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Analysing wind farm efficiency on complex terrains.

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Abstract. Actual performances of onshore wind farms are deeply affected both by wake interactions and terrain complexity: therefore monitoring how the efficiency varies with the wind direction is a crucial task. Polar efficiency plot is therefore a useful tool for monitoring wind farm performances. The approach deserves careful discussion for onshore wind farms, where orography and layout commonly affect performance assessment. The present work deals with three modern wind farms, owned by Sorgenia Green, located on hilly terrains with slopes from gentle to rough. Further, onshore wind farm of Nørrekær Enge has been analysed as a reference case: its layout is similar to offshore wind farms and the efficiency is mainly driven by wakes. It is shown and justified that terrain complexity imposes a novel and more consistent way for defining polar efficiency. Dependency of efficiency on wind direction, farm layout and orography is analysed and discussed. Effects of atmospheric stability have been also investigated through MERRA reanalysis data from NASA satellites. Monin-Obukhov Length has been used to discriminate climate regimes.

1. Introduction

Performance optimisation of wind farms is a fertile and rapidly growing subject. Developments of post-processing techniques of Supervisory Control And Data Acquisition (SCADA) wind turbine databases has proven to be the keystone for quantifying power losses and their causes.

Paradigmatic test cases have been deeply examined, especially for offshore wind farms: in [1] power losses due to wakes have been investigated for offshore Horns Rev and Nysted wind farms in Denmark. Dependency on climate and atmospheric stability is appreciably addressed in [1] and sensible decay of power performance is detected under stable conditions, with respect to near-neutral and unstable regimes.

In [2] polar efficiency is defined and exploited as meaningful parameter for testing goodness of numerical Computational Fluid Dynamics (CFD) simulations of power losses due to wake effects, for the test cases of Horns Rev and Nysted.

In [3] an introduction to wind profiles and meteorological effects on wind power generation is given; in [4] mesoscale numerical models are used for investigating effects of atmospheric stability for offshore wind farms in Denmark.

In [5] the test case of Horns Rev is studied and a systematic analysis is carried in order to highlight dependency of power deficit on wind rose, wind speed, turbulence intensity and stability of the atmosphere classified through the Bulk-Ri number.

In [6] SCADA data mining techniques are used for quantifying power and speed losses due to wakes; appreciable analysis is devoted to misalignment and yawing under downstream wake

angles. Numerical models for simulating wake power losses are investigated in [7], [8] and are employed in [9] to investigate how orography and atmospheric stability affect wind profile, especially for non-neutral regimes.

The present paper aims at giving a contribution on the issue of quantifying and explaining directional dependency of power performance for onshore wind farms: polar efficiency shall be used as the main tool, but its interpretation is even more complex than in the offshore cases.

Actually, while offshore power losses are mainly driven by wakes, which depend basically on wind rose, farm layout and climate, onshore these effects are heavily intertwined with complexity of terrain and it is far from trivial to disentangle them.

Three wind farms owned by Sorgenia Green in southern Italy, sited in terrains from gentle to extremely rough and complex, are investigated in the present paper. It shall be shown how complexity of the terrain makes it difficult even to define properly the polar efficiency and a novel, more consistent way, shall be proposed, whose consistency is demonstrated. The test case of danish wind farm at Nørræker Enge shall also be briefly analysed because it has simpler geometry and terrain. It therefore constitutes a trait d'union between the features of onshore complex terrains and offshore. Nørræker Enge datasets are freely accessible [10] and the site is currently under investigation within the Wakebench-Task 31 IEA project.

Further some issues about dependency of the polar efficiency on climate and atmospheric stability are addressed and discussed.

2. The sites under investigations

The present work deals with three onshore wind farms, owned by Sorgenia Green and sited in southern Italy. They have been chosen because of the different complexity of the terrain and farm layout.

For brevity, the layout is readable directly in the Figure 7 included for the discussion of the results and we refer the reader to it.

