ODIN-WIND
End-of-project report

EUDP jrnl. nr. 64013-0569

ENERGISTYRELSEN EUDP

28TH FEBRUARY 2018

Indhold

Projekt nr.: 217571
Dokument nr.: 1226986767
Version 2
Revision 1

Udarbejdet af JFG
Kontrolleret af MOI
Godkendt af POW

Danish Summary

Det overordnede mål med ODIN-WIND-projektet var at støtte styringen og planlægningen ved dekommissionering af havmølleparker ved at udvikle et proces baseret software. Dette software-værktøj (ODIN-WIND), der er udviklet inden for projektet, udfører optimering og planlægning af offshore-dekommissionering, der gør det muligt for slutbrugere at reducere risiko, omkostninger og tid brugt til nedlukning, samtidig med at miljøpåvirkningen minimeres ved optimal affaldshåndtering og genbrug af komponenter med resterende levetid . NIRAS har igennem projektet etablerede en platform, der blev brugt til at skabe en egentlig forretning med faktiske projekt. Dette både i designfasen, i forbindelse med drift og i forbindelse med de faktiske nedlukningsprojekter. DTU og TWI har tilsvarende tilegnet sig grundlag og viden, der kan bruges i fremtidig forskning. Maersk Broaker og Vattenfall har alle fået viden, som de har kunnet anvende til at tilpasse sig fremtidens dekommissionerings virkelighed.

English Summary

The overarching aim of the ODIN-WIND project was to support the management of the decommissioning process of offshore wind farms through a software tool. The software tool (ODIN-WIND tool) developed within the project conducts optimization and planning of offshore decommissioning enabling end-users to reduce risk, cost and time spent on decommissioning whilst minimizing the environmental impact by optimal waste management and reuse of components with remaining lifetime. NIRAS has through the project established a platform that was used for creating an actual business with real project in both, the design phase as due-diligence and on actual decommissioning projects. DTU and TWI has equally created a basis and knowledge which can be used in future research. Maersk Broaker and Vattenfall have all gained knowledge which they in each case have been able to use for adjusting to the future of decommissioning.

1 Project details

Project title	ODIN-Wind – Decommissioning of offshore wind turbines
Project identification (pro-gram abbrev. and file)	jrnl. nr. 64013-0569 ODIN-WIND
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	NIRAS, Sortemosevej 19, 3450 Allerød, Denmark
Project partners	**NIRAS**, DTU, TWI, Maersk Broaker and Vattenfall
CVR (central business register)	**DK37295728**, DK30060946, GB700170889, DK31597544 and DK24247791
Date for submission	12th of September 2013 (application submission date)

2 Short description of project objectives and results

The objectives set for the project was in large meet, in some cases the working with the subject changed the objectives making new objectives more relevant. All changes during the project work was communicated and accepted by EUDP.

The ODIN-Wind Project supported by EUDP titled "ODIN-Wind – Decommissioning of offshore wind turbines", was applied and implemented by NIRAS and its partners, DTU, TWI, Maersk Broaker and Vattenfall.

The software has been developed to support the user estimating the full process of decommissioning. This as the software tool (ODIN-WIND tool) developed within the project conducts optimization and planning of offshore decommissioning enabling end-users to reduce risk, cost and time spent on decommissioning whilst minimizing the environmental impact by optimal waste management and reuse of components with remaining lifetime. Alongside with the software development there was also made a guiding tool which guides the user through the user in planning a decommissioning project.

The software is a management tool which includes the full decommissioning process. Initially the main idea was to create a tool supporting the user in estimation during the final stage of the windfarm. However during the project work it became more and more clear that the planning tool was just as relevant for the other phases. Therefore the developed software and the decommissioning guide enables the user to benchmark and estimate offshore decommission during the initial planning of offshore windfarms, during the design phase, in the O&M phase and finally during the final stage of the wind farm.

The developed software the partners will be able to be on the forefront when designing offshore wind turbine farms, as well as generating profit on decommissioning of offshore structures with the gained and structured knowledge on offshore decommissioning.

The tool provides qualified estimates on decommissioning of wind turbine farms while at the same time guiding the user through the process of planning a decommissioning project.

