Final Technical Report

Offshore Wind Energy Systems Engineering Curriculum Development

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Executive Summary

Utility-scale electricity produced from offshore wind farms has the potential to contribute significantly to the energy production of the United States. In order for the U.S. to rapidly develop these abundant resources, knowledgeable scientists and engineers with sound understanding of offshore wind energy systems are critical. This report summarizes the development of an upper-level engineering course in "Offshore Wind Energy Systems Engineering." This course is designed to provide students with a comprehensive knowledge of both the technical challenges of offshore wind energy and the practical regulatory, permitting, and planning aspects of developing offshore wind farms in the U.S. This course was offered on a pilot basis in 2011 at the University of Massachusetts and the National Renewable Energy Laboratory (NREL), TU Delft, and GL Garrad Hassan have reviewed its content. As summarized in this report, the course consists of 17 separate topic areas emphasizing appropriate engineering fundamentals as well as development, planning, and regulatory issues. In addition to the course summary, the report gives the details of a public Internet site where references and related course material can be obtained. This course will fill a pressing need for the education and training of the U.S. workforce in this critically important area. Fundamentally, this course will be unique due to two attributes: an emphasis on the engineering and technical aspects of offshore wind energy systems, and a focus on offshore wind energy issues specific to the United States.

Introduction/ Background

Offshore wind energy systems have the potential to contribute significantly to the energy production of the United States. This energy is clean, carbon-free, and domestically produced. Offshore wind energy systems have important advantages over land-based systems. These advantages include: availability of large continuous areas suitable for major installations; proximity to large load centers with high electricity demand and prices; higher wind speeds, which generally increase with distance from shore; and less turbulence in the wind, which has the potential to increase efficiency and reduce fatigue load on turbines. In addition, offshore wind energy systems can be placed over the horizon, thereby reducing public concern.

The potential for offshore wind is enormous. Offshore of both coasts, and in the Great Lakes, there exists an excellent wind resource capable of producing an immense amount of energy. In the U.S., the developable amount of offshore wind capacity has been estimated at over 2,000 GW for water depths ranging from 30 m to 900 m. This compares with U.S. total electrical capacity of just over 1,000 GW. While commercial technology is available for shallow water (0-30 m deep), advances in science and engineering are required to realize the potential of deep water offshore wind.

To realize the potential of offshore wind, transformational and integrative research is needed to create robust, low maintenance, smart wind energy systems that function properly despite extreme events (e.g., hurricanes) and the harsh ocean environment (e.g., high fluctuating waves). Research is also needed to elucidate how to operate and maintain these systems despite little to no access, and to understand the environmental impacts of the new technology.

In order for the U.S. to rapidly develop the abundant offshore wind resources, knowledgeable scientists and engineers with sound understanding of offshore wind energy systems are critical. Offshore wind energy differs markedly from land-based systems in a number of ways, and for successful and safe development of the offshore wind resource, it is imperative that engineers are educated and trained to understand and adapt to these differences.

Objectives

As outlined in the original proposal, the objectives of this project were twofold:

1. Development of a formal course in "Offshore Wind Energy Systems Engineering." The University of Massachusetts Amherst (UMass Amherst) aims to leverage its extensive experience in offshore wind energy systems and wind energy education to develop this course. The "Offshore Wind Energy Systems Engineering" course developed at UMass Amherst will provide students with comprehensive knowledge of both the technical challenges of offshore wind energy, and the practical regulatory, permitting, and planning aspects of developing offshore wind farms in the U.S. This class will build on the wind energy curriculum already in place at UMass Amherst, and employ the textbook written at UMass Amherst for wind energy education, Wind Energy Explained. External experts in offshore wind energy systems and wind energy education from industry, academia, and national laboratories, both domestic and abroad, will be engaged as partners to critically review the developed content and provide guidance and expertise.

