HALIADE-X

OFFSHORE WIND PROTOTYPE DEMONSTRATION

PUBLIC SUMMARY REPORT

Index

0. EXECUTIVE SUMMARY

The initial scope of work was the demonstration of a 12 MW Haliade-X offshore wind turbine in Rotterdam during the period November 2018 to October 2021. The focus of the Project was the construction and installation of a demonstration plant of one turbine being the world largest offshore wind turbine Haliade X-12MW aimed at reducing significantly offshore wind LCOE. This is done by executing and validating ground-breaking aerodynamic and wind turbine models, and significantly reducing the cost for balance of plant investment.

The project was accomplished by demonstrating the following technologies:

- Direct Drive Train Technology with Permanent Magnet Generator.

- First of a Kind power curve validation of largest ever rotor diameter

- 220 rotor diameter equipped with 107m fully instrumented hybrid carbon blades through advanced system health monitoring systems by integration of advanced sensors systems

- Advanced simulation for wind farm serviceability and transport and installation case scenarios.

- Blade twist measurement.

- Flexibility to optimize performance and loads for site conditions.

Finally, the project achieved the certification, going above 12 MW initial objective. It was possible to certify the Hal-X technology up to 13.6 MW.

This project was executed with support from the Renewable Energy Transition (HER) subsidy from the Ministry of Economic Affairs and Climate.

1 PROJECT DETAILS

Project number:	The project is known to the Netherlands Enterprise Agency under reference number TEHE118004.
Project title:	The project title is “Demonstrator GE Haliade X - 12 MW offshore wind turbine”.
Coordinator and co-applicants:	The coordinator is GE Renewable Holding BV, and the 2 other applications are LM Wind Power R&D B.V. and Netherlands Organization for Applied Scientific Research (TNO).
Project period:	The project period was from 01/11/2018 to 31/10/2021.

2 FINAL REPORT ON THE CONTENT OF THE REPORT

2.1 Introduction

Reducing the costs of offshore wind energy

The ambitious of the project back in Mid 2018 was to demonstrate at full scale the largest rotor diameter for Offshore Wind Industry with a critical impact on AEP, capacity factor compared to other conventional energy production

The Project focused on technology demonstration in the Netherlands of the largest offshore wind turbine in the world: GE's Haliade X-12MW. Equipped with a 220m rotor diameter, the Haliade-X is designed to have an industry leading capacity factor of 63%+. Other product features are a gross AEP of around 67 GWh, a wind class of IEC Class IB, for a 25-year's design life, for certification by the 2nd half of 2020. The innovations and technology were thoroughly tested to secure functional reliability.

GE's Haliade X-12MW core technologies relevant for the Project were the following:
- Direct Drive Train Technology with Permanent Magnet Generator
- Up-tower electrical system
- Electrical Output: 66 kV
- Fault Tolerant Design
- WindSCADA & WindCONTROL
- Digital Wind Farm with GE's Predix Platform
- Carbon based blade design
- Design based on leveraging 30,000+ installed base experience (Onshore & Offshore)
- Flexibility to optimize performance and loads for site conditions

The project empowered a Dutch Offshore Wind Value Chain to impact noticeably LCOE.

Strengthening Dutch industry
In supporting the project, The TKI program enabled a unique Dutch Offshore Wind Cluster (GE, LM Wind Power, SIF, TNO, and Dutch stakeholders) and enhanced its ability to collaboratively perform research, development, demonstrate the world largest offshore wind turbine, and allow the development of an R&D ecosystem through this onshore prototype. This falls within the remit of TKI hernieuwbare energie.

Indeed, the project served as an incubator to private-public collaboration including an entire offshore wind segment value chain in the Netherlands. Thus, it contributed to the development of Dutch skills and competitiveness in the industry. The project aimed to create business value for the Dutch partners on the offshore wind projects in the region, with not yet export. In the long term.

Finally, in supporting the consortium with the project TKI enabled the reduction of levelized cost of energy with the involvement of local Dutch companies, accelerating the time to market of the Haliade-X turbine.

2.2 Challenges, Objectives and Expected results

The project anticipated a high contribution to the energy transition cost reduction in the Netherlands, towards zero subsidy scheme through a technology development de-risking of the largest and most efficient offshore wind turbine generation, ahead of Dutch Offshore wind projects.