Minervino wind farm features 9 turbines on a terrain with gentle slopes, but turbine distance is such as resulting in considerable power losses due to wakes, especially in the 270° sector which, as Figure 1-(b) shows, is very populated. The closest turbines are T3 and T4, but the turbines T7 and T8 can be affected by multiple wakes in the east-west direction because of their inner position. The turbine T2 instead is isolated and at a distance of more than 13 diameters from the other aerogenerators.

San Martino in Pensilis wind farm features instead 6 turbines, on a more complex and rough terrain, but the distance between each machine is considerably higher with respect to Minervino.

The most challenging test case is San Gregorio Magno wind farm: 17 aerogenerators are installed on a very complex terrain, with very high slopes (up to 60%) close to the turbines; also the layout is complex and large and there are clusters of considerably near turbines. This leads to non trivial combination of complex wind flow and wake interactions.

Nørræker Enge is instead on a very plain terrain and the geometry of the wind farm is so regular as to evoke offshore structures.

3. The Polar Efficiency Method

Polar efficiency is a meaningful parameter for quantifying goodness of performances and investigating power losses and their causes in relation with the wind speed direction. It is defined as [2]

$$\eta = \frac{\sum_{i=1}^{N} P_i}{N \cdot \bar{P}} \tag{1}$$

where N is the total number of turbines of the farm, $\bar{P}$ is the power of the most upwind turbine and P_i are the powers of each turbine. If for a given direction several turbines are upwind, the definition above can be improved with an average of upwind turbines power at denominator.

Data mining techniques allow to compute polar efficiency on the same 10 minute time basis as the SCADA datasets. Only 10 minute time steps have been considered during which every turbine of the farm has been productive for at least 80% of the time. The 80% threshold of productive time has been chosen in order to compromise between the following needs: hugeness of the datasets and proper representativeness of the wind farm producing output in unison on the largest wind speed range as possible. Figure 3-(b) for Minervino wind farm shows indeed that the wind speed range is fairly populated also at its lower tail, which would not be represented imposing a more severe data cut. Further, Minervino dataset consists of around 25000 records, ensuring statistical reliability even when filtering on extreme climate conditions.

In order for polar efficiency (1) to be consistent, it should be a number between 0 and 1.

Figure 1-(a) shows the polar efficiency for Minervino wind farm, computed according to (1), and averaged on twelve wind direction sectors according to the anemometer reference. The plot is so systematically biased, even for the relatively gentle terrain of Minervino, to make the definition (1) not consistent for onshore wind farms: a refined approach is needed.
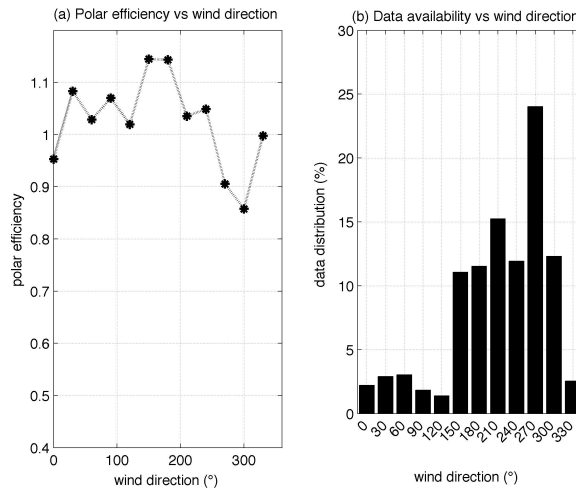

Figure 1. (a): Average Polar efficiency plot for Minervino wind farm according to Equation (1): 12 direction intervals. (b): Wind direction distribution for Minervino wind farm: 12 sectors.

The proposal is to replace the equation (1) with the following definition (2)

$$\eta = \frac{\sum_{i=1}^{N} P_i}{N \cdot \hat{P}} \qquad (2)$$

where $\hat{P}$ is the power of best performing turbine, whatever it is and irrespective of considerations of which turbine is the most upwind.

Actually complexity of the terrain induces additional turbulence and local wind flow acceleration which remarkably affects power output. Such effect is not negligible and results in the fact that the best performing turbine can not reasonably be expected to be one of the most upwind.

