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InnoTIP End Report

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InnoTIP/Introduction

InnoTIP aimed at developing and demonstrating three innovative blade tip shapes designed for offshore wind turbines. The innovative offshore blade tips aims to increase efficiency and power and in addition increase turbulence in the wake of the turbine so that recovery of the wake is improved.

Part of the project is having installed three different wing tip geometries on three different turbines during summer 2016 for a short period field test. One of these installations will be similar to already well known technologies and the two other configurations are designed to have installation processes similar to each other.

This report describes the overall process as well as results of the project which has been collaboration between LM Wind Power and the Energy Research Center of the Netherlands (ECN).

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1.0 Executive Summary

InnoTIP (Innovative rotor blade tips to improve offshore wind farm yield) is a collaboration project between Energy research Centre of the Netherlands (ECN) and LM Wind Power (LM) that aims at reducing the Levelized Cost of Energy (LCoE) of offshore wind by improving turbine yield as a result of an improved blade tip geometry.

InnoTIP is aimed at developing three different tip shapes, which have later been manufactured as retrofits for testing on ECN's 2.5 MW test turbines in EWTW (ECN Wind turbine test field in Wieringermeer). During the conceptual design phase, a number of software tools have been used to find an optimum design for each of the 3 concepts (turbulators, winglet and conventional tip). The quick analyses are done by blade element momentum theory (BEM) tools, whereas lifting line method in combination with a free wake model is used for a more accurate understanding of conceptual changes in the tip region. The final configurations are analysed by Computational Fluid Dynamics (CFD) models, which are far more accurate but are at large computational cost.

For each concept, a number of parameter variations, such as the twist angle, the sweep angle and the planform shape have been studied. The goal was to find the most optimum tip shape that results in the most beneficial LCoE decrease (aimed at increase in yield) within the specified restrictions coming from the loads, weight, manufacturing and implementation for the field tests. Once the conventional tip has been designed, the winglet has been designed to be comparable to it. Some off design conditions have also been evaluated before choosing the final tip shape. Finally, the performance of the configurations for winglet and conventional tip have been confirmed by CFD analyses. The turbulator geometry has been designed using the lifting line method LLM, since in this tip configuration the wake is of main interest.

In the detailed design phase, the issues regarding the lightning protection, structural strength, attachment and drainage have been solved for the final tip concepts. The inputs from a large number of stakeholders (including the LM Service team) have been gathered and used in the detailed design phase to optimize the design and implementation methodology. Once the designs reached a final state, prototypes of the tips have been made in full scale and installation and removal tests on a scrapped blade tip have been performed in a controlled environment. This is done to avoid any potential issues that might occur during the field test implementations of these tips, since the original blade cannot be damaged and should be restored after the field tests. Following the installation test, a structural test for the extreme loads have been performed to verify the structural strength of the tips and the connection method. Finally, the tips have been removed and the original blade tips have been successfully restored.

The field tests have been performed at EWTW, where five Nordex N80 2.5MW turbines are available for use. Besides the SCADA data of the turbines, ECN's calibrated instruments have been installed on these turbines to collect high quality data. The experiments are combined with MetMast measurements , which has been used for the verification of the wind and weather conditions. The turbulators and conventional tips have been installed and tested simultaneously in a side-by-side configuration to reduce the uncertainty coming from the monthly and seasonal changes in the wind characteristics. To quantify the effects of the new tips on the turbine performance, the changes in power production of the turbines with the new tips are compared with the changes of power production of the turbines without the tips for the periods before, during and after the test campaign.

The test results for the conventional tip have shown an increase in power of more than 4% (the effect of having a longer blade) at higher wind speeds before the rated wind speed. The actual increase due to geometry change is in the order of 2% to 9% for the wind speeds above 8 m/s. Data from the turbine operating in the wake of the turbine with the turbulator tips did not show an actual increase in power due to lack of measurement time. Since there is a limited wind direction window for this turbine to operate in the wake of the turbulator tips, a longer measurement period is required to quantify the effects of the turbulator tips on the wake reduction. On the other hand, the turbulators themselves

increase the power on the retrofitted turbine. Here, the increase in power is in the order of 2% to 10% for the wind speeds above 8 m/s.

The effect of the new tips on the offshore wind farm performance has been evaluated by using the case study in the Hyller project /1/; another project from ECN and LM where the effects of blade length on the wind farm performance were investigated. The effects of varying rotor diameters and different distances between the turbines on the yield of an offshore wind farm have been used as a baseline for this project. Both for the offshore wind farm and the standalone 5MW offshore wind turbine, the yield increase coming from the new tips is estimated to be between 1 to 3%, depending on the distance between the turbines in the wind farm and the specific turbine characteristics. The results are based on a retrofit implementation of the new tips. However, the actual benefits would likely to be higher when the solution is integrated with the design. Then no interference effects are present and a better optimization of the complete blade is possible due to less constraints in the design phase.

LCoE is the ratio of total cost over the lifetime versus electricity produced over the lifetime. From literature references, it can be found that turbine cost accounts for approximately 25% of the total cost and 22% of this cost is due to the blades. Blade costs therefore constitute only 5.5% of the overall cost of energy. Consequently, the conventional tip is not expected to have a large increase in cost as it requires a relatively small change to the current practice. However, even a 1% increase in blade cost, would be negligible when it leads to a yield increase of 3%. In conclusion therefore, it can be stated that all three options are good for implementation and reducing LCoE.

The Innotip project showed that the potential of using new tips for offshore wind turbine applications is significant. Since the potential is high, it is recommended to investigate the tip effects further in detail to quantify their full potential and to reduce the risks before applying them offshore.

2.0 Nederlandse Samenvatting

InnoTIP (Innovative rotor blade tips to improve offshore wind farm yield) is een samenwerkingsproject tussen Energieonderzoek Centrum Nederland (ECN) en LM Wind Power (LM) gericht op het reduceren van de energiekosten per kWh (Levelized Cost of Energy - LCoE) voor offshore wind energie door het verhogen van de turbine opbrengst door middel van een verbeterde vorm van het bladuiteinde, ook wel bladtip genoemd.

InnoTIP is gericht op het ontwikkelen van 3 verschillende tipvormen, welke als retrofit zijn geproduceerd en getest in een windpark met 2.5 MW turbines. In de conceptuele fase van het project zijn er een aantal software programma's gebruikt om het optimum te vinden voor elk van de 3 concepten (turbulatoren, een winglet en een conventioneel bladuiteinde). Snelle analyses zijn aanvankelijk gedaan met behulp van een code op basis van 'Blad Element Impuls Theorie' (BEM) waarna meer verfijnde analyses zijn gedaan met een 'Dragende Lijn en Vrij Wervelzog Model' (LL-FVW). Voor een beter begrip van de conceptuele veranderingen zijn dDe uiteindelijke configuraties doorgerekend met behulp van 'Computational Fluid Dynamics' (CFD). Deze methode is nauwkeuriger, maar vraagt ook een langere berekeningstijd.

Voor elk concept zijn een aantal parametervariatiesonderzocht om uit te vinden welke vorm de grootste verlaging van LCoE geeft (door verhoging van de turbine opbrengst). Dit zonder dat restricties wat betreft belastingen, massa, productie en implementatie worden gecompromitteerd. Onder de onderzochte parameters vallen de verdraaiingshoek, de zwenkhoek en de planvorm. Na het vastleggen van de vorm van de conventionele bladtip, is de vorm van de winglet bepaald, zodat een directe vergelijking tussen de concepten kan worden gemaakt. Een aantal speciale ontwerpcondities zijn onderzocht voordat de uiteindelijke tipvorm is gekozen. De aerodyamische karakteristieken van de gekozen winglet en conventionele bladtip zijn bevestigd met behulp van CFD berekeningen. De vorm van de turbulator is doorgerekend met LL-FVW aangezien het hier gaat hoofdzakelijk om het zog van de turbulator gaat.

De gekozen concepten zijn hierna meegenomen in de gedetailleerde ontwerpfase, waar problemen met o.a. het bliksemafweersysteem, sterkte van de constructie, aanhechting en drainage zijn opgelost. Gedurende de ontwerpperiode is de input van een groot aantal belanghebbenden (inclusief het LM Service team) meegenomen voor het optimaliseren van het ontwerp en de testmethodiek. In het laatste stadium van het ontwerp zijn er prototypen van de verschillende tips op werkelijke grootte geproduceerd en zijn installatietesten op een oud blad in een gecontroleerde omgeving uitgevoerd. Dit is gedaan om elke onzekerheid weg te nemen, aangezien het originele blad niet beschadigd mocht raken. Na de installatietesten zijn een aantal constructieve testen uitgevoerd om de sterkte en aanhechting van het geheel te verifiëren in het geval van extreme belastingen. . Uiteindelijk zijn de nieuwe tips verwijderd en zijn de bladen in originele staat teruggebracht.

De veldtesten zijn uitgevoerd op het testveld van EWTW waar 5 Nordex N80 2.5MW turbines in een lijn staan opgesteld. Naast de standaard SCADA data van de turbines heeft ECN ook extra gekalibreerde meetinstrumenten op de turbines toegevoegd om de kwaliteit van de metingen te verbeteren. Daarnaast zijn de metingen van een meteorologische mast gebruikt voor het verifiëren van wind- en weersomstandigheden. De turbulatoren en de conventionele bladtips zijn simultaan geïnstalleerd en getest, waarbij naar de verschillen met de andere turbines is gekeken om de onzekerheden in de vergelijking door seizoenvariaties weg te nemen. Ter voorbereiding op de testen, zijn de turbines een aantal weken van tevoren reeds uitgerust met meetapparatuur, zodat deze data ook ter vergelijking gebruikt kan worden.

De testresultaten van het conventionele bladuiteinde laten een toename zien van meer dan 4% (ten gevolge van het verlengen van het blad) van het vermogen bij de hogere windsnelheden voor vollast. De vermogenstoename puur door de vormverandering blijkt tussen de 2% en 9% te liggen voor windsnelheden boven de 8 m/s. Uit de meetgegevens van de turbine, die in het zog van de turbine met de turbulatoren staat blijkt geen eenduidige vermogenstoename. Dit komt voornamelijk doordat er in de korte meetcampagne te weinig data beschikbaar is waarbij de turbine in het zog staat. De turbulatoren zelf resulteren in een vermogenstoename van 2% tot 10% op de turbine waar ze geïnstalleerd zijn voor windsnelheden boven de 8 m/s.

Het effect van de vergroting van de rotordiameter op het niveau van een volledig windpark is geëvalueerd met behulp van resultaten van het Hyller project, een ander samenwerkingsproject tussen ECN en LM. Een gesimuleerd windpark laat zien wat het effect is van de afstand tussen turbines afhankelijk van de rotordiameter. Zowel voor een volledig windpark als een individuele 5MW turbine, kan de toename van de jaarlijkse energie opbrengst ten gevolge van de nieuwe tipvormen tussen 1% en 3% bedragen. Hierbij is aangenomen dat de tips als retrofit worden geïmplementeerd. De toename is waarschijnlijk hoger indien de tipvormen door integratie in het ontwerpproces worden geoptimaliseerd.

De LCoE is de fractie van de totale kosten over de gehele levensloop versus de geproduceerde elektriciteit over de gehele levensloop. Uit de literatuur is bekend dat voor offshore windenergie de kosten van de turbine ongeveer 25% van de totale kosten bedragen en dat hiervan ongeveer 22% voor de bladen is. Dit resulteert slechts in een fractie van 5.5% in vergelijking met de totale energiekosten. Daarom zal dat voor de conventionele bladtip waarschijnlijk geen grote kostentoename betekenen, aangezien het slechts een relatief kleine wijziging is ten opzichte van de huidige kosten. Daarnaast is een toename van de bladkosten met 1% verwaarloosbaar in vergelijking met een verhoging van de opbrengst met 3%. Daarom kan men stellen dat alle drie de tipconcepten een goede optie zijn om de LCoE te verlagen.

Het InnoTIP project heeft aangetoond dat nieuwe tipvormen voor gebruik in offshore windparken veel potentie heeft. Aangezien de voordelen groot zijn, wordt aangeraden om de concepten en hun effecten in meer detail te onderzoeken, het potentieel verder te optimaliseren en kwantificeren, en de risico’s te reduceren alvorens ze offshore toe te passen.

3.0 Project Work Flow

The project has been divided into separate work packages with a work package leader. For each of the work packages there has been communication between the 2 parties and potentially with 3th parties involved necessary to fulfil the project scope.

The most important third parties involved in the InnoTIP project are:

- TKI Wind op Zee: Funding body
- EWTW: Owner of the test turbines
- LM Wind Power – Services: Installation and removal of test articles
- Bettink: Maintenance company for the Test Turbines
- Gemeente Hollands Kroon: Municipality of the area where the test are performed
- DEWI-OCC: Certification authority
- SkySurvey: Drone Inspection for turbines

The work packages have been divided as presented in Figure 3-1.

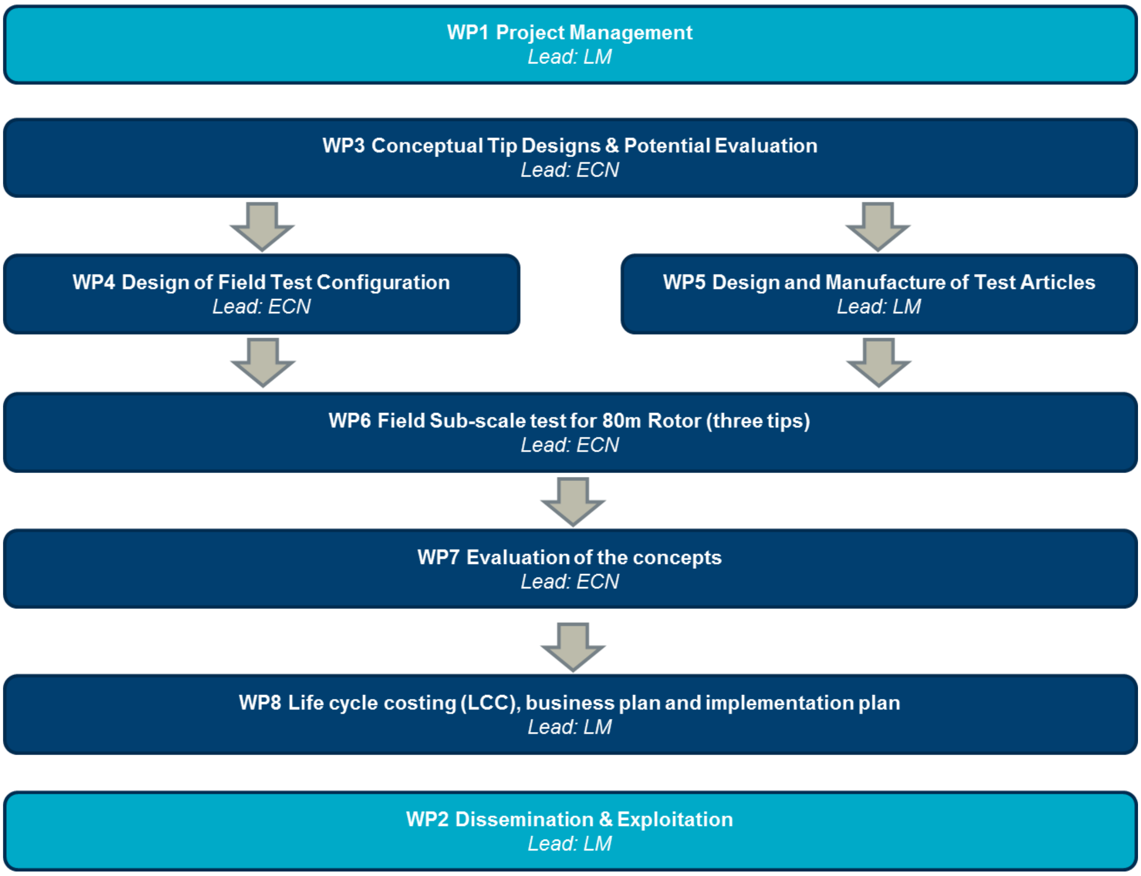


Figure 3-1: Work Package Structure for the InnoTIP project

Both work package 1 and 2 are more overall supporting packages whereas the other packages are on scientific/technological level.

4.0 Design of the Tips and the Field Test Configurations

4.1 Introduction

The Innotip Project aims to develop three different blade tip configurations: first one is the conventional tip, second one is the winglet and third one is the turbulator tip. The conventional tip is designed by removing the noise constraint from the design requirements. In offshore wind turbines, wind turbine noise does not create a problem as there are no houses nearby. As a result, the noise constraint can be removed from the design so that the blade tips can be optimized accordingly. The winglet is a known concept which brings advantages in terms of Cp improvements with low noise. In this project, the winglet is investigated as a competitor for the conventional tip or a plain blade tip extension case. Normally, the power output of a machine can be increased by simply extending the blade and since there is no noise limitations in offshore, winglets might not be as interesting as in the onshore case. In order to investigate the effectiveness of winglets in offshore applications, this concept is also taken into consideration in Innotip Project. The turbulator tip is ECN's patented concept. This tip reduces the wake effects of the wind turbine it's applied to. As a result, the downwind machine in the row can generate more power. For offshore wind turbines, wake effects are one of the biggest loss mechanisms. Moreover, the offshore wind turbines will not be used as stand-alone machines instead they will be used in the wind farms. The power output of the wind farm is more important than the power output of a single wind turbine. Taking this into account, the turbulator tip is designed to accelerate the mixing in the wake by breaking down the tip vortex earlier so that the wake can recover faster. These three tip configurations are also adapted to an onshore 2.5MW wind turbine blade to demonstrate the gains of each of these concepts in the real scale.

4.2 Methodology

For design of the innovative tips, different fidelity design and analysis codes are used in Innotip Project. Low fidelity tools enable the user to get fast results from the configuration changes in the beginning of the design process, therefore they are widely applied. However, these tools are not very reliable in terms of assessing the actual effects of the designs. Therefore higher fidelity tools are required to more accurately assess the effects of the designs. The flow from lower fidelity to higher fidelity tools is also explained schematically in Figure 4-1. The software tools used during the designs are explained below. During the project, a wide design space is chosen initially. The design space is reduced by running several analyses to find the optimum and introducing several constraints to the designs.

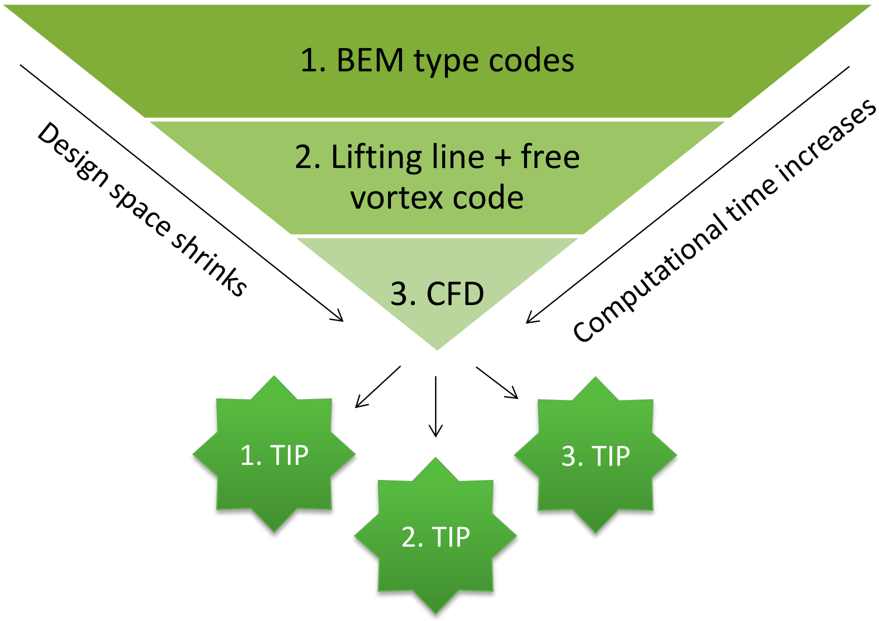


Figure 4-1: Different fidelity design concept used in Innotip Project

4.2.1 BOT *(Blade Optimisation Tool)*

This is a BEM tool coupled with an optimizer that optimizes the chord and twist angles of a blade in order to increase AEP or the power at a chosen wind speed. It can be used either as BEM analysis tool or blade optimizer /4/. The tool includes turbulent wake corrections, Prandtl tip and root corrections, and 3D lift corrections. It uses the airfoil cl-cd data from its airfoil database or user can also define the cl-cd values of the airfoils. The airfoil data is distributed according to the airfoil and blade thickness distribution using interpolations. Together with the thickness interpolation, Re number is also interpolated. BOT has been used and validated for a wide range of wind turbine sizes from a few kilowatts to multi megawatts.

The BEM methods, although they include several corrections, they are still not accurate to predict the tip effects of unconventional blade shapes. Therefore, in the tip designs they have a very limited use. In this project, BOT is only used to cross-check some of the design results and trends with BEM.

4.2.2 Aeromodule

ECN's state of the art rotor aerodynamic module which includes both BEM and a lifting line-free vortex code. For the BEM part, the implementation is very similar to the one in PHATAS /2/. The lifting line-free vortex code is called as AWSM /5/ & /6/. Aeromodule tool is developed in such a way that it can be implemented to structural solvers such as Phatas, Simpack, etc. Therefore, it has wind modelling options, it includes the tower effects and there are several dynamic stall models implemented. Any multi-body dynamics software can be coupled with Aeromodule by simply sending the blade position and velocity to Aeromodule and getting the aerodynamic forces and moments back from it. This software can also be used as stand-alone as aerodynamic analysis tool.

In lifting line-free vortex codes, the tip vortex is modelled directly, and the different blade sections effect each other. Therefore, these codes can be used to investigate the unconventional shapes. Due to this reason, in Innotip Project, AWSM part of Aeromodule is used as the main software tool because of its accuracy in describing the flow physics of the tip shapes. One disadvantage of this model is that it still reads the airfoil data from given airfoil cl-cd data which means the results always depend on the given airfoil information. Therefore, more advanced 3D CFD models are still required to obtain more realistic information about the designs. Since the 3D CFD models are more costly in terms of setting up the calculations and the calculation time, Aeromodule kind of tools are still very useful tools to scan the design matrix in a quick and sufficiently accurate way.

4.2.3 RFOIL

This tool is airfoil analysis tool used and developed at ECN. RFOIL is based on XFOIL which is originally developed by TU Delft, NLR and ECN and later further developed by ECN /7/ & /8/. It is a 2D panel code coupled with integral boundary layer method to handle the viscous effects and eN method for the transition modelling. The differences between RFOIL and XFOIL are:

- empirical corrections to improve the stall and post stall characteristics
- improvements in turbulent flow closure relations
- radial momentum equations to account for the rotational effects.

Recently, RFOIL is further developed in order to improve the lift and drag predictions of the thick airfoils. In Innotip project, RFOIL is used to assess the blade section characteristics.

4.2.4 Blademode

This is a model developed by ECN /9/ to calculate the blade eigenmodes, eigen frequencies, damping and deformations. It is based on beam theory where the torsional deformation, transverse shear flexibility as well as many aerodynamic and structural damping coupling terms for bending and torsional dynamics are included. The structural mechanical properties are modelled as “slender beam”, in terms of sectional distributions of mass and bending stiffness. Besides these, centrifugal effects, transverse shear deformation of a cross-section, cross-sectional moments of inertia, torsional stiffness and shear centre, mass centre line, and bending-torsion and tension-torsion coupling terms (which are zero for the conventional blades) are also modelled with Blademode. Pitch mechanism flexibility and the flapping flexibility of a hinge is modelled as edge constraints at the blade root. The aerodynamic loads are calculated either by a BEM model or a free vortex model which is up to the user to choose. Although this tool is not suitable for time-dependent load simulations or detailed blade response including all the dynamics of the turbine, it is used to estimate the blade response in a fast way.

In the Innotip Project, it is used to monitor the changes of the blade eigenmodes and the eigenfrequencies of the N80 machine with the application of the new tips.

4.2.5 FOCUS *(Phatas)*

Phatas /1/ is part of FOCUS software. It is developed to perform time-domain calculations of the dynamic behaviour of the wind turbines and the loads. The load simulations that are required to be performed for certification purposes are done in FOCUS using Phatas. In the Innotip project, this tool is used to check the response of the turbine with the new tips and the changes in the design loads to investigate the possible consequences of the tip additions on the operations and the loads of the wind turbine.

4.2.6 CFD

The CFD analyses done in the InnoTIP project have been done by full 3D rotor analyses using the EllipSys3D software from DTU /10/.

The 3D CFD analyses are required as the before mentioned software packages either use correction models (e.g. Prandtl Tip Loss) or include a more accurate induced velocity field but still have a dependency on 2D airfoil polars. 3D CFD will incorporate the full 3D aerodynamics taking into account the wake and local geometry and thus being independent on 2D polars.

Also, the closest possible result to a winglet solution can be done using a lifting line method, where many uncertainties exist in the winglet area (especially in the rounding radius). 3D CFD will bring great benefits on this part.

4.3 Results

4.3.1 Design space investigations and the effect of constraints

The optimum shapes of the conventional tip and the winglet are started with the design space investigation. In order to do this, effect of changing several parameters are analysed mostly using Aeromodule (AWSM) software. The changes in terms of power, thrust and flapwise bending moment are the main parameters monitored in the process. Figure 4-2, Figure 4-3 and Figure 4-4 show the geometrical parameter variations included in the design space investigations. Table 4-1 shows the summary of the effect of the each parameter on the overall performance of the wind turbine at its optimum operating point.

