	7	5.93	5.95	850	13 100.00	9 878.60	−24.59	1 660.27
Sardinia	Tula (Parte I)	28	5.91	23.80	850	57 272.73	42 209.92	−26.30	1 773.53
Sicily	Sclafani Bagni	10	5.88	8.50	850	10 813.39	14 874.74	37.56	1 749.97
Sicily	Sclafani Bagni	8	5.88	6.80	850	8 650.71	11 899.80	37.56	1 749.97
Sicily	Agrigento	10	5.42	8.25	850	11 000.00	13 004.02	18.22	1576.24
Campania	Albanella	10	4.50	8.50	850	9 074.70	8 553.75	−5.74	1 006.32
Umbria	Gubbio	1	6.14	0.90	900	2 000.00	2 460.12	23.01	2733.47
Campania	Sturno	14	5.09	14.00	1 000	15 000.00	16 648.52	10.99	1 189.18

Table 4.9: Subset 1st validation: rated power 1-3 MW

Region	Location	N° of turbines [No.]	Avg speed at 50m agl [m/s]	Total capacity installed [MW]	Single turbine power [kW]	Productivity [MWh]	Model Productivity [MWh]	Differences [%]	Equivalent hour [h]
Veneto	Badia Calavena	1	4.28	1.35	1 350	2 000.00	2 065.06	3.25	1 529.68
Tuscany	Montecatini Val Di Cecina	5	5.29	7.50	1 500	13 636.36	12 649.26	−7.24	1 686.57
Tuscany	Montecatini Val Di Cecina	6	5.29	9.00	1 500	16 363.64	15 179.11	−7.24	1 686.57
Calabria	Marcellianra	4	6.15	6.00	1 500	10 623.00	14 171.53	33.40	2 361.92
Apulia	Carapelle	9	4.40	13.50	1 500	31 050.00	18 932.19	−39.03	1 402.38
Campania	Vallesaccarda	15	6.10	22.50	1 500	35 000.00	45 681.26	30.52	2 030.28
Sicily	Ramacca	47	4.59	70.50	1 670	111 000.00	98 736.66	−11.05	1 400.52
Tuscany	Santa Luca	13	5.96	23.40	1 800	59 400.00	56 267.45	−5.27	2 404.59
Marche	Apecchio	5	5.72	10.00	2 000	16 000.00	19 311.92	20.70	1 931.19
Tuscany	Pontedera	4	4.53	8.00	2 000	10 000.00	12 610.62	26.11	1 576.33
Tuscany	Zeri	5	5.65	10.00	2 000	18 900.00	21 038.13	11.31	2 103.81
Tuscany	Scansano	10	5.52	20.00	2 000	40 000.00	40 285.24	0.71	2 014.26
Tuscany	Riparbella	10	6.14	20.00	2 000	33 964.86	46 270.43	36.23	2 313.52
Lazio	Tessennano	4	5.65	8.00	2 000	17 777.78	19 631.46	10.43	2 453.93
Lazio	Arlena Di Castro	5	5.65	10.00	2 000	22 222.22	24 539.32	10.43	2 453.93
Lazio	Piansano	21	5.99	42.00	2 000	80 000.00	97 522.75	21.90	2 321.97
Sardinia	Budduso	69	7.09	138.00	2 000	330 000.00	349 911.36	6.03	2 535.59
Sicily	Butera	8	5.47	16.00	2 000	41 500.00	42 070.04	1.37	2 629.38
Sicily	Butera	9	5.21	18.00	2 000	43 000.00	37 371.74	−13.09	2 076.21
Sicily	Cattolica Eraclea	6	5.01	12.00	2 000	16 800.00	18 175.15	8.19	1 514.60
Sicily	Cattolica Eraclea	14	5.01	28.00	2 000	39 200.00	49 715.66	26.83	1 775.56
Apulia	Laterza	6	4.82	12.00	2 000	27 272.73	22 998.28	−15.67	1 916.52
Apulia	Castri Di Lecce	11	5.69	22.00	2 000	50 000.00	57 274.00	14.55	2 603.36
Apulia	Ordona	17	4.78	34.00	2 000	57 707.10	58 248.15	0.94	1 713.18
Apulia	Castellaneta	28	4.88	56.00	2 000	130 000.00	94 578.24	−27.25	1 688.90
Apulia	Sant'Agata Di Puglia	36	6.32	72.00	2 000	110 084.40	124 745.25	13.32	1 732.57
Campania	Scampitella	16	6.17	32.00	2 000	55 000.00	79 051.54	43.73	2 470.36
Campania	Circello	13	5.57	27.00	2 000	74 500.00	49 318.11	−33.80	1 826.60
Veneto	Affi	2	4.62	4.10	2 050	6 000.00	6 067.79	1.13	1 479.95
Veneto	Rivoli Veronese	4	5.03	8.20	2 050	16 000.00	14 106.40	−11.83	1 720.29
Calabria	Torre Di Ruggero	5	5.74	10.25	2 050	25 530.00	20 197.30	−20.89	1 970.47
Calabria	Simeri Crichi	11	6.29	22.55	2 050	60 740.00	59 906.38	−1.37	2 656.60
Liguria	Quiliano	4	6.63	9.40	2 350	24 200.00	26 480.43	9.42	2 817.07
Sicily	Portanna - Contrada Magaggiari	6	6.02	14.40	2 400	40 000.00	44 509.68	11.27	3 090.95
Piedmont	Garessio	4	5.36	10.00	2 500	25 700.00	16 883.86	−34.30	1 688.39
Apulia	Manfredonia	7	4.56	17.50	2 500	33 250.00	26 176.76	−21.27	1 495.81
Apulia	Orta Nova	21	4.78	54.60	2 600	128 900.70	87 726.09	−31.94	1 606.71
Calabria	Brienza	6	5.49	18.00	3 000	30 870.00	38 961.83	26.21	2 164.55
Apulia	Gravina In Puglia	24	4.72	72.00	3 000	127 777.50	92 621.92	−27.51	1 286.42
Campania	Lacedonia	5	6.69	15.00	3 000	32 000.00	34 602.99	8.13	2 306.87
Campania	Ricigliano	12	5.46	36.00	3 000	54 091.80	61 843.41	14.33	1 717.87
Campania	San Lupo	16	7.13	48.00	3 000	128 000.00	131 269.86	2.55	2 734.79
Tuscany	Piombino	6	5.20	19.80	3 300	52 000.00	43 764.23	−15.84	2 210.31

Table 4.10: Subset 1st validation: rated power higher 3 MW

Region	Location	N° of turbines [No.]	Avg speed at 50m agl [m/s]	Total capacity installed [MW]	Single turbine power [kW]	Productivity [MWh]	Model Productivity [MWh]	Differences [%]	Equivalent hour [h]
Sicily	Mazara Del Vallo	7	5.84	23.80	3 400	51 300.00	61 444.99	19.78	2 581.72
Campania	Monteverde	3	5.54	10.35	3 450	19 909.09	21 054.99	5.76	2 034.30
Campania	Monteverde	8	5.54	27.60	3 450	53 090.91	59 456.93	11.99	2 154.24
Campania	Casalduni	10	5.78	34.65	3 465	126 000.00	88 466.98	−29.79	2 553.16
Apulia	Tamaricciola	2	4.62	8.40	4 200	14 800.00	17 487.07	18.16	2 081.79
Molise	Castelmauro	7	5.86	29.40	4 200	70 000.00	73 900.93	5.57	2 513.64