Our definition automatically leads the polar efficiency to consistently be a number between 0 and 1. Yet, our proposal Eq. (2) deserves deeper analysis: it is expected to avoid the lack of consistency of Eq. (1), without creating any problem of interpretation, when turbines are organised in regular clusters. If a turbine lies far from the others and catches undisturbed wind from most directions, it regularly extracts more power and lowers systematically the polar

efficiency Eq. (2). Minervino wind farm is a useful testing ground for this limit, since T2 lies around 13 turbine diameters far from the nearest turbine. Figure 1-(a) shows that it is nevertheless unavoidable to employ our definition Eq. (2); the distribution of maximum power of the farm among the turbines shows that it would be even less consistent to always select T2 as the upwind turbine for using Eq. (1), because T2 is not the best performing turbine in 67.13% of the cases. Therefore, even if Eq. (2) must be handled with care for uneven turbine spatial distributions, it is nevertheless the most consistent definition of polar efficiency.

Further, the consistency of the definition has been verified as follows: polar efficiency records have been stored in 12 sectors, with respect to the anemometer wind direction, and have been averaged inside each sector. If the definition (2) is consistent, the binned polar efficiency plot should highlight expected sectorial power losses, at least for the most well defined case of Minervino.
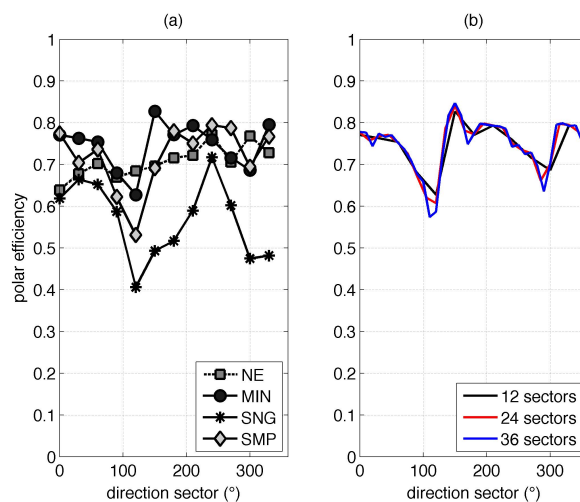
Figure 2 shows that this is indeed the case.

Figure 2. (a): Average Polar Efficiency plot with 12 wind direction intervals for the four test cases. (b): Average Polar efficiency plot for Minervino wind farm: 12, 24 and 36 wind direction intervals.

Figure 2-(b) highlights the power efficiency collapse in the 270° direction for Minervino, whose layout suggest considerable wake interactions in that sector. The trend of polar efficiency against the wind direction reveals not to be significantly dependent on the size and the number of bins. Yet, the higher the number of bins, the sharper appear polar efficiency collapses in the sectors most affected by wakes: with 36 sectors, the most relevant collapses arise for 120° and 280° sectors.

Figure 2-(a) compares polar efficiency plots on 12 averaged sectors for the four test cases: for San Martino in Pensilis the most relevant power collapse is at 120° and subsequently at 90° and 300°. The most awkward test case, San Gregorio Magno, is characterised globally by an efficiency which is considerably lower with respect to the other farms under consideration: this is expected and consistent because the conjunction of wake effects and complexity of the terrain must affect polar efficiency, resulting in decreased performances. Finally Nørræker Enge wind farm polar plot displays a much smoother trend with respect to the other test cases, reflecting its most regular and gentle structure; yet a non-negligible efficiency collapse in the 270° can be observed.

Polar efficiency dramatically tends to 1 for high wind speed because wind turbines operate extracting the rated power and lowering the thrust.

