Final report

1. Project details

Project title	TetraSpar
File no.	64017 - 05171
Name of the funding scheme	EUDP 2017
Project managing company / institution	Aalborg University, Department of the Built Environment Thomas Manns Vej 23, 9220 Aalborg Ø
CVR number (central business register)	29102384
Project partners	Stiesdal Offshore Technologies. DIS. Siemens Gamesa Renewable Energy.
Submission date	11 October 2021

2. Summary

English summary:
The purpose of the project was to optimize the TetraSpar floating offshore wind turbine (FOWT) foundation for installation. The project was a collaboration between Aalborg University, Stiesdal Offshore Technologies, DIS, and Siemens Gamesa Renewable Energy over a period of four years from 2017 to 2021. The expected result of the project was an improved TetraSpar concept composed of a hydrodynamically and structurally optimized foundation, an innovative mooring solution, and specification of a complete, safe and cost-efficient set of marine operations.

The project succeeded in reaching the desired results. The TetraSpar-concept was optimized hydrodynamically and structurally, and the mooring system was designed with innovative elements. The developed assembly methods proved the commercial benefits of the concept and during summer 2021, the foundation completed its assembly using traditional materiel and workforce, after being manufactured at and transported by existing facilities and infrastructure. The project, furthermore, investigated and formed initial experience in innovative mooring and O&M concepts for future projects.

As a result, the TetraSpar project has built experience and knowledge in methods within design, fabrication, assembly and installation of FOWTs, which will be applied further in the future market and next generation of offshore wind turbines.

Danish summary:
Formålet med projektet var at optimere det flydende TetraSpar havmøllekoncept for installation. Projektet var et samarbejde mellem Aalborg Universitet, Stiesdal Offshore Technologies, DIS og Siemens Gamesa Renewable Energy og løb over en periode på fire år fra 2017 til 2021. Det forventede resultat af projektet var en forbedret TetraSpar-løsning bestående af et hydrodynamisk og strukturelt optimeret fundament, et innovativt forankringssystem, og specifikation af et komplet, sikkert og kosteffektivt sæt af marine operationer.

Projektet opnåede de ønskede resultater. TetraSpar-konceptet blev hydrodynamisk og strukturelt optimeret, og fortøjningssystemet blev designet med innovative elementer deri. Den udviklede samlingsmetode efterviste konceptets kommercielle fordele og i sommeren 2021 blev fundamentet færdigmonteret vha. eksisterende materiel og arbejdskraft efter fabrikation og transport fra en allerede etableret fabrik og infrastruktur. Projektet har yderligere undersøgt og skabt indledende erfaringer inden for innovative forankrings- og O&M-koncepter til kommende projekter.

TetraSpar-projektet har derved opbygget erfaring og viden i metoder inden for design, fabrikation, montering og installation af flydende vindmøllefundamenter, hvilket kan anvendes videre i fremtidens marked og næste generation af vindturbiner.

3. Project objectives

The TetraSpar project aimed at improving the TetraSpar floating offshore wind turbine (FOWT) concept for a demonstrator-scale deployment as the first fully industrialized FOWT. The project investigated and optimized the foundation and mooring design through structural and hydrodynamic analysis, and investigated and described efficient marine operations.

The wind industry is thriving globally, both onshore and offshore and wind energy now overtakes coal as the second largest form of power generation capacity in Europe. While the offshore wind industry is thriving in Northern Europe, many countries are prevented from utilizing otherwise favourable offshore wind resources due to scarcity of suitable shallow water sites. On an European scale, this includes most of the Atlantic coastline from Norway to Portugal, as well as most of the Mediterranean. On a global scale, areas with good offshore wind resource that cannot or can only to a limited extent be utilized with fixed foundations include Japan and the west coast of the USA. According to the Carbon Trust, the share of the total offshore wind resource occurring at locations having more than 60 m water depth in Europe, USA and Japan is estimated to be 80%, 60% and 80%, respectively.

The solution to the challenge of deep-water offshore wind power is floating offshore wind turbines. As the designation implies, a floating wind turbine is not rigidly fixed to the seabed but floats, kept in position by a mooring system.

