Analysis of leading-edge erosion impact on the design and performance of wind farm flow control

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Abstract. Leading-edge erosion (LEE) is often observed on wind turbine blades, causing a relevant contribution to operation and maintenance costs. Offshore wind farms are particularly sensitive to LEE occurrence due to a set of conditions that are favourable to it. The appearance of LEE also causes a loss of wind turbine aerodynamic efficiency in operation, which implies a reduction in power generation. Yet, the field demonstration of the overall degradation in energy production due to LEE remains challenging. Additionally, the modification of the aerodynamic performance in a wind turbine also affects its wake, and in consequence, its flow interaction with downstream turbines in the wind farm. In consideration of those farm flow impacts, the present work raises the hypothesis that the change in aerodynamic performance due to LEE may also affect the design and performance of wind farm flow control strategies, in particular, wake steering. For this analysis, a case study is conducted on the offshore TotalControl Reference Wind Power Plant, which has been extensively used for research purposes. Within such framework, results show that, in general, erosion does not have a significant impact on wake steering wind farm flow control strategies, unless considerable erosion differences appear among wind turbines. In spite of everything, further research is necessary to generalise this conclusion.

1 Introduction

Leading-edge erosion (LEE) corresponds, as its name suggests, to the erosion that appears in the leading edge of wind turbines blades. This erosion is caused by particles that are suspended in the air (like rain or dust, for example) and can be a relevant issue, as it leads to blade damage (Figure 1). Actually, if this damage is not well addressed, it can have undesirable consequences. On the one hand, it can affect the operation and maintenance costs of the wind turbine, in terms of inspections and field repairs [1]. On the other hand, it can reduce the energy produced by the wind turbine [2, 3], although further validation with real data is needed to quantify this loss more reliably.

Offshore sites are, in general, more prone to LEE, due to four main particularities in marine environments:

- Stronger and steadier wind speeds [4]
- Higher rain rate rainfalls [5]
- Presence of sea-salt aerosols [2]

Figure 1: Wind turbine blade with LEE

- Reduced noise restrictions [6]

LEE modifies, in essence, the shape of the aerodynamic profile, which affects its aerodynamic behaviour. This causes a loss in power production [7, 8], especially at below rated wind speeds, where the control system of the wind turbine traditionally looks for the optimum operating point (maximum power) of the clean blade.

However, LEE not only reduces the power production of the turbine, but also the thrust force at the rotor, although little attention has been paid to this phenomenon in the literature. This thrust force contributes to the wake a wind turbine produces. Hence, a rotor with eroded blades produces a weaker wake than a rotor with clean blades [9]. This implies a modification in the overall performance of the wind farm, as weaker wakes cause less deficit in downstream wind turbines. Therefore, in principle LEE could have a relevant impact on wind farm flow control (WFFC) strategies, whose main objective is the optimisation of the wind farm performance as a whole taking into account aerodynamic inter-turbine interactions. The verification of this hypothesis is the main goal of this paper, in which wake steering WFFC strategies are addressed.

The remainder of this paper is organised as follows: Section 2 describes the methodology carried out in this study, whereas Section 3 presents the selected case study and obtained results, which are discussed in this section too. Last, Section 4 summarises the extracted conclusions and possible future lines of work.

2 Methodology

The methodology carried out in this work is shown as flow diagram in Figure 2 and, as can be observed, it is composed of six main steps.

The first step consists of defining the erosion levels that are going to be used in the study. In AIRE project [10] several erosion categories have been defined, but only three of them are applied herein for the sake of simplicity. Erosion category 5 (EC5) represents low-erosion level, erosion category 7 (EC7) represents medium-erosion level and erosion category 8 (EC8) represents high-erosion level. All eroded blade zones have the same C form with a transition to the original (clean) profile of 45º (Figure 3), as explained in [11].

These erosion categories are defined by three different parameters: h_e, u_e and l_e (Figure 3). In this case, h_e has been selected as 0.12% of the blade chord length for EC5 and EC7 categories, and 0.2% for EC8. u_e and l_e, which are considered equal in the present work (i.e. same eroded distance in pressure and suction zones), are 5% of the blade chord length for EC5, and 8% for EC7 and EC8. These erosion parameters are summarised in Table 1.