Therefore the directional plot might be biased if there are prevailing strong winds from a given direction: the three Sorgenia wind farms are indeed not affected by such bias. As Figure 3-(b) shows, the prevailing wind regimes are in the 5-10 m/s interval. Nevertheless it is instructive to plot polar efficiency as a function of wind speed and appreciate how it asymptotically tends to 1: in Figure 3-(a), records have been averaged on bins having 0.5 m/s of amplitude.
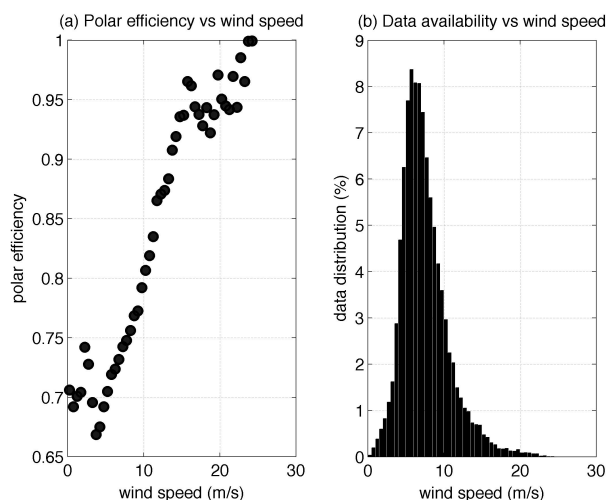

Figure 3. (a): Average Polar efficiency plot for Minervino wind farm: 0.5 m/s amplitude of wind speed intervals. (b): Wind speed distribution for Minervino wind farm.

Since San Gregorio Magno wind farm has considerable extension and lies on a very complex terrain, it is very difficult to interpret the main drivers of polar efficiency dependency on wind direction. Therefore, as a simpler and more intuitive testing ground, it has been chosen to compute the polar efficiency also only for turbines from 10 to 13. Farm layout shown in Figure 7 and small relative distance between turbines 10-13 suggest that complex terrain effects should be dominated by wakes, at least for certain sectors, like 270° and 90°. Figure 4 shows that the most important efficiency collapses appear for 300° and 60° sectors, and secondly for 270° and 90°. Yet, Figure 7-(c) shows the frequency of best performance for each turbine and it arises that, when the wind blows in the 270° sector, turbine 13 is the best performer much more often than turbine 10, which is upwind. This demonstrates that orography effects dominate, and a clear wake effect is observable only for the couple of turbines 10-11.

Further, an analysis has been carried on for investigating how the complexity of the terrain affects polar efficiency and how to disentangle it from wake effects. The ruggedness index (RIX) has been used: it is computed on 30° sectors for each turbine site. A flat site will then have a RIX of 0%, a very complex (steep) site an index of, say, 30% meaning that about one third of the terrain is steeper than a critical slope. RIX values have been averaged along each turbine of Sorgenia wind farms, resulting in 12 values summarising mean sectorial farm complexity. The first result is that Minervino wind farm displays mean sectorial RIX values around 0 and San Martino in Pensilis slightly, yet not sensibly, higher: this means that the polar efficiency is mainly driven by wakes, even if ruggedness effects slightly smear the dependency with respect to the offshore case. San Gregorio magno instead displays significant RIX values, much variable from sector to sector. Figure 5 clearly highlights that the higher the sectorial RIX, the higher is the polar efficiency. This is due to local wind flow acceleration caused by terrain complexity,
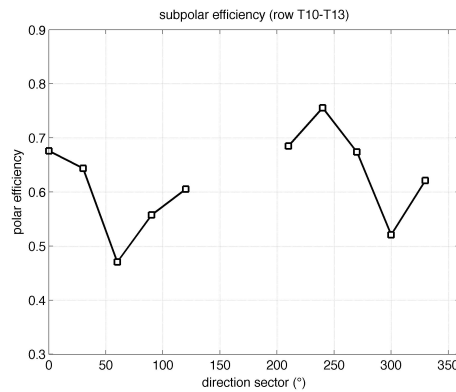
Figure 4. Polar Efficiency: Average on 12 wind rose sectors for San Gregorio - Row of turbines 10-13