Knowledge of decommissioning of wind turbine farms was initially based on experience of offshore installation and maintenance of windfarms combined with experience in onshore decommissioning of installations, structures and infrastructure. This was based on NIRAS and its partners wide knowledge in different fields of praxis and with different approaches to the subject. Information from market experts was included in the software database which strengthened the software.

Apart from the decommissioning tool, the software also includes an initial attempt on estimation of reuse of components. This both reuse of waste but also through an initial attempt to determine the remaining strength in the substructure. This approach will in a future project provide the basis for development of a tool used for re-powering and lifespan expectancy.

A procedure and tools for load-based computation of remaining lifetime of wind turbines in offshore wind farms, developed by DTU Wind Energy as part of the ODIN project. The work was demonstrated on Horns Rev 1.

Formålet for projektet er overordnet opnået. I nogle tilfælde ændrede projekt arbejdet relevansen af delmål der derfor blev tilpasset så de blev mere relevante. Alle ændringer i projektarbejdet blev meddelt og godkendt af EUDP.

ODIN-Wind projektet blev støttet af EUDP med titlen "ODIN-Wind - Decommissioning of offshore wind turbines". Projektet er ansøgt og gennemført af NIRAS og dets partnere, DTU, TWI, Maersk Broaker og Vattenfall.

ODIN-Wind er udviklet til at støtte brugeren. Softwaret estimerer hele dekommissionerings processen. ODIN-WIND-værktøj som er udviklet i projektet muliggør optimering og planlægning af offshore-dekommissionering, der gør det muligt for brugeren at reducere risiko, omkostninger og tid nødvendig for dekommissionering. Dette i kombination med at miljøpåvirkningen minimeres ved optimal affaldshåndtering og genanvendelse af komponenter med resterende levetid. Sammen med softwareudviklingen blev der også lavet et styringsværktøj, i form af en guide, der guider brugeren gennem i planlægningen af et dekommissionerings projekt.

ODIN-Wind er et planlægningsværktøj der omfatter den fuldstændige nedlukningsproces. I første omgang var hovedidéen at skabe et værktøj, der understøtter brugeren i estimater under den sidste fase af vindmølleparken. Men under projektarbejdet blev det mere og mere klart, at planlægningsværktøjet var ligeså relevant for de andre faser. Derfor giver ODIN-Wind og dekommissionerings guiden brugeren mulighed for benchmarking og estimere offshore-dekommissionering under den indledende planlægning af offshore vindmølleparker, under designfasen, i O&M-fasen og endelig i den afsluttende fase af vindmølleparken liv.

Med det udviklede software er partnerne i en førerposition i forhold til udvikling/design af havmølleparker samt minimering af omkostninger ved dekommissionering af offshore-strukturer ved at have den udformede og strukturerede viden om offshore dekommissionering.

Værktøjet giver kvalificerede skøn over dekommissionering af vindmølleparker, samtidig med at brugeren vejledes gennem processen med at planlægge et nedlukningsprojekt.

Kendskab til nedlukning af vindmølleparker var i første omgang baseret på erfaringer med offshore installation og vedligeholdelse af vindmølleparker kombineret med erfaring i nedrivning, strukturer og infrastruktur på land. Dette bygger på NIRAS og dets samarbejdspartnerens store viden inden for forskellige områder af praksis og med forskellige tilgange til emnet. Oplysninger indhentet fra markedseksperter blev inkluderet i databasen, som styrker værktøjet.

Bortset fra dekommissionering indeholder ODIN-Wind også et første forsøg på estimering af genanvendelse af komponenter. Dette både ved genbrug af affald, men også ved at bestemme den resterende styrke i komponenter af vindmøllefarmen. Denne opnåede viden vil ydermere blive anvend i fremtidige projekter og danne grundlag for udvikling af et værktøj til levetids forlængelse og levetidsestimat.

Procedurer og værktøjer til belastningsbaseret beregning af resterende levetid for vindmøller i havvindmølleparker er udviklet af DTU Wind Energy som led i ODIN-projektet. Arbejdet er ydermere blev demonstreret på Horns Rev 1.

3 Project objectives

The overarching aim of the ODIN-WIND project was to support the management of the decommissioning process of offshore wind farms through a software tool. To develop this software tool, the following activities/ objectives in the form of Work Packages (WPs) were planned and executed:

3.1 WP1: Administration

This WP was project management which was lead and performed by NIRAS. Apart from the day-to-day administration the work package also contained two deliverables, namely:

D 1.1 - DECOM offshore conference, to present the project ideas and results at a relevant offshore decommissioning conference.
D 1.2 - EWEA (now Wind Europe) offshore conference, to present the project ideas and results at a relevant offshore wind conference.