It is worth mentioning here that these erosion categories are only applied to the last 30% of the blade, as it is the blade zone with the highest linear velocity. In this zone, erosion level is considered constant with the blade length [11, 12].

Based on these erosion categories, the corresponding polars are calculated using OpenFOAM CFD software [13]. With them, four different wind turbine aeroelastic models are built, one for each erosion category and another one for a wind turbine with no erosion (called "Clean" in Figure 2). These four models are built in OpenFAST [14] and are used to obtain the power and thrust curves for each erosion category, which are inputs for the wind farm modelling tool, together with other parameters, like hub height, rotor diameter or wind rose.

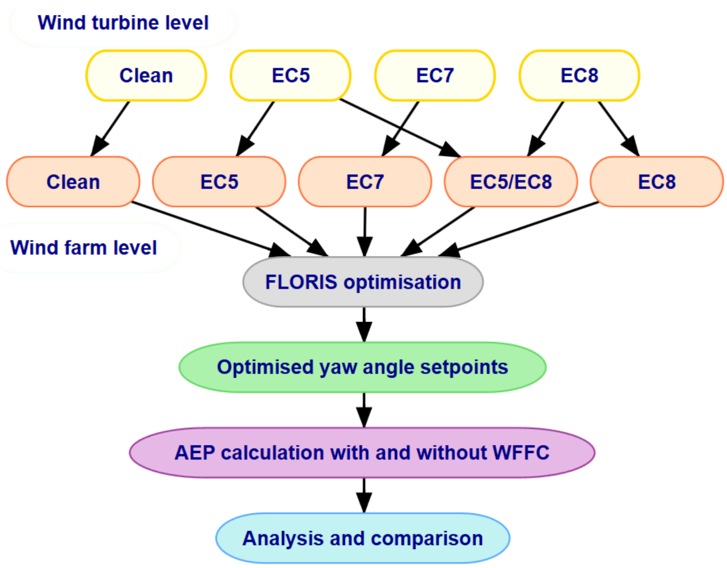


Figure 2: Methodology flow diagram

In Figure 4 the generated power and thrust coefficient curves for each erosion configuration are shown. As can be observed, there are little differences between the clean, EC5 and EC7 profiles, especially at below rated wind speeds. However, wind turbine performance with EC8 blades presents significant differences, which indicate performance is highly sensitive to h_e parameter. From 6 m/s to 15 m/s wind speed, the power produced by the turbine is much lower than for the other three configurations, and it actually reaches rated power at a higher wind speed (15 m/s instead of 12 m/s). Besides, the thrust coefficient is also much lower at below-rated wind speeds (near 0.5 instead of 0.8). This means the wake will also be notably weaker with this erosion configuration.

As shown in Figure 2, the second step in the methodology consists of building the wind farm models. To do so, FLORIS [15] is used. The wake model used is the Gaussian model [16] with default wake parameters. Yaw angle setpoint limits haven been set between 0º and 20º ,although simulations by using variable yaw setpoint ranges from -20º to 20º have also been performed to check the sensitivity of the results to these parameters. Cosine loss exponent for yaw has been set to 3, based on OpenFAST simulations.

Five different wind farm models are built. One for each erosion configuration (clean, EC5, EC7 and EC8) and a fifth one, called EC5/EC8, which represents a mixed wind farm of wind turbines with EC5 or EC8 erosion categories. In order to select which turbines have EC5 and EC8 erosion levels, wind farm layout is combined with the site wind rose. Wind turbines that are most of the time in unwaked conditions are given EC8 (high erosion) and the rest of wind turbines are given EC5 (low erosion).

Then, as third step in the methodology, optimum yaw angle setpoints for each wind farm configuration, and for each wind speed and direction, are calculated using FLORIS. With these yaw angles, annual energy production (AEP) for the cases with WFFC for each configuration is calculated, as well as the AEP for the cases without WFFC.

Last, obtained results are analysed and compared, in order to quantify the differences between each configuration.