Challenges
More specifically some of the most important challenges which the project addressed were the following.

1. Ensuring rotor stability whilst securing a large percental increase in AEP through development of an aero-structurally tailored ultra-long blade design without increased loads on the turbine sub-components is a complex trade off. The synergies between GE, LM Wind Power and TNO are critical to achieve this innovative objective.
2. Subsequently, bigger blades are more flexible, with a high grade of carbon we try to overcome this and have a higher stiffness to weight ratio then blades designed before.
3. Haliade X-12MW and its 107m blades bring a specific challenge with respect to serviceability. The solutions which the consortium developed needed to be demonstrated in a cost-effective manner.
4. Installing ultra-long blades in an efficient process, cost effective process considering potential adverse offshore wind conditions are a critical challenge. The project aims to test and demonstrate new installation methods that manage these risks and maximize the installation capabilities at elevated wind speeds with competitive lead times, again decreasing the uncertainties, and associated LCOE.
5. The conventional wind turbine system reliability testing, and commissioning lead time presents an important opportunity to further reduce LCOE. The development and demonstration of digital capabilities (asset performance management, service diagnostics and prognostics software suites.
6. The current drive train design considers components flexibility and size effect in a highly integrated configuration lay out. Assumptions in the calculations have to be thoroughly validated during final engineering and prototype phase and be maximally de-risked before the Haliade-X can enter serial production.
7. Furthermore, the dimensioning scale-up of all components involves certain level of uncertainty that needed manufacturability validation at cost whilst ensuring 25 years lifetime. Also, this is one of the first direct drive turbines with medium voltage architecture, being one the newest in the industry.

Technical objectives

The goal of the project is to validate and demonstrate the Haliade-X with the largest offshore wind rotor diameter (220m) and highest rated power (12MW) in the industry. This includes validation and demonstration of innovations in transport, installation, and serviceability and is planned to lead to a fully type certified technology by end of 2020. Technical objectives of the project:

1. To validate power curve and load validation leading to type certificate.
2. Leading edge protection robust solutions in terms of durability and serviceability.
3. Completed validation of blade bending & torsion plus measurements - follow up on VastBlades.
4. Validated and tested wind turbine control mechanism involving new failure tolerant design.
5. Improved installation and fast commissioning capability methodologies validation for >10MW offshore wind turbines together with large size installation equipment available on-time.
6. Improved O&M procedures including offshore simulations and onshore validation incorporating new technology as Virtual Reality and Augmented Reality, both for training and operational purposes.
7. large towers - dynamic fatigue modelling.
8. Secure 66KV grid solution ahead of serial production and projects in the Netherlands.

Expected results:

1. Certified power curve and load simulation model.
2. Proven wind turbine control mechanism functionality.
3. Demonstrated installation methods for >10MW offshore wind turbines within cost & time targets.
4. O&M procedures validated in the field.
5. large towers - dynamic fatigue results.
6. 66KV grid solution available for offshore wind projects in the Netherlands.

2.3 Method

The scope of work is summarized as follows. The project started in Nov 2018 and was completed in Oct 2021. The key performance indicators (KPI) actuals versus objectives are tracked during the project and integrate the engineering industrial research related to prototype and at wind farm level.

'Project management'
In the project an explicit work package is dedicated to project management and dissemination. This is to have an effective management of the project and steering towards impactful results, as formulated above in section 2.2. Project management is further elaborated in section 3.1.

'Site Engineering studies'
The Haliade-X demonstration project in Rotterdam had the following site-specific characteristics summarized in the table below.

'Delivery of installed 12MW GE Haliade X wind turbine project management'
The project was mainly focussed on the successful execution of the installation of the Haliade-X prototype in Rotterdam as described below.

Wind turbine components validation and delivery

During the duration of the project LM Wind Power was responsible for development and production of LM107.0P blades and its evaluation and further validation. Specific focus points in the project were the blade stiffness, bending stiffness and the torsional stiffness. LM Wind Power coordinated with both TNO and GE Offshore on the instrumentation of these blades and all the accompanying activities that needed to be performed the goal was to deliver the unique solution for the entire offshore wind and is considered a major step for the future of the whole sector, contributing to a development of new, larger blades. The LM 107.0 P is one of the biggest single components ever built, and it broke a previous record of the longest blade held by the 88m component.

