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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

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

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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1. Introduction

The climate change problem is assessed by countless scientific reports and research. The decarbonization pathway is the only possible way to try to respect the target of the Paris Agreement. Indeed, many challenges but at the same time opportunities are present. Several solutions and technologies are exploited and the integration of renewable electricity with water electrolysis technologies is one of these. The thesis presented is in this direction, with a top-level estimate of Italian wind turbine production.

The wind farms with a total installed capacity higher than 200 kW are mapped and, after the data collection part, a model is implemented to approximate the yearly farm productivity. To accomplish this, a new procedure is proposed by the author. After, the environmental profile of 1 kWh_{el} produced by wind turbines is assessed using the Life Cycle approach and the process-based Life Cycle Assessment method. The focus is on the climate change (CC) impact category and the resulting climate profile is obtained for five rated power (600, 850 2000, 3000 and 4200 kW).

After the validation of the models implemented with two procedures, a Monte Carlo analysis is computed to assess the robustness of the results. In conclusion, an interactive map is created by the author. In this map, the characteristics of the mapped farms are reported with the estimated equivalent hours. The new database of climate profiles is implemented as well. This can be useful to determine the potential environmental impact of hydrogen production and compare it with the EU taxonomy threshold of 3.38 tCO_2/tH_2 [1]. A first rough approximation with state-of-the-art water electrolysis technologies is performed.

2. Wind turbine electricity production model

The data collection procedure was carried out by comparing the farm's information from different sources. The database of Terna, an Italian company operating the electricity transmission networks, was the reference one [2]. Only wind farms with total installed capacity higher than 200 kW, or even higher than 1 MW in some regions, were considered. The hourly wind profile for modelling the production was obtained from an anemometer database and scaled later according to the Italian Atlas.

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 technique proposed by the author is a spline cubic approximation fixing three points: at the beginning (cut-in speed), in the middle and in the end (rated speed) of the power curve. The resulting approximation is, compared to the literature, the second best option but saving computational time. With this procedure, the yearly farm productivity and its equivalent hours are computed.

3. Life cycle assessments

The outcome of the mapping procedure was the input for the LCA. The analysis's functional unit was set to 1 kWh of electricity produced by the wind turbine. Indeed, the amount of electricity produced during their lifetime was the principal input for spreading the entire emissions embodied in all the life cycle phases. The Life Cycle inventories (LCIs) were obtained by a report of the Paul Scherrer Insititute (PSI) [3]. From this report, the activity processes and the associated exchange input, which is the exchange flow with the world, are retrieved. Three different inventories were present, each associated with a specific wind turbine model. Therefore, in accordance with the ecoinvent database, three clusters were created depending on the rated power of the wind turbine: $<$ 1MW, between 1-3 MW and $>$ 3 MW. The reference database for computing the LCA associating for each activity a value of impact categories is ecoinvent, version 3.9.1 cut-off [4]. The characterization method used was the Environmental Footprint 3.1 characterization (100-year time horizon).
Before the assessment, due to the format of the inventories, a scaling procedure was performed to be able to assess the impact of wind turbine models different from the reference ones of the PSI report. The inventory was adapted case by case according to proportionality relationships presented by Caduff et al. [5].

4. Validation and Monte Carlo

Two validation procedures are implemented to assess the quality of the wind turbine model. At first, the information on the estimated wind farm production was found on operating company websites for 73 farms. The model's outputs were compared for these farms. Secondly, the overall region production from 2021 was present in the Terna database. After scaling the amount according to the actual installed capacity modelled in this thesis, the results were compared.
On the subset of farms considered in the first validation procedure a Monte Carlo analysis was performed. This was useful to assess the error propagation of the model implemented. Two MCs were performed: one considering the inherent uncertainty embodied in the ecoivent database, and the other aggregating this last with the uncertainty of the wind turbine model. The comparison led to a review of the research outcomes and bright out the most important aspects.

5. Results

The farms mapped are 513, with a total installed capacity of 10.6 GW. The capacity mapped corresponds to 94% of the 11.8 GW onshore Italian capacity of 2021. Instead, the modelled capacity in this thesis is 9.3 MW due to missing information on the power curve. This corresponds to around 80% of the Italian wind capacity. Table 1 reports the capacity considered at each step; subset power refers to Terna's capacity considered for the modelling, hence higher than 200 kW or 1 MW in some regions.

Table 1: Total installed capacity in the different steps

Italian onshore capacity	11 848.4	MW
Subset power	11 314.10	MW
Mapped power	10 593.07	MW
Modelled power	9 311.01	MW

In the literature, several techniques to model wind electricity production were found. Focusing on polynomial techniques for power curve approximation, Weibull, cubic approximation and spline interpolation were tested. In this latter technique, a spline cubic approximation is performed between all the couple-point wind speed-power of the power curve. It is a demanding effort from the inputs required but it replicates almost exactly the wind turbine performance. Indeed, it was used as a reference to compute the quality of the other techniques. In the figures below, the dotted blue line is the result of this holistic spline cubic.