Table 1: Properties of blade erosion categories

Erosion category	h_e [%/c]	u_e [%/c]	l_e [%/c]	**Max. efficiency loss** [%]
5	0.12	5	5	22.47
7	0.12	8	8	38.72
8	0.20	8	8	66.60

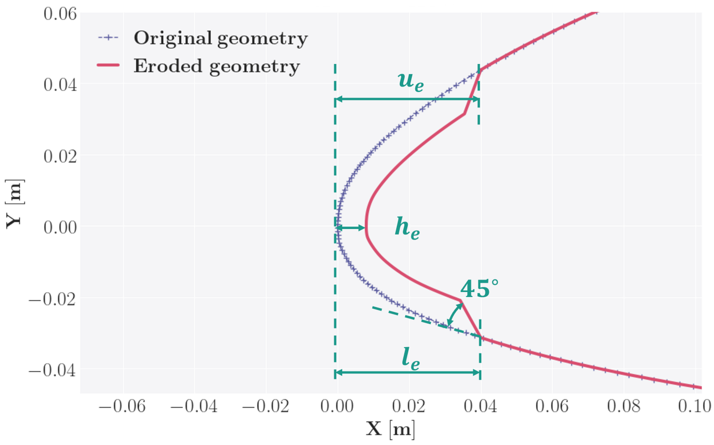
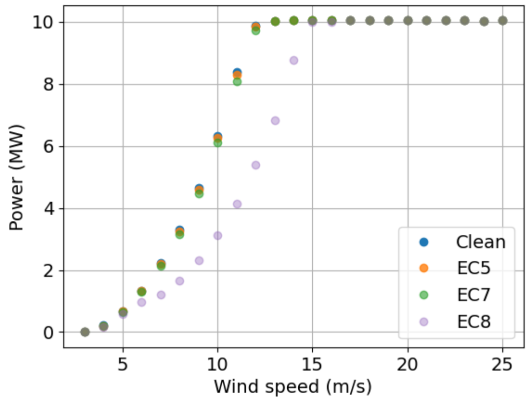
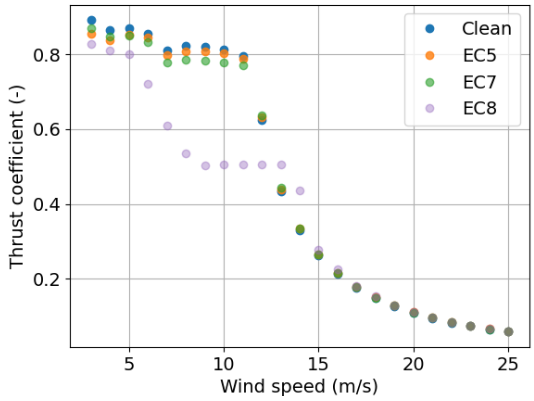


Figure 3: Erosion categories definition



(a) Power curve



(b) Thrust coefficient curve

Figure 4: Power and thrust curves for clean (blue), EC5 (orange), EC7 (green) and EC8 (purple) erosion categories

3 Case study

In this section, the methodology described in Section 2 is applied to a practical case, in order to check its validity and study the results.