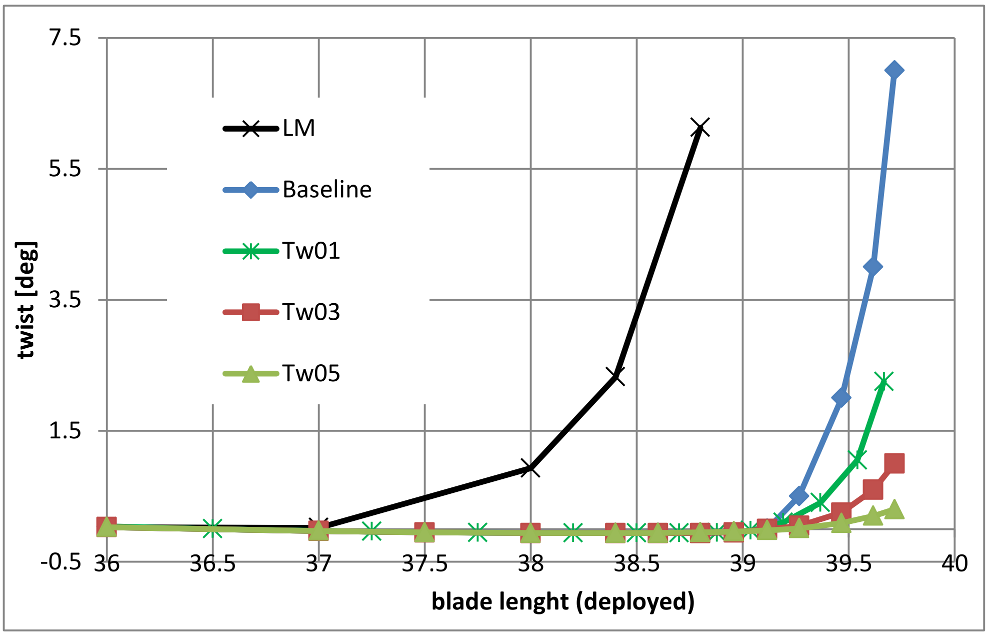


Figure 4-2: Tip twist angle variations shown on the last 4m of the blade

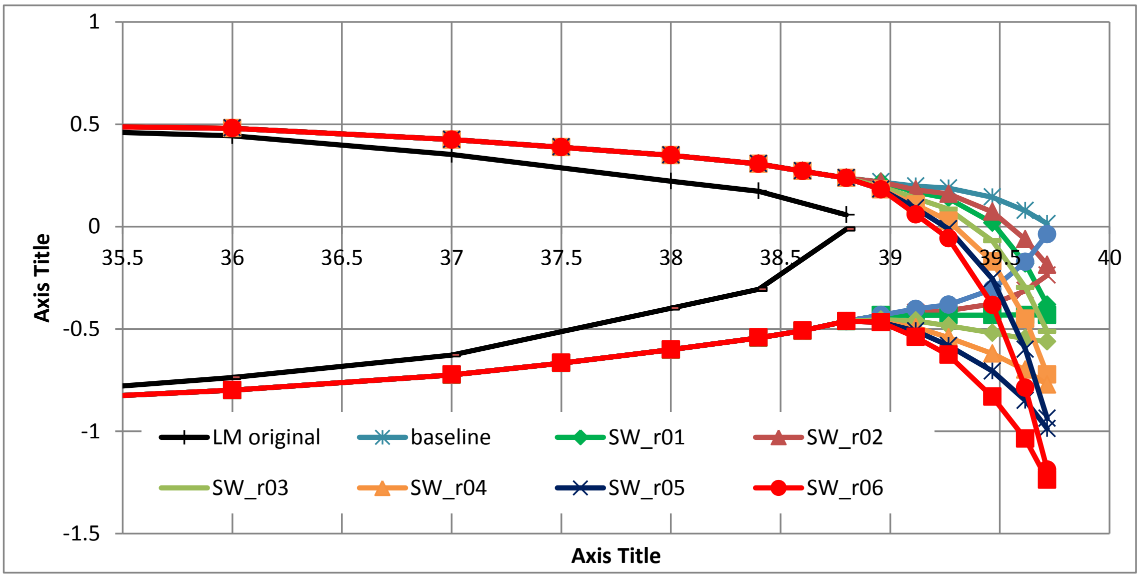


Figure 4-3: Tip sweep angle variations shown on the last 4.5m of the blade

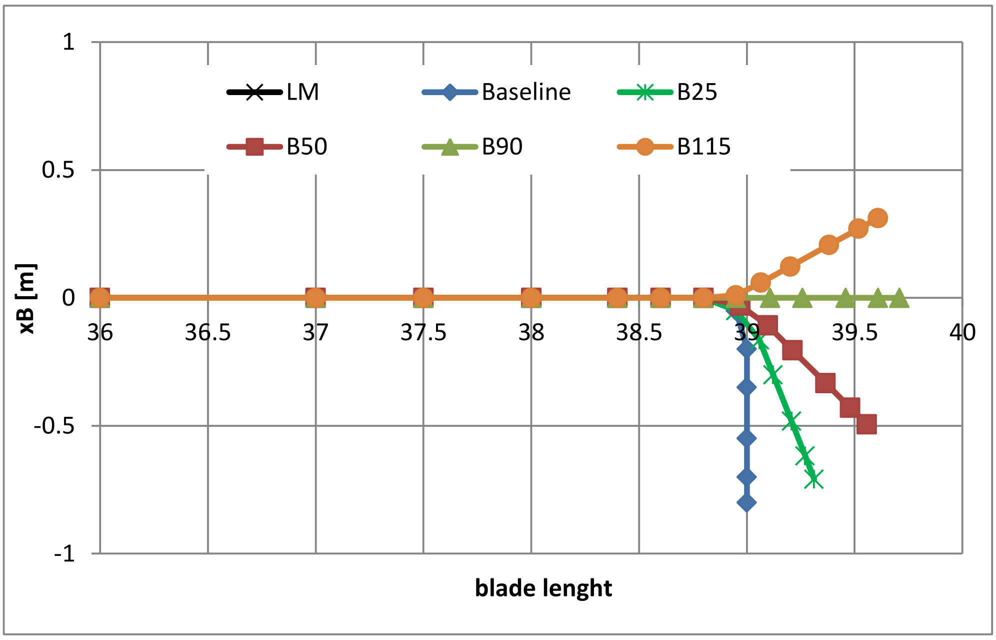


Figure 4-4: Winglet bending angle variations shown in terms of the blade center line versus the blade length

Turbine	blade tip		shape parameter	Cp [-]	Diff [%]	Flap Bend mom [kNm]	Diff [%]	power [kW]	Diff [%]
N80	LM original (38.8)		original	0.5087	0.00%	1528.01	0.00%	961.9	0.00%
	swept (39.8)		negative	0.5082	-0.10%	1649.58	7.96%	1009.5	4.95%
			straight	0.5107	0.39%	1654.77	8.30%	1014.5	5.47%
			positive	0.5143	1.10%	1663.53	8.87%	1021.7	6.21%
	winglet	twist (@39m) [deg]	7	0.5202	2.25%	1607.36	5.19%	993.4	3.28%
			3	0.5205	2.32%	1607.76	5.22%	994.1	3.35%
			1	0.5207	2.35%	1607.97	5.23%	994.3	3.37%
			0.3	0.5204	2.28%	1607.52	5.20%	993.7	3.31%
		bend [deg]	0 (39)	0.5202	2.25%	1607.36	5.19%	993.4	3.28%
			25 (39.3)	0.5168	1.58%	1623.34	6.24%	1002.2	4.19%
			50 (39.5)	0.5147	1.18%	1639.70	7.31%	1009.1	4.91%
			90 (39.7)	0.5123	0.70%	1652.63	8.16%	1013.2	5.33%
			115 (39.6)	0.5141	1.05%	1655.05	8.31%	1011.7	5.18%
		swept (@39m) [deg]	0	0.5202	2.25%	1607.36	5.19%	993.4	3.28%
			-10.20	0.5214	2.50%	1606.37	5.13%	995.8	3.52%
			-20.91	0.5207	2.35%	1606.68	5.15%	994.4	3.38%
			-29.34	0.5221	2.63%	1605.75	5.09%	997.1	3.66%
			-37.67	0.5233	2.85%	1604.96	5.04%	999.3	3.89%
			-43.14	0.5249	3.18%	1604.77	5.02%	1002.4	4.21%
			-50.89	0.5270	3.58%	1604.93	5.03%	1006.3	4.62%

Table 4-1: Overview of the initial design space investigations with the parametrical study

To implement the tip shapes with the highest potentials to an existing operating blade as a blade retrofit, several constraints have to be introduced to the designs. Although during a new blade design, these constraints do not apply, there is less freedom in applying a new tip to an existing blade. As a natural consequence of this fact, the gains and the benefits of the new retrofitted tips are limited. Figure 4-5 shows the change of the blade planform after the introduction of several constraints. Figure 4-6 shows the effect of this change compared to the no constraints case in case of the winglet.

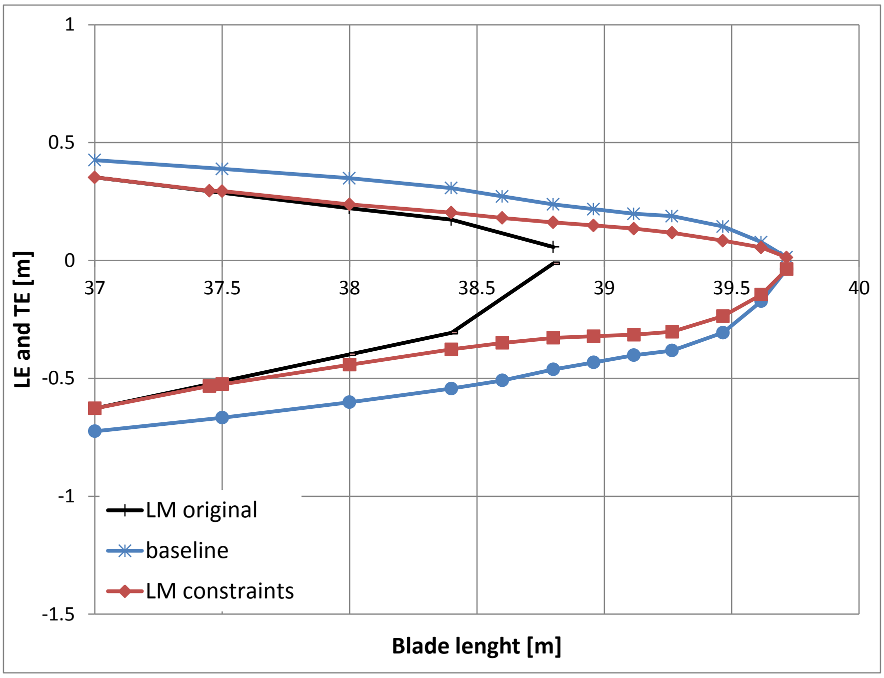


Figure 4-5: Change of the planform shape of the tip before and after the constraints (intermediate designs)

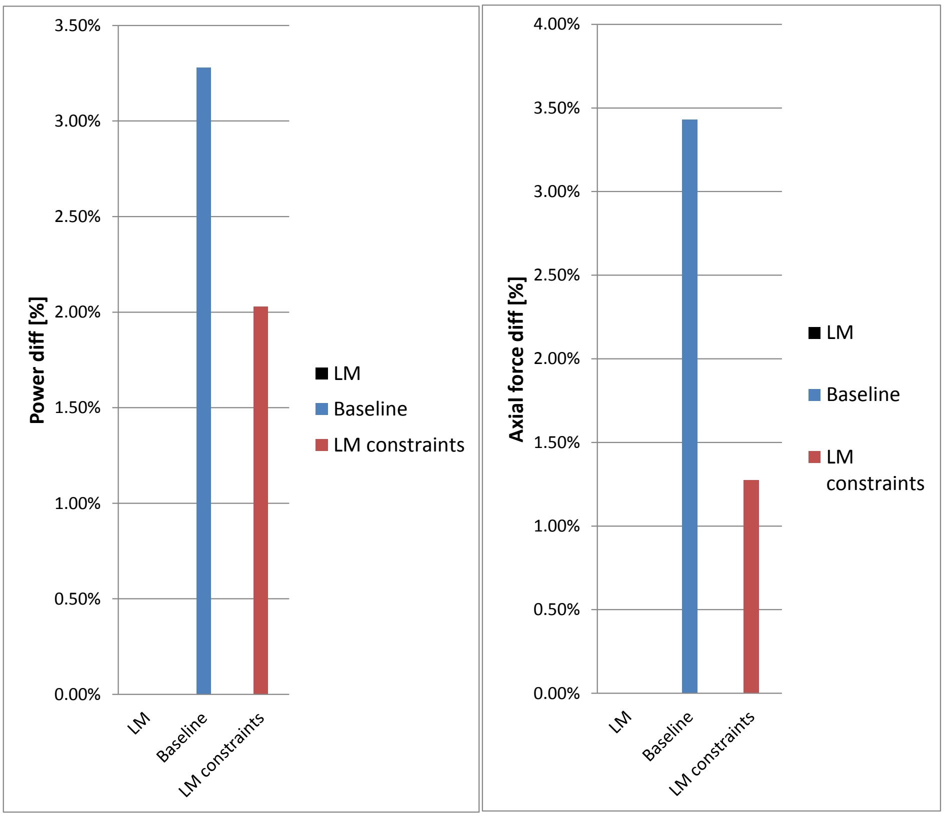


Figure 4-6: Comparison of the overall power and axial force differences w.r.t. the LM blade. Calculated for the winglet configuration using the planform change shown as deployed in Figure 4-5

4.3.2 Conventional Tip and Winglets

Conventional tip shape is investigated parametrically. The objective is to come up with a conventional tip and a winglet configuration where they would be comparable to each other. In order to assess the additional benefits of having a winglet instead of a tip extension, two geometries should be designed geometrically very similar to each other. As a result of this motivation, the final selection of the designs are done by comparing the results of conventional tip and winglet with each other. In Figure 4-7 and Figure 4-8, several geometrical variations are compared. In Figure 4-7, “LM tip suggestion” and “ECN’s initial tip” are shown in Figure 4-5. In Figure 4-8 however, “LM tip suggestion” is referred as “LM_sug”.

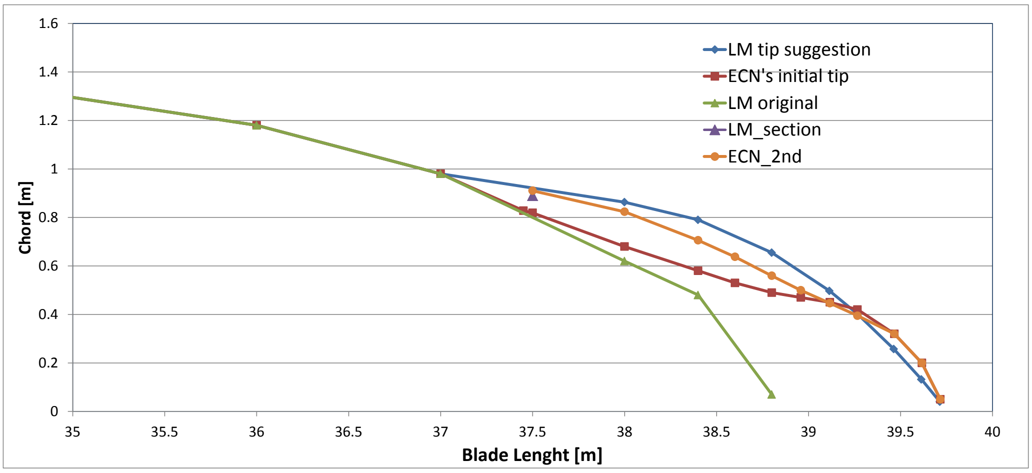


Figure 4-7: Tip chord variations and alternatives including the constrained chord length (purple triangle)

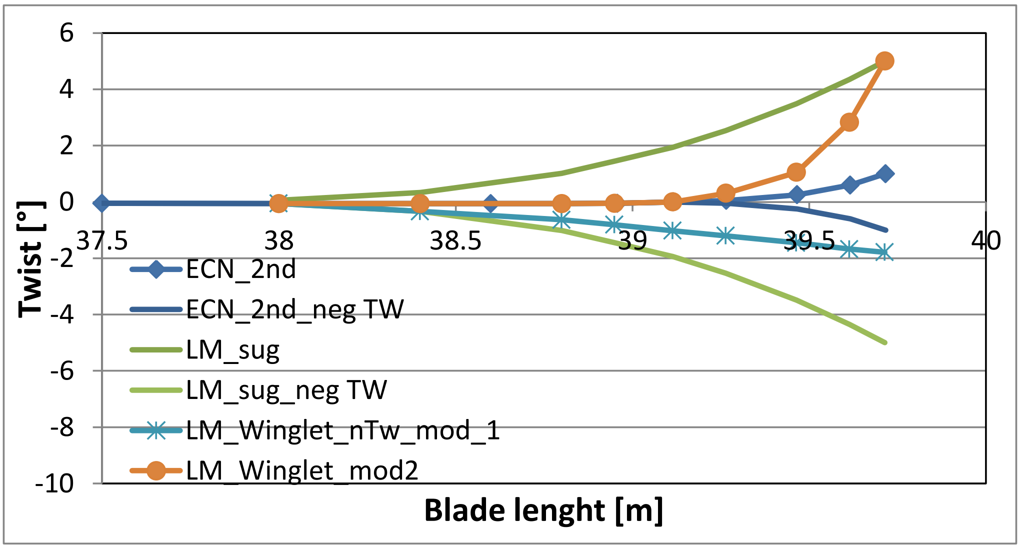


Figure 4-8: Twist variations and alternatives both for the conventional tip and the winglet

The force distributions along the blade of these geometries are compared in the following figures. Figure 4-9 and Figure 4-10 show driving and normal forces respectively. The absolute change of the local force magnitudes are only visible from around 37m onwards, where the tips are applied. In addition to this, Figure 4-11 and Figure 4-12 show the distribution of the cl and the axial induction, where the differences start to be visible from around 34m onwards. To see the differences of these parameters at the winglet part only; Figure 4-14 and Figure 4-15 is used. In these figures, the winglet length is measured from root of the winglet towards the tip as shown in Figure 4-13. It can be observed in both figures that the negative twist version of the winglets give higher Cl and axial induction values. Table 4-2 gives a summary of the overall power and thrust values of these configurations. For the winglet, the versions with the negative angle of attacks end up with slightly higher power values.

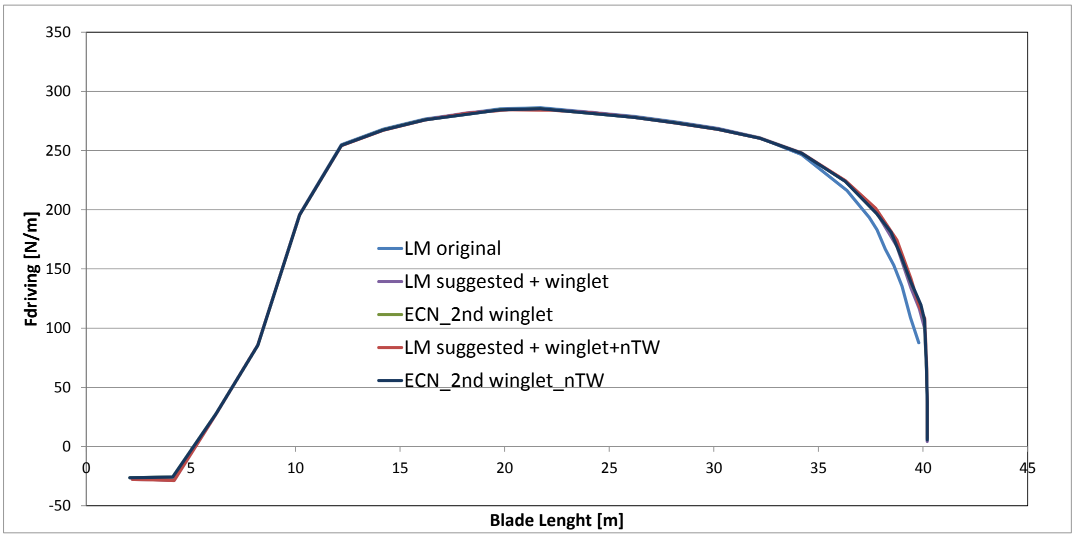


Figure 4-9: Driving force along the blade length for the configurations in Figure 4-7 and Figure 4-8

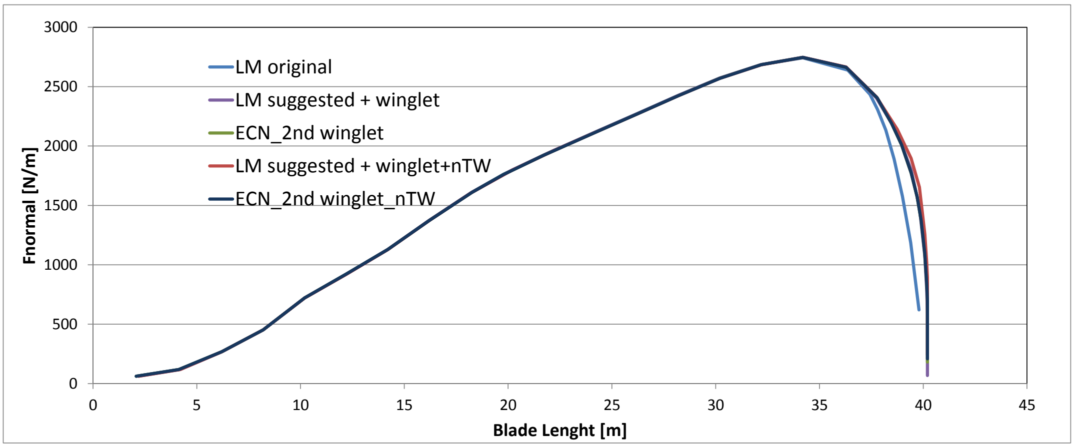


Figure 4-10: Normal force along the blade length

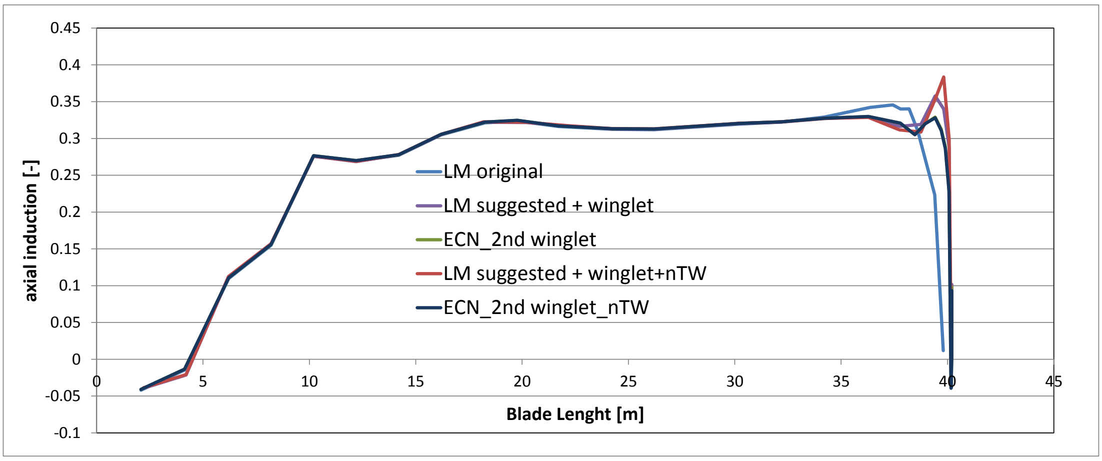


Figure 4-11: Axial induction along the blade

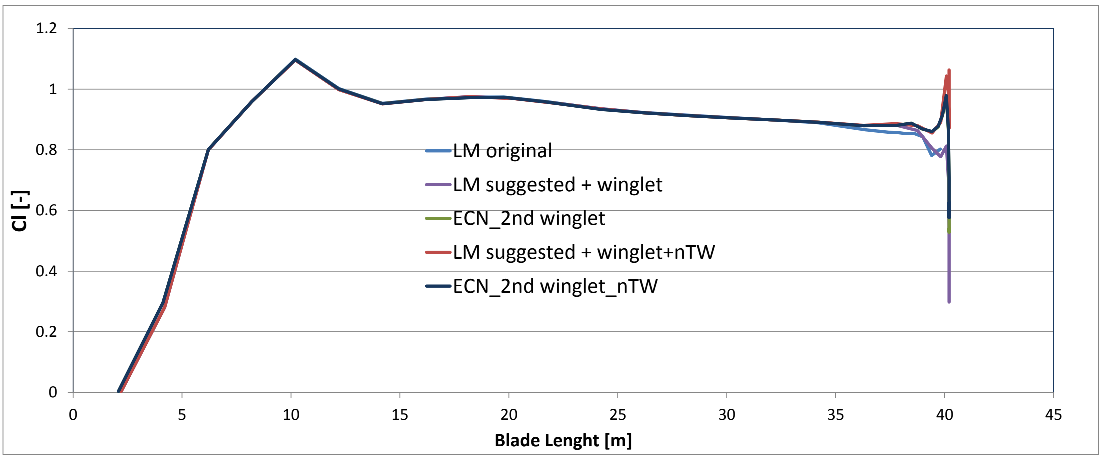


Figure 4-12: Lift coefficient along the blade

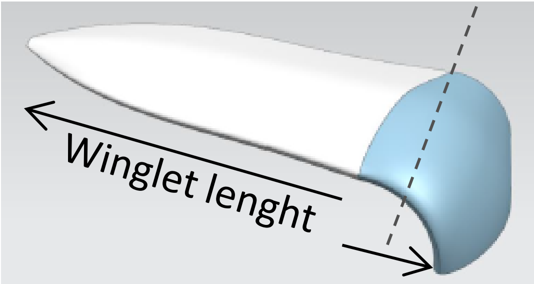


Figure 4-13: The winglet configuration used for the forces along the winglet

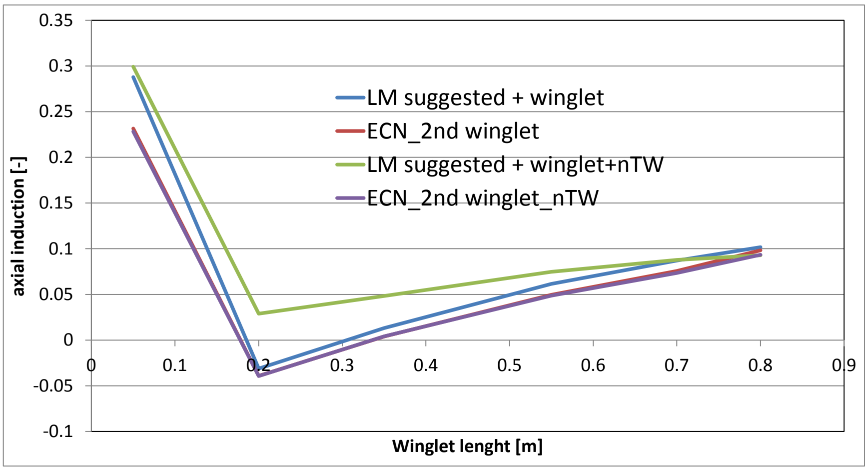


Figure 4-14: Axial induction on the winglet

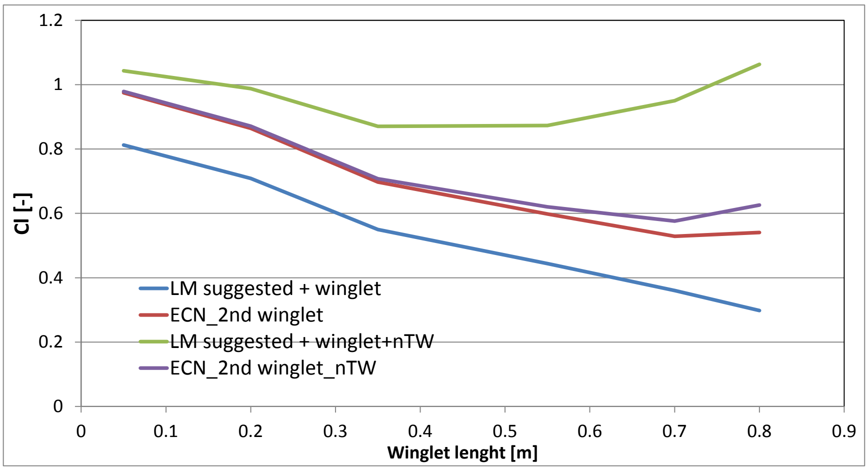


Figure 4-15: Cl on the winglet

	Power [kW]	Thrust[kN]
LM38.8P	931.996 (0.00%)	179.945 (0.00%)
LM suggested	969.928 (4.07%)	186.010 (3.37%)
ECN’s 2nd tip	972.685 (4.37%)	186.465 (3.67%)
LM suggested, winglet	955.033 (2.47%)	183.543 (1.99%)
ECN 2nd tip, winglet	956.066 (2.58%)	183.530 (1.99%)
LM suggested, winglet, negative TW	958.336 (2.82%)	184.056 (2.28%)
ECN 2nd tip, winglet, negative TW	956.627 (2.64%)	183.573 (2.01%)