2. Broad dissemination of the course content and materials for use across the U.S. The materials developed for this course, including lectures, problem sets, and more will be disseminated on the web, allowing for easy transfer of this knowledge to other institutions and educators. To tackle this formidable challenge of developing large scale offshore wind energy, qualified engineers across the U.S. will be needed to join the wind industry workforce. By making the content of this course broadly accessible, the knowledge developed can be rapidly transferred to other institutions. Moreover, by ensuring a focus on the challenges inherent to U.S. wind energy systems, this class will be especially applicable for institutions across the U.S. involved in workforce development.

Prerequisites

The offshore wind energy course developed under this contract is assumed to be a successor to a wind energy fundamentals course, such as the University of Massachusetts' MIE 573: *Engineering of Windpower Systems*. That course covers the following topics: context and background, wind resource, wind turbine aerodynamics, mechanical design, design standards, wind turbine electrical issues, controls, system integration, economic considerations, and environmental issues. MIE 573 in turn has a number of basic engineering courses as prerequisites: statics, dynamics, strength of materials and fluid mechanics.

Results and Accomplishments

The content developed for the course "Offshore Wind Energy Systems Engineering" is comprehensive, covering the unique technical challenges for offshore wind energy systems, and the policy and regulatory environments that are critically important to understand when designing, planning, and developing offshore wind farms. Thus, the content developed for this course provides engineers with the necessary knowledge and skills needed by the wind industry today for the development of offshore wind energy systems. Moreover, the course focuses on issues and challenged specific to the U.S., giving the graduates unique qualifications to contribute to the U.S. wind energy workforce. The graduates gain both the engineering knowledge needed for advancing offshore wind energy technology, and the broader contextual understanding of the planning and development of offshore wind energy systems in the U.S.

The course is divided into 17 subtopics. A brief discussion of each subtopic follows.

1. Introduction

In this section, a historical background is provided and the current technology is introduced. The advantages and disadvantages of offshore wind power compared to land based wind power are discussed and the general trends in offshore wind power development are given.

2. Ocean Engineering

The basis of many of the topics studied in offshore wind power engineering can be found in the study of ocean engineering. Ocean engineering is the study of the ocean and the surface below the water, including the energy and resources that can be obtained from it. This includes shore engineering and deep-water engineering. The experience that has accumulated in the study of ocean engineering can inform many of the issues of offshore wind power engineering.

3. Offshore Wind Resource

As with onshore wind turbines, the wind itself is relevant to offshore wind energy in two major ways: 1) it determines the amount of energy that is produced and 2) it affects the design of the wind turbines. The term "wind resource" relates primarily to the energy production aspect whereas wind as an external design condition relates to the design of the turbine. This section is concerned with the energy production aspect. This section provides a summary of the key characteristics of the wind resource in general, focusing on that aspect.

4. External Conditions

For the design of wind turbines on land, the primary external condition to consider is the wind itself. The wind affects the design of the rotor/nacelle assembly and support structure both in terms of extremes and fatigue. Offshore, however, waves can be of comparable importance. They are of particular relevance to the design of the support structure, both in terms of extremes and fatigue. Currents can also be important. They affect the design of the support structure and the selection of the type and amount of rip-rap or other scour protection. In certain locations, floating ice can be quite significant. It can particularly affect the design of the support structure. Other conditions, such as salinity and temperature may also be significant. This section provides a discussion of all of these external conditions and how they impact the design of offshore wind turbines and wind farms.

5. Wind Farm Aerodynamics

This section concerns the aerodynamics of wind turbines as it relates to their behavior in offshore wind farms. That is, we focus on the wakes of wind turbines and how they affect each other when situated in a farm. This is important to consider since wake effects and turbine interactions play an important role in power production, especially with the trend of building larger and larger offshore wind farms. Turbulence in wakes can also affect the fatigue life of the structures. A review of individual turbine aerodynamics is given, followed by a discussion of single wakes and multiple wakes and models that describe these phenomena.