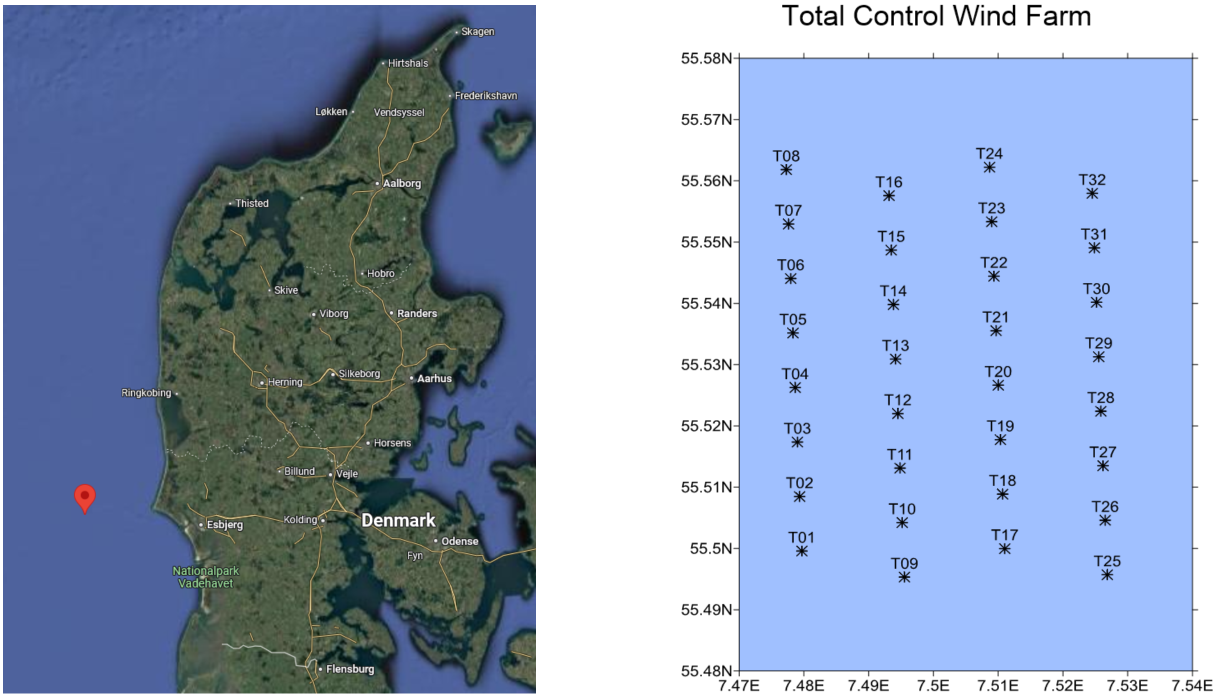
3.1 Definition

The analysed case study is defined by the following information:

- The selected wind farm is the virtual offshore TotalControl Reference Wind Power Plant [17], which is located in the west coast of Denmark (Figure 5a) and has the layout shown in Figure 5b. It consists of 32 DTU 10MW Reference Wind Turbines [18].

- Site wind resource data have been used [20, 21, 22] (Figure 6). For comparison purposes, resource data from another site have also been used to check the impact of site conditions on the results. Ulsan, in South Korea, has been selected as this second site ([23]), since its wind rose is very different to the TotalControl Reference Wind Power Plant site one (Figure 7).

  For the TotalControl site, most likely winds come between NW and SW (Figure 6) directions. Therefore, for the mixed EC5/EC8 wind farm, wind turbines from T01 to T16 (two leftmost



(a) Wind farm location [19]

(b) Wind farm layout

Figure 5: TotalControl Reference Wind Power Plant

columns) are considered to have EC8 (high erosion) and turbines from T17 to T32 (two rightmost columns), EC5 (low erosion).

As seen in Figure 6, the wind rose of the TotalControl site does not have a remarkable predominant wind direction and most probable wind speeds are quite high. On the other hand, Ulsan site wind rose (Figure 7) is very directional and has a lower mean wind speed[1].

- Erosion takes place on blade profile FFAW3241 [24].
- As explained above, wind turbines are modelled using OpenFAST and wind farms using FLORIS. Yaw optimisation is also done using FLORIS.

3.2 TotalControl wind distribution

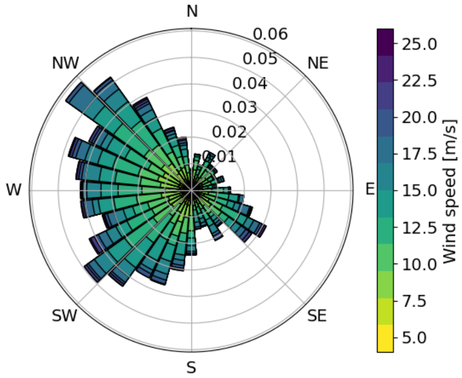
In this subsection results for the original wind distribution of the TotalControl wind farm site are presented and analysed.