In the WP2, LM Wind Power's task was not only delivering a major part of the turbine – 1 rotor set of 3 LM107m blades – but also to validate this important component and obtain necessary certifications. This demonstration included measuring the loads on the turbine, stiffness, torsion, and leading-edge protection.

The blade Bending stiffness validations were done on a blade #1 and blade #2. Both blades did withstand the static tests loads. The validation of the bending stiffness was only based on blade #1 because blade #2 was strongly truncated and its displacements were hard to measure accurately. Blade #1 appeared to behave a little less flexible compared with the model predictions in the order of 5% which is an acceptable small amount. Blade #0001 was truncated to 101m (full length is 107m) and tested on static strength in flap wise and edgewise direction. Blade #0002 was strongly truncated to a length of 69m and was tested on static edgewise loading. In one single case some small damage was detected in blade #0001 and repaired. After repairing, this blade still succeeded to withstand the repeated Min Flap static test load. The differences are within the margins for blade stiffness evaluation, from which one may conclude that the bending stiffness evaluation was successful.

Another point in the Work Package was to develop and test a leading-edge protection for the LM107p. Since wind turbine blades are built to last over 2 decades, and with ever-increasing blade lengths and turbines operating in harsher weather conditions, an innovative leading-edge protection (LEP).

Transport and Installation

The work in these work packages addresses the transport (WP4) and installation (WP5) (T&I) execution phases of the GE Haliade X. For the sake of simplicity, we have joined the description of the two in one. for a future offshore wind farm in the North Sea. The first part describes the transport and installation of the prototype in Rotterdam and the second part describes the transport and installation modelling of a representative future offshore wind farm in the North Sea and the learnings thereof.

The initial installation strategy consisted of having tower sections T0 and T1 installed first, then T2 just before the nacelle/T3, then blades. Having the tower been delivered and partly installed according to the plan.

TNO, together with GE, have modelled the transport and installation of 65 GE Haliade X wind turbines at a representative location in the North Sea. They have performed the study in five stages:

- Development of 780 MW reference offshore wind farm model at the North Sea
- Acquiring transport and installation modelling inputs from the project workshops
- Transport modelling and installation of 65 top parts of wind turbines, towers, nacelles, and blades starting on September 1st, 2025, and analyzing the cause of the weather downtime with the Install tool
- Sensitivity studies are conducted based on project starting dates and operations that cause most weather downtime, such as lifting the blade during installation and jacking up and jacking down operations
- Discussion on potential (additional) modelling capabilities in the Install tool that can add values in T&I for large offshore wind farms project modelling

The Install tool is useful to align the transport and installation process and planning across (e.g., research institutes to OEM, developers) and within the organization. During the project, there have been many discussions on the further improvement of the Install tool that can give even more value to the industry for installation modelling. The main goal is to elaborate more on statistical results and add modules that provide a quick result without completing the whole inputs and process description, and complete weather simulation.

In conclusion, transport and installation of very large offshore wind turbines (>12 MW) will be a prominent challenge to the offshore wind industry (from contractors, wind turbine manufacturers and developers). Using modelling tools and performing simulations will benefit the stakeholders to create many scenarios in less risky environment. The stakeholders can predict project planning and costs and take a close look at the project bottlenecks. It is also recommended to evaluate the risks when other transport and installation campaigns will start later or early in the overall offshore wind farm construction project.

Wind turbine commissioning

Different lessons learnt were achieved during the commissioning of the Haliade X product platform. The following elements summarize the lessons learnt for the following components, including HALX overall design feedback from Commissioning:

- Tower cabinet
- Nacelle & Tower Fire detection System
- Airco
- GIS 66KV
- Hailo lift
- Aviation light
- Yaw
- BMS
- Converter ABB
- ABB transformer
- Weather station
- Profinet network
- Electrical system (cabinet & connection)
- Rotor brake

Wind turbine service

The following tables describe the technical challenges and innovations for service with some complementary qualitative information.