6. Support Structures

Support structure design is an important aspect of overall offshore wind farm design as support structures make up a significant portion of the overall cost of offshore wind farms. The type of support structure that is appropriate for a given location depends on water depth and seabed conditions at the site. Support structures for shallow (fixed bottom structures), transitional and deep (floating structures) waters are introduced and design models are discussed. The types of fixed bottom structures of particular interest on are monopiles, gravity base structures (GSBs) and multi-member structures, such as jackets.

7. Floating Systems

The discussion from the previous section is continued with an in-depth discussion of floating support structures. Floating support structures considered are barges, spars and tension-leg platforms (TLPs).

8. Dynamics and Control

This section focuses on dynamic control of offshore wind turbines and variable speed, pitch controlled turbines are discussed exclusively. The control objectives are power production, speed regulation and load mitigation. Control systems are designed to fulfill all of these criteria. A review of standard turbine control is given followed by a discussion of additional load mitigation concerns and control issues specific to offshore wind turbines. Advanced topics in control of offshore turbines such as individual pitch control, smart rotors and control of floating turbines are discussed.

9. Loads and Design Codes

The interaction between the loading and the structural dynamics of the wind turbine determine the wind turbine structural response, and eventually the component lifetime and failure mechanisms. Thus it is critical to understand the loads on an offshore wind turbine (even more severe than an onshore turbine), how the loads impact the lifetime of the components, and the tools that can be used to model the offshore wind turbine. Sources and effects of these loads are given. A discussion of hydrodynamics, wave theory, fatigue, ultimate loads and resonance is included. Finally, design codes are introduced.

10. Electrical Issues

This section provides a review of basic electrical concepts including both AC and DC concepts. Electrical devices used in power systems, with particular attention paid to offshore transformers, different types of generators used in offshore wind turbines, power electronic converters, ancillary equipment, substations, switchgear, capacitors and reactors. Power transmission, especially submarine cables, is another important issue and is discussed in this section.

11. Offshore Wind System Materials

Offshore wind turbines are in a marine environment and are therefore subject to dynamic and static loads, chemical interaction with the ocean and heating and cooling fluxes. The materials used in the design of the farm should be able to withstand these conditions. Thus, offshore wind systems must be protected to reduce damage from the aggressive marine environment and assessing the environmental conditions and the correct choice of materials is most important.

12. Wind Farm Design

The goal of this section is to describe the design process for an offshore wind farm. By necessity, the design must be integrated because there is a wide range of: subsystems, stakeholders, design criteria, constraints and life cycle phases. Optimizing with respect to one of these will certainly not result in an optimal overall system and therefore the system must be viewed as a whole. The aspects that go into the overall design of offshore wind farms are discussed and prioritized. The design process is discussed in detail.

13. Installation, Operation and Maintenance

The installation and operation of offshore wind farms are very different from onshore generation, with great attention given to reliability and access. The proponents of offshore wind systems have noted that the installation of wind turbines and their support structures is a major factor in the design of offshore wind farms, with a specific challenge of having to perform multiple repeated operations in difficult offshore locations. Thus, the key issues to be realized for the appropriate techno-economic feasibility of an offshore wind farm are: 1) Maximization of access feasibility, 2) Minimization of operation and maintenance requirements.

With this background, this section addresses the three interrelated components of offshore wind engineering: wind farm installation, access, and operation and maintenance.

14. Standards

As described in this section, the purpose of offshore wind design standards is to ensure reliability and safety to the public and those responsible for their well being. These include: 1) insurance companies, 2) financial institutions, and 3) manufacturers. The scope of the standards described here include additional requirements beyond standard land based turbines (IEC 61400-1) that include assessment of the external conditions at an offshore wind turbine site and essential design requirements to ensure the engineering integrity of offshore wind turbines. Particular attention is given to the international standard for the design of offshore wind turbines, IEC 61400-3.