For a better visualization of these findings, Figure 4.14 is reported. The statistical box plot for the three cases is carried out according to the percentage difference. As can be seen, the performances are very similar with a median value, highlighted by the blue line in the middle of the box, around 20%. This value is very close in each case to the mean of the samples, represented by the red point. The box blue borders are the first (Q_1) and third (Q_3) quartiles of the distribution. The range within these two values is called the interquartile range (IQR). On the other hand, the upper and lower black lines stand for the maximum and minimum values of the relevant range. If a value is outside the upper and lower whiskers, it is considered an outlier and the blue dotted point in the third cluster is an example. This value is outside the reasonable statistical range given by the equation below:

$$[Q_1 - 1.5 \cdot IQR;\; Q_3 + 1.5 \cdot IQR] \tag{4.1}$$

From Table 4.10, it can be seen that this outlier refers to the park in Casalduni, Campania. The value of production found on the commissioning website was around 126,000 MWh, which would correspond to more than 3,600 equivalent hours per year. This value is quite optimistic considering a more likely range of equivalent hours that goes from 1500 to 2500 hours. Indeed, it is possible that the value proposed by the company could be overestimated. This is confirmed also by the fact that this is the only case in which it happens; in the other parks where the difference is such negative, the equivalent hours computed with the modelled power are low as well. Indeed, it is more likely in this case that an underestimation from the model happened instead of a misleading reference value of production. An example is the Carapelle park in Apulia in Table 4.9. The percentage difference is -39% with an equivalent hour of 1402 hours. It is more likely in this case that the discrepancy is due to the model implementation rather than a misleading value in the production estimation. In fact, the 31050 MWh found would correspond to a reasonable value of around 2300 equivalent hours.

In Table 4.14 the numerical values of the statistical indicators referred to the Figure 4.14 are reported for completeness. As noted, the model's output is more likely to be an overestimation rather than an underestimation. The second quartile, which is the median, is always greater than zero, and the interquartile range is always shifted a little bit more on positive values rather than negative ones. The performance for the three cases is comparable even if, for the case higher than 3 MW, the sample is small from a statistical point of view. This is also highlighted by the dispersion of the maximum and minimum values, which is narrower with respect to the first two clusters. In this case, having the second cluster a bigger sample with respect to the first one (44 versus 23 parks) can be

assessed for the slightly better performance of the latter.
In general, the results indicate that the model overestimates the electricity production of the farms. The medians of the distributions, as can be seen in Table 4.11, are positive numbers. In absolute terms, the average difference all the whole subset of 73 parks is around 18%. This value is taken into account for further considerations, reported in section 4.5.

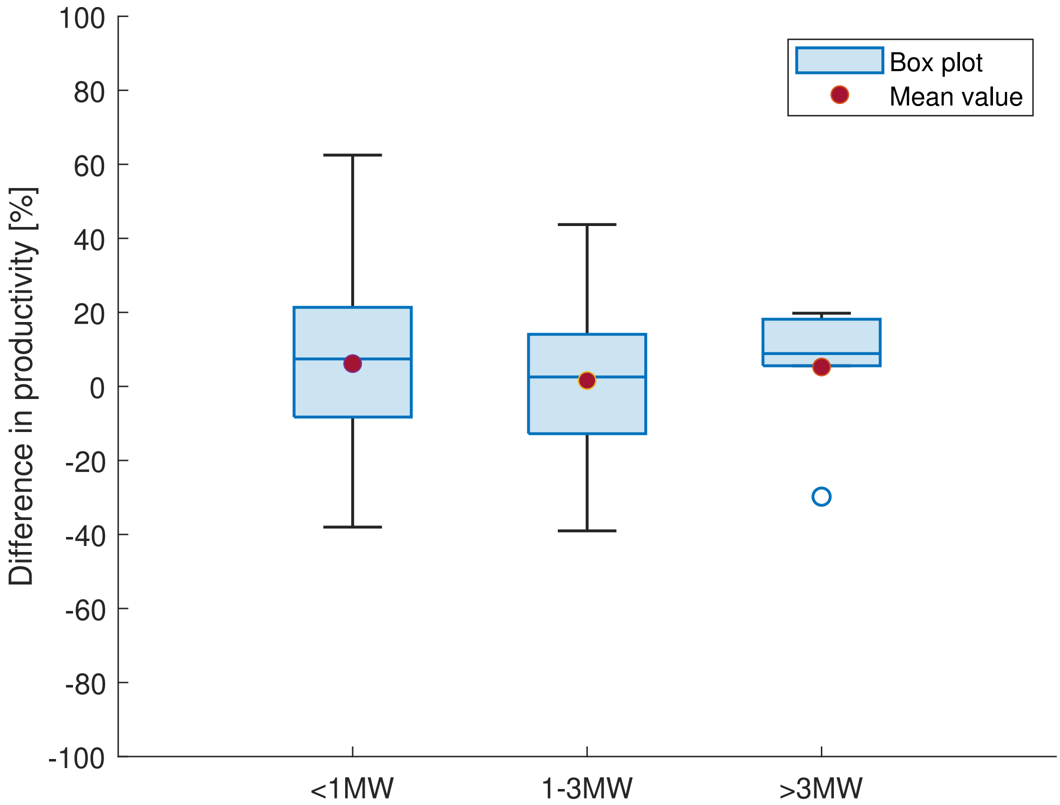

Figure 4.14: Box plot of the three classes

Table 4.11: 1^{st} validation, statistical indicators - values in [%]

Cluster	Minimum	1^{st} quartile	2^{nd} quartile	3^{rd} quartile	Maximum	Mean
<1MW	-29.06	-10.82	9.21	21.37	69.64	6.16
1-3MW	-30.06	-12.78	2.55	14.08	54.36	1.59
>3MW	-8.35	5.57	8.87	18.16	37.03	5.24

A further chart is reported regarding these 73 parks. In Figure 4.15 every park is reported in relation to the distance between the related anemometers. The x-axis is the distance in kilometers while on the y-axis percentage values are present. Indeed, the vertical coordinate is the absolute difference of production, hence the absolute value of the second-to-last column in Tables 4.8, 4.9 and 4.10.