The two deliverables where part of the dissemination. The project was presented several times at relevant conferences covering the set up deliverables. Dissemination is further explained in chapter 5.

3.2 WP2: Determination of the decommissioning software module

This WP was led by NIRAS with TWI and DTU providing technical support, and Maersk Broker and Vattenfall providing relevant data from their respective organizations that fed into the development of the software module. The potential for using existing software (as background IP) from participating partners plugged-into the ODIN-WIND tool was considered. Three Deliverables were submitted as part of WP2, namely:

D 2.1 - Report describing the data model

D 2.2 - Report describing the planed software

D 2.3 - Standard data sheet for data collection

Furthermore the decommissioning database was made dynamic in the model meaning that learning can be added to the database when it is retrieved.

Other data for WP 4 and 5 had the key risk that limited historical data was shared as there were concerns based on confidentiality of such data. However, information relating to the type/ format of data was provided. Also, there were brain storming sessions resulting in data being obtained based on experiences of the participating organizations.

3.3 WP3: Data administration and good practices

This WP was led by NIRAS with TWI providing inputs to the good practice guidance covering relevant existing regulations in different jurisdictions.
Three Deliverables were submitted as part of WP3, namely:

D 3.1 - Database containing data pertaining decommissioning

D 3.2 - Report on key factors, applicable regulations and good practice in decommissioning

D 3.3 - List of links to relevant standards, which will be part of the ODIN-Wind software

Key challenge: There being not many decommissioning of wind turbine structures, ODIN-WIND has had to rely on the offshore oil and gas decommissioning experiences. Furthermore great data for the decommissioning part of the software data was retrieved through questionaries' with field experts, where contacts to the experts was provided by direct contacts through the partners.

3.4 WP4: Approaches and Tools for estimating remaining lifetime of wind turbine components

This WP was led by DTU with support from TWI and NIRAS. There were five tasks to the work package 4:

- Environmental data analysis
- Component load history
- Development of a remaining life prediction model for rotor blades
- Development of a remaining life prediction model for substructure
- Condition monitoring for better end-of-life prediction

This WP involved extensive research and development and resulted in 10 deliverables to fulfill the five tasks, namely:

D 4.1 - Establishment of method to set up the historical environmental impact on each wind turbine in a park

D 4.2 - Method to compute load history

D 4.3 - Develop method to establish damage map to Blades

D 4.4 - Report on probabilistic model to compute remaining life of blades

D 4.5 - Prediction of remaining blade life under different operational conditions for selected wind farms

D 4.6 - Database of operational data relevant for sub structure life prediction

D 4.7 - Report on probabilistic model to compute remaining life on sub structure

D 4.8 - Prediction of remaining sub structure life under different operational conditions for selected wind farms

D 4.9 - Report on relevant condition monitoring techniques

D 4.10 - Link provided to ODIN-Wind user to inform end-users as to the best available condition monitoring techniques.

Task 1: Environmental data analysis & Task 2: Component load history

A method to set up the historical environmental impact on each wind turbine in a wind park (D4.1) and a method to compute load history (D4.2) have been

stablished. These two deliverables (D4.1 & D4.2) are completed in terms of the methodology and the methods were used in the paper by Galinos et al. (2016).

The methods also are implemented in the DTU software module which is part of the ODIN software. The work and DTU Wind Energy software module were presented at the Decommissioning forum day at DTU Risø on March 31 2017.

Task 3: Development of method to predict remaining lifetime for rotor blades & Task 4: Development of method to predict remaining lifetime for sub structures

A probabilistic model to compute remaining life of blades (D4.4) and sub-structures (D4.7) have been stablished. Prediction of remaining life under different operational conditions for selected wind farms is then possible both for blades (D4.5) and for (D4.8).

The methods are implemented in the DTU software module which is part of the ODIN software. The work and DTU Wind Energy software module were presented at the Decommissioning forum day at DTU Risø on March 31 2017.