3.2.1 Optimised yaw angle setpoints

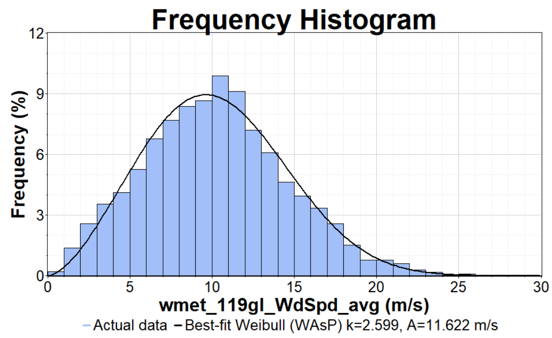
In Figure 8 the optimised yaw angle setpoints of three turbines are shown with respect to wind direction for the case of 7 m/s. The turbines selected are WT01, WT20 and WT32, which represent three different wind farm zones. WT01 (south-westernmost turbine), for example, has 0º yaw angle setpoint for northern and eastern wind directions, as there are no wind turbines downstream and hence, there is no need for wake steering. However, for wind directions where there are downstream turbines (marked as grey-shaded areas in the figure; green-shaded areas represent upstream turbines), optimised yaw angle setpoints take non-zero values, in order to steer the wake and minimise its impact on downstream turbines. In any case, the most important thing to notice here is that most of the optimised yaw angle setpoints are very similar for every erosion configuration.

The biggest differences that can be appreciated are between the mixed wind farm (EC5/EC8) and the rest of wind farm erosion configurations, for some specific wind directions. For instance, for WT01 (with

[1] For the sake of simplicity, the mixed EC5/EC8 wind farm configuration is maintained for Ulsan site wind resource.

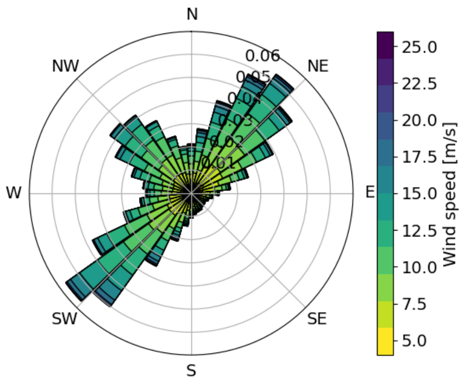


(a) Wind rose

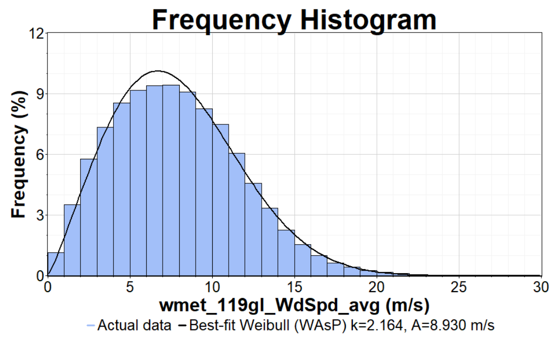


(b) Weibull distribution

Figure 6: TotalControl Reference Wind Power Plant wind rose (a) and Weibull distribution (b)



(a) Wind rose



(b) Weibull distribution

Figure 7: Ulsan wind rose (a) and Weibull distribution (b)

high erosion within the mixed configuration), EC5/EC8 wind farm optimised yaw angle setpoints for western wind directions are higher than for the rest of configurations. This might happen due to the fact that there are less eroded wind turbines downstream. These turbines are able to produce more energy, hence it makes sense that upstream machines (more eroded) are more yawed to minimise wake affection in EC5 wind turbines and therefore maximise the overall wind farm power. For wind turbines WT20 and WT32 (with low erosion in that mixed wind farm configuration), the opposite happens. For eastern wind directions, optimised yaw angle setpoints for mixed EC5/EC8 configuration are in general slightly lower than for the other configurations. The reason might be that there are more eroded turbines downstream and, in consequence, the optimisation algorithm tries to maximise the power of less eroded wind turbines upstream (that means smaller yaw angle setpoints), as wakes are not going to further penalise the energy produced by the overall wind farm. Actually, it can be seen that the graphs for WT01 and WT32 are symmetrical for all configurations, except for the mixed one, for the reasons explained above.

There are also some slight differences between EC8 and lower erosion categories (EC5 and EC7), for very specific wind directions (west for WT01 and east for WT32), but they are considered not to be very significant.

These conclusions are also drawn for the rest of wind turbines and wind speeds, and changing optimised yaw angles limits in FLORIS does not affect the conclusions either. This way, it can be concluded that optimised yaw angle setpoints for a homogeneously eroded wind farm are very similar as the erosion category evolves, and noticeable differences appear only if there are significant differences in the erosion category between wind turbines.