Table 4-2: Summary of power and thrust outputs of different configurations

4.3.2.1 Off Design Conditions

The optimum operating condition of the blade is at 8.5 m/s with a tip speed ratio of 8.0. Table 4-3 shows the off design conditions used for the next figures. Figure 4-16, Figure 4-17 and Figure 4-18 include axial induction, angle of attack and Cl distribution at the tip for the design and off design conditions of several tips. The name “0a” is the tip “LM_sug” from the previous chapter. “1a” is the version shown in Figure 4-22. In these figures, off-design conditions shown with dashed lines of the same colours. All the design and off-design condition values are consistent and as expected. The Cp and Ct results of the conventional tip and the winglet are shown in Figure 4-19 and Figure 4-20 respectively. The main difference come from the fact that winglet has a rotor diameter same as the original LM blade; however, the total blade area is larger which gives a higher Cp.

Wind speed [m/s]	Lambda [-]	Pitch [deg]
5.5	9.2	0.1
8.5	8.0	0.1
11.5	6.2	0.16

Table 4-3: Off design points investigated in details

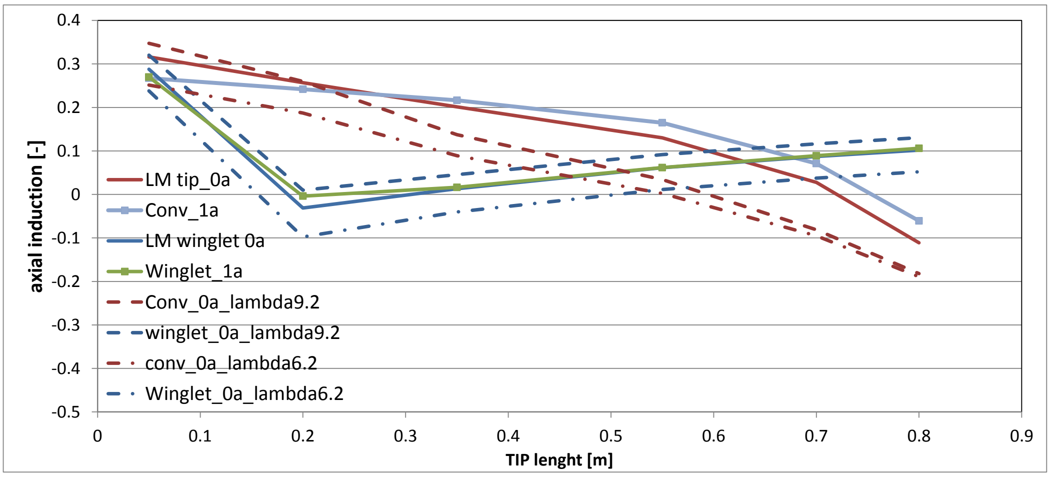


Figure 4-16: Axial induction along the tip or winglet

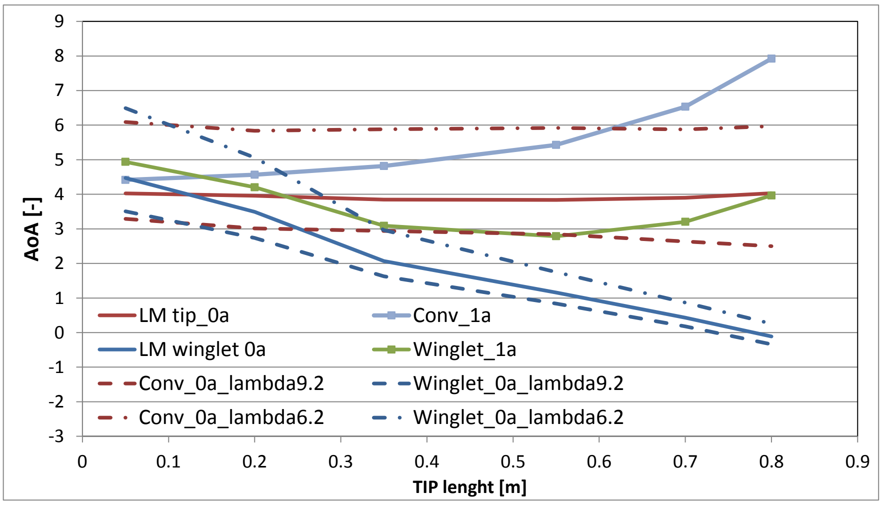


Figure 4-17: Angle of attack distribution along the tip or winglet

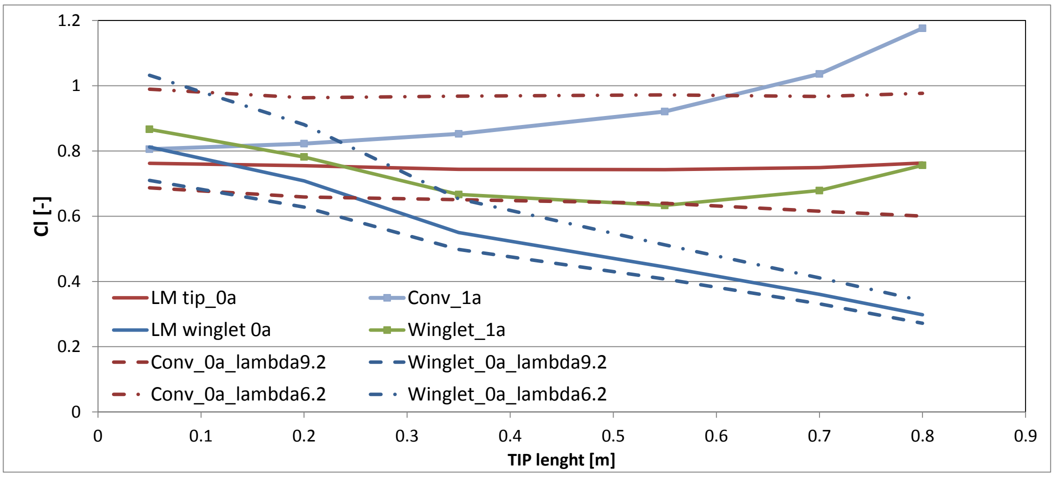


Figure 4-18: Cl distribution along the tip or winglet

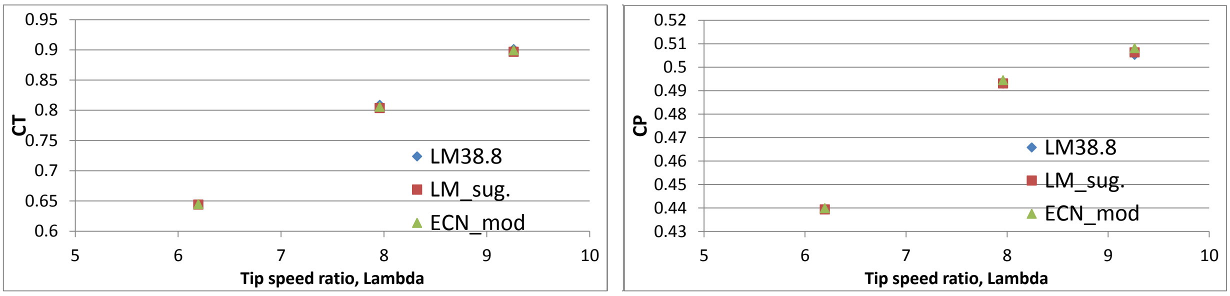


Figure 4-19: Thrust (left) and power (right) coefficients versus tip speed ratio for the conventional tip

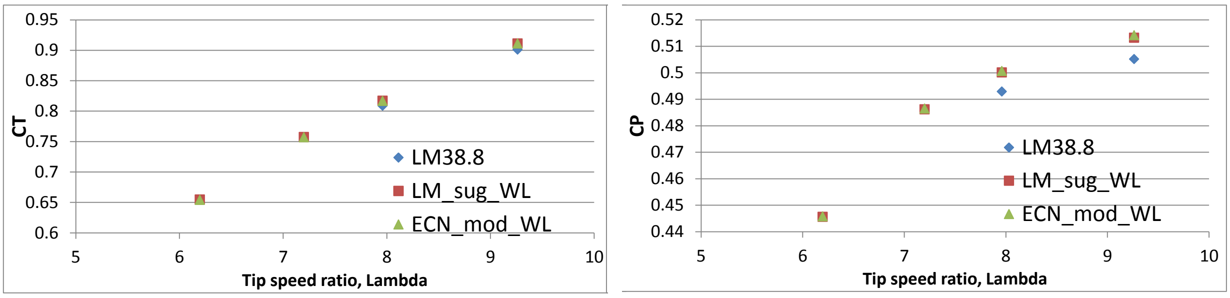


Figure 4-20: Thrust (left) and power (right) coefficients versus tip speed ratio for the winglet

4.3.2.2 Final Configurations

The final configuration selection is done after the final assessment using the most optimum parameters. The 3D geometries of the final conventional tip and the winglet configuration is shown in Figure 4-21. The twist distribution used for the final assessment is as in Figure 4-22. Again, the angle of attack, the axial induction and the cl distribution along the tips of these configurations are compared in Figure 4-23, Figure 4-24 and Figure 4-25. After these comparisons it is concluded that the conventional tip 1b and the winglet 1c gives the optimum and measurable differences. Therefore, these configurations are chosen as good candidates to be implemented to the field test turbines. The effects of the tip additions to the blade and the turbine response, the design loads and the turbine controller are also investigated and these results can be found in /12/.

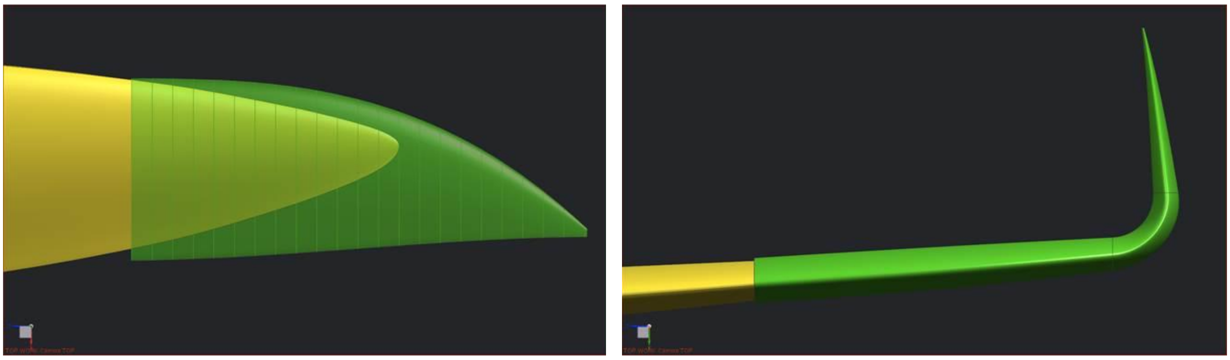


Figure 4-21: Final conventional tip (left) and winglet (right) configurations

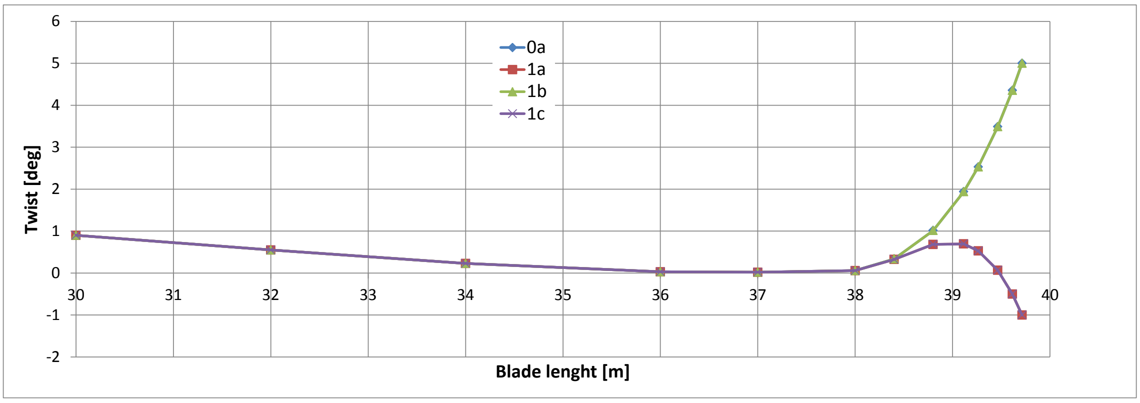


Figure 4-22: Twist angle variation of the final configurations. 1a is negative twist, 1b is swept back and 1c is negative twist and swept back geometry

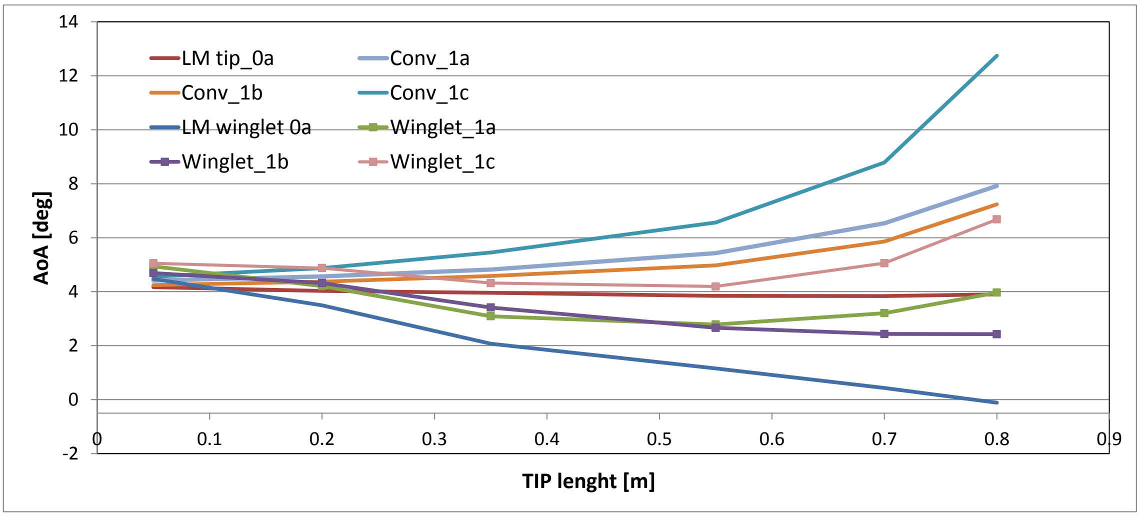


Figure 4-23: Angle of attack distribution of all configurations compared with each other

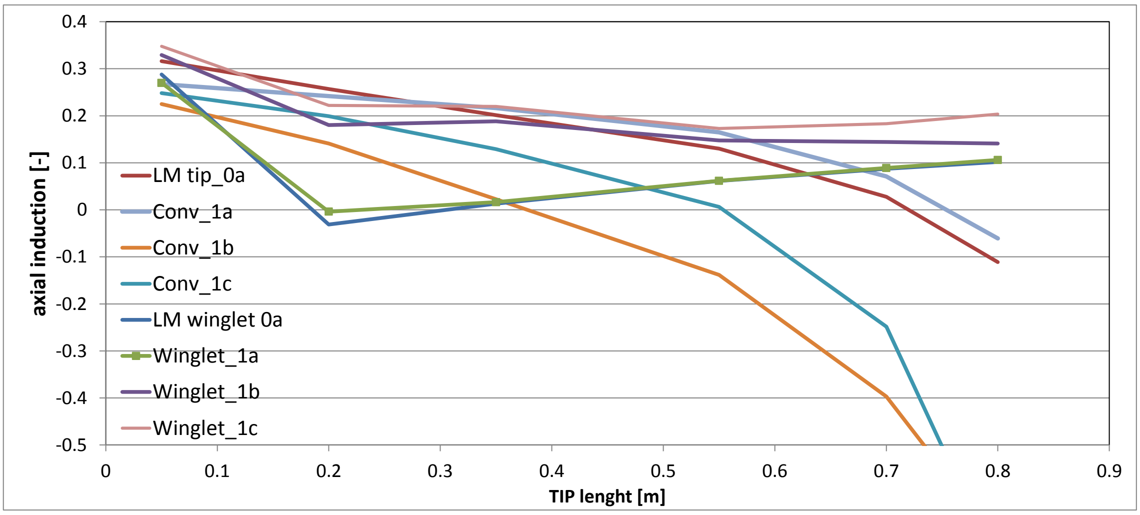


Figure 4-24: Axial induction distribution of all configurations compared with each other

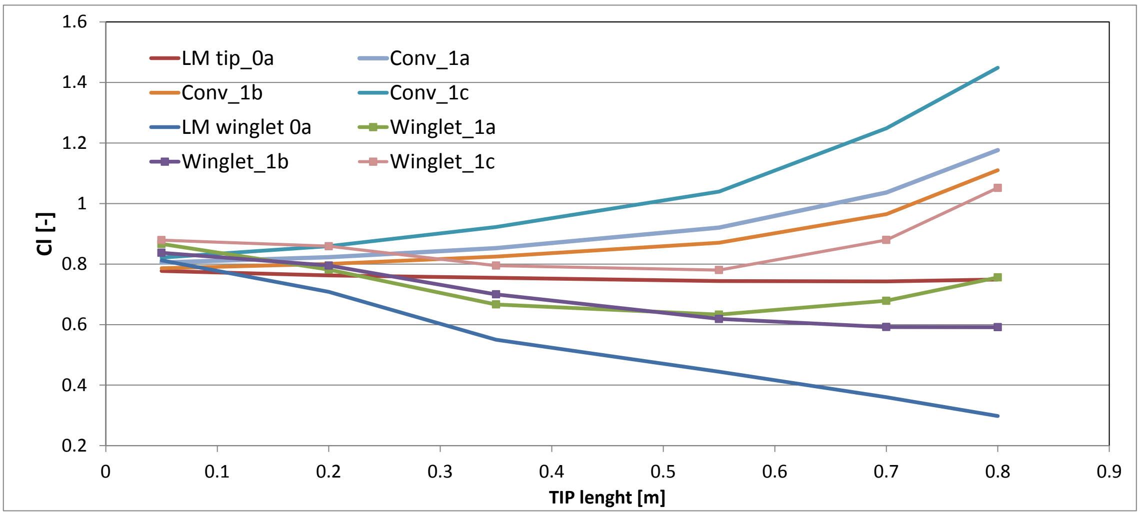


Figure 4-25: Cl distribution of all configurations compared with each other

4.3.2.3 CFD Analyses

Several CFD analyses have been done to verify the work results from mainly the lifting line method. Results for the conventional tip and winglet at 8.5 m/s and 12.5 m/s are compared to the original LM38.8P configuration at the same wind speed. They are shown in Table 4-4 and Table 4-5.

	Mechanical Power [kW]	Difference	Thrust [kN]	Difference
Original LM38.8P	868.38	0.00%	178.53	0.00%
Conventional	911.52	4.97%	186.31	4.36%
Winglet	893.56	2.90%	183.52	2.80%

Table 4-4: Comparison of Conventional and Winglet Configuration at 8.5 m/s from CFD

	Mechanical Power [kW]	Difference	Thrust [kN]	Difference
Original LM38.8P	2499.05	0.00%	286.47	0.00%
Conventional	2601.92	4.12%	296.87	3.63%
Winglet	2557.08	2.32%	292.76	2.20%

Table 4-5: Comparison of Conventional and Winglet Configuration at 12.5 m/s from CFD

It should be noted that the tip speed ratio of the conventional tip has slightly increased to keep the RPM values similar for the different cases. From the CFD results it is clear that the winglet has both a lower mechanical power output as well as a lower thrust output at the evaluated wind speeds than the conventional geometry, yet both tips increase power and thrust compared to the original case.

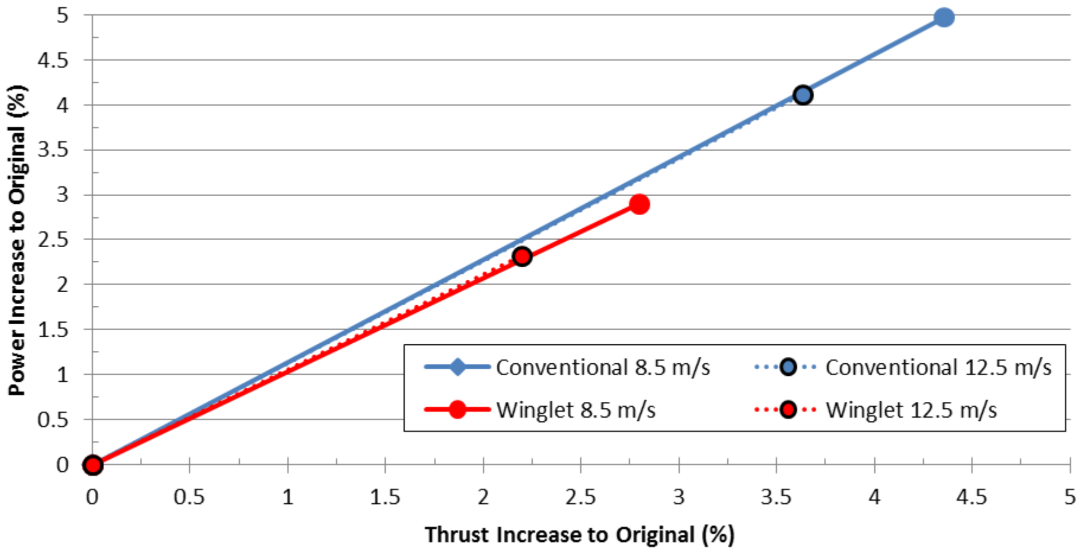


Figure 4-26: Thrust and Power increase compared to original LM38.8P from CFD

Figure 4-26 shows the power increase versus the thrust increase for the 4 cases. This graph indicates that the conventional tip will have a relative higher power output on thrust cost basis. The streamlines on the different blade tips are presented in Figure 4-27.