As can be noted from Figure 1, the Weibull and Cubic approximation have a marked discrepancy. On a sample of three models and 95 farms, the percentage difference is 32% for the Weibull (yellow line) and 13% for the Cubic approximation (green line).

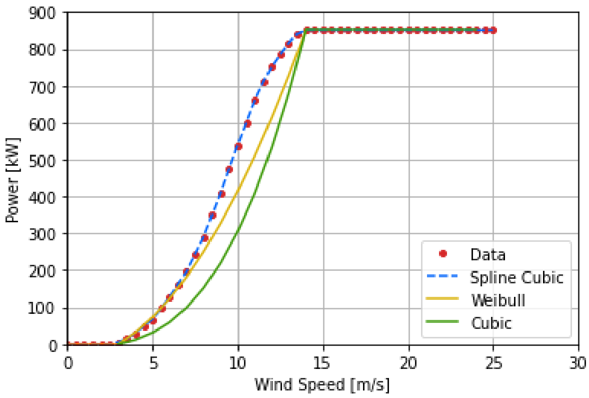

Figure 1: Weibull and Cubic approximation

The difference with the approach proposed by the author can be immediately seen in Figure 2. The two curves are almost overlapped and the difference obtained with the sample is around 2-3%. A quite remarkable result with far less data input with respect to the spline cubic approximation.

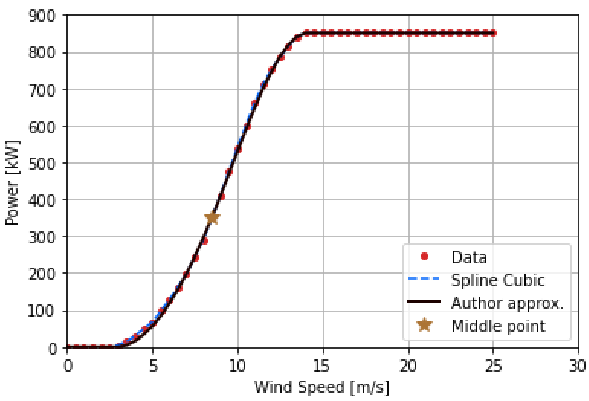

Figure 2: Author's proposing approximation

The interpolation proposed is still based on the spline cubic technique but without considering all the coupled speed-power. Instead, three points were fixed on the power curve: the cut-in speed, a middle point where the inflexion point is present, and at rated speed. The spline cubic is implemented in the two areas delimited by the middle point (yellow star in Figure 2). This pair of speed-velocity values was the additional information needed with respect to the Weibull and the Cubic approximation. The additional input increases the accuracy of the approximation in an acceptable way for almost all engineering purposes. The performance is comparable with the holistic spline cubic technique, but the computation demand is far less.

The LCA was performed for five rated powers, decided according to the most common one. For the cluster lower than 1 MW, the rated power is 600 kW and 850 kW, for the middle cluster 2000 kW and 3000 kW, while for the rated power higher than 3 MW, one value was chosen, 4200 kW. With this decision, around 67% (4550) of the total 6457 wind turbines modelled are covered. According to the region and the average wind speed at 50 m above ground levels, the farms were divided and the LCA was performed roughly for 100 farms. The range of wind speed was divided from 5 m/s to 7 m/s with a step of 0.5 m/s. Below and above the limit the farms were grouped. In case more than one farm was present inside the same wind speed range, the one with more wind turbines was selected for the LCA.
As a result, an updated and specific climate change emission factor database for Italian wind electricity was obtained. A weighted average according to the number of turbines for each region is done, in order to have a national value for the five rated power. This overall impact is reported in the second column of Table 2. The highest value for wind turbines of 4200 kW is associated with a higher relative amount of raw materials. With further analysis of the LCIs, the sum of raw materials with respect to the total amount of electricity production is higher for this rated power. Indeed, the increase in raw materials needed is not counterbalanced by the increase in electricity production. This is one of the reasons, but not the only one, why the CC for 4200 kW is the highest.

In Table 2 are also reported the values of the first approximation of emissions embodied in hydrogen production. According to the state-of-art alkaline water electrolysis (AEL), which is the most common technology, the impact would be lower than the EU limit value in all the cases. The third and the fourth columns of the table reported the results according to the minimum and maximum value of AEL energy consumption respectively. This is a remarkable result that confirms the goodness and the potential of this technological solution.