Unfortunately, while floating offshore wind turbines represent the technical solution to the challenge of deep-water offshore wind power, the concepts implemented or proposed prior to project initiation do not represent viable commercial solutions. The problem is that the implementations are generally based on solutions from the oil and gas industry. The foundations are designed and manufactured using conventional methods suitable to one-off systems, leading to heavy and costly structures taking months to manufacture. As a result, the levelized cost of energy (LCOE) from floating offshore wind power is much higher than from bottom-fixed offshore wind power, and is generally at a level that makes it unattractive relative to other renewable energy technologies.

The TetraSpar floating foundation was proposed by Stiesdal Offshore Technologies and aimed at solving this problem and bring wind energy from FOWTs to a genuinely competitive level. The TetraSpar concept utilizes a combination of the core benefits from the three foundation archetypes, allowing both shallow water port assembly, inherent towing stability, and improved installed stability via a ballasted keel, see Figure 1. More importantly, the key focus of the concept is to solely use construction components and methods suitable for large-scale industrialization to further drive down the LCOE.

The objective of the EUDP project TetraSpar, was to significantly optimize the concept design for deployment at pilot scale and decrease uncertainties by experimental and numerical validation of the concept. The primary target of the prototype project was to demonstrate the overall viability of the concept, commercial viability and the further long-term LCOE reduction potentials. This project aimed at supporting the pilot project design by assessing design impacts on CAPEX and OPEX, combining efforts from industry and academia. This constellation covered the entire range from deeply specialized knowledge within academia to the experience-based understanding of structures, processes and cost drivers hereof within the industry.

In order to achieve the overall objective of optimizing the TetraSpar for demonstrator deployment, the following objectives were defined:

- <u>Improve the TetraSpar concept through hydrodynamic and structural optimization of the foundation:</u> At project kick-off, the foundation was still at a relatively early design stage and mostly at a conceptual state. Through numerical models and experimental tests, the project aimed at optimizing the overall foundation design and dimensions, securing stability and dynamic response, which satisfies the design requirements. Simultaneously, the structure was aimed at being designed and optimized to secure structural reliability, while also identifying an optimal design, which both provides a satisfying global dynamic response and internal structural response. In order to meet the objective, the project aimed at investigating and developing optimal numerical modelling approaches and validate them against experimental data.

- <u>Identify and design novel and reliable mooring solutions:</u> In recent years, much attention has been put into mooring solutions in the offshore renewable sector due to its significant influence on the LCOE. So far, there has been a tendency to apply traditional mooring solutions from the oil and gas sector due to its long and well-established history of deploying offshore structures. These moorings are typically combinations of heavy steel chains and anchors, leading to expensive solutions. The present project aimed at investigating and optimizing the mooring arrangements for floating wind turbines by means of alternative layouts and materials, while identifying a reliable system for the TetraSpar demonstrator. Furthermore, by optimizing the hydrodynamic modelling approaches, the project targeted at improving the mooring design procedure and investigate its effect on reliability and cost. Combining numerical modelling with experimental work allows for further validation and improvement of methods and procedures and investigation of relevant systems and identification of their advantages and drawbacks.

- <u>Analyse and describe efficient and safe O&M strategies and marine operations:</u> Investigations of marine operations are included as an objective to ensure a full understanding of the deployment process. The TetraSpar concept allows installation of the wind turbine onto the floating foundation in the port, using a land-based crane. Following installation of the turbine, the complete turbine-foundation assembly is towed to the permanent site using ordinary tugs and is connected to pre-installed mooring and power cable arrangements. In this way, the use of costly and highly specialized installation ships is avoided. The pre-installation of the mooring and power cable arrangements and the subsequent towing and hooking-up of the foundation represent new processes in the offshore wind industry, and here as elsewhere it is necessary to avoid reverting to costly methods from the offshore oil and gas industry. Hence, the development of optimized marine operation in detail is expected to require several iteration loops.

- Increase the Technology Readiness Level (TRL) and decrease LCoE: Because of the above objectives, the TetraSpar project targeted at increasing the TRL of the concept by allowing for a pilot scale deployment. As a criterion for implementation of all choices related to structure, design, mooring and marine operations, the LCOE must be considered. Hence, the project aimed at evaluating the LCOE and each design choice's effect thereon, searching for solutions that reduce the LCOE and which bring FOWT closer to a competitive level.