which prevails over wake effects. Figure 5 therefore sheds light on the fact the efficiency of San Gregorio wind farm is mainly driven by complexity of the terrain.
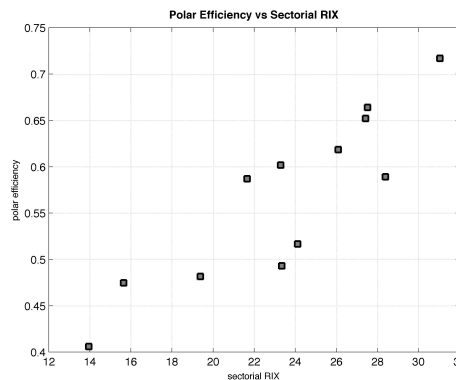

Figure 5. Sectorial polar efficiency against mean farm sectorial RIX value: San Gregorio wind farm

Summarising, a novel approach for computing polar efficiency has been proposed, due to novel challenges for onshore wind farms on complex terrains. The discussion above and the results shown in figures 2 and 4 show that the method is consistent even for wind farms on very complex terrains.

4. Influence of climate conditions

Climate conditions affect non trivially power efficiency. Yet, for very complex terrains it is extremely difficult to highlight climate effects, because multiple agent concur: orography, wakes, turbulence, wind speed, atmospheric stability.

For the present work an analysis has been carried on in order to investigate possible dependency of efficiency losses on atmospheric stability. This issue has been addressed in [1] and sensible decay of power performance is detected under stable atmospheric condition, with respect to near-neutral and unstable regimes.

MERRA reanalysis data from NASA satellites [11] have been employed for this task. These have pros and cons: on one hand their resolution is too coarse in order to capture details of the climatology on the scale of farm layout. On the other side, they are extremely manageable and easily accessible: vastness of data sets at disposal is expected to highlight regimes of great stability and instability.

Monin-Obukhov length L has been chosen in order to distinguish atmospheric stability regimes: in [1], time stamps obeying the condition $0 < L < 10z$, where z is hub height, have been considered stable. $-10z < L < 0$ corresponds instead to unstable and $|L| > 10z$ corresponds to neutrality. Stability regimes can also be derived from Pasquill classes [12]. The limit of absolute value of Monin-Obukhov length for isolating near-neutral conditions onshore is usually lower with respect to the offshore case. In the present work the value of $|5z|$ has been used for discriminating. Size of data sets indicates as reasonable also pushing to a lower value for discriminating regimes. This shall be investigated in further developments of the present work.

The main driver of polar efficiency is wind speed: polar efficiency dramatically increases and tends to 1 for high wind intensity. Therefore, data have been analysed both without wind speed filter and filtering on wind speeds less than 10 m/s.

The analysis has been carried out only for Minervino wind farm, because its dataset was the biggest at disposal.

The intertwining of mechanical and atmospheric turbulence makes it difficult to highlight a clear expected dependency of polar efficiency on stability regime. Yet, the main driver of polar efficiency trend is the wind speed distribution and near-neutral conditions are expected to lead to better efficiency with respect to stable conditions because high wind speeds are expected to be prevailing [13].

For Minervino wind farm it has been seen that near-neutral conditions are associated to better performances with respect to unstable and especially stable ones. This is particularly highlighted in the 270° sector, which is the most populated.

If, as expected, polar efficiency trend under different climate conditions is mainly driven by the distribution of high wind speeds, filtering on speeds less that 10 m/s should smear this effect out and unstable conditions should be privileged. Figure 6 shows that this is indeed the case: especially for the main direction sectors, unstable conditions are associated to a mean polar efficiency comparable, if not higher, than near-neutral. Polar efficiency under stable conditions is considerably suppressed with respect to both near-neutral and unstable.

The same analysis has not been carried out for San Martino in Pensilis and San Gregorio Magno because of the smaller size of the dataset, which makes it impossible to disentangle significant effect of atmospheric stability on such complex terrains.

Therefore a simpler analysis has been performed, yet instructive to understand complexity of polar efficiency on rough farm layouts: the distribution of maximum power output has been studied as a function of wind direction.