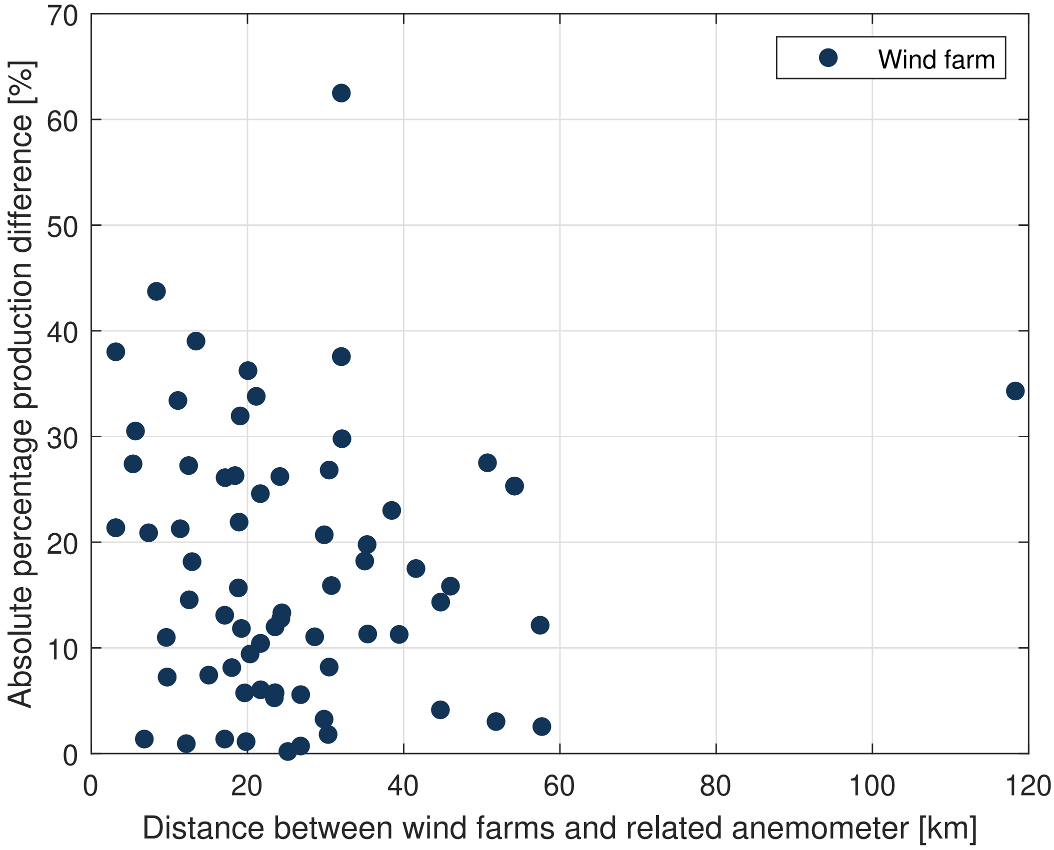

Figure 4.15: Model difference with respect distance

There is no visible trend such as a lower accuracy of the model productivity when the distance is increasing. This could be explained by the low number of farms considered: of the total 513 only 14% are considered in this validation procedure. On the other hand, as can be noted by the figure, the distance is in the order of some kilometres. Thus, the topography of the terrain and the resulting wind profile could be influenced a lot even for a distance of a few kilometers. A further analysis should be conducted. In the end, other factors besides the distance tweak the results.

4.3.2. 2^{nd} validation

The second procedure to test the quality of the model was done on the whole set of parks. Table 4.3 reports the amount of installed capacity modelled in the project. Therefore, to compare the total productivity of the parks considered in the model, a shrinkage of the amount expressed in the last column of Table 2.3 is needed. This amount of gross electricity production dated 2021, was scaled down linearly according to the mapped capacity. The result is reported in the third column of Table 4.12 named "Scaled Gross Production".

The first column, basically the same as the last columns of Table 4.3, reports the capacity modelled for each region. The fourth column lists the sum of the outputs of the model for each region. These are the values needed for the comparison. Indeed, the difference is reported both with signs (positive value for overproduction) and in absolute terms. Thus, the goodness of the model can be assessed with the whole dataset considered.

Table 4.12: 2^{nd} validation

Regions	Modelled Power [MW]	Scaled Gross Production [MWh]	Model Production [MWh]	Differences [%]	Absolute diff. [%]
Piedmont	18.50	21 742.26	31 693.18	45.77	45.77
Aosta Valley	2.55	4 146.66	2 479.55	-40.20	40.20
Veneto	13.35	22 466.92	22 242.64	-1.00	1.00
Liguria	102.80	134 153.26	267 598.63	99.47	99.47
Emilia Romagna	43.30	80 263.36	79 698.15	-0.70	0.70
Tuscany	139.85	280 733.37	293 044.57	4.39	4.39
Umbria	2.40	1 928.94	5 406.36	180.28	180.28
Marche	10.40	20 464.34	19 792.10	-3.28	3.28
Lazio	69	140 055.51	157 410.64	12.39	12.39
Abruzzo	243.45	433 025.18	397 071.30	-8.30	8.30
Molise	402.84	713 459.59	809 948.38	13.52	13.52
Campania	1 436.12	2 772 557.94	3 104 797.67	11.98	11.98
Apulia	2 118.17	3 808 621.71	3 947 810.43	3.65	3.65
Basilicata	993.06	1 785 032.63	1 962 489.94	9.94	9.94
Calabria	1 039.55	1 944 329.28	2 361 571.55	21.46	21.46
Sicily	1 834.65	2 933 438.97	3 439 654.14	17.26	17.26
Sardinia	841.02	1 330 112.87	1 539 827.59	15.77	15.77
Total	9 311.01	16 426 532.78	18 442 536.83	22.00	29.00

The average absolute difference between the model output and the value from Terna is around 30%, which the author considers a great achievement. Even more, if one considers that this value is skewed by two regions in particular. Liguria And Umbria present the worst performance; the model output is 100% and 180% times higher with respect to the Terna value. This means the output is not reliable in these two specific cases.

In Umbria only two parks were mapped: one in Gubbio characterized by only one turbine of 900 kW, and one in Fossato di Vico composed of two turbines NEG Micon 44/750. The first one is presented in the first validation part, as can be seen in Table 4.8. In this case,

the difference with respect to the estimated production is around 23%, hence much less. Indeed, either the model output is by far higher for the park in Fossato di Vico, or the production in this region was deficient in 2021. Unfortunately, no other parks with that specific model of Neg Micon are present in Table 4.8 to be able to have a comparison.
A similar assessment can be stated for the Liguria case. Two parks were analysed in the previous validation. One in Table 4.8 composed of 3 turbines for a total capacity of 2.4MW, and the other one is located in Quiliano with a total power installed of 9.4MW reported in Table 4.9. The percentage differences are 27% and 9% respectively. In this case, the total parks mapped are slightly more: 24 in total for a region capacity of 102.8 MW. Indeed, some of the park models are present in the three previous tables, in which the difference was not so marked. Again, either some specific parks are highly overestimated, or 2021 was characterized by low production in Liguria. In fact, it needs to be highlighted how the yearly production is modelled with a wind profile considering the 15-year span from 2004-2018.
All these considerations find validation on the box plot of Figure 4.16, where the values of the last column of Table 4.16 are considered. As can be noted, the two values of Liguria and Umbria are statistically not relevant and considered outliers. The reasoning is the same as explained for the previous box plot in Figure 4.14. Indeed, the statistical indicators are reported hereafter in Table 4.13. The minimum value, given by equation 4.2 is not reported because of the choice of the samples.

$$Q_1 - 1.5 \cdot IQR; \tag{4.2}$$

The lower whisker is zero due to the use of absolute values. It is worth highlighting the difference between the median and the mean value. In such cases, the two outliers wrongly influence this latter value and could lead to misleading conclusions. Again, from a statistical point of view, these two high values should not be considered, and the resulting performance would be much better: the median is around 12% difference.
Furthermore, in this specific case, Liguria and Umbria cover a slight part of the whole Italian capacity; hence the relevance on the final result is even less. Confidently, the quality of the model can be assessed without these two extreme cases.

By erasing these two outlier values of production difference, the average absolute value would be around 14%, much closer to the median value. This is a powerful result that states the robustness of the model. The Italian capacity, according to this second validation approach, is replicated reasonably by the model proposed by the author.