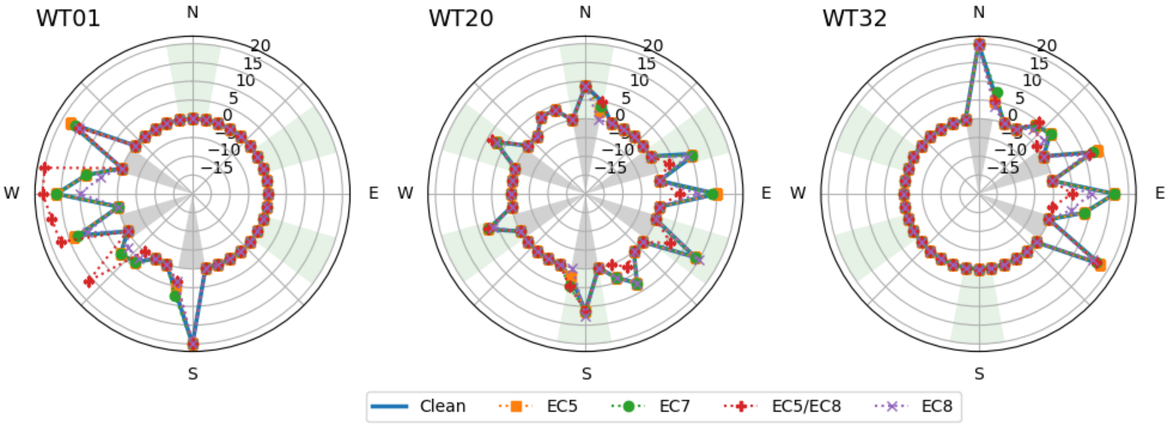


Figure 8: Optimised yaw angle setpoints for 7 m/s wind speed. Grey-shaded areas represent sectors with downstream turbines and green-shaded areas, sectors with upstream turbines

3.2.2 Annual energy production

Annual energy production (AEP) for every wind farm erosion configuration has also been calculated (using FLORIS), with results shown in Table 2, for both with and without WFFC cases. To obtain the wind farm AEP, the wind turbine power curve of each configuration has been combined with the wind distribution of each site, considering wakes that can affect some wind turbines under certain wind conditions.

Table 2: AEP comparison for different wind farm erosion configurations (TotalControl wind distribution)

WF erosion type	**AEP - no WFFC [GWh]**	**AEP erosion loss - no WFFC [%]**	**AEP - WFFC [GWh]**	**AEP erosion loss - WFFC [%]**
Clean	1623.73	-	1650.20	-
EC5	1615.70	0.49	1641.84	0.51
EC7	1598.52	1.55	1623.71	1.61
EC5/EC8	1387.11	14.6	1405.53	14.8
EC8	1149.18	29.2	1159.33	29.7

Table 3: AEP wakes loss and WFFC gain for different wind farm erosion configurations (TotalControl wind distribution)

WF erosion type	**AEP wake loss - noWFFC [%]**	**AEP gain with WFFC [%]**
Clean	7.58	1.60
EC5	7.54	1.59
EC7	7.46	1.55
EC5/EC8	6.94	1.31
EC8	6.85	0.88

As expected, the greater the erosion level, the lower the AEP value is, regardless if it has WFFC or not. Actually, AEP losses due to erosion are small for EC5 and EC7 configurations, with values between 0.5% and 1.6%, which is aligned with the results seen in the power curve (Figure 4a) and in the literature

[11]. The other two configuration cases (EC5/EC8 and EC8) present a much greater loss, with values between 14% and 30%, which is also in line with the power curve seen in Figure 4a. It is interesting to notice here again that, between EC7 and EC8 erosion categories, only h_e parameter has changed, increasing from 0.12% to 0.2% of the blade chord length. Therefore, the high sensitivity of AEP losses to this parameter is confirmed. Furthermore, in spite of having very similar values, AEP losses due to erosion are slightly higher for the cases with WFFC.

As erosion increases, wakes become weaker too, and so does the AEP loss due to wakes in the case with no WFFC (Table 3), which is in line with [9]. However, these AEP wake loss values remain quite similar among different erosion configurations. By contrast, the AEP loss due to overall effect of erosion (Table 2) can attain higher percentages and presents more disparate values among erosion configurations. In this sense, it can be said that, for this case study, high erosion levels affect much more power production than induced wake.