Figure 7 shows, for all the test cases, the two most populated wind rose sectors: the scale of grey in the figure corresponds to the frequency of maximum power output for each turbine. Black means most frequent and white means less frequent. Figure 7 shows that even for the most populated sectors of the wind rose the best performing turbines are often not consistent with what is expected from the layout of the farms: unexpected effects appear even for the most simple layout of Nørræker Enge in the 240° sector. Minervino layout is somehow peculiar, because Turbine 2 is isolated, at more than 10 diameters from the others: therefore it decouples from the cluster of the other 8 turbines and it catches undisturbed wind in most cases: yet clear wake effects in the 270° arise, especially if one looks at which turbines are disadvantaged. The same effect arises for San Martino in Pensilis, where Turbine 6 is far enough from the other turbines to catch undisturbed wind in most cases. San Gregorio case is the most interesting and
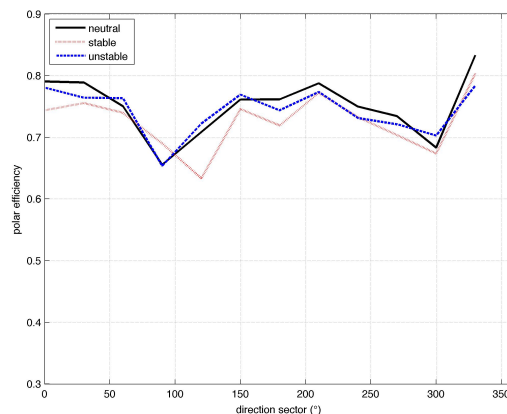
Figure 6. Polar Efficiency in near-neutral, stable and unstable atmospheric conditions for Minervino wind farm. Averaged on 12 wind rose sectors for wind speed less than 10 m/s

reveals that strong effects from the complexity of the terrain arise: for the most populated 270° sector, Turbine 13 appears as one of the most frequent best performers, even though it should be affected by wakes from Turbines 10-11-12.

The number of occurrences of maximum power output out of the range of the two best performing turbines is considerable, justifying our proposal for the definition (2) of the polar efficiency, and is summarised in the following Table 1. The table below shows hierarchically the four most populated sectors of the wind rose, and the percentage of occurrences of maximum power out of the two best performing turbines: these percentages show once again that it is impossible to avoid our definition (2) of the polar efficiency, in particular for the most complex terrain of San Gregorio Magno.

Table 1. Maximum power output: percentage of exceptions from the two best performing turbines - Minervino and San Gregorio Magno. The sectors are in order of population

Sector - Minervino	Percentage	Sector - San Gregorio Magno	Percentage
270°	33.04	270°	47.42
210°	56.19	240°	40.08
300°	44.73	30°	72.57
180°	42.87	0°	63.69

5. Discussion

In the present paper an analysis has been performed about polar efficiency for onshore wind farms. Onshore, polar efficiency not only depends mainly on wind rose, climate and farm layout (wake effects), but complexity of the terrain induces not negligible additional turbulence and local wind flow acceleration.