15. Environmental Impacts

The purpose of this section is to analyze the positive and negative environmental aspects of offshore wind energy. This section begins with an overview of the positive environmental effects, such as the very low production of greenhouse gases per unit of electricity generation. In addition, a review of each of the negative or adverse environmental impacts or risks is included. A discussion is provided regarding the following potential negative impacts of offshore wind: visual impact, noise impact, impact on radar and radio signals, impact on sea birds, impact on fish, impact on marine mammals, impact on benthos, electromagnetic fields and marine organisms and ship collisions. The discussion is structured to include a problem definition, the source of the problem, quantification or measurement of the problem and reference resources or tools to address the problem.

16. Permitting and Regulations

There are many permitting issues associated with offshore wind turbines and the majority of them have to do with the turbine location, i.e. in the ocean or Great Lakes. Some are common to all large wind turbines. The location of the farm is essential, where federal vs. state waters can be a key distinction in terms of permitting. This section lists important topics, legal basis and agencies involved in this process. The permitting of the proposed Hull Offshore Wind Farm Project is given as a case study.

17. Economics

This section concentrates on the differences between onshore and offshore wind systems. It discusses the capital costs, operation and maintenance costs, and delivered cost of energy for offshore wind systems. It should also be noted that the difference between the cost of wind energy and the market value (price) of wind energy and that the price depends very much on the institutional setting in which the wind energy is delivered. Economics and costs of state-of-the-art offshore wind energy systems are reviewed and tools for modeling the given costs are discussed.

Reviewers

Reviewers from the National Renewable Energy Laboratory (NREL), TU Delft, and GL Garrad Hassan have reviewed the content of this material and thus provided the input for a revision of the course content notes during the course of this contract.

Follow-on Activities

This course will be continued to be offered as to seniors and graduate students as MIE 674 at the University of Massachusetts and will be a part of the requirements for a Graduate Wind Energy Certificate program. As given in the presentation and seminar (see Appendix) at the 2012 AWEA Annual Meeting, course materials can be obtained at the public ftp site:

http://rerl.org/ftp/outgoing/OFFSHORE-COURSE-NOTES/

The materials at this site include

1) PowerPoint slides for all the course sections

2) A course syllabus

3) Selected lecture notes including appropriate references

4) Selected problem sets and solutions

In addition, the course material contained here will be updated (on the existing web site) as new course material and information develops.

Conclusions/ Recommendations

This contract provided the support for the development of an upper-level engineering course in "Offshore Wind Energy Systems Engineering." As offered on a pilot basis in 2011 at the University of Massachusetts it provided a course designed to provide students with a comprehensive knowledge of both the technical challenges of offshore wind energy and the practical regulatory, permitting, and planning aspects of developing offshore wind farms in the U.S. The course consisted of 17 separate topic areas emphasizing appropriate engineering fundamentals as well as development, planning, and regulatory issues. A public Internet site has been developed where references and related course material can be obtained.

This course will fill a pressing need for the education and training of the U.S. workforce in this critically important area. Fundamentally, this course will be unique due to two attributes: an emphasis on the engineering and technical aspects of offshore wind energy systems, and a focus on offshore wind energy issues specific to the United States. We recommend that this course be continued to be taught at the University of Massachusetts (scheduled for Spring 2013) and other appropriate undergraduate/graduate engineering teaching institutions. In addition we recommend that the material contained in this course be used as a basis for a textbook on the subject of "Offshore Wind Engineering."

APPENDIX

The paper that was presented at the 2012 American Wind Energy Association annual meeting in Atlanta GA follows.