With start of the test and validation period of the turbine, led by the New Product Introduction Engineering function, the field operations team was fully engaged to manage the activities on site supporting all the tasks that where necessary to achieve the type certificates of the Haliade-X. This was not only a great opportunity to learn about and familiarize with the new technology but as well used to gain experience for service readiness and validation of the developed service strategy for the to-come commercial projects with respect to lowest LCOE at best AEP.

It was not only the challenge to safely coordinate engineers and experts from 10 different nations where most of were non-native English speakers but align timing and schedules of the different trades to fit in the master plan sometimes confronted with changes and variances on short notice due to weather changes or other circumstances. The day-to-day work was clearly felt as a team spirit, which finally made the project a success.

The work addresses innovations in the field of operations and maintenance of the turbine. Specifically, the aim is the development of new O&M procedures by performing simulation of offshore farms operations and development of innovations around the turbine to reduce the O&M costs. The innovations are validated on the onshore demonstrator of the offshore wind turbine.

TNO, together with GE, has performed the study in four stages:

- Review and analyze the preventive maintenance philosophy and practices. This was based on experience and lessons learnt from existing offshore wind farms, onshore wind parks and

other industries. The inputs were fed directly to various departments within GE for implementation.
- The onsite preparation workshop with TNO, site engineers from Haliade X and service experts from GE France and GE Germany. In this workshop the main tasks and resources were identified and scheduled – Tasks to be performed
  - Documentation required
  - Tooling required
  - Manning resources required
- The third phase was the actual verification workshop, where all the identified innovations and tasks were performed, by a team comprising of GE service experts, onsite engineers, various subcontractors of GE and TNO, – Tasks executed: 52 Tasks
  - Design changes identified: 32
  - Maintenance Field instruction (MFI's) & tools improvements identified: 20
  - Lock Out Tag Out safety procedure improvements: 5
- The fourth phase was analyzing the data collected in the workshop. Analyzing the data and identifying the key factors, finding solutions, and distributing actions to relevant parties for improved Annual Energy Production, reduced Levelized Cost of Energy, and safety of operation

Innovations in wind turbine certification methods

Wind measurement is probably the most essential input for any wind energy technology applications. The wind speed and turbulence intensity are traditionally and still popularly measured with cup anemometer or sonic anemometer.

In recent years lidar technology, and particularly nacelle lidar technology, emerged in the wind energy industry with its many advantages: reduced cost compared to meteorological mast; always measuring in front of the wind turbine to enable a wider measurement sector with high correlation to wind power; measuring at more ranges; measuring over a plane or volume instead of a point; potability; assisting smart wind turbine control etc. It is adopted by the industry through various pilot and commercial projects over the world for warranty Power Performance Testing already. The IEC standards based on the best practices for ground based lidar, nacelle mounted lidar and floating lidar are coming on their way. However, lidar is still not accepted for turbulence measurements.