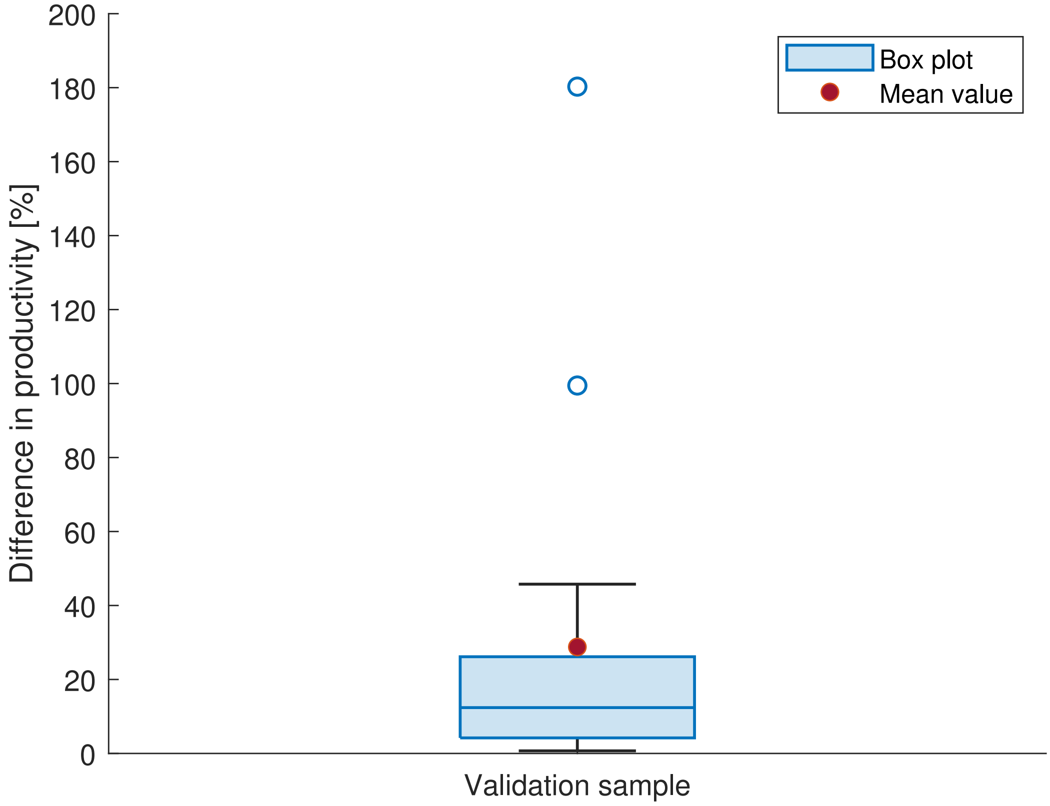

Figure 4.16: Box plot of the "Absolute differences"

Table 4.13: 2^{nd} validation, statistical indicators - values in [%]

Cluster	1^{st} quartile	2^{nd} quartile	3^{rd} quartile	Maximum	Mean
All regions	4.20	12.39	26.14	59.05	28.78

4.4. Life Cycle assessments stochastic outcomes from Monte Carlo method

4.4.1. Monte Carlo implementation

Tables 4.8, 4.9 and 4.10 show the virtual average turbines. One for each cluster, these hypothetical wind turbines and their characteristics were used for the Monte Carlo analysis. These are reported in Table 4.14 where the three macro-clusters can be detected by the first row with the rated power of the virtual turbine..ù All the variables are calculated from the tables mentioned above; except the last two, all the others are the average value of the parks reported in the respective table. On the contrary, the production of a single wind turbine is simply computed by dividing the model productivity by the average number of wind turbines. This value is crucial because is the one to be inserted in the LCI as electricity production after being spanned for the lifetime. The Geometric Standard Deviation (GSD) is reported in the last row. This latter is computed according to the absolute value of the "Differences" columns in Table 4.8 for the cluster "$<$ 1MW", Table 4.9 for the cluster "1-3MW" and Table 4.10 for the last one. As reported in section 3.2, this parameter is also essential for the LCA; the standard deviation of the lognormal distribution chosen for the electricity production is the natural logarithm of the GSD. In the end, it is a parameter that indicates the dispersion of the distribution. The higher, the more widespread the outcomes of the MC would be.

The outcomes of the 1000 executions are statistically analysed and the results are presented hereinafter.

As already mentioned, the procedure was repeated two times. In the first case, the uncertainty of the wind turbine model implemented is considered alongside the inherent uncertainty on the activity processes collected from ecoinvent 3.9.1. This latter is referred to as LCA model uncertainty from here after. This vagueness is already implemented in the calculation procedure; with the same input database, the environmental impact would be slightly different due to this uncertainty on the exchange amount. On the other hand, the wind turbine model uncertainty is coming from the first validation procedure, as men-

Table 4.14: Characteristics of the virtual wind turbines

Variable	Unit	Virtual averages wind turbine		
Rated power	[kW]	709.17	2 120.23	3 694.17
Rotor	[m]	48.67	79.82	114.00
Hub height	[m]	46.22	92.53	108.50
Avg speed at 50m agl	[m/s]	5.66	5.50	5.53
Model Productivity	[MWh]	10 701.41	51 941.14	53 635.31
Equivalent hour	[h]	1 766.96	2 025.61	2 319.81
Avg No. of turbines	[-]	7.79	12.33	6.17
Production 1 turbine	[MWh]	1 373.44	4 214.09	8 697.62
GSD	[-]	3.45	2.96	1.99

tioned previously.
In the second case, the electricity production is considered fixed, with no uncertainty. This allows a range of values to be given by the causality of the database. In addition, the results can be compared with the first MC procedure to understand the influence of just adding a distribution function on the electricity amount. Obviously, this is a key parameter and, as expected, the influence is not negligible.
Figure 4.17 and Figure 4.18 report the box plot of the two MC outcome. Similarly in the previous section, in Table 4.15. the quartile values are reported in gCO_2eq/kWh_{el}. In addition, in Table 4.16, other statistical indexes of the 1000 iterations are reported to quantify the difference. Indeed, the samples' mean, upper and lower standard deviation are computed and listed. Ultimately, both tables report the same concepts but with different indexes.

The influence of the additional wind turbine model uncertainty is easily visible by comparing the two charts. For each cluster, the mean values are close in the two cases; from Table 4.16 can be noted that, in the first case, the mean is slightly higher. This is in accordance with the width of the box plots. The mean value also takes into account the outliers, while the median no. Indeed, by comparing the two charts and looking at Table 4.15, can be seen how the median of the distributions, hence the second quartile, is closer with respect to the mean value. The median values are similar by excluding the outliers, which have no relevance from a statistical point of view. For the cluster "$>$ 3MW" is almost the same value in the two cases.

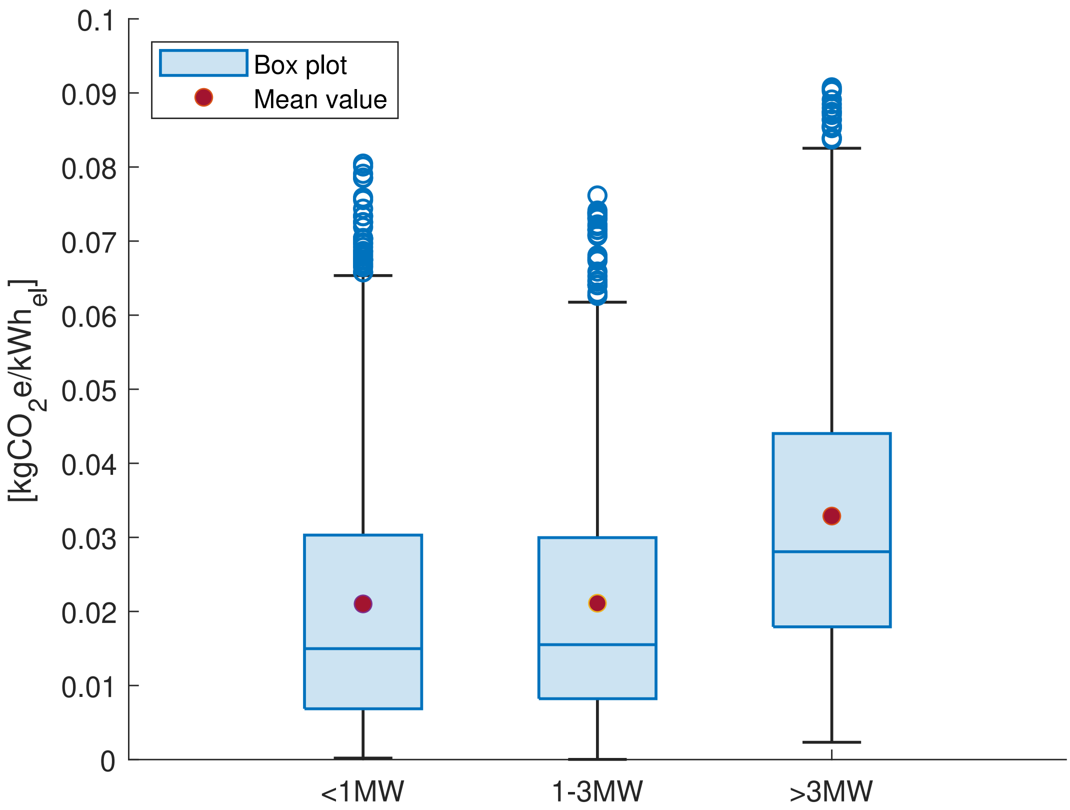

Figure 4.17: Box plot of the MC outcome considering wind model and LCA model uncertainty