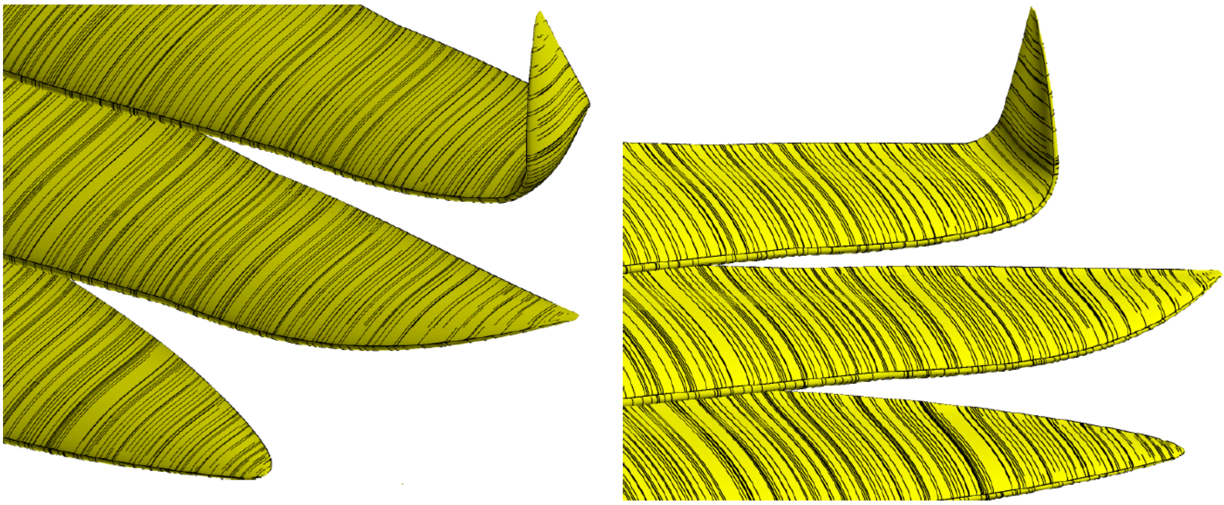


Figure 4-27: Limiting Streamlines on the three tip geometries

The results from CFD suggest that the conventional tip will be more optimum aerodynamic wise. Having a winglet could be beneficial on other grounds (noise, height restriction etc.), however for AEP the CFD analyses suggest that the conventional tip will be more favourable.

4.3.3 Turbulators

For the turbulator tip designs, two main parameters are used. The first one is size of the teeth which is represented in terms of percentage of its local chord length. The second one is the number of teeth. For the simulations, the teeth shape is approximated as triangles which are added to the blade planform as shown in Figure 4-28. With this approximation, there is a local extension of the chord length where the chord distribution along the blade span is not anymore continuous. This is shown in Figure 4-29 for a 4-teeth configuration for different turbulator chordwise dimension. The resulting blade planform shapes with these turbulator dimensions are shown in Figure 4-30 together with the original blade planform shape.

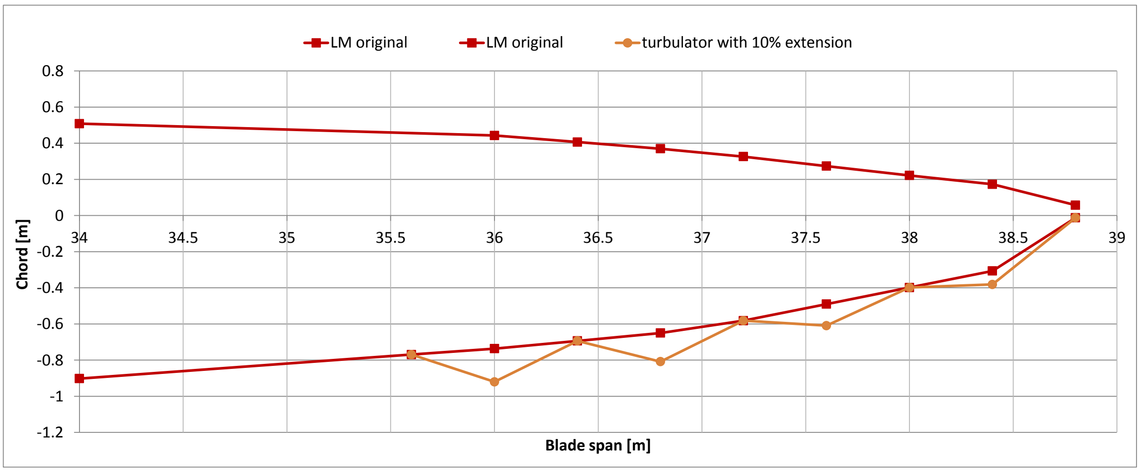


Figure 4-28: Planform shape of the last 5m of the blade with and without the turbulator

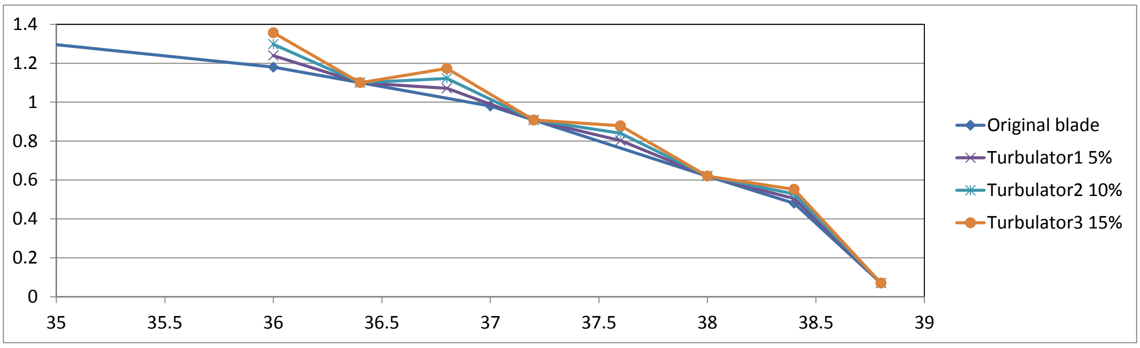


Figure 4-29: Chord distribution along the tip for 4 teeth configuration, for different turbulator lengths

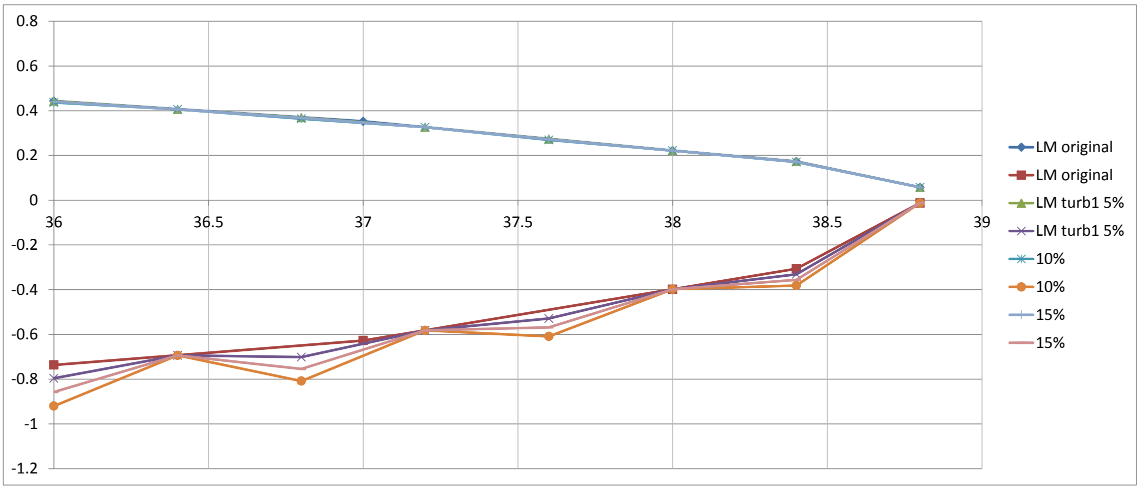


Figure 4-30: Planform configuration of the blade with and without turbulators. Only for 4 teeth configuration

The turbulator shapes have been analysed with Aeromodule AWSM (lifting line code) and compared with each other and with the original blade. Besides the parameters like load distributions, flow angles, circulation, etc, also the wake which is just behind the turbine is monitored. In Figure 4-31, a two teeth configuration with the original blade is compared. The influence of the teeth is visible which deforms the wake around the max teeth location. This early deformation of the wake results in earlier break-up of the tip vortex which is already visible in the AWSM results without taking into account the freestream turbulence and the mixing of the outer flow with the wake. Figure 4-32 shows how the wake develops at near and far field of the rotors with different turbulator configurations. A regularly shaped wake of the original rotor changes into a more non-regular wake behind the rotors with the turbulators.

In terms of the change in the overall power and thrust values, the comparisons are given in Figure 4-33 and Figure 4-34. Although, the main motivation of the turbulator should come from the turbine next in the row in a wind farm, there is already a power increase observed for the rotors with turbulators. However, these aspects need to be further investigated and quantified with more detailed software tools and experiments.

The final configuration of the turbulators applied to the blade in the test field is shown in Figure 4-35.

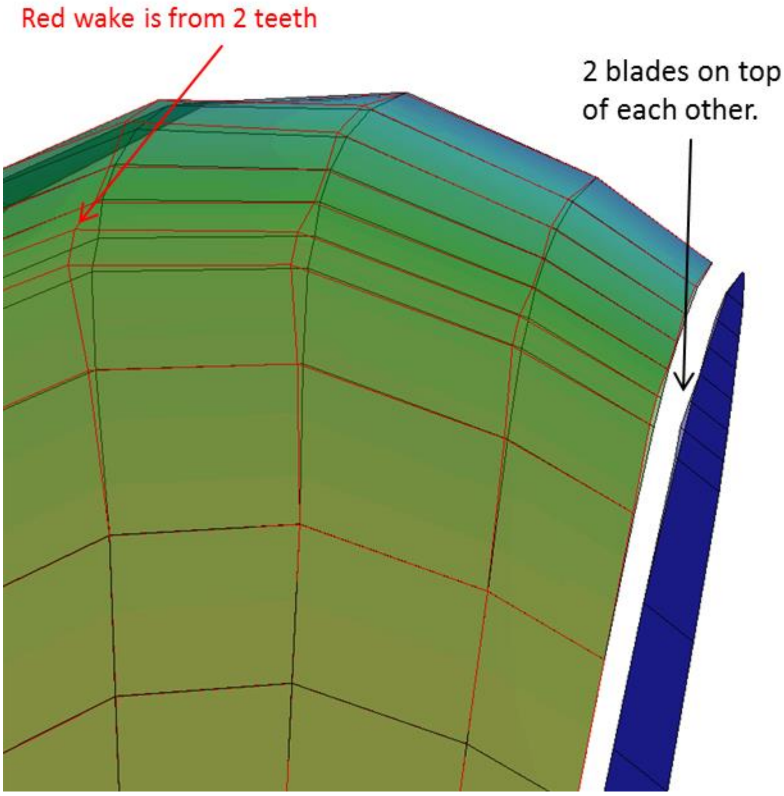


Figure 4-31: Change of the wake and the tip vortex after applying turbulators

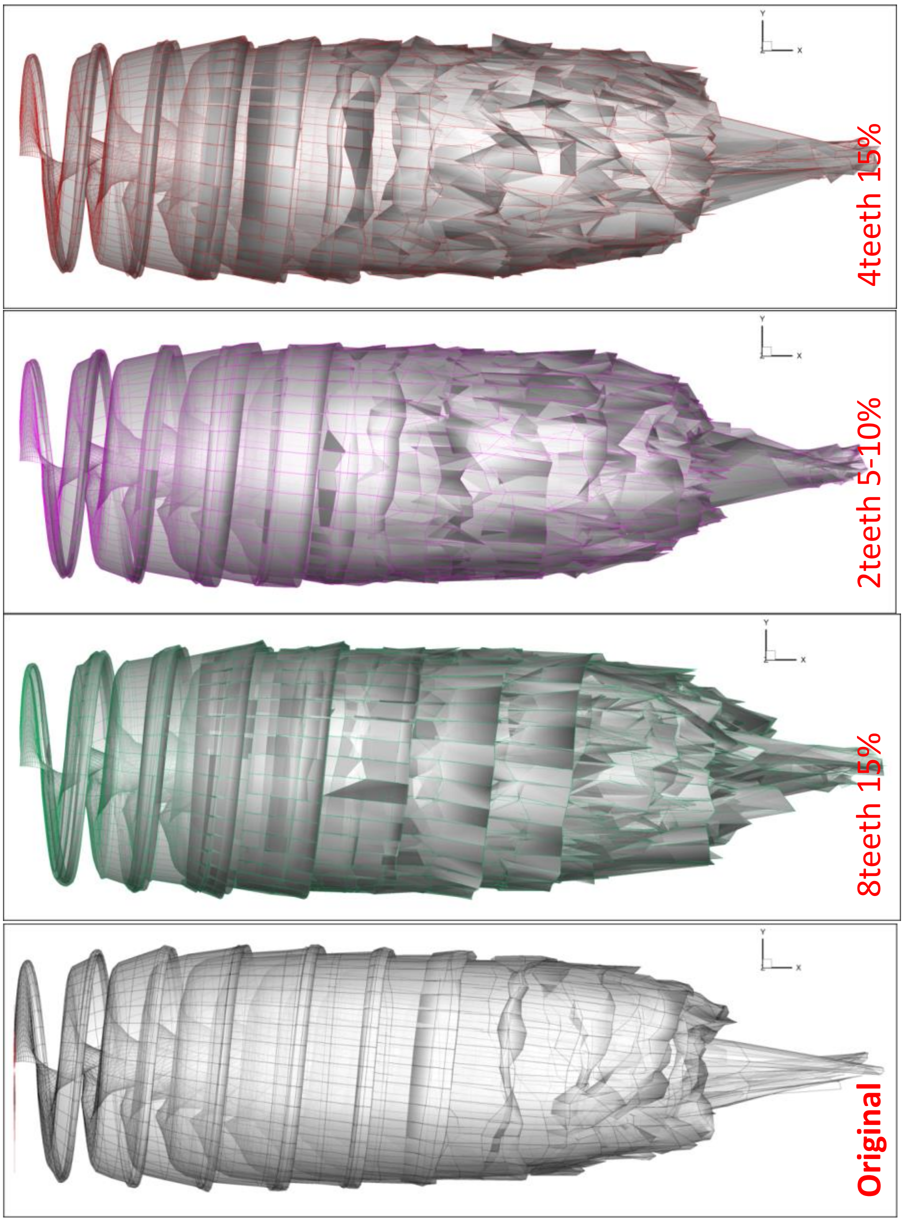


Figure 4-32: Breaking down of the tip vortex shown in the wake plots and compared for different number of tooth configurations

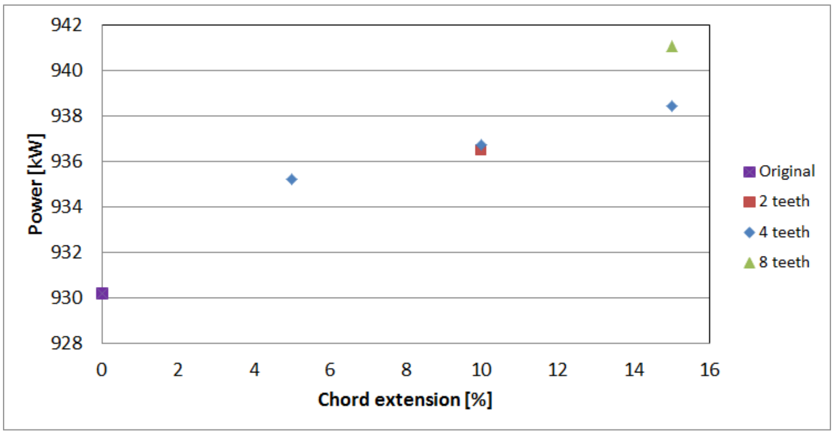


Figure 4-33: Power change with the different turbulator configurations

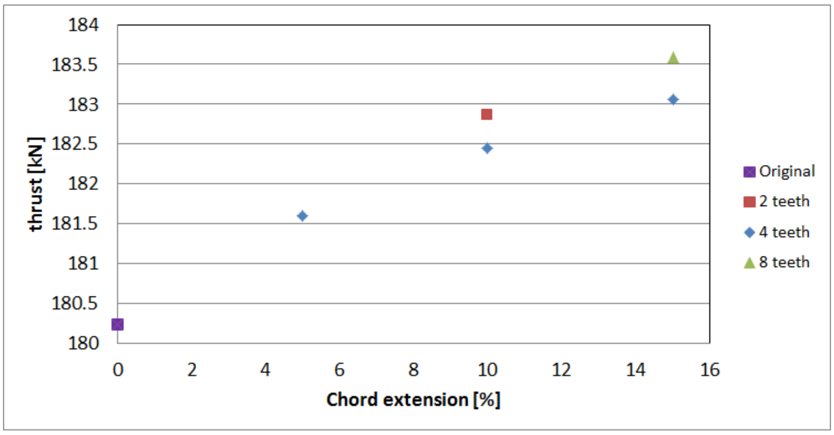


Figure 4-34: Thrust change with the different turbulator configurations

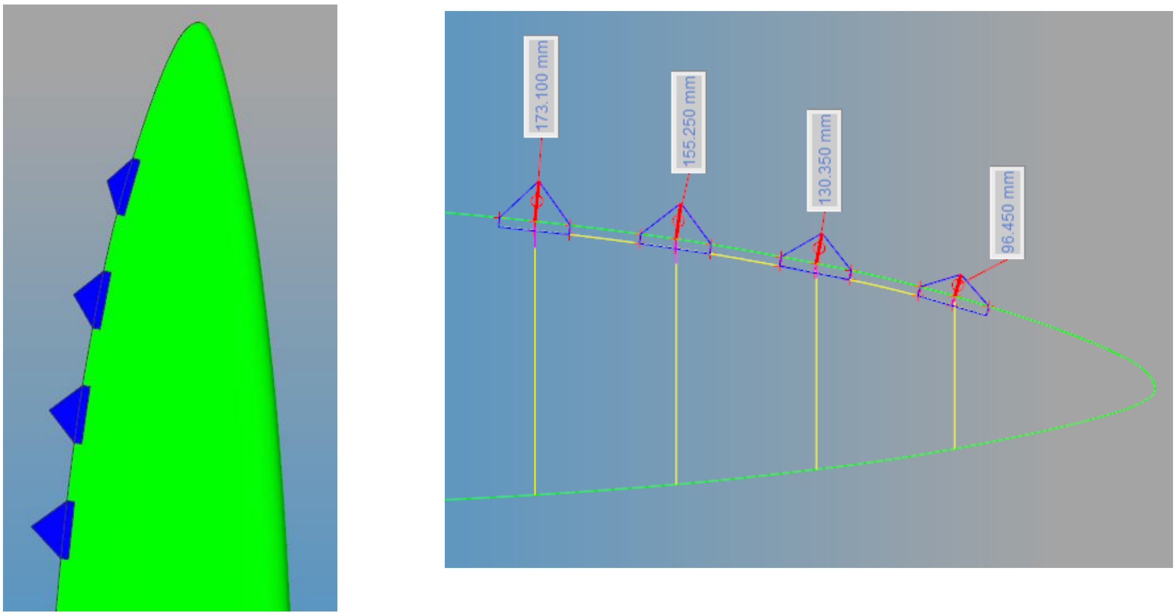


Figure 4-35: Final turbulator configuration applied to the blades of the test wind turbine

5.0 Detailed Design

5.1 Conceptual Design

After the optimum geometry of the tips have been evaluated, the concept for attaching the tips to the blades have been prepared. Several design aspects had to be dealt with in order to have the safety of the design in place. These encompass e.g. lightning protection, drainage system blade tolerances in the field, internal and external shape, mounting procedures, structural design and alignment to the existing blade.

For all uncertainties in the design, several conceptual solutions have been found and the best solution has been used in the final design. In order to determine which solution is best, several stakeholders have been giving input to the ideas giving the optimum from e.g. structural engineering, manufacturing, services as well as maintaining as much as possible to intended aerodynamic shape. Also, during the complete design phase, the intent of the project to remove the tips after testing has been taken into account. Something that made the design and installation procedures complex.

Below the conceptual designs from the conventional tip as well as the winglet are presented.

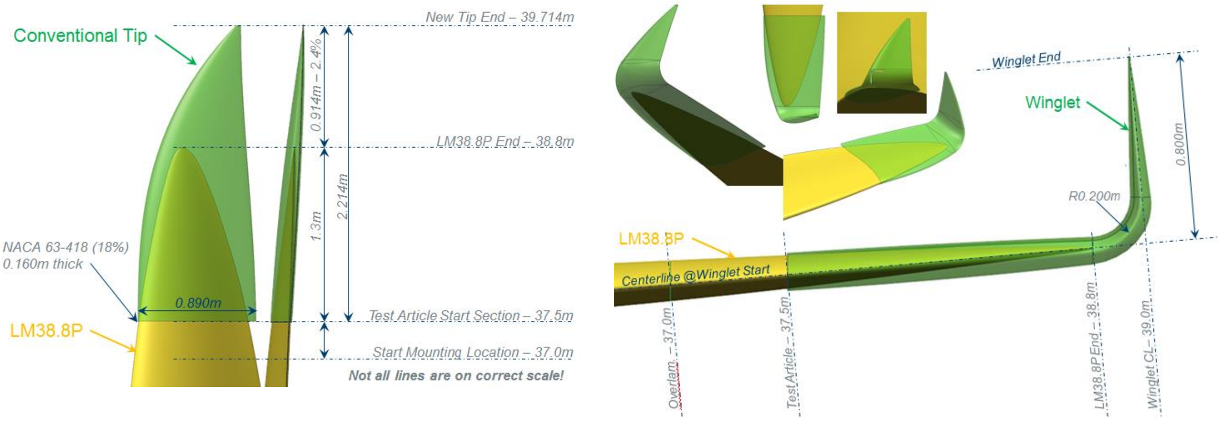


Figure 5-1: Geometries of the Conventional Tip as well as Winglet

5.2 Pre-Installation set-up

Prior to the installation several preparations have been done in order to have the tests performed as optimal as possible. These are:

1. Installation of Representative Blade Tip
2. Manufacturing of different geometries, including prototype extension
3. Clearance Measurements

Ad. 1) A scrapped LM38.8P blade (similar to those where the field installation is going to be performed upon) has been identified and the outer 4.2 meters have been cut off. A foundation has been welded to support the tip which is used during manufacturing and for the installation and removal tests. This foundation is mounted stuck on both the test hall wall and floor. Additionally the tip is able to rotate around its own axis.

The foundation with mounted LM38.8P tip is shown in Figure 5-2.

Figure 5-2: LM38.8P tip mounted on rotatable support used for manufacturing and testing

Ad. 2) Different geometries have been milled in order to optimize and prepare the test. Initially the internal geometry has been milled out of Styrofoam in order to check the fitting of this geometry on the existing blade tip. This geometry is shown in Figure 5-3.

Figure 5-3: Styrofoam negative – checking the internal geometry

Following this, half of the geometry has been manufactured to indicate the manufacturability of the geometry. Handling of the geometry could be checked with this piece. This half part is shown in Figure 5-4.


Figure 5-4: First Half part – Checking handling of foam

A prototype extension has been manufactured to do the installation tests. This prototype is made out of 3D CNC machined Armacell foam, hand laminated with 8 layers of glassfiber. The manufactured tip is based on the conventional tip design. This tip will be used for the static tests of the extreme loads.

The prototype conventional tip extension is shown slided over the LM38.8P tip in Figure 5-5.


Figure 5-5: Prototype Conventional Tip slided over LM38.8P Tip

The tip is made of a sandwich layup made of glass-foam-glass where the foam is 3D CNC machined to give the correct geometry. The complete layup (including foam) is presented in Table 5-1. Note that all layers are from leading edge to trailing edge.

Ply no.	Start	End	Material
[-]	[m]	[m]	[-]
-1	-37.50	-38.800	COMBI 900
0	-37.50	-39.716	Foam
1	-37.50	-39.716	CSM
2	-37.50	-39.716	BIAX 450
3	-37.55	-39.600	BIAX 450
4	-37.50	-39.716	UD 661
5	-37.60	-39.550	UD 661
6	-37.70	-39.450	UD 661
7	-37.65	-39.500	BIAX 450
8	-37.50	-39.716	COMBI 900

Table 5-1: Glass lay-up for extensions

In Figure 5-5 (right) it is possible to see that the edge is rather large which give rise to a large laminate lay-up before a good over-lamination can be made. Prior to installation this edge is grinded smooth, a learning that will be applied to all tips to be manufactured. The grinded tip is shown loose and slided over the LM38.8P tip in Figure 5-6.

Figure 5-6: Grinded prototype tip for smooth transition

Ad. 3) In order to have a check on the internal clearance, a number of clay pieces are placed on the overlapping part of the blade (on both upwind and downwind side) – see Figure 5-7. Sliding the prototype over the existing tip will deform the soft chalk. After removal of the tip, the thickness of clay is measured. Thickness of clay indicates how much clearance is available.