On the other side, as mentioned before, the AEP gain when applying WFFC is slightly reduced as erosion increases. For the clean, EC5 and EC7 configurations, a gain of nearly 1.6% is achieved, whereas for EC5/EC8 and EC8 configurations values are notably smaller (1.3% for EC5/EC8 and less than 0.9% for EC8). From these data, it can be clearly seen that, as erosion increases, wakes are reduced, which causes a lower potential benefit of WFFC, although for low and medium erosion levels this is barely noticeable.

3.3 Ulsan wind distribution
In this subsection results for the Ulsan site wind distribution are presented and compared with the ones obtained for the original wind distribution of the site.

3.3.1 Optimised yaw angle setpoints
FLORIS yaw optimisations do not depend on the wind rose, hence optimised yaw angle setpoints obtained for this wind distribution are the same ones as in the previous section (Figure 8).

3.3.2 Annual energy production
With this wind distribution, energy results are notably different, as the wind farm layout has not been optimised for these dominant wind directions. This means that wakes have, in general, higher impact than in the previous case. This, together with lower wind speeds, makes that AEP values are always lower than for the case with the TotalControl wind distribution, as observed in Table 4.

Table 4: AEP comparison for different erosion configurations (Ulsan wind distribution)

WF erosion type	**AEP - no WFFC [GWh]**	**AEP erosion loss - no WFFC [%]**	**AEP - WFFC [GWh]**	**AEP erosion loss - WFFC [%]**
Clean	1050.98	-	1067.04	-
EC5	1043.44	0.72	1059.24	0.73
EC7	1028.90	2.10	1044.04	2.16
EC5/EC8	862.93	17.9	874.36	18.1
EC8	678.18	35.5	684.29	35.9

AEP losses due to wakes are obviously higher, but again, all the configurations have similar values, except EC5/EC8 and EC8, which have slightly lower values. Despite these differences, the trend is the same as with the original TotalControl wind rose. AEP gains with WFFC are similar compared to the previous site (see Table 5. AEP loss due to erosion is small (between 0.7% and 2.2%) for EC5 and EC7 wind farm configurations and much bigger for EC5/EC8 and EC8 (18% and 36%, respectively), as can be seen in Table 4. Therefore, conclusions extracted from the case with the original wind distribution can be applied to Ulsan site conditions too.

4 Conclusions and future work
In this work, an analysis of the LEE impact on wake steering static WFFC strategies has been carried out, taking into account different erosion categories, wind farm erosion configurations and wind distributions.

Table 5: AEP wakes loss and WFFC gain for different wind farm erosion configurations (Ulsan wind distribution)

WF erosion type	**AEP wake loss - noWFFC** [%]	**AEP gain with WFFC** [%]
Clean	9.44	1.50
EC5	9.40	1.49
EC7	9.27	1.45
EC5/EC8	8.61	1.31
EC8	7.97	0.89

From the control point of view, the main conclusion is that the calculated optimised yaw angle setpoints are very similar for every erosion configuration, if the erosion level in all turbines is similar. By contrast, if there are large discrepancies in the erosion category within the wind farm, yaw angle setpoints may be different for some wind directions.

From the wind farm performance point of view, several interesting conclusions have been extracted. First of all, and as expected, the energy produced by eroded wind farms is lower than the energy produced by the clean farm. For low and medium erosion levels, this AEP reduction is small, but it can increase up to very significant values if the erosion is high enough. On the other hand, the energy lost by wakes in the case without WFFC is similar in every erosion configuration, although it gets slightly lower as erosion increases. In consequence, static yaw optimisation for wake steering improves the energy produced by the wind farm by a similar amount for each erosion configuration, but this gain gets smaller as erosion increases.

Therefore, overall it can be concluded that, for the analysed cases, erosion does not have a relevant impact on static wake steering WFFC strategies, as long as high erosion levels do not appear on some wind turbines.

As future work, the performed analysis could be repeated for other wind turbines and wind farms, to check if conclusions can be generalised. More erosion configurations could be studied too, in order to see more in detail from which erosion differences on optimised yaw angle setpoints and AEP losses start being significant. It could also be explored whether conclusions are similar for other WFFC strategies.

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