AWEA 2012 PRESENTATION

Development Highlights of an Offshore Wind Energy System Engineering Course

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Wind Energy Center, University of Massachusetts Amherst
160 Governors Drive, Amherst, MA 01003

Abstract

Utility-scale electricity produced from offshore wind farms has the potential to contribute significantly to the energy production of the United States. In order for the U.S. to rapidly develop these abundant resources, knowledgeable scientists and engineers with sound understanding of offshore wind energy systems are critical. This paper summarizes the development of an upper-level engineering in "Offshore Wind Energy Systems Engineering." This course is designed to provide students with a comprehensive knowledge of both the technical challenges of offshore wind energy and the practical regulatory, permitting, and planning aspects of developing offshore wind farms in the U.S. Under a U.S. DOE contract, this course was offered on a pilot basis in 2011 at the University of Massachusetts and the National Renewable Energy Laboratory (NREL), TU Delft, and GL Garrad Hassan have reviewed its content. As is summarized in this paper, the course consists of 17 separate topic areas emphasizing appropriate engineering fundamentals as well as development, planning, and regulatory issues. In addition to the course summary, the paper gives the details of a public Internet site where references and related course material can be obtained. This course will fill a pressing need for the education and training of the U.S. workforce in this critically important area. Fundamentally, this course will be unique due to two attributes: an emphasis on the engineering and technical aspects of offshore wind energy systems, and a focus on offshore wind energy issues specific to the United States.

1.0 INTRODUCTION

The content developed for the “Offshore Wind Energy Systems Engineering” is comprehensive, covering the unique technical challenges for offshore wind energy systems, and the policy and regulatory environments that are critically important to understand when designing, planning, and developing offshore wind farms. The content developed for this course provides engineers with the necessary knowledge and skills needed by the wind industry today for the development of offshore wind energy systems. Moreover, the course focuses on issues and challenged specific to the U.S., giving the graduates unique qualifications to contribute to the U.S. wind energy workforce. The graduates gain both the engineering knowledge needed for advancing offshore wind energy technology, and the broader contextual understanding of the planning and development of offshore wind energy systems in the U.S. It should be noted that this course presumes familiarity with the fundamentals of conventional land based turbines, such as is provided in the University of Massachusetts' course, Engineering of Windpower Systems (MIE 573), or the equivalent.

2.0 COURSE CONTENT

The course is divided into 17 subtopics. A brief discussion of each subtopic follows.

1. Introduction:

   In this section, an historical background is provided and the current technology is introduced. The advantages and disadvantages of offshore wind power compared to land based wind power are discussed and the general trends in offshore wind power development are given.

2. Ocean Engineering:

   The basis of many of the topics studied in offshore wind power engineering can be found in the study of ocean engineering. Ocean engineering is the study of the ocean and the surface below the water, including the energy and resources that can be obtained from it. This includes shore engineering and deep-water engineering. The experience that has accumulated in the study of ocean engineering can inform many of the issues of offshore wind power engineering.

3. Offshore Wind Resource:

   As with onshore wind turbines, the wind itself is relevant to offshore wind energy in two major ways: 1) it determines the amount of energy that is produced and 2) it affects the design of the wind turbines. The term "wind resource" relates primarily to the energy production aspect whereas wind as an "external design condition" relates to the design of the turbine. This section is concerned with the energy production aspect. This section provides a summary of the key characteristics of the wind resource in general, focusing on that aspect.

4. External Conditions:

   For the design of wind turbines on land, the primary external condition to consider is the wind itself. The wind affects the design of the rotor/nacelle assembly (RNA) and support structure both in terms of extremes and fatigue. Offshore the wind also affects the RNA. In addition, waves can be of comparable importance. They are of particular relevance to the design of the support structure, both in terms of extremes and fatigue. Currents can also be important. They affect the design of the support structure and the selection of the type and amount of rip-rap or other scour protection. In certain locations, floating ice can be quite significant. It can particularly affect the design of the support structure. Other conditions, such as salinity and temperature may also be significant. This section provides a discussion of all of these external conditions and how they impact the design of offshore wind turbines and wind farms.

5. Wind Farm Aerodynamics:

   This section is on the aerodynamics of wind turbines as it relates to their behavior in offshore wind farms. That is, we focus on the wakes of wind turbines and how they affect each other when situated in an offshore farm. This is important to consider since wake effects and turbine interactions play an important role in power production, especially with the trend of building larger and larger offshore wind farms. Wakes can also affect the design, in that the turbulence in the wakes can exacerbate the fatigue of the many of the turbines' components. This section provides a review of individual turbine aerodynamics. It also includes a discussion of single wakes and multiple wakes and models that describe these phenomena.