In the end of 2016 DTU Wind Energy signed a NDA with Vestas, so we could get detailed information about the V80 blades, which were used for the Horns Rev 1 wind park. We got access to geometry, material and design data for the blades in October 2016. We have established a detailed finite element model of the blades and the purpose of the work is to study the response of the HR1 V80 blades to loading and in particular to study how damage in the blades initiates and develops over time. This can then be correlated with the more coarse probabilistic model implemented in the DTU software module which is part of the ODIN software.

In order to calculate the remaining lifetime of the wind turbine components, the lifetime damage-equivalent fatigue load is calculated for each turbine in the farm by integrating the outputs of the surrogate load function over the distribution of wind conditions (wind direction, wind speed and turbulence). Since the exact design criteria used in constructing the wind turbines under consideration are not known, a realistic reference load is used under the assumption that the turbine is designed to the limit, i.e. that the fatigue lifetime of its components is exactly sufficient to withstand some reference conditions. In the present case the most appropriate reference condition is the IEC wind turbine design class 1A as this is what the majority of Vestas V80 turbines should be designed for. Under this assumption, the lifetime equivalent fatigue loads for each turbine in the farm are compared against the equivalent fatigue loads computed for the reference IEC class, using the same load mapping function. Then the fraction of the lifetime used at the last year of the intended operation is computed as the ratio between the turbine-specific lifetime equivalent loads, and the reference IEC 1A lifetime equivalent loads.

Task 5: Condition monitoring for better end-of-life prediction (TWI)

TWI contributed to the remaining life prediction for substructure by proposing a fracture mechanics based approach that determines the acceptability of crack like flaws (discovered during inspection) using TWI's software[1] . The software was

linked to the ODIN-WIND software and a demonstration was made during the ODIN-WIND conference in Denmark on 31 March 2017.

TWI co-authored a report (with extensive inputs from DTU) on condition/ structural health monitoring of wind turbine components for better end of life prediction.

3.5 WP5: Strategies to decommissioning process and identification of key performance indicators (KPIs)

This WP was led by TWI with support from NIRAS and DTU. Work done in this WP built on work done in WP3 and resulted in a deliverable report making up the two deliverables:

D 5.1a – Good practice guide for decommissioning process in offshore wind farms

D 5.2b – Review on Good practice guide for decommissioning process in offshore wind farms

The WP5 work was closely linked to the WP3 deliverable D 3.2.

3.6 WP6: Software programming and database update

This work was led and performed by NIRAS with support from DTU and TWI. The programming was such that it was compatible with existing prototype software owned by NIRAS. Interfaces with DTU and TWI software were developed so that the ODIN-WIND users could call on such functionalities as required.

There were three deliverables in this WP related to prototype development and testing, Namely:

D 6.1 - Functional decommissioning software prototype, ready for testing

D 6.2 - Functional software including wind turbines remaining lifetime too, ready for testing

D 6.3 - Software updated according to errors and trials testing

Decommissioning has previously been seen as the reverse procedure of commissioning, in ODIN-WIND this was changed by looking at the challenge as more diverse and complex operation. In other words as a process in itself rather than only related to something else. It was found prudent to address the future challenge of offshore wind farm decommissioning, avoiding the situation of similar industries. This understood to create a tool which assisted the user in planning in good time based on existing knowledge rather than an unprecise prediction.

Data was known to be key. Therefore it was important to gather some of the knowledgeable partners in the industry. Equally it was important to make ODIN-Wind Dynamic to be able to update with knowledge as it comes along. ODIN-Wind address the issue of decommissioning as a whole, considering the full process and all the associated sub-processes. Data are collected from the sub-processes and used to create a management-software-tool which guides/assists the user in creating a decommissioning-model. This to forecast and outline the decommissioning of the wind farm at an early stage. Hereby making it possible to

optimize on the project on the actual. Either during design, in the O&M phase or during the final stage of decommissioning.

3.7 WP7: Demonstration of ODIN-WIND on Horns Rev 1

Starting in the end of 2016 a preliminary version of the ODIN software was tested on actual and hypothetical test cases. This to fulfill the two deliverables:

D 7.1 - Report on ODIN-Wind software including list of found errors and suggestion for improvement.

D 7.2 - Decommissioning report from ODIN-Wind on Horns Rev 1.