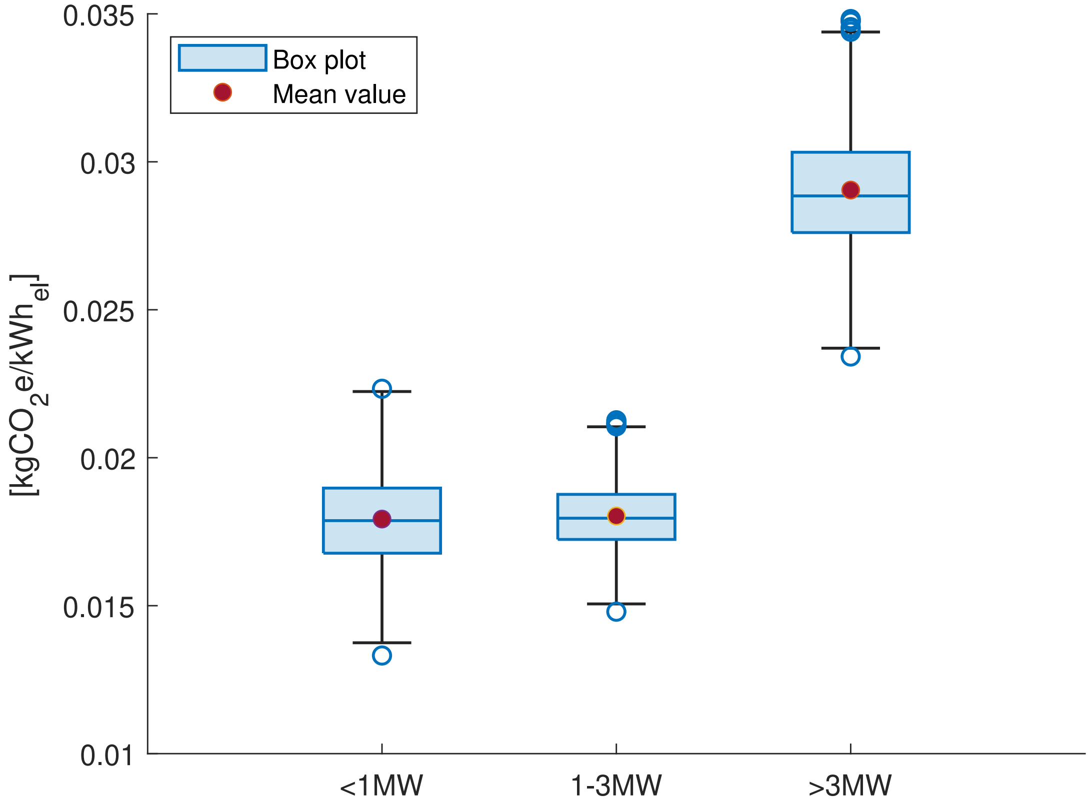

Figure 4.18: Box plot of the MC outcome considering only LCA model uncertainty

Even with these similarities, the biggest difference is the width of the blue box, delimited by the first and third quartiles, and therefore the minimum and maximum values highlighted by the black line. This discrepancy in a quantitative way can be appreciated in Table 4.15. For the case where only LCA uncertainty is considered, the width of the IQR is around 2 gCO_2eq/kWh_{el} for the first two clusters and around 3 gCO_2eq/kWh_{el} for the highest cluster. This states the robustness of the life cycle assessment methodology because, also by looking at the standard deviation in Table 4.16, the range is within $\pm 10\%$. The same can not be stated with the aggregation of the lognormal distribution of electricity production. The range would increase, with the quartiles and the standard deviations of the same order of magnitudes of the mean and median values. This can be justified by the crucial role of electricity production in this environmental assessment. The functional unit strictly depends on the park's productivity; a slight change in this amount would lead to a bigger difference in the outcome. These assessments confirm this; from the previous validation steps, the percentage difference was a maximum of around 30%, but in the LCA outcomes the uncertainty is higher. The only solution to overcome this problem

Table 4.15: MC results: quartiles of the distribution - values in [gCO_2eq/kWh_{el}]

Cluster	1^{st} quartile	2^{nd} quartile	3^{rd} quartile	Model's uncertainty considered
<1MW	6.86	14.98	30.31	
1-3MW	8.22	15.51	29.97	Wind turbine + LCA
>3MW	17.92	28.06	44.02	
< 1MW	16.77	17.87	18.97	
1-3MW	17.24	17.96	18.76	LCA
>3MW	27.61	28.85	30.32	

would be a better approximation of the park's productivity, which is quite challenging. The modelling technique proposed is quite reliable, therefore a change in the wind speed dataset could be a solution.

As stated in section 2.1.1, a trial with the hourly wind speed data ERA5 was performed. The positive aspect of this database is the possibility of using the wind farms' location. With this input, the average wind speed at 100 m a.g.l. and the wind hourly profile is obtained. Nevertheless, despite this positive side, the resulting performance was worse. The production of ten parks from the subset reported in Table 4.8, 4.9 and 4.10 was compared. Only in one case, the use of the ERA5 database was better for a few percentage points. Most of the time, an underestimation of the farms' production of several tens was obtained. Therefore, the use of anemometers was considered more reliable.
A further analysis was performed to double-check this statement; similarly to the procedure used for anemometers, a scale factor was applied. Thus, rather than the numerical values, from ERA5 it was exploited the wind profile. With this trick, the differences of the 10 parks were similar to the ones obtained with the anemometers. Consequently, the result obtained was not sufficiently better to refute the procedure used in this thesis.

In the end, the performances for each cluster are very similar, and comparing the two Monte Carlo analyses leads to the same consideration for the three clusters. It can be noted that the lower range is generally narrower with respect to the upper range. The upper standard deviation in Table 4.16 is higher than the lower one, and in Table 4.15 the difference between the quartiles is higher in Q_3-Q_2.

From this analysis, the key role of the electricity production value can be stated. The inherited variability of the natural world that affects the LCA model has an impact on the final results of around 2-3 gCO_2eq/kWh_{el}. If the wind turbine model uncertainty is also considered, the range of the results increases more, with an upper and lower standard deviation of the same order of magnitude as the median value. To overcome this

Table 4.16: MC results: additional indicators - value in [gCO_2eq/kWh_{el}]

Cluster	Mean	STD upper	STD lower	Model's uncertainty considered
< 1MW	21.02	25.18	12.89	
1-3MW	21.11	23.09	12.20	Wind turbine + LCA
> 3MW	32.87	23.77	15.22	
< 1MW	17.93	1.71	1.54	
1-3MW	18.03	1.19	1.05	LCA
> 3MW	29.05	2.29	1.93	

variability, a lower difference between real productivity and the modelled one would be sought. Nevertheless, even if the emission factor falls in the upper range of the outcome distribution, the competitiveness of the technology and its low environmental impact with respect to standard power plants remain.