Table 2: Climate change and hydrogen emissions

Rated Power	Climate change	AEL	
		min	max
[kW]	[$gCO_2e/kWhel$]	[tCO_2e/tH_2]	
600	15.91	0.88	1.04
850	20.02	1.11	1.31
2000	16.97	0.94	1.11
3000	16.72	0.93	1.10
4200	37.10	2.06	2.44

The validation procedures assess the quality of the production model implemented. As stated, the comparison for 73 farms is computed and the outcomes are reported in Figure 3. Divided by the three clusters, the percentage difference between the production of the model and the one found on the operating company's website is reported in a box plot. A positive value means the modelled production is higher than the reference one, the opposite for negative values. The performance is quite similar in all three cases even if for the cluster > 3 MW the sample consists of only 6 farms, hence the results are less accurate from a statistical point of view. For the first two cases, the first and third quartiles are around -10% and 15-20% respectively. In absolute terms, the average difference considering all the 73 farms is around 18%; this a quite remarkable achievement. This property is also confirmed by the second validation procedure that considers all the 2021 productivity, scaled according to the 9.3 GW mapped. The average absolute difference is 29% but with the presence of two outliers: in Liguria and Umbria the model production value is more than double than the Terna one. A possible explanation is the comparison with only one specific year, while the wind profile considered in the model is an average of 15 years. Without these two extreme cases, the absolute average difference would become 14%, closer to the median distribution of the samples.

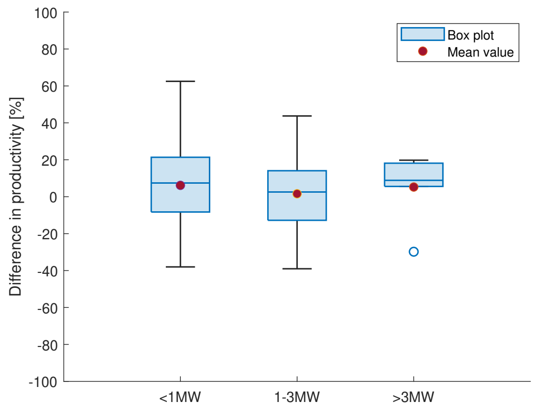

Figure 3: Validation outcomes

The Monte Carlo analysis is based on the subset of 73 wind farms considered in the first validation procedure. Three virtual average wind turbines were created to perform the LCA while considering a lognormal distribution of electricity production. In this case, 1000 iterations were performed two times: once considering the model's uncertainty on the electricity production and the uncertainty on the LCA databases, and the second one considering only this last. As expected, the role of electricity production is crucial and determined for the climate change emission factor. Indeed, the only inherited variability of the LCA model has an impact on the final results of around 2-3 gCO_2/kWh_{el}. If it is added the uncertainty of the wind turbine model the standard deviation of the resulting distribution is of the same order of magnitude as the median value. Nevertheless, even with an emission factor in the upper range, the competitiveness of the technology and its low environmental impact with respect to standard power plants remain. This is established also by the first approximation of hydrogen production which total emissions would be lower than the EU taxonomy in any case considered.

To overcome the model's variability, a better performance of this latter would be sought. The limit is on the wind profile database rather than on the approximation technique. Indeed, it was performed for a small sample of farms, around 10, a comparison of modelled production with another wind dataset: ERA5 hourly data on single levels from 1940 to the present. In conclusion, the use of the anemometer files was not refuted.

6. Conclusion

The range of the climate change emission factors obtained for Italian wind electricity goes from 13.62 and 44.58 gCO_2eq/kWh_{el}. The lower and upper limit is computed by considering the 18% uncertainty of the electricity production model (1^{st} validation procedure). It was applied on the 600 and 4200 kW wind farms, which are characterised by the lowest and highest Italian CC according to to the thesis' assumption and model. This climate profile range is compared with the value of the ecoinvent 3.9.1 background database in Figure 4. There is an increase of 6 and 13 gCO_2eq/kWh_{el} for the lower and upper boundaries of the ecoinvent dataset, respectively. Indeed, the impacts obtained by the models implemented in this work are aligned with the ecoinvent values and the literature. Furthermore, the novelty of this thesis is the creation of more specific emission factors, based on rated power, geographical position and average wind speed. The implementation of these results in the interactive map creates a complete database, with a first degree of approximation, of the Italian wind energy.

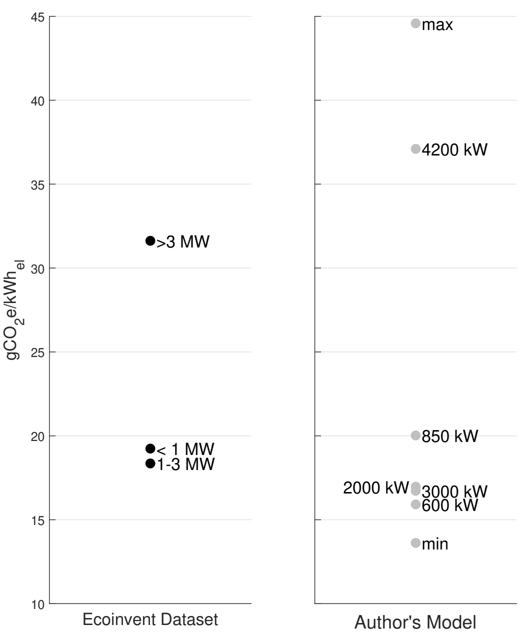

Figure 4: Range of CC versus ecoivent value

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