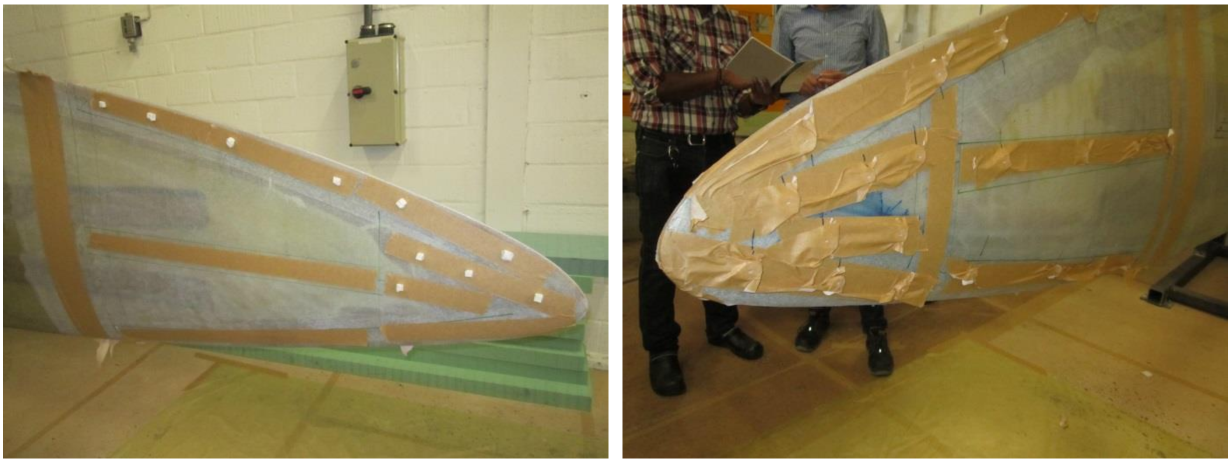


Figure 5-7: Clearance measurements – pre- and post-deformation

5.3 Installation Test

Installation of the prototype is done according to the following steps:

1. Removal of the existing receptors;
2. Grinding the surface of the LM38.8P tip on the surfaces to be glued and laminated;
3. Marking of blade for gluing, drain holes, receptor location, alignment and distance plugs;
4. Installation of distance plugs;
5. Application of glue on the LM38.8P;
6. Sliding of the prototype tip;
7. After curing grinding for smooth intersection;
8. Laminating the connection
9. After curing grinding the connection smooth
10. Applying gelcoat on grinded surface (part of the gelcoat will be applied already) and
11. Installing lightning receptor, diverter strips and drill new drain holes.

Note that the process for installation and removal is highlighted in reference /11/.

Below the process is presented while applied in the test facility. Note that not all steps have been performed for this test blade as some steps will be based on standard service instructions already widely applied by the installation agent (e.g. application of gelcoat). Instead focus is given to the challenging parts of this installation.

The installation test is initiated by having the LM38.8P blade tip grinded ready for gluing. Hereafter, distance plugs between 3 and 7 mm thick are mounted on both upwind and downwind side of the LM38.8P tip. This is presented in Figure 5-8.

Figure 5-8: Grinded LM38.8P surface and installed distance plugs

Location of drain holes as well as receptor location is marked on the LM38.8P blade outside the overlapping region in order to find the same location back after installation. The drain holes are to be covered to avoid ingress of glue during installation. Receptor removed and markings on the blade are made for alignment of the tip and locating the gluing areas. This is shown in Figure 5-9 and Figure 5-10.

Figure 5-9: Markings on the blade for drain holes and anchor block after grinding

Figure 5-10: Marking blade for alignment and gluing areas

The glue is applied on the LM38.8P surface at the indicated areas prior to installing the new tip. The glue used is standard GT60 glue. The gluing process is shown in Figure 5-11, it should be noted though that the gluing process may need some adjustment as some issues were found with the amount of glue in the tip. A drill&fill solution could be used to overcome these issues.

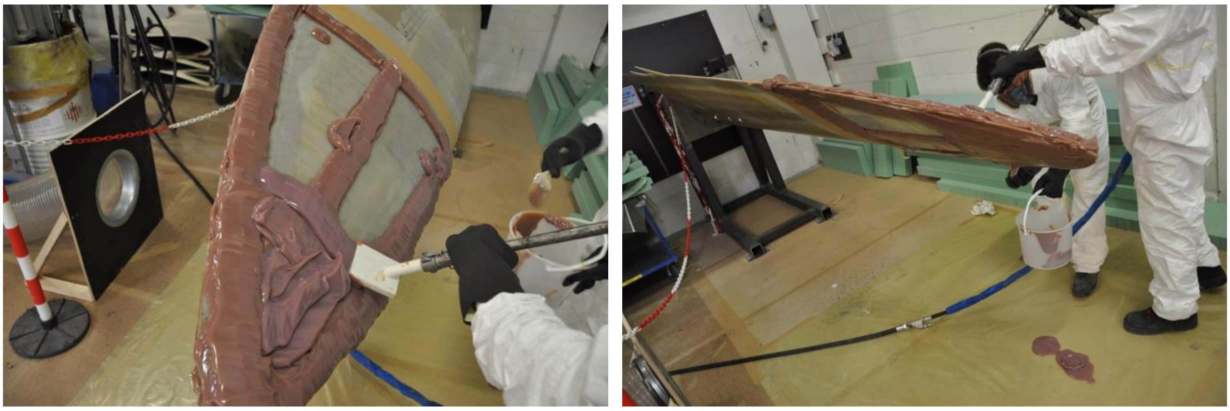


Figure 5-11: Application of glue on the LM38.8P blade

The prototype tip is pressed over the LM38.8P tip and placed at the right location. Hereafter the glue is set to cure for several hours until grinding and lamination can be done. The glued connection before and after grinding the transition is presented in Figure 5-12.

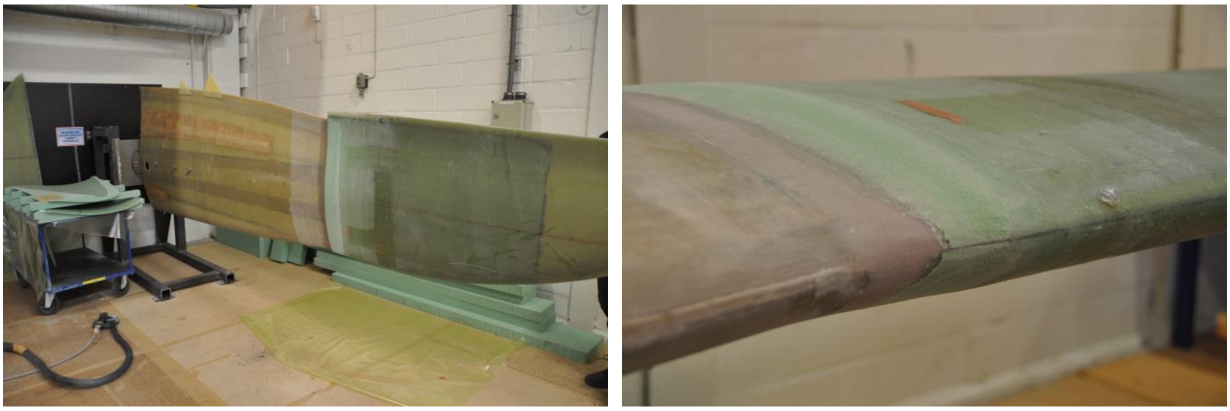


Figure 5-12: Glued tip pre- and post-grinding

After grinding the over-lamination is applied. At this test the lamination is done with single colour sheets. In the field the first layer will be red to ensure that the original shape of the blade can be restored when removing the over-lamination.

Note that for this installation test the final grinding after over-lamination has not been done as this would only be required for aerodynamic performance. Neither has there been applied gelcoat. These steps will be done in the field to ensure the smoothness and protection of the connection.

The connection after lamination is shown in Figure 5-13.

Figure 5-13: Connection after over-lamination process has finalized

After glue is cured, laminate (which has been grinded) is re-built by over-lamination. For the over-lamination same laminate scheme is used as given in Table 5-1. However, Biax plies are extended. The over-lamination is performed using the glass layup as shown in Table 5-2. Most of the ply's are mirrored around the intersection point (-37.50 meters) except 2 of the UD layers and the first identification layer. Note that this installation is considered a repair.

Ply no.	Start	End	Material
[-]	[m]	[m]	[-]
1	-37.00	-37.70	COMBI 900 Red Yarns
2	-37.25	-37.75	BIAX 450
3	-37.60	-37.80	UD 661
4	-37.55	-37.85	UD 661
5	-37.10	-37.90	UD 661
6	-37.05	-37.95	BIAX 450
7	-37.00	-38.00	COMBI 900

Table 5-2: Glass Lay-Up for Over-lamination

A check is done to see if the drain holes and receptor location can be accurately found. The installation of a new receptor is standard procedure and is not fully tested. It should be noted that due to the large distance to the anchor block, a special tab is to be used for receptor installation (threading into the anchor block).

Note that the receptor block can be accurately found using a metal detector (Fisher M101).

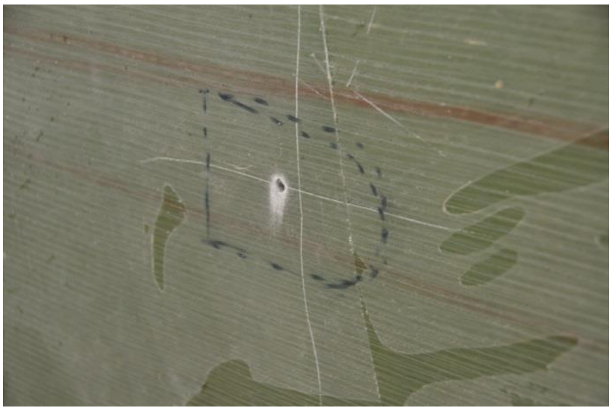


Figure 5-14: Drilled drain holes and receptor hole for extending lightning protection

5.4 Static Tests

5.4.1 Conventional Tip

The structural validation of the prototype as well as the connection is done by static extreme load tests. The extreme loads are applied to the tip divided into 2 positions in order to obtain the design moment at the connection (37.5 m). The loads are obtained by ECN and documented in Appendix C of reference /12/. As per IEC-61400-23, design loads are multiplied by partial factor of 1.1 to obtain target test loads (reference /13/). The loads from ECN are shown together with the loads applied in Table 5-3.

	Edgewise	Flapwise
	Nm	Nm
Design Loads (ECN)	6700	10700
Target Test Load	7370	11770
Applied Loads	8253	11977
Ratio Applied to Target Test Load	1.12	1.02

Table 5-3: Loads at 37.5 meters for Static Extreme tests

This is initially done separately and afterwards combined. The loads applied to the tip (for a period of 10 seconds) are presented in Figure 5-15.

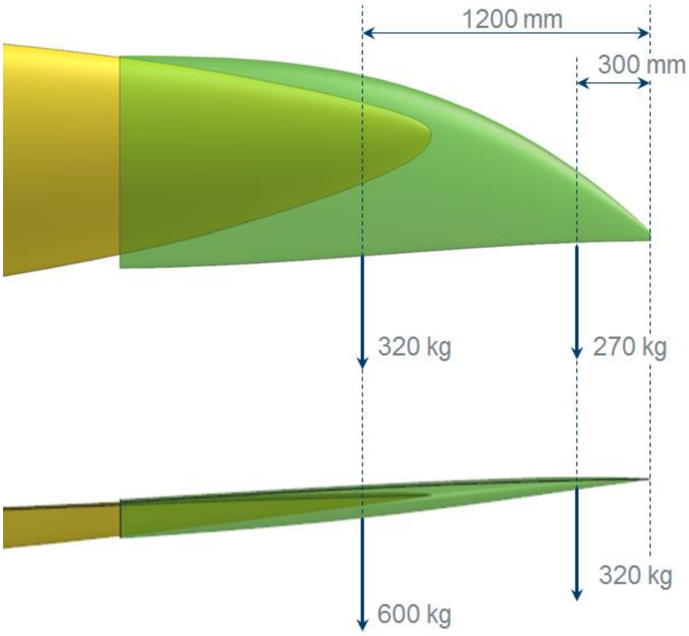


Figure 5-15: Static Extreme loads Applied on the Connection

The edgewise test has been performed first (lowest loads) in order to ensure that the foundation of the set-up could withstand the loads. The loads have been applied by hanging concrete weights by straps (anchored by additional rope system) on the tip at the indicated locations. The loads have been applied from leading edge to trailing edge direction.

The edgewise static test for both weights is shown in Figure 5-16.

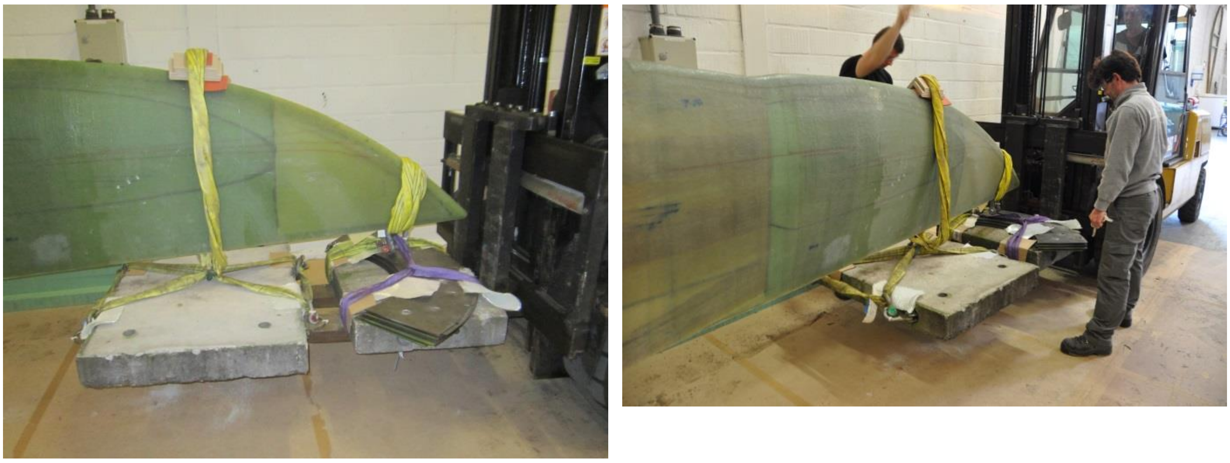


Figure 5-16: Static Extreme load test - Edgewise direction

The flapwise extreme load test has been performed by applying the loads in flap to downwind direction as shown in Figure 5-15. The application is shown in Figure 5-17.

Figure 5-17: Static Extreme load test – Flapwise direction

During and after the test, there has not been any indication of damage on either LM38.8P blade, the prototype tip or connection. Both the prototype tip and LM 38.8 P tip section withstand extreme loads without any signs of buckling or cracks.

5.4.2 Winglet

The bending moments on the radial section of the winglet has been tested separately. The winglet is loaded with extreme loads based on /12/. Note that the bending moments at section 38.8 (prior to bending radius) for the conventional tip have been used as these loads are deemed conservative as well as most representative for the winglet radial section. Also in this test, the design loads are multiplied by partial factor of 1.1 according to IEC 61400-23 (/13/).

Loads and reserves are presented in Table 5-4.

	Edgewise	Flapwise
	Nm	Nm
Design Loads (ECN)	790	1380
Target Test Load	869	1518
Applied Loads	1253	1909
Ratio Applied to Target Test Load	1.36	1.26

Table 5-4: Loads at 38.8 meters for Static Extreme tests Winglet

The loads applied to the tip (for a period of 10 seconds) are presented in Figure 5-18.

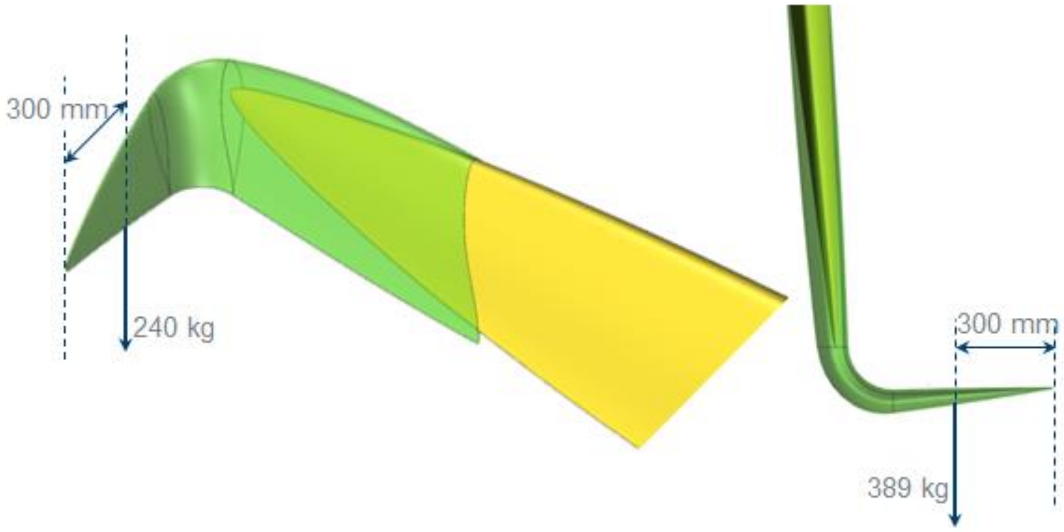


Figure 5-18: Static Extreme loads Applied on the Winglet

The edgewise static test for extreme loads is shown in Figure 5-19.

Figure 5-19: Static Extreme load test Winglet - Edgewise direction

The flapwise extreme load test has been performed by applying the loads in flap to downwind direction (i.e. bending the flap towards straight) as shown in Figure 5-18. The application is shown in Figure 5-20.

Figure 5-20: Static Extreme load test Winglet – Flapwise direction

During and after the test, there has not been any indication of damage on the Winglet Prototype tip.

5.5 Removal

The removal of the tip has been done by the following steps:

1. Removal of lightning receptors;
2. Cutting of the extended part of the prototype (this is done outside of the LM38.8P tip to not damage the original tip);
3. Trimming the trailing edge to ensure no glass-to-glass connection is present (again, this is done outside the LM38.8P tip overlap);
4. Cutting the leading edge to split glass in two sections;
5. Grinding the overlap area as much as possible to release the half-parts without damaging the original blade;
6. Grinding the surface to its original shape;
7. Applying new gelcoat and
8. Restoring the lightning protection system by installing new receptors.

The result after steps 1 to 5 is shown in Figure 5-21.

Figure 5-21: Removal of tip by cutting away tip, leading edge and trailing edge – grinding the connection and removing the glass cover

After grinding the remainder of the prototype tip, the original blade shape is restored. The intermediate steps are presented in Figure 5-22.

Figure 5-22: partially grinded LM38.8P surface (left) and fully grinded LM38.8P surface (right) after removal of prototype extension

It has been seen that the glue between the LM38.8P tip and prototype tip has cracked at several locations (due to extreme load tests). However, the glue at all locations kept sticking on the surfaces. Furthermore, the glue filled out all area between the tips. Some of the cracking is shown in Figure 5-23.

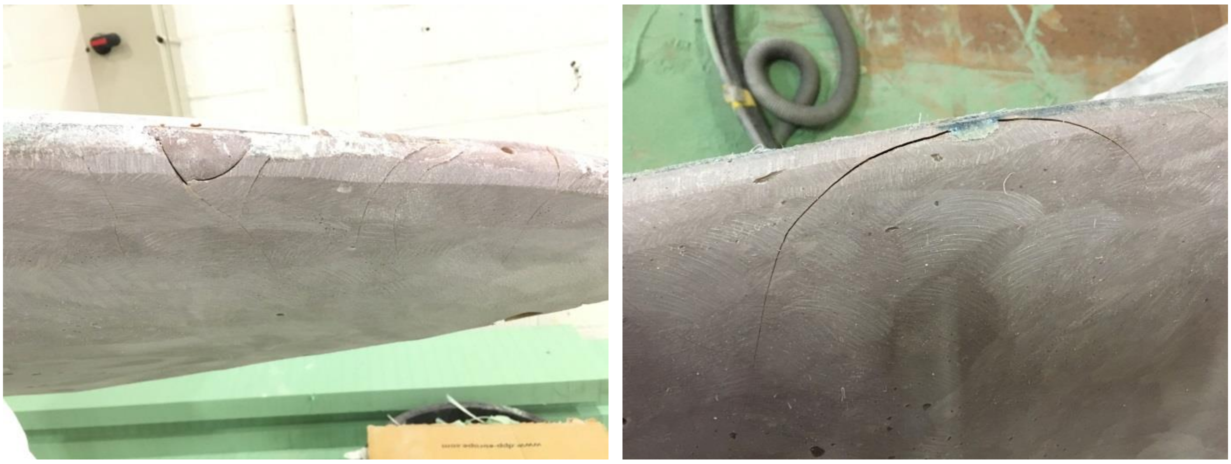


Figure 5-23: Glue cracking as seen after extreme load test

6.0 Field Testing

6.1 Introduction

This chapter describes the measurement instrumentation used for the experiments in Innotip Project and the results of the measurement data after the measurements.

Four turbines are equipped with a similar measurement setup, i.e.:

- calibrated power measurement
- blade loads and acceleration measurement in one blade per turbine
- nacelle wind speed measurement using a calibrated anemometer
- rotor position & rotor speed measurement
- Nordex N80 PLC data measurement
- Ground based LiDAR measurement
- Meteorological mast 3 (MM3) measurement

For environmental data MM3 is used together with a dedicated ground based LiDAR approximately 255m north of Nordex 6 next to the canal.

6.2 Test Environment

6.2.1 Test site EWTW

The ECN Wind turbine Test site Wieringermeer (EWTW) is situated in the Wieringermeer, a polder in the North East of the Province North-Holland, The Netherlands, 3 km North of the town of Medemblik and 35 km East of ECN Petten, see Figure 6-1.

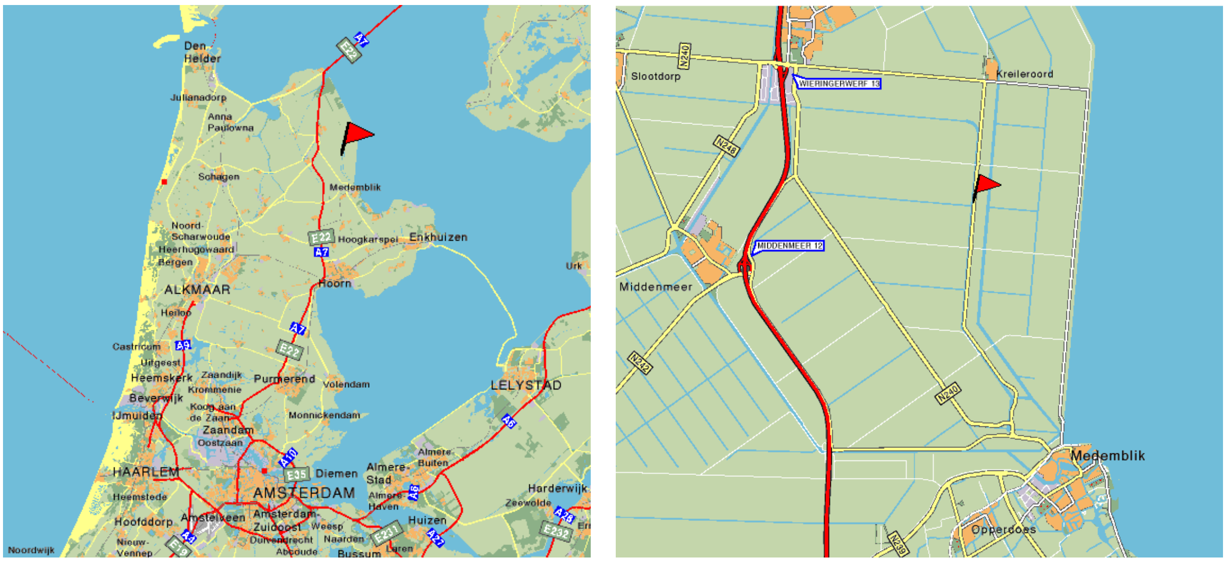


Figure 6-1: Map of the province North-Holland, The Netherlands and a detailed map of the test site EWTW in the polder Wieringermeer. ECN Petten at the North Seas coast is also indicated

The test site and its surroundings are characterized by flat terrain, consisting of mainly agricultural area, with single farmhouses and rows of trees. The lake IJsselmeer is located at a distance of 2 km east of meteorological mast 3. The site has 6 prototype locations, as well as 5 locations on which a research wind farm has been realized. In addition there are 5 meteorological masts and there is a measurement office. A layout of the test farm EWTW can be found in Figure 6-2.

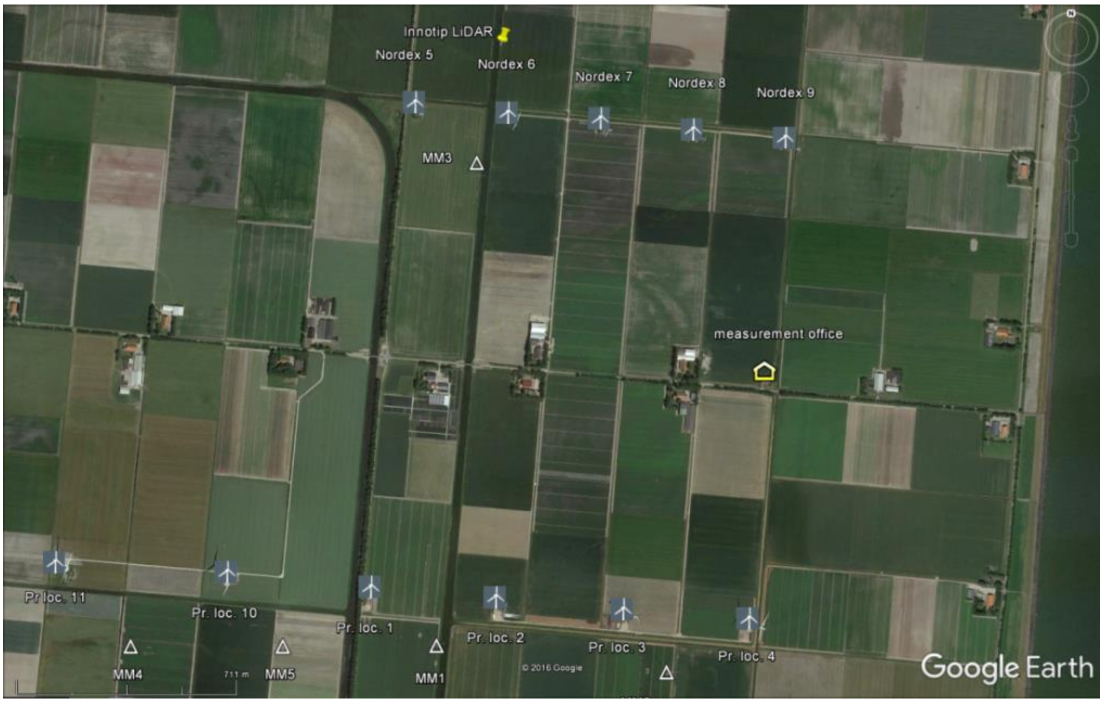


Figure 6-2: Layout of the test site with the research turbines (Nordex 5 - 9), the prototype turbines, the meteorological masts, the measurement office and the Innotip LiDAR location. The top side of the figure resembles north

6.2.2 Meteorological mast 3

For the meteorological parameters, signals from meteorological mast 3 (MM3) are used. The position of MM3 is shown in Figure 6-3. The MM3 data is available in the Innotip database from 28-03-2016 onwards.