4.4.2. Stochastic results and water electrolysis technologies

The same approach used in section 4.2.1, the stochastic LCA outcomes are reviewed with the potential value of energy consumption of water electrolysis technology. Due to the reasons mentioned in the previous section, the emission factor values are reported in Table 4.15, hence the quartiles of the probability distribution. The division per cluster and per uncertainty considered is kept while, for better visualization, three different tables are reported, one for each quartile.
Table 4.17 for the first quartile, Table 4.18 for the median values and, lastly, Table 4.19 where the highest values are listed because linked to the third quartile.
It should be noted how these results are linked with the 73 parks analysed in the validation procedure and later in the MC procedure. The main outcomes are the following ones. At first, the differences according to the model's uncertainty considered carried out in the previous section are found also in this case. This is inherent in the procedure; the difference between the quartiles is very narrow. For example, for the maximum emissions of AEL technology, if supplied with electricity from the cluster of 1-3 MW, the value for the first quartile is 1.10 tCO_2eq/tH_2 and for the third 1.25 tCO_2eq/tH_2. The range of value becomes wider if the wind turbine model's uncertainty is considered. In the same case, the minimum emissions embodied is 0.54 tCO_2eq/tH_2 while the maximum is 1.97 tCO_2eq/tH_2. This is strictly related to the broader range of electricity production, hence the broader range of climate change emission factors.
In all the cases the outcomes are lower than the threshold assessing the goodness and the potential of coupling water electrolysis technologies with the Italian wind electricity.

Table 4.17: Emissions embodied in hydrogen production - 1^{st} quartile

Cluster	1^{st} quartile [gCO_2eq/kWh_{el}]	AEL [tCO_2eq/tH_2]		General technology [tCO_2eq/tH_2]		Model's uncertainty considered
		min. emissions	max. emissions	min. emissions	max. emissions	
<1MW	6.86	0.38	0.45	0.27	0.50	Wind turbine + LCA
1-3MW	8.22	0.46	0.54	0.33	0.59	
>3MW	17.92	1.00	1.18	0.72	1.30	
<1MW	27.61	1.54	1.81	1.11	2.00	LCA
1-3MW	16.77	0.93	1.10	0.67	1.21	
>3MW	17.24	0.96	1.13	0.69	1.25	

Table 4.18: Emissions embodied in hydrogen production - 2^{nd} quartile

Cluster	2^{nd} quartile [gCO_2eq/kWh_{el}]	AEL [tCO_2eq/tH_2]		General technology [tCO_2eq/tH_2]		Model's uncertainty considered
		min. emissions	max. emissions	min. emissions	max. emissions	
<1MW	14.98	0.83	0.98	0.60	1.08	Wind turbine + LCA
1-3MW	15.51	0.86	1.02	0.62	1.12	
>3MW	28.06	1.56	1.84	1.12	2.03	
<1MW	28.85	1.60	1.89	1.16	2.09	LCA
1-3MW	17.87	0.99	1.17	0.72	1.29	
>3MW	17.96	1.00	1.18	0.72	1.30	

Table 4.19: Emissions embodied in hydrogen production - 3^{rd} quartile

Cluster	3^{rd} quartile [gCO_2eq/kWh_{el}]	AEL [tCO_2eq/tH_2]		General technology [tCO_2eq/tH_2]		Model's uncertainty considered
		min. emissions	max. emissions	min. emissions	max. emissions	
<1MW	30.31	1.69	1.99	1.21	2.19	Wind turbine + LCA
1-3MW	29.97	1.67	1.97	1.20	2.17	
>3MW	44.02	2.45	2.89	1.76	3.18	
<1MW	30.32	1.69	1.99	1.21	2.19	LCA
1-3MW	18.97	1.06	1.25	0.76	1.37	
>3MW	18.76	1.04	1.23	0.75	1.36	

4.5. Climate change emission factors with uncertainty

In this last section, a final and conclusive analysis is reported. After having all the results presented so far, the last step was to consider these latter together. It was performed an analysis, not exhaustive, but still meaningful.
As stated in the validation section 4.3.1, the model output has an average difference, in absolute terms, of around 18%. The deterministic range of climate change emission factors found in section 4.2 does not include this aspect. Indeed, this average difference was considered to obtain a more realistic range.

Table 4.20: Climate profile comparison for the 600 kW wind turbines

Region	CC [gCO_2eq/kWh_{el}]	CC w/ +18% [gCO_2eq/kWh_{el}]	Difference [%]
Emilia Romagna	20.62	17.40	15.64
	12.71	10.96	13.78
	11.25	9.72	13.62
Tuscany	13.88	11.78	15.10
Lazio	18.86	16.19	14.14
Abruzzo	16.62	14.28	14.06
	14.95	15.62	4.51
Apulia	16.74	14.39	14.08
	9.92	8.59	13.42
	8.72	8.98	2.89
Campania	30.29	25.89	14.51
	26.79	16.41	38.76
	16.25	13.96	14.05
	15.01	12.91	13.97
	12.78	11.02	13.78
	Total		14.42

For a first degree of approximation, it was applied only for the wind turbine power cluster of 600 kW (lowest CC of 15.91 gCO_2eq/kWh_{el}) and 4200 kW (highest CC of 37.10 gCO_2eq/kWh_{el}). For all the wind farms in these two categories, the climate profile was performed again by considering the average difference of 18% in electricity production. For the cluster 600kW, the electricity production was increased by 18%, in order to get the minimum value. On the other hand, for 4200 kW, a lower amount of electricity production was considered and the range upper limit was obtained. Table 4.20 and Table 4.21 list the results for wind farms of 600 kW and 4200 kW respectively. The wind park's region is reported in the first column, while in the second column, the values of climate change emission factors with the modelled electricity production are reported. These are the same listed in the comprehensive Table 4.4. The third column instead shows the new emission factors: "CC w/ +18% in Table 4.20 stands for the value considering an increase of 18% in electricity production. Similarly, in Table 4.21, the new emission factors are computed with lower equivalent hours. In the last column, the percentage difference is reported for each farm; for a better visualization, it is always positive even if for 600 kW wind turbine the climate profile is lower and for 4200 kW is higher.
In the last row the average difference is reported. This is used to estimate the minimum and maximum value of the author's CC model range. Indeed, from the value of 15.91 gCO_2eq/kWh_{el}, a decrease of 14.42% is applied; similarly, from the CC for the 4200 kW an increase of 20.17% is used. The average value of the CC was not used because a weighted

Table 4.21: climate profile comparison for the 4200 kW wind turbines

Region	CC [gCO_2eq/kWh_{el}]	CC w/ -18% [gCO_2eq/kWh_{el}]	Difference [%]
Liguria	33.43	40.11	19.98
Sicilia	41.35	49.77	20.36
Puglio	35.07	42.11	20.08
Molise	38.55	46.36	20.24
	Total		20.17

average was applied to calculate the Italian average value (see section 4.2). Table 4.22 and Figure 4.19 show the results.

The minimum value is 13.62 gCO_2eq/kWh_{el} and the maximum 44.58 gCO_2eq/kWh_{el}. This resulting range is compared with the national one from the background life cycle inventory database ecoinvent. This latter, as stated previously, is divided into three clusters: < 1 MW, 1-3 MW, and > 3 MW. Figure 4.19 shows on the right-hand side the ecoinvent dataset values and, on the other side, the author's model range. By the side of each point, the related category/cluster is reported for better visualization. Table 4.22 reports the numerical values of the figure.