After testing and evaluation a report on ODIN-Wind software including list of found errors and suggestions for improvements was made by DTU Wind Energy and delivered to Niras in February 2017 fulfilling deliverable 7.1

The final version of the software has been demonstrated on Horns Rev 1 calculating the remaining lifetime of blades and sub-structure for each individual wind turbine in the wind park.

A decommissioning report from ODIN-Wind on Horns Rev 1 is made describing remaining lifetime of the wind turbine components, process and planning of the decommissioning and waste management. This was part of the end report for the project and thereby fulfilling deliverable 7.2.

4 Project results and dissemination of results

The main activities and technical results of the project are described in the previous section.

The project succeeded in realizing its objectives this of course differently from partner to partner who has a different approaches to the use of research projects. NIRAS has through the project established a platform that was used for creating an actual business with real project in both, the design phase as due-diligence and on actual decommissioning projects. DTU and TWI has equally created a basis and knowledge which can be used in future research. Maersk Broaker and Vattenfall have all gained knowledge which they in each case have been able to use for adjusting to the future of decommissioning. For NIRAS one of the biggest findings was the importance of including detailed planning of decommissioning at an early stage.

For NIRAS the project has created a platform which has enabled us to assist our clients during planning, design, estimation during operation and actual planning for decommissioning of offshore windfarms. This both national and international. NIRAS has gone from the field of knowledge being an investment to having an actual income and employees fully working with decommissioning.

NIRAS have had the following presentations, papers and articles:

- Presentation: "The future of Offshore decommissioning of OWF" Offshoreenergys Årsmøde 23-24 oktober 2014, Odense
- Presentation and paper: "Preparing for the future - the full process of decommissioning" EWEA Offshore 2015, 10th March Copenhagen.

- Presentation and chapter on decommissioning of OWF:" The full process of offshore decommissioning", The Marewint project, 2nd September 2016 Glasgow.
- Presentation: "Decommissioning of OWF, Planning and managing obsolescence and the full decommissioning process" O&M Conference 20th September 2016, London
- Poster Presentation:" THE FULL PROCESS OF DECOMMISSIONING AND ITS
- IMPORTANCE FOR REDUCING COST IN OFFSHORE WIND" AWEA 25-26 October 2016, USA
- Workshop with several presentations: WORKSHOP see attached agenda, 31st march 2017, Risø Denmark
- Presentation: "ODIN-WIND the full process of offshore wind decommissioning Project resume and lesson learnt", OWIB/Offshoreenergy.dk, 18th May 2017.
- Poster presentation:" ODIN-WIND The full process of Decommissioning and its ability to reduce cost of offshore wind", Wind Europe, 6th June 2017, London

The project and NIRAS work with offshore decommissioning of windfarms has been in the media several times, some are listed in the links below:

- JP Finans: 9th July 2014 " Niras vil score milliarder fra havvindmølleskrot" https://finans.dk/artikel/ECE6862461/Niras-vil-score-milliarder-fra-havvindm%C3%B8lleskrot/?ctxref=ext
- Ingeniøren 20th February 2016 "Aldrende havmølleparker åbner marked for klog nedrivning" https://ing.dk/artikel/aldrende-havmolleparker-abner-marked-klog-nedrivning-182308
- Shippingwatch.dk 31st October 2017 "Niras skifter fokus for skrot-forretning" https://shippingwatch.dk/secure/Offshore/article9982716.ece
- 4C Offshore 2nd November 2017 "NIRAS plans French decommissioning works" http://www.4coffshore.com/windfarms/niras-plans-french-decommissioning-works-nid6617.html
- Offshorewind.biz 2nd November 2017 "French Offshore Wind Developer Thinks Decommissioning Before Final Investment Decision" https://www.offshorewind.biz/2017/11/02/french-offshore-wind-developer-thinks-decommissioning-before-final-investment-decision/
- NIRAS.dk 1st November 2017 "Fransk havvindmølleprojekt får NIRAS som rådgiver for fremtidig skrotning" https://www.niras.dk/nyheder/fransk-havvindmoelleprojekt-faar-dansk-raadgiver/

DTU have furthermore disseminated the methods and the results are described in more details in the two scientific papers related to this task:
1) Mapping Wind Farm Loads and Power Production – A Case Study on Horns Rev 1 by C. Galinos, N. Dimitrov, T. J. Larsen, A. Natarajan and K. S. Hansen [1].
2) Surrogate models for representing wake-induced loads in wind farms by N. Dimitrov [2].