4. Project implementation

The TetraSpar project was initiated in November 2017. The initial efforts were aimed at defining the baseline of the project, investigating relevant design tools, procedures and identifying the current state of the technology. Initial LCOE estimations were stated and used for later comparison and evaluation of design permutations and project progress. The project was originally intended to be a theoretical and paperwork project, investigating, developing and bringing the concept closer to and ready for full-scale demonstrator deployment, but a large commercial interest in both the concept and project, lead to an accelerated development of the demonstrator, to which the present project became directly related.

Since beginning, the project has been comprised of a close collaboration between all project partners from the industry and academia, while the intensive commercial development also allowed for interaction and incorporation of and with the industry out of the project consortium – both in terms of developers and suppliers.

The work progressed initially as a combined work between all the project partners as both research and commercial development. Efforts were put into development of numerical models and modelling procedures, while experimental work was carried out both for providing data for validation but also for understanding of hydrodynamic behaviour during marine operation and in the final operating stage. Structural design and investigations were carried out simultaneously, both in the search of the optimum design, but also for understanding of the connected influence of design choices on material usage, structural response and potential risks. The work was carried out as smaller and continuous design loops, where different design permutations were tested and evaluated, before they were used or discarded in the next iterations.

As the design and development progressed, several investors joined the commercial demonstrator project, in which the knowledge, experience and findings from the EUDP project were utilized. Parallel to the commercial development, scientific work was carried out by Aalborg University and published in peer-reviewed scientific journals. Novel mooring configurations, hydrodynamic modelling approaches and marine operations were investigated.

In 2020, the manufacturing of the TetraSpar demonstrator was initiated at WELCON A/S in Give, Denmark. This allowed for the evaluation of the concept's design criteria of being highly industrialized and solely relying on existing supply chain. The manufacturing was completed in time, and components transported from Give to the Port of Grenaa using existing infrastructure and machinery. The assembly took place relying on existing port infrastructure, workforce and standard onshore cranes. After deployment in the harbor basin, the wind turbine was installed using an onshore crane and the TetraSpar was towed to Norway and hooked up to the mooring and power cable. This achievement was reached by the end of summer 2021 at the same time as the ending of the EUDP TetraSpar project. During the final part of the project, while the demonstrator was assembled and installed, the project focused on future topics, and hence investigated novel mooring layouts and O&M operations.

Several risks were associated with the project, as the work progressed. The relatively new technology naturally meant that many uncertainties were related to numerical modelling and the design processes, inducing a risk of design errors. The project aimed at understanding these better and cope with the risks. Since the technology was new, the experience in the process was limited. Consequently, a significant risk of extending the design process into too many iterations were present. Since the concept started at a relatively low TRL and the project included scientific work, an evident risk of spending too much time on development and investigation was present, and could result in an overextended process where not enough time was left to make the final analysis and dimensioning of the design.

Similarly, the market for FOWT is relatively new, meaning that the requirements to documentation is more comprehensive and less known. A risk occurred in the final stages of the project due to the fact that many of the new and future sites for FOWTs are for lower water depths, where e.g. mooring found in the project potentially could not be applied. This was addressed by investigating novel mooring concepts applicable for also more shallow water depths.

Overall, the project progressed as planned and the goal of a deployment of the demonstrator during the project period was reached. The latter made possible by extending the project for six additional months. This secured that the final experiences related to manufacturing, deployment and installation was obtained, while also future relevant topics within the field of FOWTs were investigated.

5. Project results

The objectives of the project were obtained and all desired results achieved. The goal of the project to improve the concept towards a pilot scale deployment was fully achieved in summer 2021 when the TetraSpar demonstrator was installed at the Norwegian coast, see Figure 2. A summary of the achieved results and objectives is listed below:

- Improve the TetraSpar concept through hydrodynamic and structural optimization of the foundation: Based on comprehensive numerical and experimental analysis, the foundation design was optimized. The overall structural geometry was tested and defined based on experimental and hydrodynamic numerical simulations. Dimensions, masses, keel depth etc. were investigated and tested in a number of iterations, and combined with structural analysis of all components in the structure. Effort was put into validating and improving numerical modelling approaches, while the last part of the project investigated more novel methods using higher order models and finally applying an approach, which introduces flexibility and hence, allows for simultaneously identifying global motion response and internal loads.