Table 4.22: CC ecoinvent versus author's model numerical values

Cluster	CC [gCO_2eq/kWh_{el}]	Source
< 1 MW	19.24	
1-3 MW	18.36	ecoinvent 3.9.1
> 3 MW	31.62	
min	13.62	
600 kW	15.91	
850 kW	20.02	
2000 kW	16.97	Author's model
3000 kW	16.72	
4200 kW	37.10	
max	44.58	

The results of the author's model (electricity model + LCA) are aligned with the ecoinvent 3.9.1 background dataset. For the cluster 1-3 MW the outcomes of 2000 kW and 3000 kW rated power are very close. For the < 1 MW group, the values of 600 kW and 850 kW create a range of 5 gCO_2eq/kWh_{el} in which lies the ecoinvent value. The greatest difference, however, less than 6 gCO_2eq/kWh_{el}, is between the 4200 kW value and the cluster $>$ 3 MW. Globally the results reasonably widen the climate profile range given by the ecoinvent dataset. Furthermore, the use of the model's uncertainty increases the range of 6 and 13 gCO_2eq/kWh_{el} for the lower and the upper limits respectively. This outcome is obtained according to the assumption made in this thesis, the source used and the model implemented. Indeed, these conclusions should be supported with the use of primary data in order to obtain more solid statements.

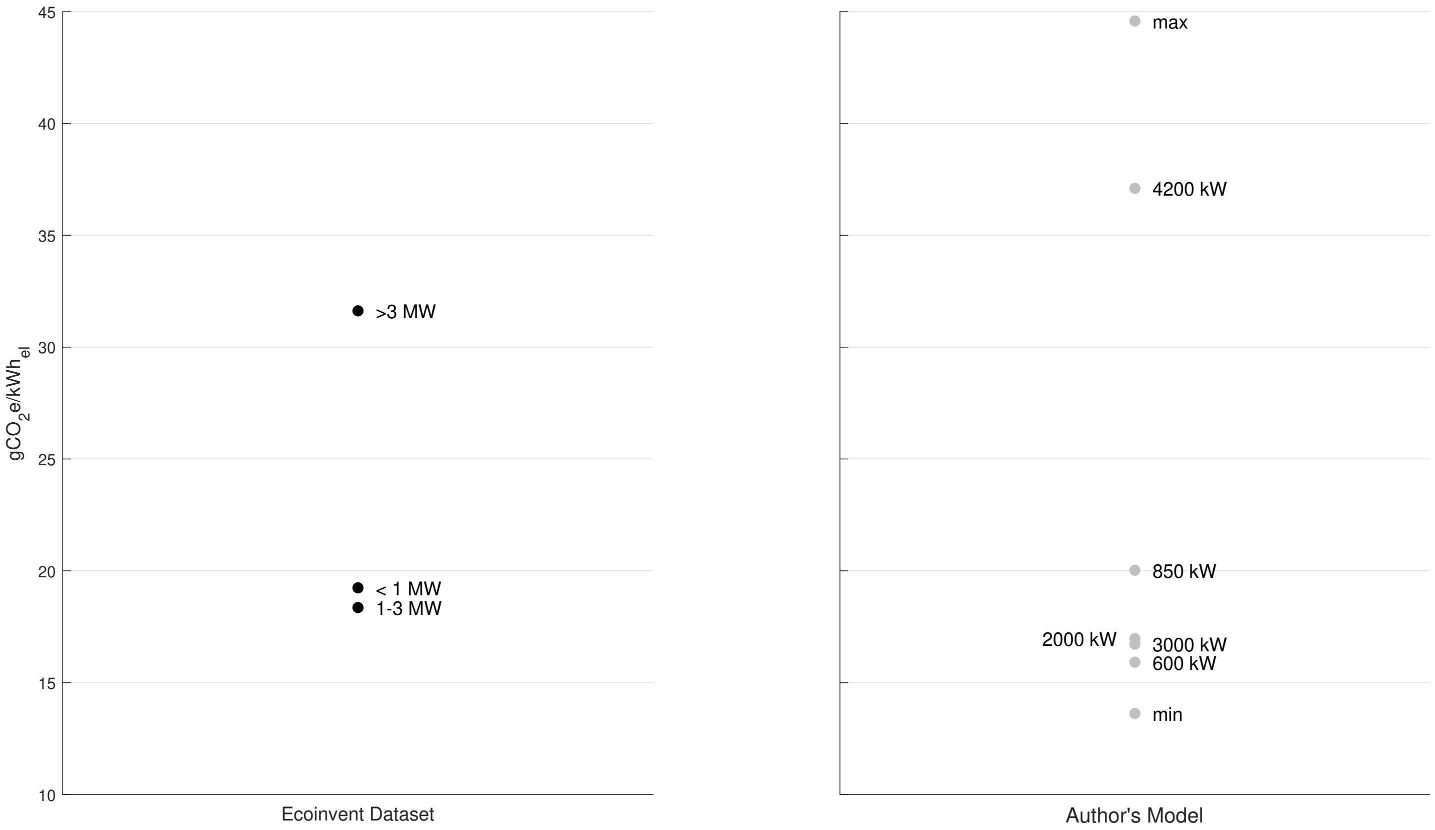

Figure 4.19: CC ecoinvent versus author's model

5 | Conclusions and future research steps

This thesis assesses the climate profiles of wind electricity production from on-shore turbines installed in Italy with a first degree of approximation. The carbon footprint of 1 kWh_{el} produced by the turbines was evaluated according to (i) the geographical location, (ii) the wind speed, and (iii) the characteristics of the wind turbines installed (rated power). The motivation for this research lies in closing the gap in the literature to the state-of-the-art of Italian wind farms. The creation of an updated wind turbine map is an important achievement. Besides this, the climate profile of wind electricity is assessed with a higher level of detail with respect to the literature or ecoinvent dataset: regional division, grouping according to average wind speed and power rating.

The farms mapped are 513, with a total installed capacity of 10.6 GW and a nominal power equal to or higher than 200 kW. The capacity mapped corresponds to 94% of the whole capacity installed in Italy (11.8 GW, according to Ternal for 2021). In contrast, the capacity of the farms modelled within the work is equal to 9.3 MW due to missing information for implementing the analysis (equal to 78%, if compared with Terna data).

The hourly wind profile of each farm was obtained using different anemometers with epw file. Only one source was used for coherence in the result. The wind profile was scaled according to the average wind speed at 50 m a.b.g. obtained by the Italian atlas. Therefore, the profile was adjusted to the hub height of the wind turbine considered.

Once obtained the wind profiles, the electricity production was assessed through the approximation of the power curve. This was derived using data from manufacturers. The interpolation was implemented using the spline cubic technique applied, fixing three points (approach proposed by the author): (i) at the beginning, (ii) in the middle, and (iii) at the end of the region 2 shown in Figure 2.1. The method was tested and compared with: (i) holistic cubic spline considering all the couple speed-power, (ii) Weibull, and (iii) cubic techniques fixing two out of three points mentioned above (at the beginning and at the end). The holistic cubic spline was the best one replicating almost exactly the power curve. Nevertheless, it was unfeasible to collect all the data points of all the wind turbine power curve. The technique proposed by the author was chosen as the second best option for the approximation given (2-3% uncertainty) but saving computational time if compared with the holistic cubic spline (most reliable).

The wind turbine electricity production model was validated through two steps. At first, productivity value from the commission's website was found for a total of 73 wind farms. For this subset, the average absolute difference of the production modelled is around 18% (generally the model's output is an overestimation). Secondly, the gross productivity of 2021 by Terna was scaled according to the mapped installed capacity and used for comparison. The average absolute difference is 29% considering two extreme regions (Liguria and Umbria). without these two outliers, probably due to year-specific data, the average decreases to 14%. Given the modelling technique performance, this discrepancy is mainly due to the wind speed profile.