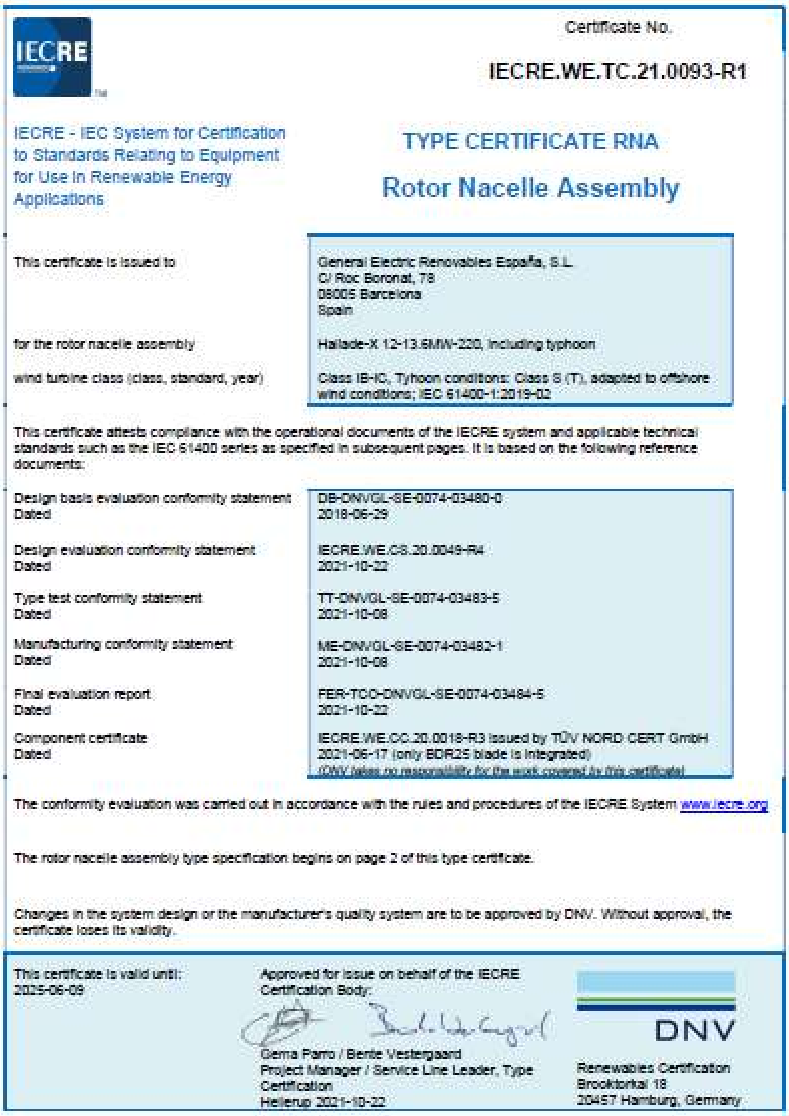
A novel application of Machine Learning for lidar measurement was developed by TNO Wind Energy, based on Gaussian Process regression, to produce reconstructed wind field from lidar measurements. Here, the potentials of using Gaussian Process regression to improve the wind turbulence intensity for lidar wind measurements are studied with several Gaussian Process implementation tests: up sampling the data to higher frequency, filling missing data, predicting in space, and predicting in the center of the beams. For a two-beam lidar, although the Gaussian Process does not show effective improvements for calculating turbulence intensity. The main reasons are firstly that its bias towards the mean values when predicting away from measurement data, and secondly that it relies on the methods of converting the radial wind speeds to horizontal wind speeds. However, the results do demonstrate that Gaussian Process can be applied to almost any lidar system to predict beam radial wind speeds in space and time. And there is still potential to improve turbulence intensity by using lidar with more beams for predictions within a volume as opposed to a plane, or by further developing Gaussian Process mechanisms to calculate turbulence intensity with different methods.

Leosphere is acknowledged for using their lidar data in this project.

2.4 Results, general discussion, conclusions, and follow-up activities

2.4.1 Results

With the support of a Dutch Offshore wind value chain, the results of the project consisted into delivering a certified turbine based on next generation technology in time up to 13.6 MW, with the following type certificates.



IECRE

Certificate No.

IECRE.WE.TC.21.0093-R1

IECRE - IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

TYPE CERTIFICATE RNA

Rotor Nacelle Assembly

This certificate is issued to	General Electric Renovables España, S.L. C/ Roc Boronat, 78 08005 Barcelona Spain
for the rotor nacelle assembly	Haliade-X 12-13.6MW-220, including typhoon
wind turbine class (class, standard, year)	Class IB-IC, Tyhoon conditions: Class S (T), adapted to offshore wind conditions; IEC 61400-1:2019-02

This certificate attests compliance with the operational documents of the IECRE system and applicable technical standards such as the IEC 61400 series as specified in subsequent pages. It is based on the following reference documents:

Design basis evaluation conformity statement Dated	DB-DNVGL-SE-0074-03480-0 2018-06-29
Design evaluation conformity statement Dated	IECRE.WE.CS.20.0049-R4 2021-10-22
Type test conformity statement Dated	TT-DNVGL-SE-0074-03483-5 2021-10-08
Manufacturing conformity statement Dated	ME-DNVGL-SE-0074-03482-1 2021-10-08
Final evaluation report Dated	FER-TCO-DNVGL-SE-0074-03484-5 2021-10-22
Component certificate Dated	IECRE.WE.CC.20.0018-R3 issued by TÜV NORD CERT GmbH 2021-06-17 (only BDR25 blade is integrated) (DNV takes no responsibility for the work covered by this certificate)

The conformity evaluation was carried out in accordance with the rules and procedures of the IECRE System www.iecre.org

The rotor nacelle assembly type specification begins on page 2 of this type certificate.