6. Support Structures:

   Support structure design is an important aspect of overall offshore wind farm design as support structures make up a significant portion of the overall cost of offshore wind farms. The type of support structure that is appropriate for a given location depends on water depth and seabed conditions at the site. Support structures for shallow (fixed bottom structures), transitional and deep (floating structures) waters are introduced and design models are discussed. Fixed bottom support structures discussed include monopiles, gravity base foundations and multi-member structures, such as jackets.

7. Floating Systems:

   The discussion from the previous section is continued with an in-depth discussion of floating support structures. Floating support structures considered include spars, barges, and tension leg platform.

8. Dynamics and Control:

   This section focuses on dynamic control of offshore wind turbines. The focus is on turbines variable speed, pitch controlled rotors. The control objectives are power production, speed regulation and load mitigation. Control systems are designed to fulfill all of these criteria. A review of standard turbine control is given followed by a discussion of additional load mitigation concerns and control issues specific to offshore wind turbines. Advanced topics in control of offshore turbines such as individual pitch control, smart rotors and control of floating turbines are discussed.

9. Loads and Design Codes:

   The interaction between the loading and the structural dynamics of the wind turbine determine the wind turbine structural response, and eventually the component lifetime and failure mechanisms. Thus it is critical to understand the loads on an offshore wind turbine (even more severe than an onshore turbine), how the loads affect the lifetime of the components, and the tools that can be used to model the offshore wind turbine. Sources and effects of these loads are given. A discussion of hydrodynamics, wave theory, fatigue, ultimate loads and resonance is included. Finally, computer based design codes are introduced.

10. Electrical Issues:

    This section provides a review of basic electrical concepts including both AC and DC concepts. Electrical devices used in power systems are discussed. Particular attention is given to offshore transformers, types of generators used in offshore wind turbines, power electronic converters, ancillary equipment, substations, switchgear, capacitors and reactors. Offshore electrical power transmission is another important issue and is also discussed in this section.

11. Offshore Wind System Materials:

    Offshore wind turbines are in a marine environment and are therefore subject to dynamic and static loads, chemical interaction with the ocean and heating and cooling fluxes. The materials used in the design of the farm should be able to withstand these conditions. Thus, as shown from the previous examples, offshore wind systems must be protected to reduce damage from the aggressive marine environment and assessing the environmental conditions and the correct choice of materials is most important. This section provides an overview of the materials that are commonly used in offshore wind turbines.

12. Wind Farm Design:

    The goal of this section is to describe the design process for an offshore wind farm. By necessity, the design must be integrated because there is a wide range of: subsystems, stakeholders, design criteria, constraints and life cycle phases. Optimizing with respect to one of these will certainly not result in an optimal overall system and therefore the system must be viewed as a whole. The aspects that go into the overall design of offshore wind farms are discussed and prioritized. The design process is discussed in detail.

13. Installation and Maintenance:

    The installation and operation of offshore wind farms are very different from onshore generation, with great attention given to reliability and access. The proponents of offshore wind systems have noted that the installation of wind turbines and their support structures is a major factor in the design of offshore wind farms, with a specific challenge of having to perform multiple repeated operations in difficult offshore locations. Thus, the key issues to be realized for the appropriate techno-economic feasibility of an offshore wind farm are: 1) Facilitation of access, 2) Minimization of operation and maintenance requirements.

    With this background, this section addresses the three interrelated components of offshore wind engineering: wind farm installation, access, and operation and maintenance.

14. Standards:

    As described in this section, the purpose of offshore wind design standards is to ensure reliability and safety to the public and those responsible for their well being. These include: 1) insurance companies, 2) financial institutions, and 3) manufacturers. The scope of the standards described here includes additional requirements beyond standard land based turbines (IEC 61400-1) that include assessment of the external conditions at an offshore wind turbine site and essential design requirements to ensure the engineering integrity of offshore wind turbines. Particular attention is given to the international design standard for offshore wind turbines, IEC 61400-3.