  As a result, the TetraSpar foundation was optimized until reaching the stage, where manufacturing and installation was possible. The foundation was fully assembled by summer 2021, towed to Norway and reached the final installed position by the end of the project.

- Identify and design novel and reliable mooring solutions: By project start, mooring design for FOWTs had greatly relied on the well-known experience from existing offshore sectors, relying primarily on steel components like wire and chain. The project investigated various mooring configurations and finally designed a system for the demonstrator, with novel synthetic ropes as part of the lines. The system was installed in summer 2021 and was found to be both efficient to install and economically feasible.

  During the last part of the project, other types of mooring solutions were tested for future deployments. A study was conducted to validate the feasibility of a single point mooring system and investigate its effect on overall response. Effort was put into designing the power buoy used in such system.

- Analyse and describe efficient and safe O&M strategies and marine operations: Due to the relatively new technology, O&M strategies for FOWT are sparsely described. During the project, plans for O&M have been identified and described. All marine operations were defined in order to secure high efficiency and safety. Several test campaigns were conducted in order to evaluate response during operations and provide the necessary knowledge to formulate detailed plans.

  The feasibility of novel O&M concepts for exchange of turbine components was experimentally tested. The test campaign led to the conclusion that the concepts are feasible and relevant for further engineering and investigation. Finally, novel mooring solutions were tested, which allow for more easy, and hence, cost efficient installation, by simplifying all related marine operations. The concept will need further development in the future.

- Increase the Technology Readiness Level (TRL) and decrease LCoE: By project start, the TRL of the TetraSpar concept was estimated to TRL 4. The concept had prior to the project kick-off been validated in laboratory scale and illustrated a successful proof-of-concept. During the project, the conducted work and final installation of the demonstrator resulted in reaching a TRL 7 by the project ending. Within near future, the concept will reach TRL 9 after being proved in operational environment.

The project has by now resulted in much new knowledge and experience in all aspects and stages related to floating wind turbines. During the project, it was proven that the TetraSpar concept provides a fully industrialized solution. It was proven that all manufacturing is possible at established facilities relying solely on existing supply chain, while efficient assembly can be performed onshore using existing workforce and machinery. Finally, the concept has been shown to be scalable and by now, experience from the project has already been used in up-scaled concepts according to next generation of wind turbines. All together, the introduction of the concept and process related thereto is expected to reduce LCOE of floating wind energy.

The commercial results will be used in the future by forming competitive offers – the first orders and agreements already defined.

Throughout the project period, the project has seen extensive interest, both national and international. The project and the TetraSpar concept have been covered in numerous news articles, conferences, peer-reviewed journal articles and news broadcast (TV and radio). A list of relevant dissemination can be found on the next pages.

Type of dissemination	Title
Journal Articles	• Thorsen Bach-Gansmo, M., Kielland Garvik, S., Thomsen, J. B., & Andersen, M. T. (2020). *Parametric Study of a Taut Compliant Mooring System for a FOWT Compared to a Catenary Mooring.* Journal of Marine Science and Engineering, 8(6), [431]. https://doi.org/10.3390/jmse8060431 • Borg, M., Walkusch Jensen, M., Urquhart, S., Andersen, M. T., Thomsen, J. B., & Stiesdal, H. (2020). *Technical Definition of the TetraSpar Demonstrator Floating Wind Turbine Foundation.* Energies, 13(18), [4911]. https://doi.org/10.3390/en13184911 • Thomsen, J. B., Têtu, A., & Stiesdal, H. (2021). *A Comparative Investigation of Prevalent Hydrodynamic Modelling Approaches for Floating Offshore Wind Turbine Foundations: A TetraSpar Case Study.* Journal of Marine Science and Engineering, 9(7), [683]. https://doi.org/10.3390/jmse9070683 • Thomsen, J. B., Bergua, R., Jonkman, J., Robertson, A., Mendoza, N., Brown, C., Galinos, C., Stiesdal, H., (2021), *Modelling the TetraSpar Floating Offshore Wind Turbine Foundation as a Flexible Structure in OrcaFlex and OpenFAST*. Submitted to Energies.
Conference participations	• Thomsen, J. B., & Andersen, M. T. (2018). *Sensitivity and Cost Analysis of Mooring Solutions for Large Renewable Energy Structures.* I ASME 2018 Proceedings of the 37th International Conference on Offshore Mechanics and Arctic Engineering OMAE2018. American Society of Mechanical Engineers. Proceedings https://doi.org/10.1115/OMAE2018-78238 • Andersen, M. T., Tetu, A., & Stiesdal, H. (2018). *Economic Potential of Industrializing Floating Wind Turbine Foundations.* I ASME 2018 Proceedings of the 37th International Conference on Offshore Mechanics and Arctic Engineering – OMAE. American Society of Mechanical Engineers. Proceedings https://doi.org/10.1115/OMAE2018-77660 • Pereyra, B. T., Jiang, Z., Gao, Z., Andersen, M. T., & Stiesdal, H. (2018). *Parametric Study of a Counter Weight Suspension System for the TetraSpar Floating Wind Turbine.* I Proceedings of ASME 2018 1st International Offshore Wind Technical Conference, IOWTC 2018. American Society of Mechanical Engineers. https://doi.org/10.1115/IOWTC2018-1079 • Jonkman, Jason M and Bergua, Roger and Medoza, Nicole and Robertson, Amy and Thomsen, Jonas Bjerg and Borg, Michael and Brown, Cameron and Galinos, Christos (2021). *Verification of Substructure Flexibility and Member-Level Load Capabilities in OpenFAST Against OrcaFlex for the TetraSpar Floating Offshore Wind Turbine Prototype.* Wind Energy Science Conference WESC2021.