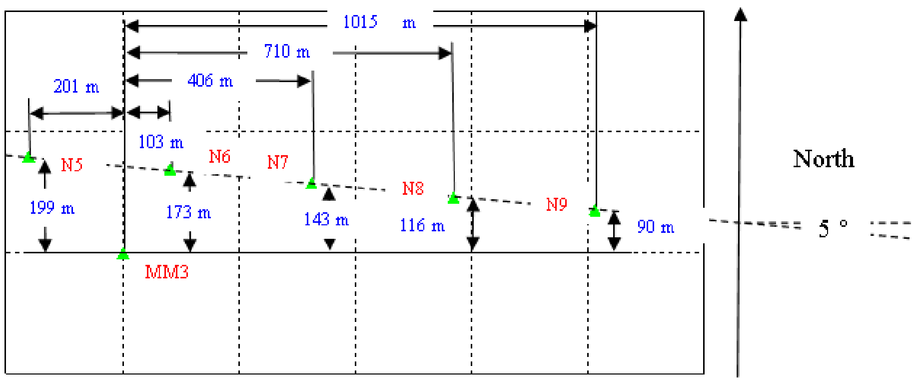


Figure 6-3: Locations of the five Nordex N80 turbines and Meteorological Mast 3

For analyses purposes, different wind sectors can be used. The undisturbed wind sectors of the different N80 locations have been estimated and can be found in /14/ together with the detailed information on the instrumentation of the meteorological mast 3.

Figure 6-4: Photograph of MM3 at the EWTW test site, taken from N6

6.2.3 Wind turbine Nordex N80

The EWTW research turbines are Nordex N80's, see Figure 6-5. The N80 is a 3-bladed, pitch controlled wind turbine with a rated power of 2.5MW and with a hub height and rotor diameter of 80m. The distances relative to each other and relative to MM3 are illustrated in Figure 6-3. The PLC data of all Nordex N80 turbines are collected and saved in the Innotip database. The N80 PLC data is available from 28-02-2016 in the Innotip database.

Figure 6-5: Photograph of Nordex 7 on the EWTW with Innotips installed

6.3 Measurement system layout

The measurements for the Innotip project consist of the following items:

- calibrated power measurement in N5 to N8
- blade loads and acceleration measurement in one blade in N5 to N8
- nacelle wind speed measurement using a calibrated anemometer on N5 to N8
- rotor position & rotor speed measurement in N5 to N8
- Nordex N80 PLC data measurement in N5 to N9
- Ground based LiDAR measurement

The set-up of the measurement system is a combination of Dante Frontend systems and CompactRIO Data Acquisition systems. For the Dante Frontend and CompactRIO system each sensor or group of sensors is connected to a module. The Dante module provides the power supply to the sensors (in case of MM3) and provides facilities for scaling. The CompactRIO module is dedicated for the measurement of the signals and provides facilities for scaling also. Detailed information about the data acquisition systems and different types of modules is reported in /14/.

In N5 to N8 measurement systems are placed in the hub, nacelle and tower-base. N9 is not directly used for the Innotip experiments and therefore only the PLC data is measured.

In the mast base of the Nordex turbines Dante Frontends are placed to measure the Nordex Messbox signals (PLC). In the nacelle and hub of N5 to N8 a CompactRIO system is installed to measure the signals from the nacelle and hub. In the hub of N5 to N8, a CompactRIO is installed to measure the signals from the blades. The meteorological mast signals of MM3 are measured by a Dante Frontend placed at the base of MM3.

The MM3, Nordex N80 mast base and nacelle systems are connected to the fiber optic network which is available at the test site and also available in the Nordex N80 turbines to the nacelle. The network connection at the rotor as well as the LiDAR location is provided by a Wireless LAN connection.

The data storage is done by a Host-PC which is located in the measurement office. This Host-PC is connected by a glass fiber Ethernet network to the individual Dante Frontends and CompactRIO systems. On this network also a GPS clock is present which ensures that the time stamp of the individual Frontends, the Compact Rio systems and also the LiDAR systems are correctly synchronized. On a daily basis, the measurement data of the Host-PC is transferred to a data server called 'Informatix' at the ECN main office in Petten, where it is imported into the Innotip database. The ground based LiDAR data is directly downloaded from the LiDAR using FTP.

6.3.1 Ground based LiDAR

Additional to the meteorological measurements of MM3 a Windcube V2 ground based LiDAR with ID: WLS7-258 is installed to measure the wind speed and wind direction north of the Nordex turbines to enlarge the measurement sector of the Nordex turbines, especially for N5 and N6.

The position of the LiDAR is shown in Figure 6-3. The LiDAR is configured to measure the wind speed and wind direction at 10 different heights. The lidar data is available in the Innotip database from 27-03-2016 until 06-10-2016.

Figure 6-6: Zoomed in layout of the test site with the research turbines (Nordex 5 - 9, the meteorological mast 3 and the Innotip LiDAR location. The top side of the figure resembles north

For analyses purposes, different wind sectors can be used. The undisturbed wind sectors of the different N80 locations can be found in /14/.

6.4 Results of the measurements

A detailed report is written for the data analysis of the measurements /15/. In the current report, only a brief summary of the results are included. WTG refer to wind turbine generator in this chapter.

6.4.1 WTG N7 Power

The power ratios pre-upgrade and post-upgrade are shown in Figure 6-7 and Figure 6-8. The quadratic fit gives much more confidence in the mean than the histogram, due to the extra information encoded in the assumption of a quadratic relationship. Nevertheless, due to the divergences between histogram and best fit line, results at the lowest and highest wind speeds are best obtained by using the histogram.

Figure 6-9 gives the final results. At lower wind speeds, no significant efficiency increase is found, however, by 8 m/s an increase of 5-12% is seen.

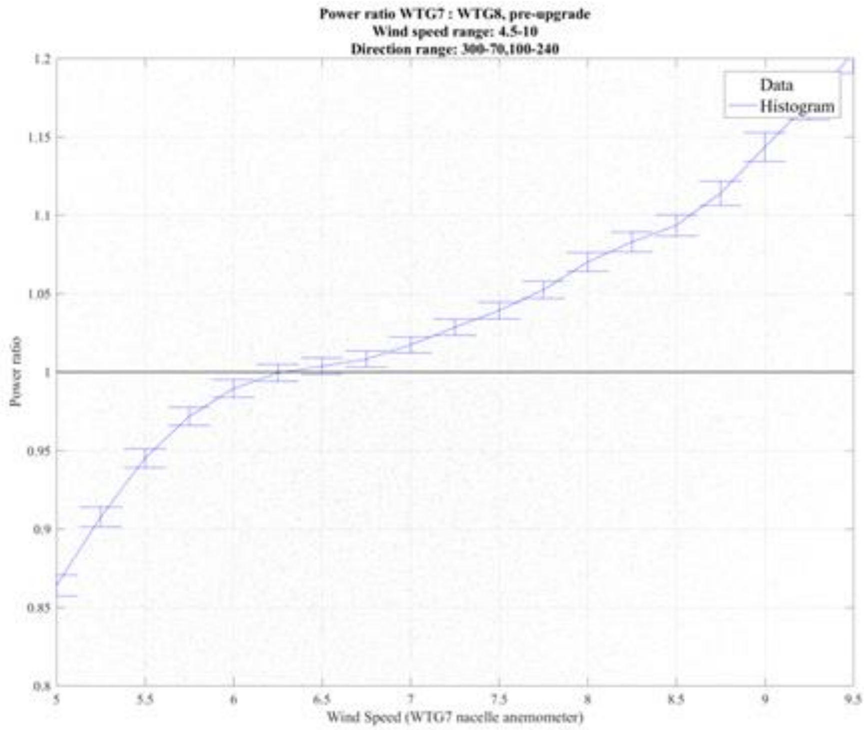


Figure 6-7: WTG N7 : WTG N8 power ratio, pre-upgrade. It gives a local-fit histogram on which the final results are based

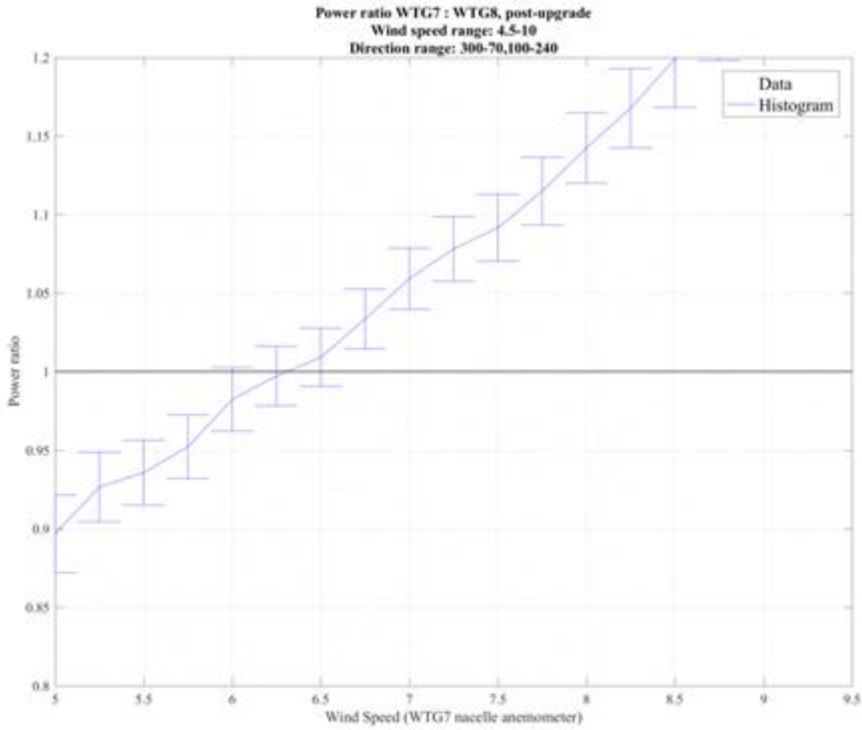


Figure 6-8: WTG N7 : WTG N8 power ratio, post-upgrade. It gives a local-fit histogram on which the final results are based

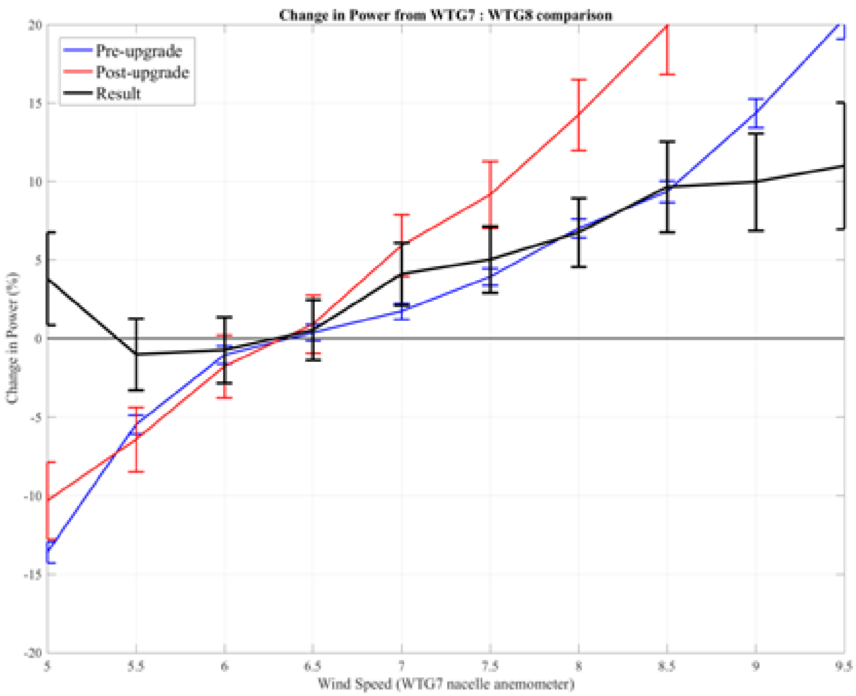


Figure 6-9: WTG N7 efficiency increase due to the upgrade

Figure 10 demonstrates (using the same method as for the power output) that the rotor speed increased by approximately 1-2% post-upgrade. This is expected, since the additional aerodynamic torque is not balanced by the generator torque, since the controller set point was not changed.

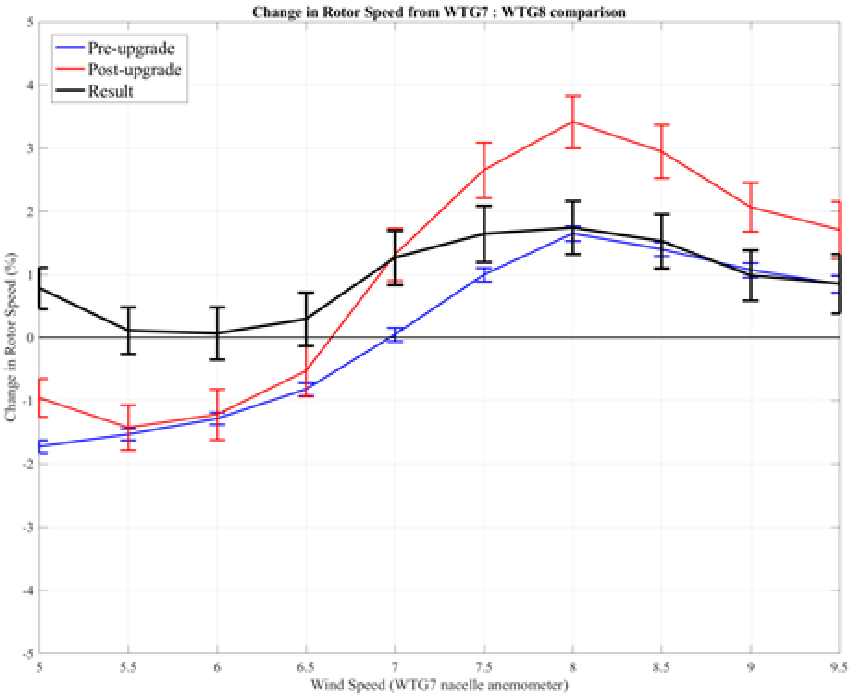


Figure 6-10: WTG N7 rotor speed change due to the upgrade

6.4.2 WTG N7 Predictions compared with measurements

The increase in power shown in Figure 6-9 is reproduced in Figure 6-11 and compared to the predictions. The blue line shows the lifting line predicted power change due to the new conventional tip addition. These results are coming from the analysis that are performed in the beginning of the project. In addition to this, the lowest pink dashed line shows the maximum theoretical increase that is expected to come from using a longer blade. In other words, the difference between the red line and the blue line is the actual benefit coming from having a different tip shape.

The slightly higher pink dot-dashed line shows the increase that is expected due to the blade repair and the blade length extension. During the installations of the conventional tip, significant damage was seen on one of the blades of N7. This means N7 power performance during the pre-campaign phase was somewhat reduced.

In order to get an idea of how much of the power increase should be expected from the blade fix, some analysis are performed with the lifting line code. The last 50cm of the blade is modified by applying a “bad” airfoil there. The “bad” airfoil has around 60% less efficiency compared to the original. A comparison is shown in Figure 6-12. The analyses are performed by assuming all three blades were damaged instead of only one. Although this is not a good representation of reality, the results are put in this comparison in order to get an idea about the order of magnitude of such an effect.

In summary, the increase in power performance in the measurements is clear and more than 4% which is purely from having a longer blade. The actual benefit of having a different blade tip is in the order of 2-9% for wind speeds above 8.0 m/s.

Predictions should be reproduced by using exactly the same operating conditions (measured rpm, pitch, actual Re numbers, surface condition etc.) in order to validate the analysis results properly.

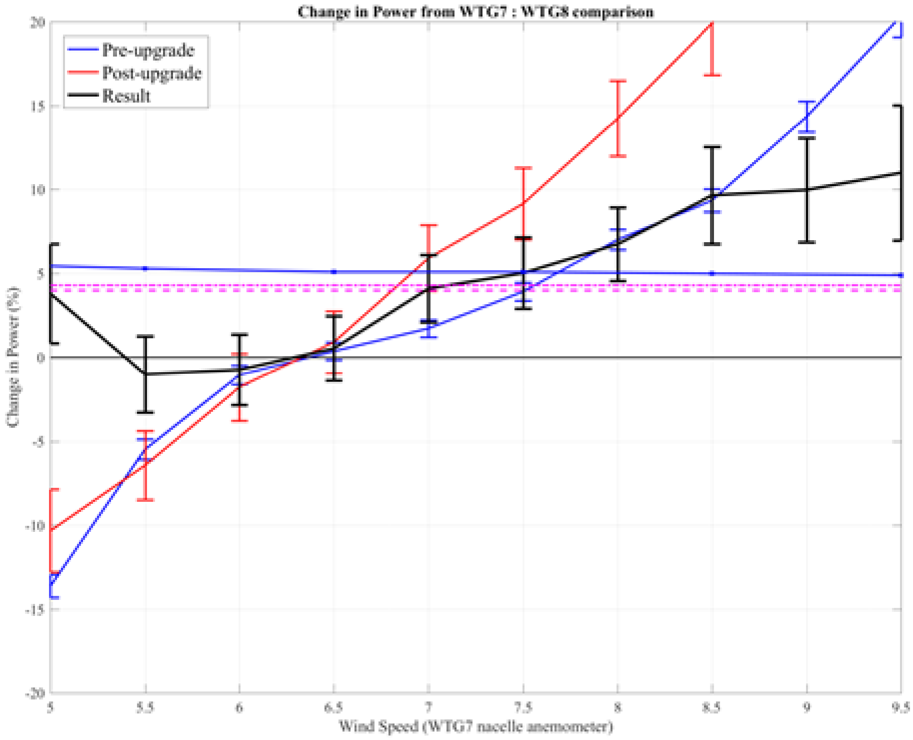


Figure 6-11: Expected power increase compared with measurements, using the data from Figure 6-9

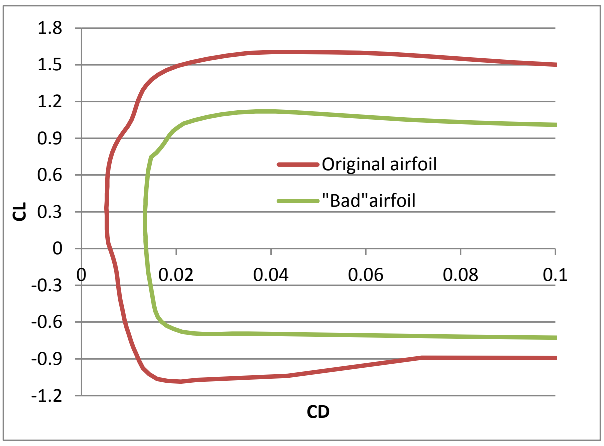


Figure 6-12: Tip airfoil modification to represent the damaged blade

6.4.3 WTG N6 Power

The power ratios between WTG N5, WTG N6 and WTG N8 are shown in Figure 6-13, Figure 6-14, Figure 6-15 and Figure 6-16. The resulting derived variation in WTG N6 is shown in Figure 6-17.

Despite the surprisingly generous amount of data collected post-upgrade when N6 is in the wake of N5, there is so much scatter that no significant change in power performance can be detected.

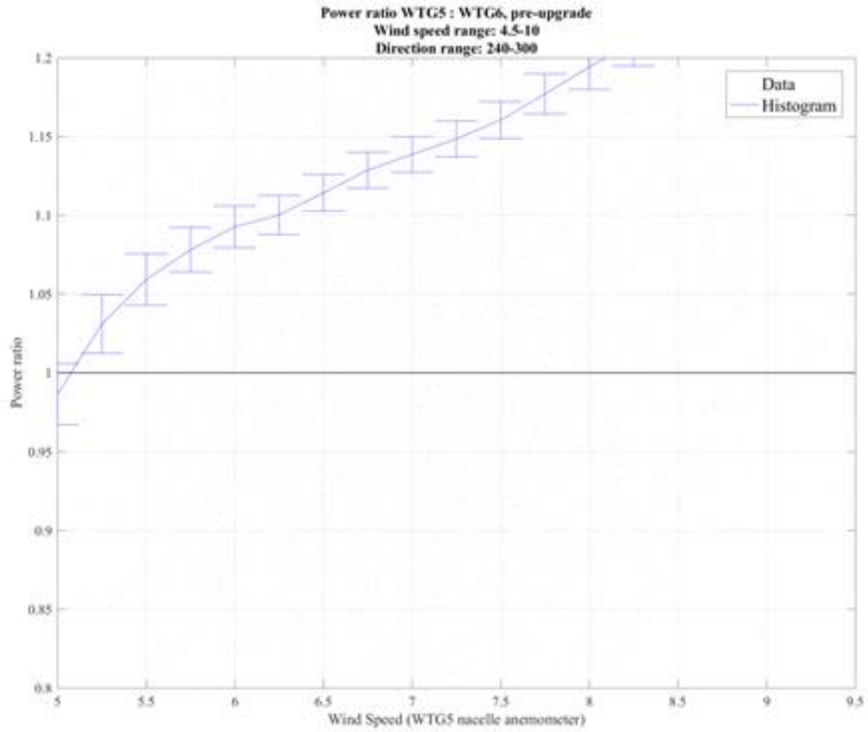


Figure 6-13: WTG N5: WTG N6 power ratio, pre-upgrade. It gives a local-fit histogram on which the final results are based

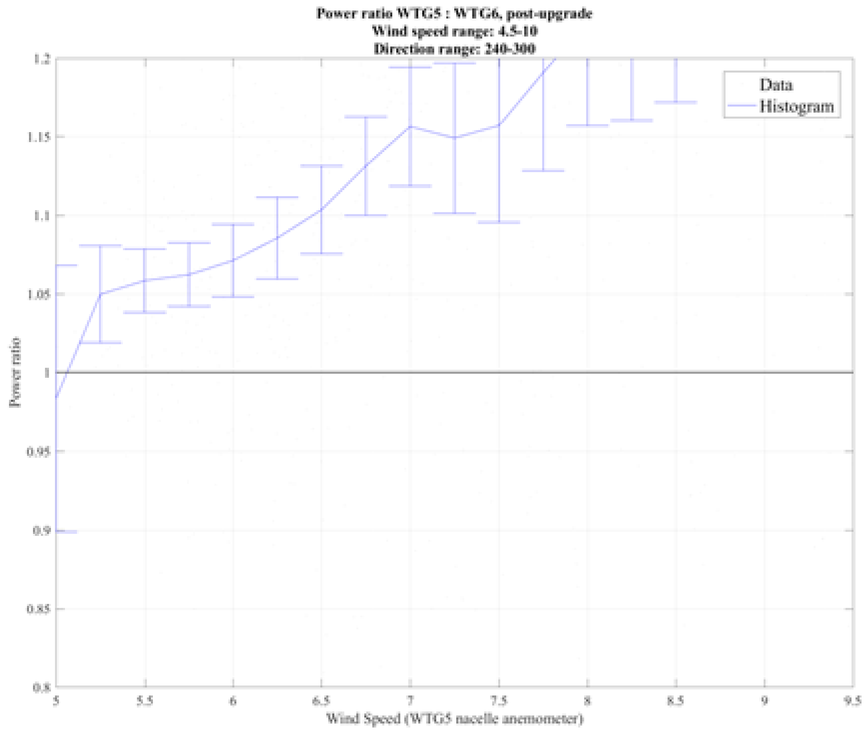


Figure 6-14: WTG N5: WTG N6 power ratio, post-upgrade. It gives a local-fit histogram on which the final results are based