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3.0 COURSE MATERIAL DISSEMINATION

This course will be continued to be offered as a graduate course at the University of Massachusetts and will be a part of the requirements for the Graduate Wind Energy Certificate program. As given in the presentation (attached) at the 2012 AWEA Annual Conference, course materials can be obtained at the public ftp site: http://rerl.org/ftp/outgoing/OFFSHORE-COURSE-NOTES/

The materials at this site include:

1) PowerPoint slides for all the course sections
2) A course syllabus
3) Selected lecture notes including appropriate references
4) Selected problem sets

In addition, the course material contained here will be updated as new course material and information develops.

Wind Energy Center

DEVELOPMENT HIGHLIGHTS OF AN OFFSHORE WIND ENERGY SYSTEMS ENGINEERING COURSE

J. G. McGowan, J. F. Manwell, Matthew A. Lackner, Meltem Duran
Wind Energy Center
Department of Mechanical and Industrial Engineering
University of Massachusetts Amherst

OVERVIEW & HISTORY

•Designed to provide students with comprehensive knowledge of both the technical challenges of offshore wind energy and the practical regulatory, permitting, and planning aspects of developing offshore wind farms in the U.S.

•Fill a pressing need for the education and training of the U.S. workforce in this critically important area.

•Unique due to two attributes: an emphasis on the engineering and technical aspects of offshore wind energy systems, and a focus on offshore wind energy issues specific to the United States.

•Was offered on a pilot basis in 2011 at the University of Massachusetts Mechanical and Industrial Engineering Department

• Has been reviewed by the National Renewable Energy Laboratory (NREL), TU Delft, and GL Garrad Hassan.

• Consists of 17 separate topic areas emphasizing appropriate engineering fundamentals as well as development, planning, and regulatory issues.

•Public internet site where references and related course material can be obtained.

LEARNING OBJECTIVES & DELIVERABLES

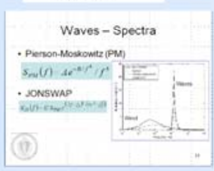
The learning objectives are categorized as:

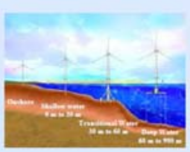
- Skills and Information: The students will gain skills marketable in the offshore wind industry, especially in the U.S.
- Knowledge: The students will learn about all relevant aspects of offshore wind farm development and have a firm theoretical and practical understanding of the issues discussed.

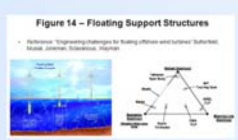
The deliverables for the project are:

- Initial course content: During the first year of the project, main topic areas were determined and a detailed curriculum and homework assignments were developed. Similar courses from TU Delft were used as reference.
- Course content review: Course content was reviewed in-house as well as by reviewers from NREL, TU Delft and GL Garrad Hassan.
- Implementation of course: The material was used to teach an upper-level Mechanical Engineering course at UMass Amherst.
- Course Revision (in progress): Critical review , refinement and further development of the course content is ongoing.
- Dissemination of course material: The course material is available to the public on the website: ftp.ecs.umass.edu/pub/rerl/outgoing/OFFSHORE-COURSE-NOTES/

COURSE OUTLINE & HIGHLIGHTS







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- Electrical Issues
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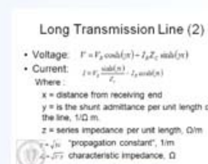
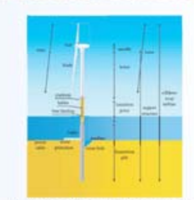
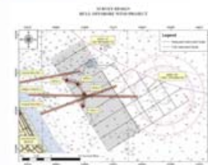
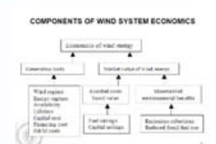
- Economics









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