The climate profile was assessed using the Life Cycle approach and the process-based Life Cycle Assessment method. The life cycle inventory data were derived from the ecoinvent 3.9.1 background database, cut-off system model. The emissions of carbon dioxide equivalent were assessed using the Environmental Footprint 3.1 characterization method (100-year time horizon). The data provided by the ecoinvent library were scaled up into five rated power (i.e., 600, 850, 2000, 3000 and 4200 kW), considered representative of the sample (covering 67% of the 6754 wind turbine), using power relationships found in the literature. Table 4.4 shows the climate profile divided per region, per average wind speed and per rated power.

A Monte Carlo analysis is performed on the 73 subset parks' climate profiles. It states the key role of electricity production and modelling it with the lowest error possible. The only uncertainty linked to the ecoinvent database modifies slightly the profile ($\pm$ 2-3 gCO_2eq/kWH_{el}). On the other hand, the performance of the model strongly affects the results with a standard deviation of the same order of magnitude.
In the end, the 18% model productivity difference is implemented in LCA assessments for 600 kW and 4200 kW to obtain a more reliable climate profile range

The results achieved derived the following conclusions for onshore turbines installed in Italy:

- the climate profile ranges from 13.62 to 44.58 gCO_2eq/kWh_{el}, considering the uncertainty related to the annual production of 73 subset farms;
- the average Italian results for the five rated power analysed are, in ascending power

order, 15.91, 20.02, 16.07, 16.72 and 37.10 gCO_2eq/kWh_{el};

- the results, if compared with ecoinvent, increase the range of the 6 gCO_2eq/kWh_{el} in the lower limit and 13 gCO_2eq/kWh_{el} in the upper one (Table 4.22). The ecoinvent dataset provides for Italy three values equal to 19.24 ($<$ 1 MW), 18.36 (1-3 MW) and 31.62 gCO_2eq/kWh_{el} ($>$ 3 MW);

- the results are in line with the scientific literature available for Italy and increase the level of detail of the emission factors (specific per region, rated power and average wind speed);

- the climate profile of the kWh_{el} produced with wind turbines is suitable for green hydrogen production by water electrolysis technologies. In all the cases the outcomes are lower than the European Taxonomy threshold, assessing the goodness and the potential of coupling these technologies with Italian wind electricity. If an alkaline water electrolysis is supplied with electricity from wind farms of 4200 kW, which has the highest CC impact, the emissions embodied would be 2.44 tCO_2eq/tH_2, hence well below the 3.38 tCO_2eq/tH_2 limit value.

The interactive map and the codes used are reported in Appendix A.

Future research should address the uncertainty rooted in the data The starting point for future improvements can be summarised in:

- increasing the performance of the wind turbine electricity production model. The limits are on the wind hourly dataset (use of primary data of anemometers installed in the wind farm location);

- improve the primary data on yearly electricity production of wind farms to increase the reference sample for testing the model;

- improve the inventory of data used for the LCA model by collecting primary data for a representative sample of turbines at different sizes.

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A | Appendix

As a support of the thesis presented, a OneDrive folder (2023_Acconito_Thesis) is created by the author and can be viewed as follows:

- **clik here - OneDrive Folder**[1]

The following files are provided in the folder:

- "ReadMe.txt" - txt files with a short description of the files provided;
- "Interactive_map_Italy_V3.html" - this is the interactive map created by the author that groups all the findings of the thesis;
- "Interactive_map_code.ipynb" - Brigthway code for the map creation;
- "Compute_MWh.py" - Python code for the wind turbine electricity production model. This code was used to assess the different modelling techniques, to compute the yearly farm production and so on;

The author reserves the right to modify or add files/information. All changes will be outlined as clearly and completely as possible.

[1] https://1drv.ms/f/s!Anl1oicNtWMQiFS-jO9enbG3IYKb?e=BHD9dI

List of Figures

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List of Symbols

Variable	Description	SI unit
$\boldsymbol{a}$	Hellman exponent	-
$\boldsymbol{a, b}$	Cubic approximation parameters	-
$\boldsymbol{a_1, b_1}$	Weibull parameters	-
$\boldsymbol{A_{rotor}}$	rotor area	m^2
$\boldsymbol{CO_2}$	carbon dioxide	-
$\boldsymbol{CO_2eq}$	carbon dioxide equivalent	-
$\boldsymbol{D}$	rotor diameter	m
$\boldsymbol{h}$	(hub) height	m
$\boldsymbol{H}$	(hub) height	m
$\boldsymbol{k}$	shape parameter	-
$\boldsymbol{kWh_{el}}$	electrical kilowatt hours	-
$\boldsymbol{M_{electroniccables}}$	electronic and cables mass	kg
$\boldsymbol{M_{foundation}}$	foundation mass	kg
$\boldsymbol{M_{nacelle}}$	nacelle mass	kg
$\boldsymbol{M_{rotor}}$	rotor mass	kg
$\boldsymbol{M_{tower}}$	tower mass	kg
$\boldsymbol{Nm^3}$	Normal cubic meter	Nm^3
$\boldsymbol{P_{captured,max}}$	maximum power captured	W
$\boldsymbol{P_{el}}$	electric power	W
$\boldsymbol{P_{kinetic}}$	kinetic power	W
$\boldsymbol{P_r}$	rated power	W
$\boldsymbol{P_{spec}}$	specific power	W/m^2

Variable	**Description**	**SI unit**
$\boldsymbol{Q_1}$	first quartile	-
$\boldsymbol{Q_2}$	second quartile	-
$\boldsymbol{Q_3}$	third quartile	-
$\boldsymbol{\eta_{generator}}$	generator efficiency	-
$\boldsymbol{\eta_{losses}}$	losses coefficient	-
$\boldsymbol{\rho_{air}}$	air density	kg/m^3
$\boldsymbol{u}$	solid displacement	m
$\boldsymbol{uf}$	fluid displacement	m
$\boldsymbol{v}$	velocity	m/s
$\boldsymbol{vcut, in}$	cut-in velocity	m/s
$\boldsymbol{v_{cut,off}}$	cut-off velocity	m/s
$\boldsymbol{v_{hub}}$	velocity ad hub height	m/s
$\boldsymbol{v_{rated}}$	rated velocity	m/s
$\boldsymbol{V_{mean,anemometer}}$	average anemometer wind velocity	m/s
$\boldsymbol{V_{mean,atlas}}$	average wind speed from atlas	m/s

List of Abbreviations

Abbreviation	Explanation
a.b.g.	above ground level
AEL	Alakine water ELectrolysis
AEOLIAN	Atlante EOLico ItaliANo
AR6	Sixth Assessments Report
CCS	Carbon Capture and Storage system
CC	Climate Change
COP	Conference Of the Parties
DoE	Department of Energy
EC	European Commission
EF	Emission Factor
EF	Environmental Footprint
epw	EnergyPlus Weather
EoL	End of Life
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gases
GSD	Geometrical Standard Deviation
GSE	Gestore dei Servizi Energetici
GWP	Global Warming Potential
IEA	International Energy Agency
IQR	InterQuartile Range
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MC	Monte Carlo

Abbreviation	Explanation
NDCs	Nationally Determined Contributions
OAT-SA	One-At-a-Time Sensitive Analysis
PEM	Proton Exchange Membrane water electrolysis
PSI	Paul Scherrer Institute
PV	Photovoltaic
SF	Scale Factor
SOEC	Solid Oxide Electrolysis Cell
TMY	Typical Meteorological year
WT	Wind Turbine