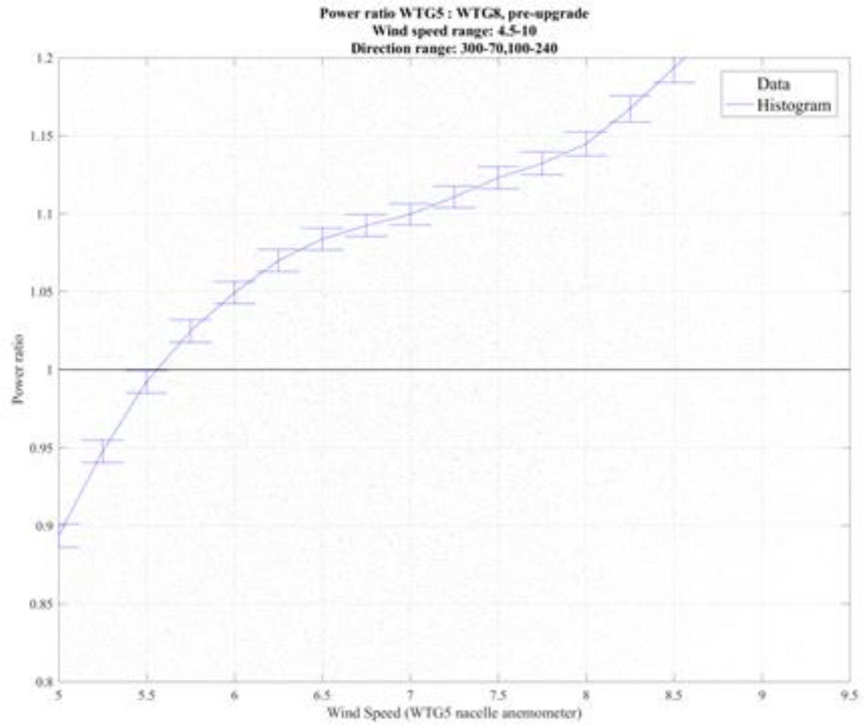


Figure 6-15: WTG N5: WTG N8 power ratio, pre-upgrade. It gives a local-fit histogram on which the final results are based

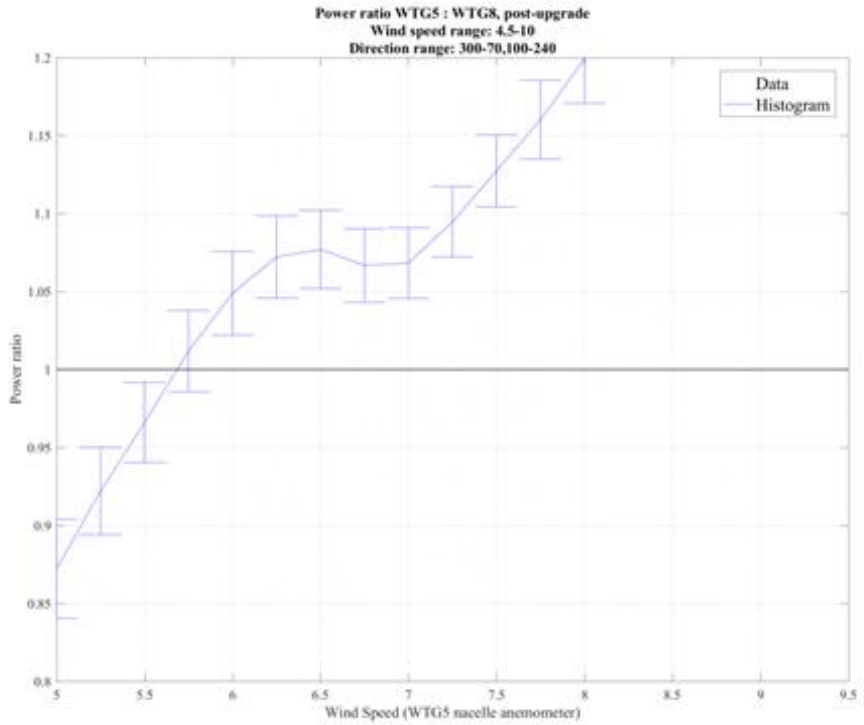


Figure 6-16: WTG N5: WTG N8 power ratio, post-upgrade. It gives a local-fit histogram on which the final results are based

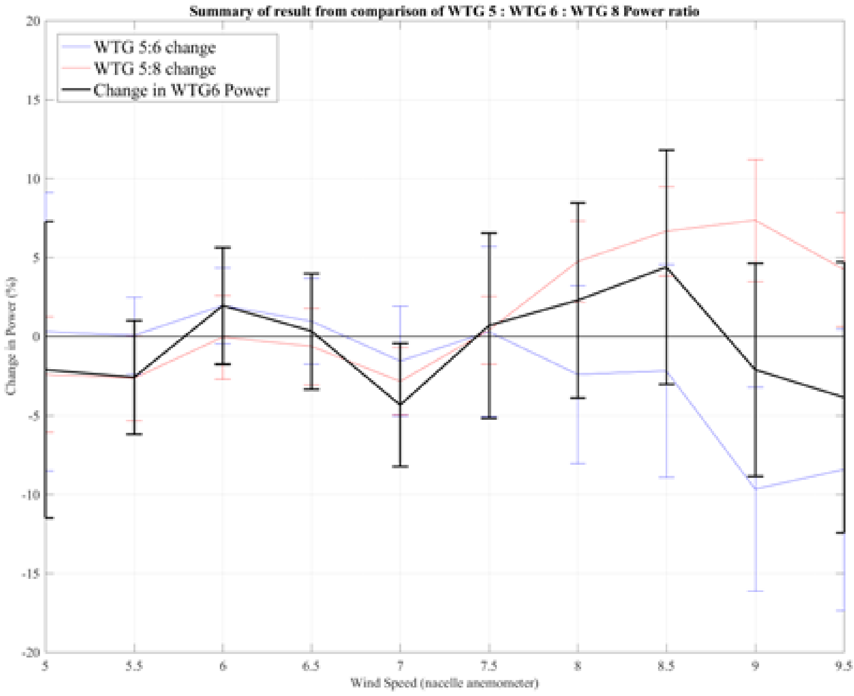


Figure 6-17: WTG N6 efficiency increase due to the turbulator installation

The ratio of WTG N5:WTG N8 (see Figure 6-15 and Figure 6-16) is now analysed in the same way as for WTG N7 to determine the change to this turbine's output caused by the addition of turbulators. As can be seen from Figure 6-18, above 8.0 m/s, a power increase of 2–10% could be claimed.

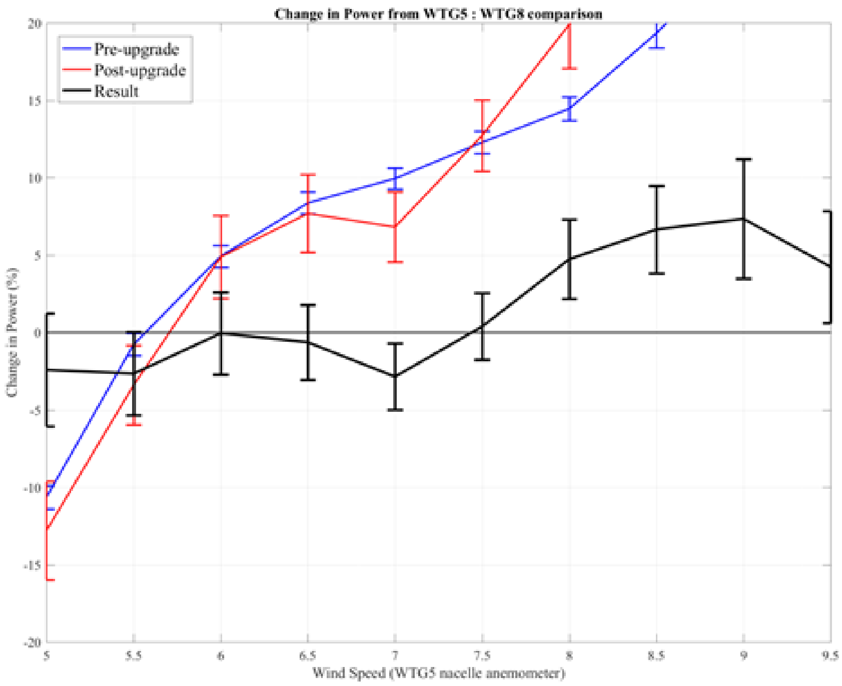


Figure 6-18: WTG N5 efficiency increase due to the turbulator installation

7.0 Evaluation of the Concepts

In this work package, the evaluation of the tip concepts investigated during the project are evaluated. The evaluations are done based on the wind farm case studies and the wind turbine concepts used in the Hyller Project /1/. In this project, Task 8.1 is about the wind farm optimization taking into account the varying rotor diameters where several rotor diameter increase in a wind farm is analysed using FarmFlow tool /1/ in order to take into account the wake effects. Together with the change in the rotor sizes, the distance between the turbines have an influence in the wake effects as well. Therefore, these simulations are performed for varying distance between the turbines in the same wind farm layout. The results of these investigations are used in Innotip Project in order to evaluate the effect of the tips on the overall wind farm operations.

7.1 Methodology and assumptions

In Hyller project, a 5MW offshore wind turbine with 126m diameter rotor size is used as reference. The rotor size is enlarged to 130, 135, 140, 146m and their effects in power, thrust and the annual energy production is calculated for a Weibull distribution shown in Figure 7-1. This Weibull distribution is a typical for the offshore wind class.

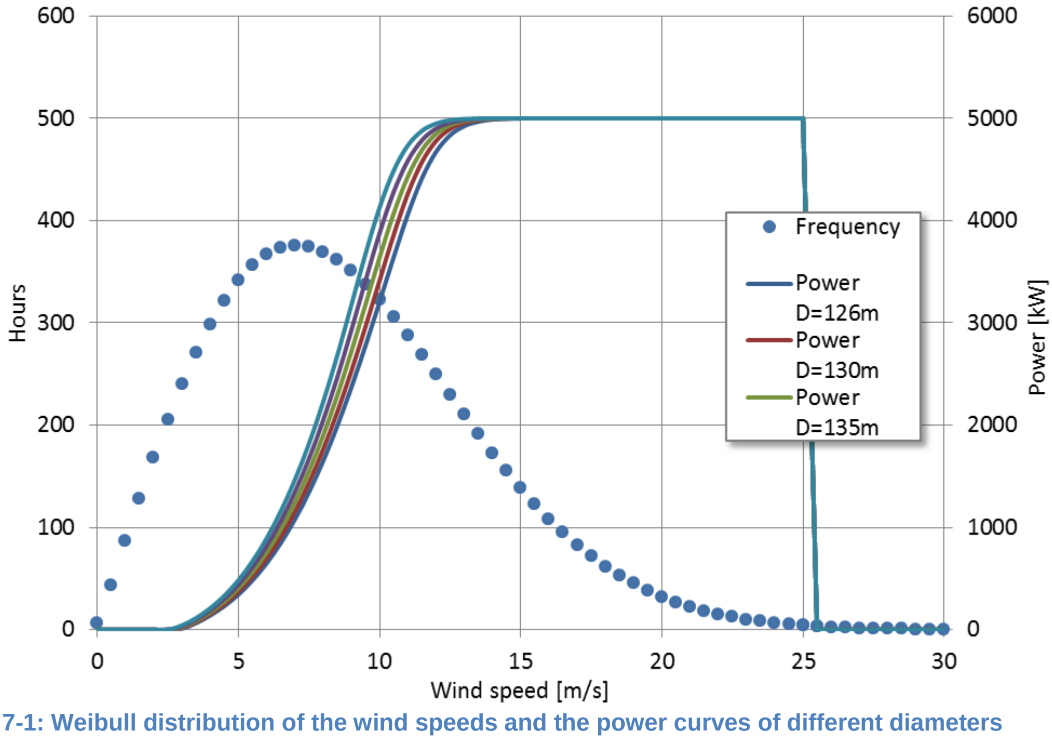


Figure 7-1: Weibull distribution of the wind speeds and the power curves of different diameters

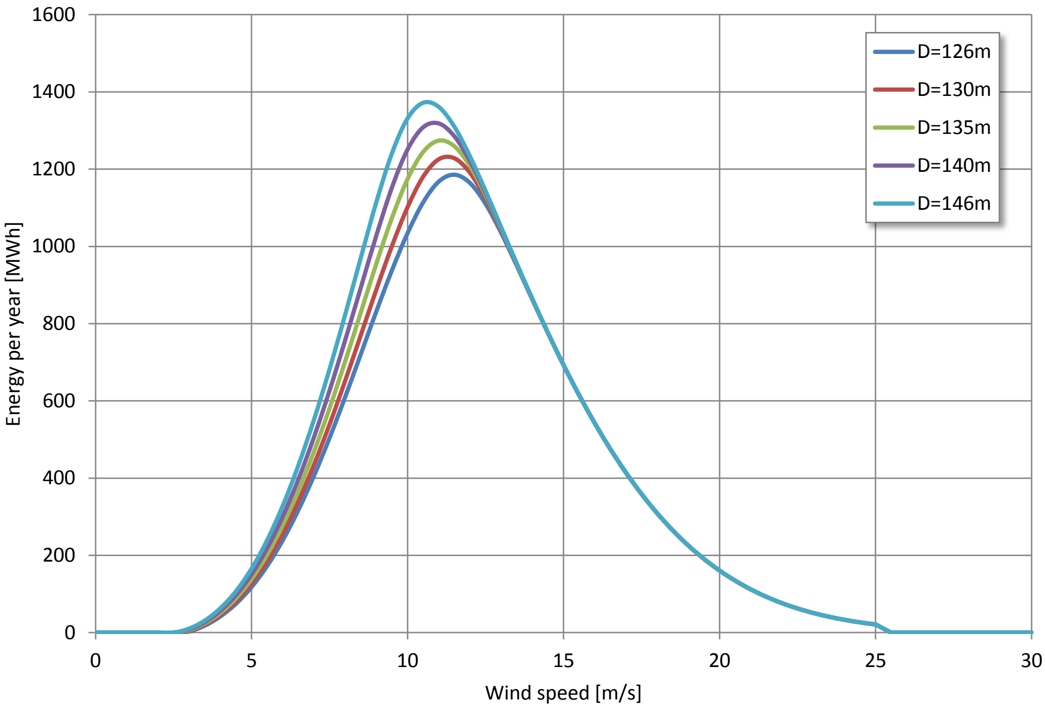


Figure 7-2: Energy per year for different diameter rotors for the given wind probability distribution

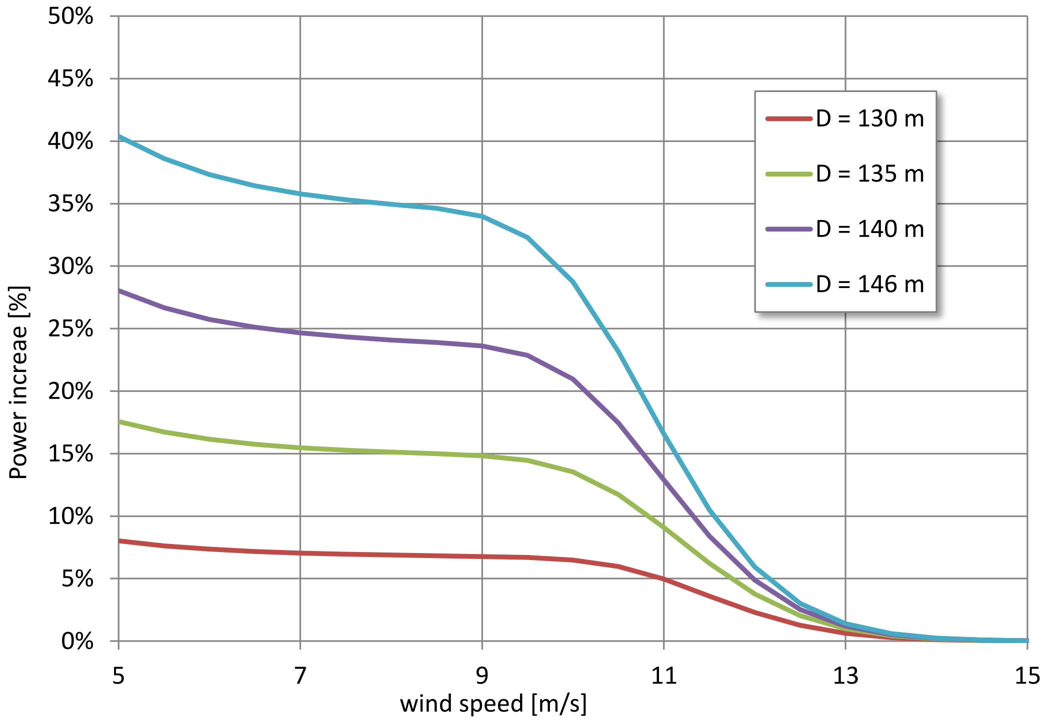


Figure 7-3: Power increase percentages with respect to the reference 5MW machine (126m diameter)

The tip concept which gave the highest gain as a result of the experiments and calculations is considered first. According to the results, conventional tip concept showed the largest gain in terms of power increase. In order to extrapolate this gain in the power of a 2.5MW machine to a 5MW reference turbine used in /1/, the following assumptions are made:

- The gain in power by adding new tips to a 2.5MW are assumed to be equal also in 5MW offshore turbine.
- The new tips are considered to be added as a blade retrofit: This is one of the limiting factors of the potential gain of the new tips in the Innotip Project. Figure 4-6 shows a comparison of the gain in power coming from the new tip before and after the additional design constraints introduced. There is around 35% reduction in the gain because of the constraints in this condition. Therefore the results used in this task is showing only the limited benefits of the new tips; not the total benefits. On the other hand, with this assumption, the results of the wind farm evaluation will stay in the conservative side.
- The measured power increase with the new tips is not constant; see Figure 7-4. Although the maximum increase measured is around 9% for higher wind speeds, for this analysis, it is assumed to be comparable with the increase shown in Figure 7-3 with D=130m which is around 7%. It is also assumed that the reduction from 9% to 7% compensates the limited power increase measured in low wind speeds for the conventional tip concept.

The actual diameter increase of the tested N80 machine was from 80m to 81.6 meters which is 2% increase in diameter. On the other hand, 130m diameter is 3% increase to 126m diameter turbine. According to the third assumption above, the measured effect of the Innotip conventional tip concept in terms of power increase is represented with an additional 1% diameter increase in this study.

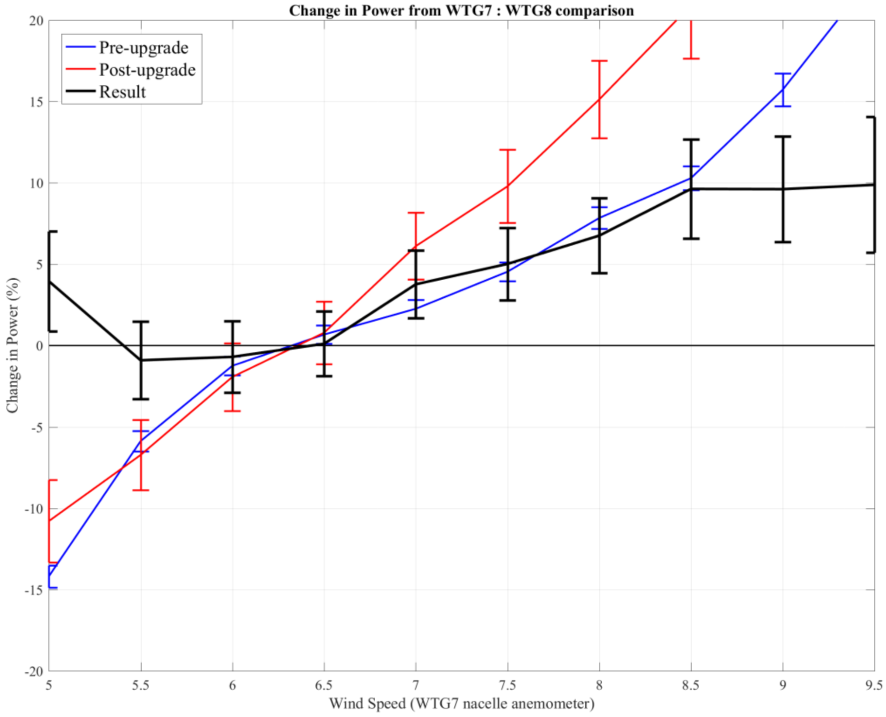


Figure 7-4: Measured power increase of conventional tip versus wind speed is shown by black line

7.2 Results

The change in the rotor diameter of the reference wind turbine rotor and the corresponding annual energy production change with respect to the reference is given in Figure 7-5. The 130m diameter which corresponds to Innotip conventional tip concept increased the annual energy production more than 3%.

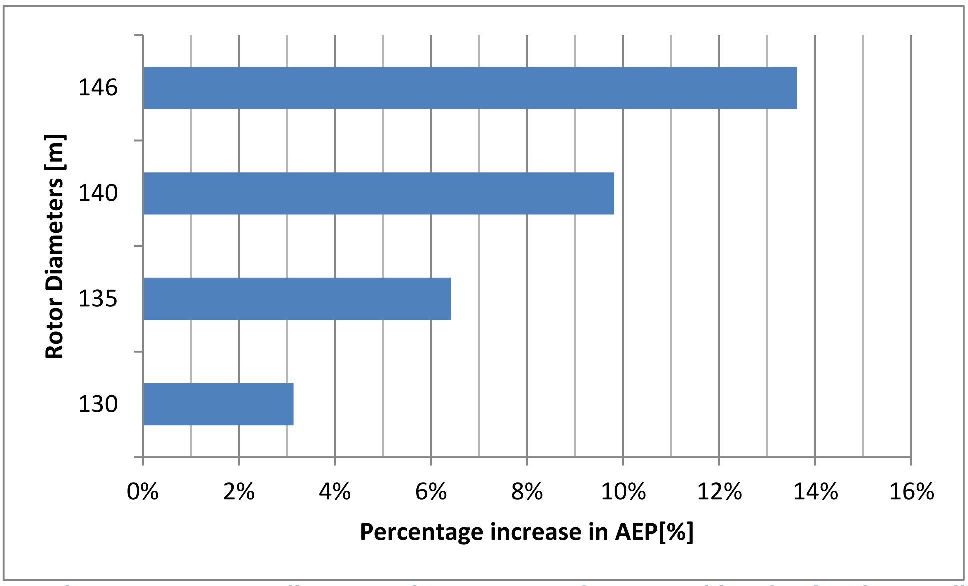


Figure 7-5: AEP increase wrt 126m diameter reference rotor of 5MW machine, for the given Weibull distribution

Calculated increase in AEP is only true for a stand-alone machine. In the wind farm, the wake effects should also be taken into account to obtain a more realistic potential of the tip concepts. In order to do this, a reference wind farm is used with the layout shown in Figure 7-6 consist of 80 wind turbines of 5MW with the equal spacing of *S*. The spacing between the turbines is changed to find the most suitable spacing for the concepts. Farmflow analysis are performed for this layout for the wind climate in Figure 7-1 with a turbulence intensity of 6% which is a common value for offshore applications and the computations are done for every 5 degrees of wind direction. The results are given in terms of column averages for the wind directions between 220-270 degrees. Due to the symmetry, these results are identical for the sector of 270-330. As a result, these analyses are valid for entire westerly wind directions and comparing results for this sector gives a clear view of how the turbines will act on the wind farm environment.

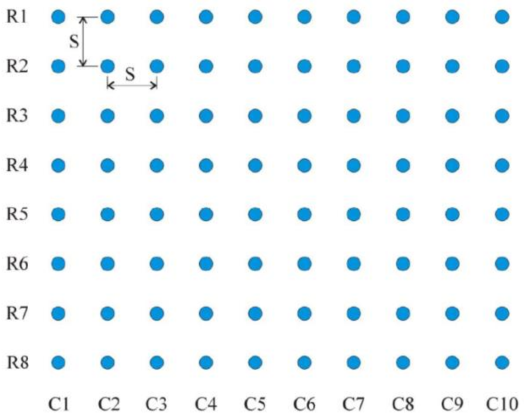


Figure 7-6: Reference wind farm layout used in the evaluations

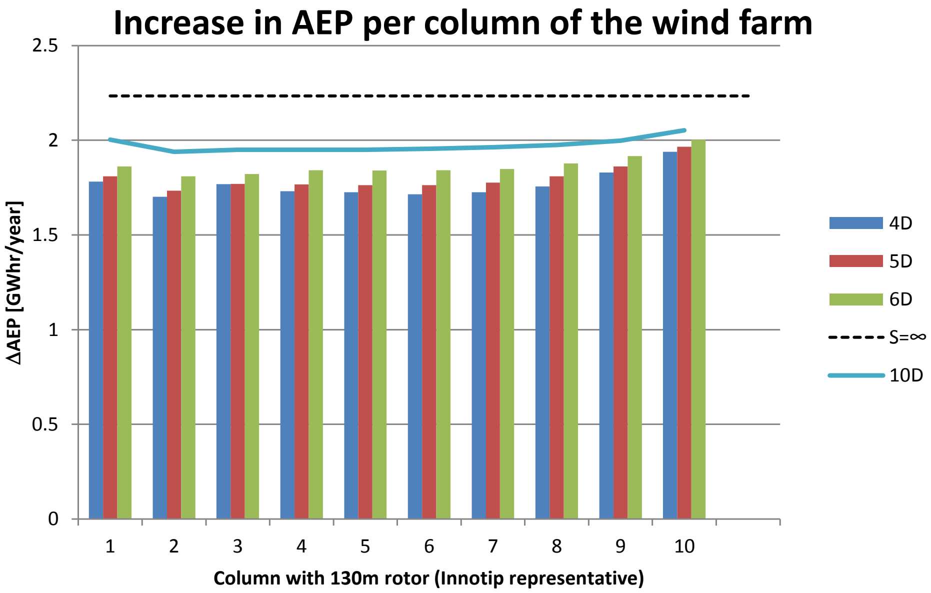


Figure 7-7: AEP increase with Innotip concept in the wind farm

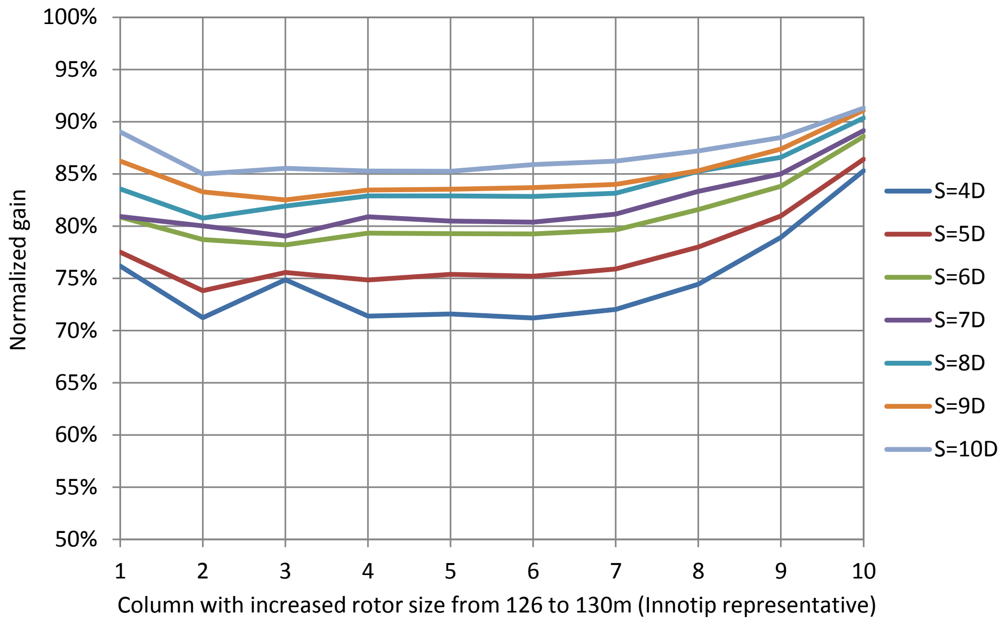


Figure 7-8: Normalized gains going from no shown for the column of the wind turbines, western quadrant only

In Figure 7-7, increase in AEP per column is given for different "S" spacing between the turbines. The maximum possible increase is indicated with black dash lines and the blue line represents the increase with a spacing of 10D. As can be seen in this figure, the potential of the power output of the turbines are limited in the wind farm environment. More spacing between the turbines are advisable in order to reduce the wake effects, and realize the outmost benefit of using Innotip tip concept. Figure 7-8 shows the normalized gain on different columns for the same condition. The normalization is done with respect to the S=infinity which means no wake losses.