Changes in the system design or the manufacturer's quality system are to be approved by DNV. Without approval, the certificate loses its validity.

This certificate is valid until:
2025-06-09

Approved for issue on behalf of the IECRE Certification Body:

Gema Parro / Bente Vestergaard
Project Manager / Service Line Leader, Type Certification
Hellerup 2021-10-22

DNV
Renewables Certification
Brooktorkai 18
20457 Hamburg, Germany

2.4.2 General Discussion and Conclusions

Firstly, the project was part of a larger industry movement whereby larger and more efficient offshore wind turbines are developed to lower overall LCOE for offshore wind. As set out earlier, this is primarily driven by increased AEP and achieving a lower CAPEX/infrastructure cost per MWh installed. GE's technology roadmap and how the project helped to find solutions to address them are summarized below.

The main technology challenge which the consortium faced and which through the project the consortium addressed was to secure in a very constrained time to market the largest offshore wind turbine that needed the industry's expectations in terms of competitive weight performance targets and expected availability. This was made furthermore challenging and a great opportunity by integrating into the design at the same time, the return of experience of +30,000 onshore and 2GW of offshore wind turbines installed under construction or planned, field stretch maintainability and installation requirements, and failure tolerant technologies.

In conclusion, the project was a key enabler of the Haliade X-12MW program and its benefits to the industry, as it will allow to validate and demonstrate a string of innovations with a potential for a significantly reduced LCOE in offshore wind energy, by achieving Technology Readiness Level 7 for a 12MW offshore wind turbine equipped with a 220m rotor diameter, with optimized weight, and proven efficient installation techniques.

3 EXECUTION OF THE PROJECT

3.1 Project management

Project organization
The project was being managed firstly by setting up a clear project organization. According to the so-called Prince2 methodology the project has a steering committee, a project board, and further responsibilities at work package and/or task level. Here, the decision power is with the steering committee and the project is managed on a daily basis by the project board. These two layers are organized as follows:

- Steering committee: Morten Schaap-Kristensen and Vincent Schellings (GE), René van den Berg and Martijn Koelers (LM Wind Power), Marc Langelaar and Peter Eecen (TNO)
- Project board: Ronan Guiziou (program manager, GE), Emilia Skowronska (LM Wind Power), Jan Willem Wagenaar (TNO)

During the timeframe of the project, the project board frequently and actively informed the steering committee.

Regular project meetings were organized directly in Rotterdam with the project team, the same together with RVO to proceed to yearly formal project reviews.

3.2 Public relations and Dissemination

Below we summarize the various dissemination moments regarding press, journal contributions and general and specific dissemination.

Press items:

- ‘NOS Journaal’ of Friday 16th of August 2019 broadcasting the erection of the turbine in Rotterdam
- ‘RTL Nieuws’ of Friday 16th of August 2019 broadcasting the erection with comments of Peter Eecen
- ‘NPO Radio 1’ of Friday 16th of August interviewing Peter Eecen
- ‘BNR nieuwsradio’ of Tuesday 1st of October 2019 interviewing Jan Willem Wagenaar
- Inauguration of the GE Haliade X: 17th of December 2019
- ‘RTV nieuws‘ of 17th of December 2019, inauguration of GE Haliade X interviewing Marc Langelaar
- ‘NRC article’ of 20th of March 2020 interviewing Peter Eecen
- Offshore Windbizz, World record energy production in 24h (Dec 2019: 262MWh, Feb 2020: 288MWh, Nov 2020: 312MWh)
- Offshore Windbizz, Preliminary type certificate (12MW) June 2020
- Offshore Windbizz, Full type certificate (12MW) November 2020
- Offshore Windbizz, Announcement of 14MW configuration for Dogger Bank C, December 2020
- Offshore Windbizz, Full type certificate (13MW) January 2021