1. C. Galinos, N. Dimitrov, T. J. Larsen, A. Natarajan and K. S. Hansen (2016) Mapping Wind Farm Loads and Power Production – A Case Study on Horns Rev 1. Journal of Physics: Conference series 753(3), p. 032010
2. N. Dimitrov (2017) Surrogate models for representing wake-induced loads in wind farms. To be submitted.

5 Utilization of project results

Offshore decommissioning is a natural end for offshore windfarms. This also the farms which undergoes re-powering. Energy supply from offshore windfarms is growing potentially together with alternative and renewable energy forms such as solar energy. Basically energy forms such as coal have been passed in regards to cost per kWh and the other energy forms are predicted to be passed in the following years. This is in accordance with the general trend where OFW are planed all around the world. With this perspective the farms needs to consider decommissioning both during planning, O&M and the final stage. The optimization and clarification which a detailed planning of the end scenario (decommissioning) brings is enormous for the sector as it brings a solution for the final stage of the OWF as well as making the design better and cheaper in regards to the planning and design.

Therefore NIRAS and the partners have placed them self's in a sweet spot which should prepare them for the predicted future of decommissioning. This said the project the dissemination and the general market possibilities has made the competitors equally aware of the potential and importance to include decommissioning of offshore windfarms in their portfolio of skills. This can easily be traced by a simple browsing their homepages where they all have decommissioning as part of their provided services, something that could not be found just a few years ago.

NIRAS has through the project established a platform that was used for creating an actual business with actual projects in both, the design phase as due-diligence and on actual decommissioning projects. DTU and TWI has equally created a basis and knowledge which can be used in future research. Maersk Broaker and Vattenfall have all gained knowledge which they in each case have been able to use for adjusting to the future of decommissioning. All the partners have added to their knowledge on the offshore wind sector.

NIRAS has had success in projects with Ørsted, CIP, Engie and Vattenfall both in Denmark, France, USA and Taiwan. This both in planning, estimation during operation and planning of the final decommissioning. Large decommissioning projects are presently being conducted by NIRAS and in the future NIRAS will include and bid on decommissioning together with NIRAS existing offshore wind experts and departments. TWI is working on future collaboration with ODIN-WIND participants in the offshore wind sector using the H2020 funding mechanism or any national funding mechanisms from the UK or Denmark. For DTU the work and results achieved in the ODIN Wind project is now being used as a basis for a new EUDP funded project and is also being used in a DTU Wind Energy internal initiative.

It is obviously hard to take out patents on the method, but it is obvious that the partners have taken a great leap and are very knowledgeable in a field which will only grow. NIRAS being a consultant believe that the project has put them in a market leading position not only in Denmark but globally. In general it can be said that EUDP with its funding has assisted in putting the partners in front in regards to decommissioning of OWF.

6 Project conclusion and perspective

State the conclusions made in the project. Try to put into perspective how the project results may influence future development.

6.1 Conclusion

Offshore wind decommissioning experience is relatively limited. However the ODIN-WIND software tool provides valuable support to stakeholders, which has given NIRAS the lead position in providing consultancy on offshore decommissioning of windfarms. This not only in regards to the final stage of decommissioning but also as an important tool for the initial planning and design of offshore wind farms as well as a good tool for estimation of cost and planning during operation which is used for EoL estimation. The support is by way of optimization and planning of offshore decommissioning enabling end-users to reduce risk, cost and time spent on decommissioning, whilst minimizing the environmental impact by optimal waste management and reuse of components with remaining lifetime.

6.2 Perspective

The perspective is enormous, initially in regards to planning and design as well as estimation. With time actual planning will grow as the OWF reach their design life. This prediction is already the reality for NIRAS why NIRAS will follow the development closely, integrate the learnt skills in its portfolio and not the least continuously ensure to be in the lead with its skills. Furthermore the market for is not just offshore wind but also offshore oil and gas decommission sector which is expected to be worth about +70 billion Euro for North Sea as per estimates from the UK's Oil and Gas Authority [2].

[2] https://www.ogauthority.co.uk/news-publications/publications/2017/ukcs-decommissioning-2017-cost-estimate-report/