7.3 Discussions and Conclusions

The potential of power increase from three tips are calculated and two of them are demonstrated in the field. The extrapolation of the field test results to a 5MW offshore wind turbine shows more than 3% increase in annual energy production for a standalone machine equipped with Innotip conventional tip. The Innotip conventional tip gives a benefit of an additional 1% tip extension of a classical blade tip which reduces the costs of such an application and limits the added loads. Moreover, the wake effects will be less with the addition of Innotip conventional tip because it is shorter and therefore the actual benefit in the wind farm environment is higher compared to classical blade tip extensions. Due to the scatter in the data collected during the turbulator tip experiments, the actual potential on the next turbine is not yet demonstrated. However, it is demonstrated that the turbulator concept can bring additional potential of 2 to 10 percent power increase on the turbine it is applied. As a result, it is advisable to apply both tips at the same time in order to enhance the power output further; without changing the rotor area.

All these improvements are realized by the results obtained with the assumption that these tips are added to existing blades as blade retro-fit solution. However, when these tip designs are integrated into the blade design process, this potential will be doubled as shown in the earlier analysis. In order to obtain the full potential of the turbulators for the next turbine in the row, longer experiments are required and more configurations are necessary to be tested.

8.0 Conclusions of Innotip Project with Life Cycle Cost Analysis

In this final chapter of the report, overall conclusions of the Innotip Project is summarized by analysing the life cycle costs of the tips designed in Innotip Project. A comparison between different tip shapes and their potential in reducing the LCoE is shown. In 8.1, the background explanation on how the costs for different tips are considered is explained. In 8.2, the methodology of the LCOE (levelized cost of energy) calculation is shown and the results are summarized in a table to compare different tips in terms of their potential in LCOE reduction. Some remarks are added in section 8.3 to clarify the applications as retrofitting to both onshore and offshore wind turbines. Finally, in 8.4, the summary of the project is given with the recommendations for the future work.

8.1 Overhead look on the differences in cost for the different geometries

As a detailed analysis of the changes in cost are very uncertain, a more global view on the difference in cost on the applications of the 3 tip shapes is given in the below outline. Note that the description for turbulators is divided into 2 shapes; 1 where the turbulators are applied like in the field test (as serration type add-ons) and 1 where the intended shape (a wavy surface and trailing edge) is being used.

From a global perspective it can be expected that the cost for manufacturing new blades with the new tip geometry integrated will change. It should be noted that the below description is based on the presumption that the blades will be equipped with the new tips (integrated) from production and that this will not be a retrofit solution (as done in the field test) and as such does not incorporate an increase in blade length.

The description will be based on different posts from which production cost will be the main contributor as this will be on each produced blade. Design will be on the level of blade type and will therefore have a much lower influence. Note though that after 1 blade type design optimization is done, the tip might become a default tip which will reduce optimization cost on all following blade types, making the design a 1 time expense. Remainder of the overhead posts (e.g. sale, transportation etc.) is presumed to be unchanged compared to current practice.

<u>Winglet:</u>
Production: The winglet will require a special mould and production techniques if it is directly to be integrated in the blade product. This will require new lay-up as well as infusion techniques. Alternately the production could be done by manufacturing the tips separately and mount them afterwards to the remainder of the blade. This is done by some manufacturers already. Either way, the production cost will be higher when applying a winglet, mainly due to the increased complexity.

Design: the design of the winglet will have several additional parameters compared to a standard blade tip. Optimization will be more time consuming and both conceptual and structural design as well as testing and validation will require more input. The design will therefore probably slightly increase in cost.

<u>Conventional Tip:</u>
Production: There will not be a very large difference in cost for integrating the new conventional tip shape in a mould. Also, the production techniques used currently do not have to be altered significantly to have the conventional tip shape produced. As such, the estimate is that there will not be any additional cost by changing to the conventional tip shape.

Design: The conventional tip will not differ too much from current practices although having a straight trailing edge fixes 1 parameter which was optimizable in the past. As such the cost for design might be slightly reduced.

Turbulators (add-ons):
Production: The production of these add-ons is rather well known. Depending on the optimum size, the cost of producing and attaching these add-ons is very low compared to total blade production cost. The blade geometry itself will not change. As such a very small increase in total production cost is expected.

Design: Turbulators as add-ons can have a completely separate design flow. Like serrations, default set-up could be made to fit similar turbines. The design will only be done in an initial stage and commercialized. There would be a continuous improvement involved in this type of add-ons. The cost of the blade design itself will not alter but total cost (blade with turbulators) will increase.

Turbulators (Wavy Surface):
Production: Like the winglet, the wavy shape turbulators (as they have been suggested originally) will require a special mould and production techniques. There will be many technical challenges to implement this, and likely more material will be needed to keep the structural strength of the blade. Several solutions could be thought of, but in any case the mould and production time will increase. As such the production cost will very likely increase.

Design: As turbulators are affecting the flow, the current knowledge of their optimum shape is not very well known. As such optimization for each blade type will take long and as a concept, it will require more structural design hours. On the design phase, the turbulators as wavy surfaces and trailing edges will very likely be the concept with most cost increase.

8.2 Reduction in Levelized Cost of Energy

The Levelized Cost of Energy (LCoE) is defined as the ratio of total energy cost with energy production:

$$LCoE = \frac{Total\ Cost\ over\ Lifetime}{Electricity\ Produced\ over\ Lifetime}$$

The 2 main contributions to cost of energy are the blade cost and gain of the turbine. As such, the gain in Annual Energy Production (AEP) should be worth the increased cost of the altered tip shape.

A 2013 study /17/ shows that the LCoE of offshore wind is not yet competitive to other established energy sources, but as prices are decreasing and gains are increasing the offshore wind energy market is getting more competitive.

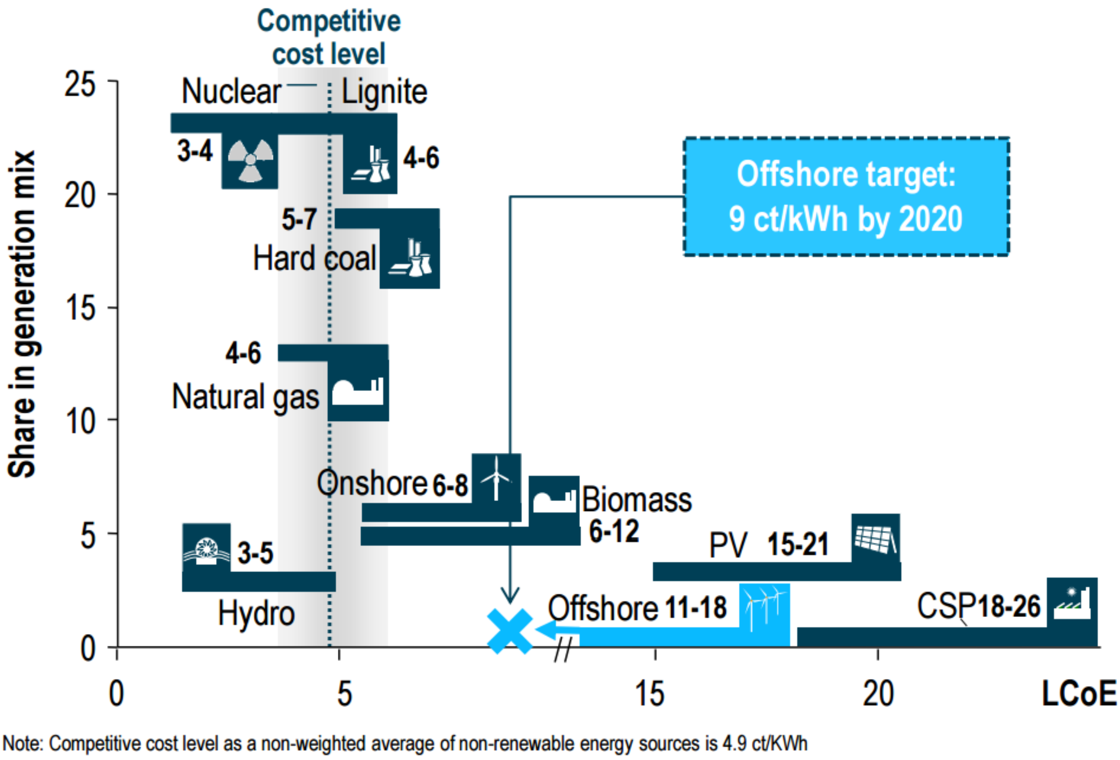


Figure 8-1: LCoE 2012 in Europe in €ct/kWh (from /17/)

From the same source the cost breakdown shows that around 25% of the overall lifecycle cost is due to the turbine (see Figure 8-2). While Figure 8-3 (from /18/) shows that around 22% of the WTG cost is due to the blades.

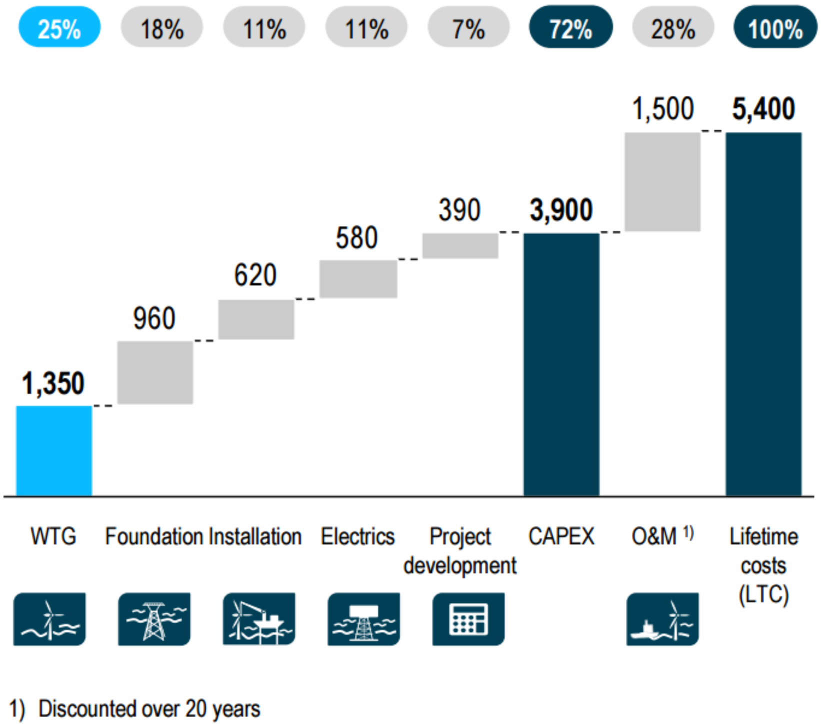


Figure 8-2: Cost Structure of Wind Farm Lifetime in k€/MW (from /17/)

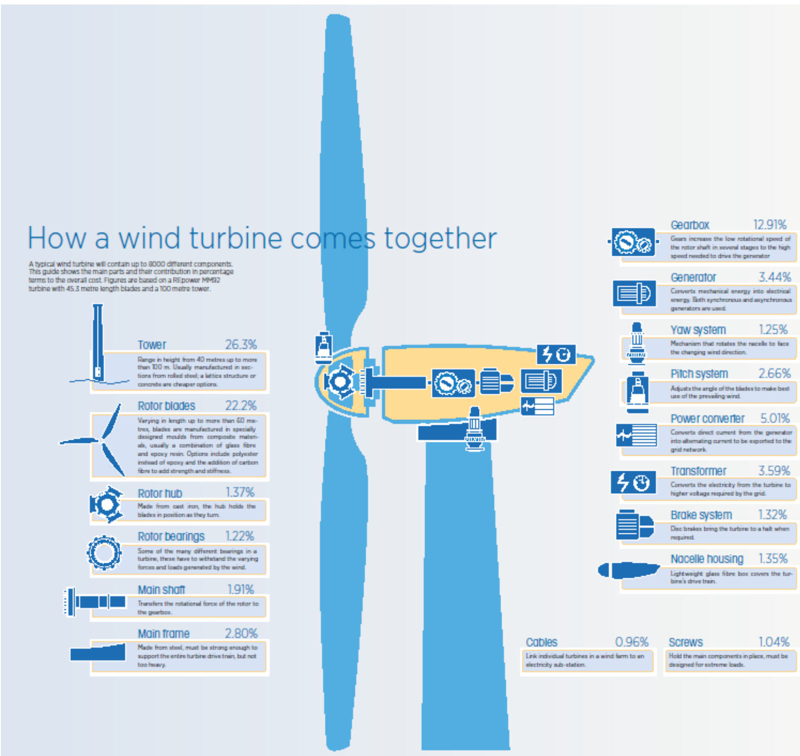


Figure 8-3: Cost Breakdown of a typical wind turbine (from /18/)

Taking the before mentioned numbers, it can be calculated that typically the turbine blades costs are 5.5% of the overall turbine lifetime cost. Using the presented results from previous chapters and the cost percentage above the estimated LCoE reductions can be calculated as presented in Table 8-1.

	Conventional	Winglet	Turbulator Add-On	Turbulator Wavy Surface
Turbine AEP Increase	1.0%	0.57%[1]	1.0%	1.0%
Relative Blade Cost	5.5%			
Blade Cost Increase[2]	0.1%	1.5%	0.1%	2.0%
Relative Blade Cost Increase	0.0055%	0.0825%	0.0055%	0.11%
LCoE Reduction	1.0%	0.49%	1.0%	0.89%

1. Winglet AEP increase is based on difference from CFD and results from paragraph 7.3
2. Blade cost increase is estimated based on complexity of the shape compared to current practices

Table 8-1: Estimated LCoE Reduction of the 4 tips

With these numbers it should be noted that the assumption is made that the only cost increase is in the blades. From Table 8-1 it can be seen that the increase in cost on blade part has very little effect on the LCoE. This is due to the blades being a small amount of the overall turbine lifetime cost. In contrary, the increase in power of the blades shows directly in the LCoE. As such uncertainties on the power increase are about 18 times more visible in the LCoE than uncertainties in the blades cost increase.

8.3 Short note on Retrofitting

A short note given on using the methodologies developed in the InnoTIP project to implement these geometry changes as retrofits. It should be noted that for onshore turbines this retrofit could definitely pay off in case a blade has enough structural reserve available from design. However the cost made in the project has to be extended to offshore turbines (as this is the aim of the InnoTIP project). Some notes to be made are summarized as bullet points below:

- The installation has to be done from a platform as rope access at this point in time is not capable of doing such installation, especially offshore where positioning line can't be fixed into any on ground point. Problem here is that there are limited platform designs available that can handle this type of installation offshore.
- Looking at the general cost related to waiting time while working offshore, proportion is 60% to 30% in onshore.
- The working hours will increase as in general, while working offshore, a typical working day is much shorter. This as transfer to and from the turbine usually takes much longer than for onshore.
- Preparation may take longer as platform would have to be assembled and disassembled each day which is always more time consuming than in case of ropes.

As a conclusion, retrofitting offshore turbines with completely different tip geometry is currently very expensive and might be difficult to get a business case upon.

Note that the above extension to offshore is not valid for the turbulators as the installation is relatively fast and can be done with rope access. Traveling time will need to increase though.

8.4 Project Summary and Recommendations

The objective of the Innotip project was to reduce the cost of energy by increasing the power output of large offshore wind turbines and offshore wind farms by using innovative blade tip concepts. The goal was to reach up to 6% reduction in LCoE by purely increasing the AEP by improving the blade tip designs where these improvements were to be quantified on 2.5MW wind turbines with field measurements. This 6% LCoE reduction goal includes also the blade length extension, although the goal of the project was the specific tip designs; not the length extension.

Three tip concepts have been designed and evaluated in the project; the conventional tip, winglet and turbulator. For testing, the conventional tip and winglet have been manufactured to be installed on top of the blade tips on the 2.5MW wind turbines in the test field. The turbulators have been glued to the trailing edges of the existing blade tips. Due to the time restrictions of the testing period, the winglet was not installed, therefore only the turbulators and the conventional tips have been tested in the field. The results of the experiment showed 2 to 9% increase in power with the conventional tips and 2 to 10% increase with the turbulators. The results for the turbine in the wake of the turbulators did not show much change due to the lack of data. On the other hand, this power increase coming from the turbulators on the turbine they were installed which was not predicted. For the conventional tips, theoretically, about 4% of the power improvements should come from the fact that the blade length is extended 2%. However, higher than 4% power increase was measured which means the specific tip design contributes to the power increase significantly. Using these results in the cost analysis indicated that the new innovative tips as designed and applied in Innotip project, can reduce the LCoE at least 1% excluding the blade length extension. This is a conservative value and it does not reflect the full potential of the innovative tips due to the design limitations included in the implementation phase coming from the fact that the new tips were applied as retrofit solutions and the tip designs were not integrated in the blade designs. In reality, when the new tip designs are integrated in the actual blade designs, more potential is expected; at least 35% more by looking at the earlier analysis performed in the project.

Innotip project showed that there is significant potential in using different tip concepts for the large blades of the offshore wind turbines. Several recommendations for the further developments and investigations are listed here:

- A fully integrated blade-tip design should be performed and compared with the current design methods to quantify the actual benefits coming from the innovative tips.
- Although more accurate analysis tools are used in the project for the design and for the analysis of the new tips, none of these software tools were able to predict the increase which was measured in the field tests. These tips should be tested in the wind tunnels to investigate the tip vortex and its effects on the power production. The models should be validated with these tests.
- Turbulator concept should be investigated in more detail and different configurations and implementations should be considered such as blade-integrated wavy trailing edge instead of add-on solution.
- Another field test campaign should be realized to explain where exactly the measured power increase is coming from. Beside other aspects, the surface pressure on the blades should be measured and the wake behind the turbine should be characterised during these tests. This is necessary to quantify the effects of the tips on the wind turbines and the turbines next in the row.

- A longer testing period is necessary for the turbulator tip concept so that sufficient data can be collected for the turbine operating in the wake of the turbine with the turbulator tips.
- The potential of the retrofit tip implementations especially on the onshore turbines should be investigated further as power improvements have already been measured on the onshore turbines.
- The combination of the conventional tip and the turbulators should be investigated to find whether it would be possible to combine the benefits coming from both tip shapes or not.
- The LCoE calculations should be updated with the recent developments in the Dutch offshore wind market.

9.0 Bibliography

/1/ Bot, E.T.G., *Effect of varying rotor size in offshore wind farms on AEP*, ECN-X--16-003, January 2016, Petten.

/2/ *Focus version 6.39427.1*, Knowledge Centre WMC, Wieringerwerf, The Netherlands

/3/ Herman, K.W.; Orsi, L.M.; Ceyhan, O., *LM38.8 tip extension analysis*, ECN-X-16-058, Petten, May 2016

/4/ Bot, E.T.G.; Ceyhan, O., *Blade Optimisation tool user manual*, ECN-E-09-092, Petten, the Netherlands

/5/ A. van Garrel, *Development of a wind turbine aerodynamics simulation module*, Technical Report ECN-C-03-079, ECN, 2003

/6/ K. Boorsma, F. Grasso, J.G. Holierhoek, *Enhanced approach for simulation of rotor aerodynamic loads*, Technical Report ECN-M--12-003, ECN, 2011

/7/ Ramanujan G., Ozdemir H., Hoeijmakers H.W.M, *Improving airfoil drag prediction*, ECN-M--16-022, 2016, Petten, NL.

/8/ Ramanujan G., Ozdemir H., *Improving airfoil lift prediction*, AIAA-2017-1999, AIAA Scitech 35th Wind Energy Symposium, 9-13 January 2017, Texas, USA.

/9/ Lindenburg C., Holierhoek J.G., *Blademode User Manual*, ECN-C-02-050_r08, Petten, the Netherlands

/10/ Olle N., http://www.the-numerical-wind-tunnel.dtu.dk/EllipSys, March 25th 2015, consulted March 2017.

/11/ *Conventional & Winglet Installation and Dismantling*, LM38.8P Service Instruction. May 2016, SI-00372/A1.

/12/ Hermans, K.W. and Orsi, L.M., *LM 38.8 Tip Extension Analysis*. ECN-X—16-058, ECN, May 2016.

/13/ IEC 61400-23, *Wind Turbines – Part 23: Full-scale structural testing of rotor blades*.

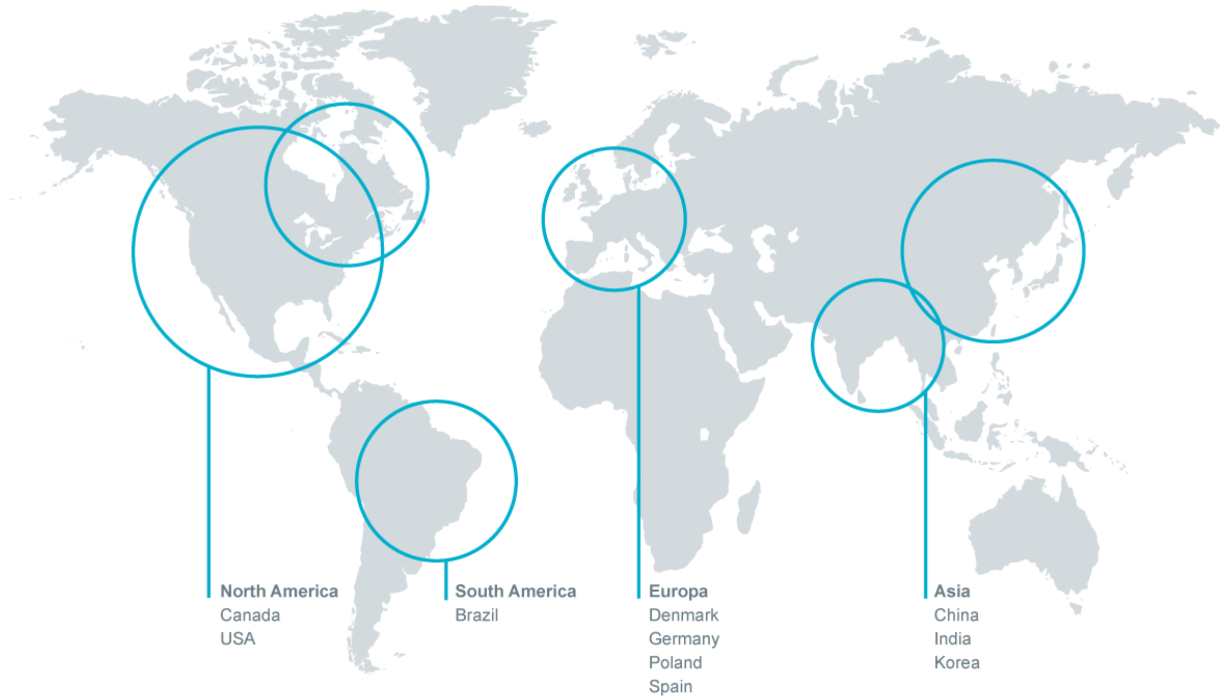
/14/ Bergman G., *Innotip instrumentation report*, ECN-X--16-179, Petten, December 2016.

/15/ Stock-Williams C., Ceyhan Yilmaz O., *Analysis of the tip effects as measured during Innotip tests*, ECN-X--16-180, Petten, December 2016.

/16/ Bot, E.T.G, *Farmflow validation against full scale wind farms*, ECN-E--15-045, August 2015, Petten.

/17/ Roland Berger, *Offshore wind toward 2020; on the pathway to cost competitiveness*, 2013

/18/ IRENA International Renewable Energy Agency, *Renewable Energy Technologies: Cost Analysis Series Volume 1: Power Sector – Wind Power*, June 2012



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