	• Thomsen, J. B., Stiesdal, H. (2021), *The TetraSpar Concept: Towards a fully Industrialized FOWT foundation.* Wind Energy Science Conference WESC2021.
Stakeholders meetings	• November 2017: Project Kick-off meeting. • June 2018: TetraSpar Practical Installation Workshop. • August 2018: TetraSpar Technical Design Workshop with Shell. • November 2019: TetraSpar - Technical discussion with developers, contractors and project managers. • January 2020 Mooring Workshop. • September 2020: Full-consortium Project Status meeting. • Februar-March 2021: SPM workshops. • Weekly/monthly project meetings.
Reports	• Thomsen, J. B., Têtu, A., & Andersen, M. T. (2020). *Experimental Testing of the TetraSpar in Towing and Installation Configuration.* Department of Civil Engineering. DCE Contract Reports Nr. 214 • Thomsen, J. B., Têtu, A., Lai Laursen, D., Stiesdal, H., & Christian Hyldahl, P. (2021). *Experimental Testing of a Single Point Mooring System for Floating Offshore Wind Turbines.* Department of the Built Environment, Aalborg University. BUILD Contract Reports Nr. 16 • Thomsen, J. B., Têtu, A., & Bjerre Pedersen, J. (2021). *Experimental Testing of an O&M Concept for Floating Offshore Wind Turbines.* Department of the Built Environment, Aalborg University. BUILD Contract Reports Nr. 17 • Jensen, B. G., Laursen, D. L. (2020), *Mooring systems for floating foundation for wind turbine generator.* • Stiesdal (2021), *LCOE and TRL state and forecast.* • Lynderup, H. F. (2019), *TetraSpar Demo Execution Plan*. • Blue Power Partners (2020), *TetraSpar Demonstrator, Assembly and installation process.* • Blue Power Partners (2021), *TetraSpar Demonstrator O&M*. • DIS (2021), *SPM workshop.* • Thomsen, J. B., Stiesdal, H., Laursen, D. L., Pedersen, J. B., Têtu, A., & Andersen, M. T. (2021). *Summary of the EUDP TetraSpar project.* Department of the Built Environment. Build Contract Reports Nr. xx

Misc	• The TetraSpar project has gained much attention in national and international media, conferences, seminars and exhibitions.
	  ○ Presentations
	  ○ Industry relevant news articles.
	
	• The TetraSpar project and the gained experience, knowledge and results have formed part of the content in master level courses at Aalborg University. Lectures have been given within the course *Renewable Energy Structures*.
	
	• Several bachelor and master level projects have taken their basis in the TetraSpar project. Master thesis projects have covered mooring design, towing response, higher order hydrodynamic computing and investigation of local hydrodynamic phenomena.
	