Four test cases have been considered: three modern wind farms, owned by Sorgenia Green, on terrains from gentle to very rough and complex. Further Nørræker Enge wind farm has been considered because the site is so gentle as to represent a trait d'union between the features of offshore and onshore wind farms.
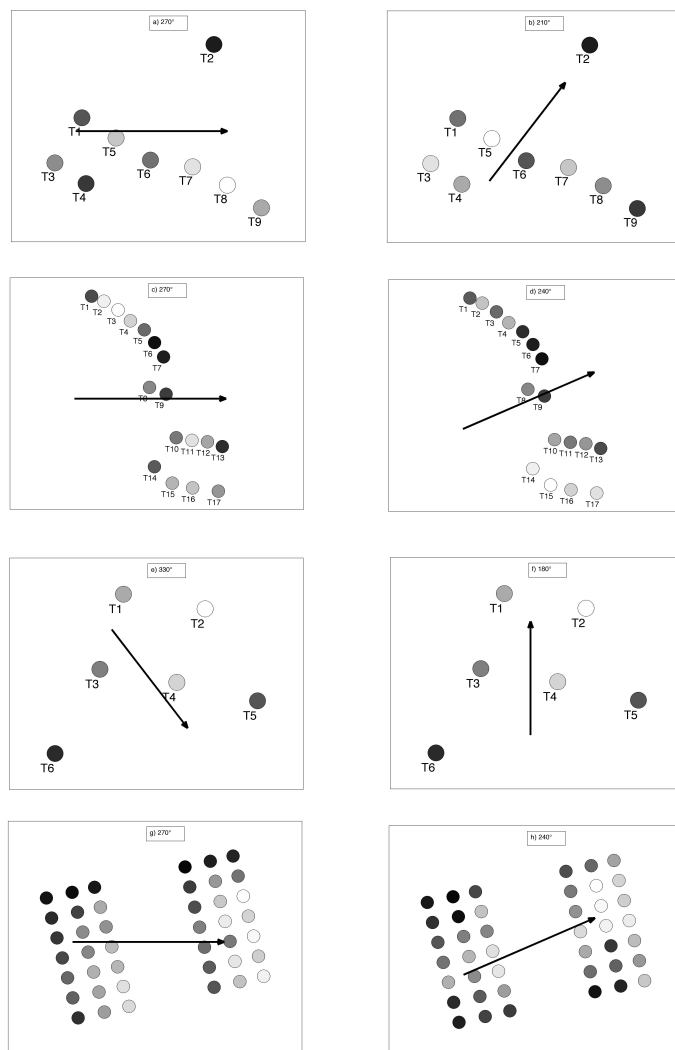
Figure 7. Distribution of maximum power output for the four test cases in the two most populated sectors: Minervino (a,b), San Gregorio (c,d), San Martino (e,f) and Nørræker Enge (g,h). Black corresponds to most frequent, scaling to white for the less frequent.

A preliminary result is that polar efficiency can not be defined as usually in wind energy literature for onshore wind farms. A more consistent definition has therefore been proposed, which takes into account the fact that not negligible is the chance that the turbine with maximum power output of the farm is not one of those upwind.

Consistency of the definition has been demonstrated, showing that it captures brilliantly power losses trends of the test case wind farms. Further the distribution of maximum power output has been analysed and it is shown that even for the most gentle Minervino wind farm, in the most populated sectors of the wind rose even 50% of the times the turbine with maximum power output is not among the most common best performers (which are usually upwind). Therefore the definition of polar efficiency proposed in the present work is not only consistent, but necessary for onshore wind farms.

An analysis has been further carried on for disentangling and quantifying terrain effects from wake effects: this has been done using the ruggedness index (RIX value), which has been computed on 12 direction sectors for each turbine site and averaged on the turbines, in order to have at hand an index of mean sectorial complexity of the wind farm. Minervino and San Martino in Pensilis wind farms display RIX values around 0, and this implies that the dependency of polar efficiency on wind direction is mainly driven by wakes, even if ruggedness smear the effect with respect to the clearest offshore cases. San Gregorio wind farm instead displays significant RIX values. It has been seen that the higher the RIX value, the higher is the polar efficiency. Therefore efficiency is mainly driven by terrain complexity for San Gregorio wind farm and is due to local wind flow acceleration which dominates over wake effects.

Further an analysis has been carried on for quantifying effects of atmospheric stability: MERRA reanalysis data from NASA satellites have been exploited and Monin-Obukhov Length has been used for discriminating stable, unstable and near-neutral conditions.

Minervino wind farm has been considered because its data set was the biggest at disposal. It has been observed that near-neutral conditions are associated to better efficiency with respect to unstable and especially stable conditions. This trend becomes sharper for the most populated direction sectors and is expected, because mainly driven by high wind speed distribution, prevailing under near-neutral conditions. Filtering on wind speeds less than 10 m/s, it has been seen that unstable conditions display an efficiency comparable, if not higher, than near-neutral ones.

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