	• A video presenting the experimental test campaigns in the project has been published at: https://www.linkedin.com/posts/jonas-bjerg-thomsen_floatingwind-fowt-tetraspar-activity-6816647440465231872-DYUq

6. Utilisation of project results

The project has succeeded in reaching a TRL 7, where the TetraSpar concept has been deployed in a pilot-scale project. The knowledge and experience obtained in the project can and will be utilized by all project partners and external partners outside the consortium. The results will be applied in future projects to provide cost-competitive offers. The project has already gained significant international attention and many of the findings and learnings have been published in scientific papers, which secures that also other developers will be able to utilize some of the results, thereby benefiting the entire FOWT sector.

The project has provided insight into the applicability of certain technologies on a proof-of-concept scale. E.g. novel and untested O&M concepts for offshore exchange of turbine components without use of cranes has been tested. The next step on the way to introduce the O&M option for the offshore market is to initiate further engineering on the tools together with interface studies with the WTG and later perform more testing before doing a full-scale demonstrator.

All project partners have gained new experience, knowledge and a larger network. During the project, the partners have seen an increase in employments related to the FOWT technology and the offshore sector in general. It is the expectation, that all partners will experience a continuing growth in the coming years.

The FOWT sector has increased significantly during the project period and several competitive technologies exists globally:

- WindFloat by Principle Power: The WindFloat FOWT foundation is a semi-submersible type foundation. At present, the foundation has been or is planned for utilization in a prototype project (2 MW), the WindFloat Atlantic (20 MW), the Kincardine Offshore Windfarm (50 MW), Eoliennes Flottantes du Golfe du Lion (24 MW) and WindFloat Japan (<6MW).
- Damping Pool by BW IDEOL: The FOWT is a barge type foundation. Currently, the foundation has been or is planned for utilization in Floatgen (2 MW) and Hibiki (3 MW), together with other pre-commercial projects.

- Hywind by Equinor: The FOWT is a spar type foundation, and has been or is planned for utilization in Hywind Demo (2.3 MW), Hywind Scotland (30 MW) and Hywind Tampen (88 MW).

However, the TetraSpar concept benefits from already being fully industrialized and has now proven the applicability of existing supply-chain, infrastructure and workforce.

The implementation of the FOWT technology highly aids in achieving the climate goals and particularly the goals for offshore wind. Several countries have limited access to offshore wind energy due to large water depths. FOWT and the TetraSpar concept result in the possibility to reach locations that previously have been unreachable. Due to the utilization of existing supply-chain and infrastructure, no larger new investments are required in order to implement the technology, thereby securing a quicker and more cost-efficient introduction to the market. Due to the optimized structure and marine operations, a much lower structure mass and more simple offshore operations are needed, thereby also securing a lower LCOE.

The project has been a cooperation between academia and industry and has, therefore, been utilized in numerous disseminations activities. The project and its work has been part of more than 35 news articles, conference and seminar presentations, while work has been presented in four scientific journal articles. The work has been part of courses given at Aalborg University, while also being related to a number of student projects at both Aalborg and other universities.

7. Project conclusion and perspective

The project obtained all the desired results. The TetraSpar concept was hydrodynamically and structurally optimized, and the developed assembly method proved the commercial benefits of the concept. Where assembly by welding of only one, large girder in a floating wind turbine foundation normally requires at least a week of work, the assembly of the TetraSpar demonstrator only lasted 32 minutes for a girder, and the entire foundation was assembled with a net time-consumption of only 2.3 days. The marine operations were developed to a highly efficient level for the prototype and the mooring has innovative elements in it by means of synthetic ropes as part of the lines. This proved to be both an economical solution and resulted in easy installation.

The work has resulted in increased knowledge of and experience in the design procedure, tools and methodology related to FOWTs and TetraSpar in particular. Furthermore, the project has highlighted future perspective in mooring solutions, O&M and numerical design methodologies. The conclusions from the project on novel O&M concepts and applicability of e.g. single point moorings is expected to continue development and application in future projects.

In combination, the above forms the baseline for designing a floating foundation suitable for the future market and next generation of wind turbines, aiding in fully introducing floating wind energy into the global energy mix and secure a constant and equitable supply of renewable energy.

8. Appendices

- Relevant documents are listed in Section 5.
- Publications can furthermore be found at https://vbn.aau.dk/en/projects/tetraspar
- Information, pictures and videos of the TetraSpar demonstrator can be found at: https://www.stiesdal.com/offshore-technologies/