Final Technical Report

Project Title:

**An Undergraduate Minor in
Wind Energy at Iowa State University**

DOE Award Number: DE-EE0003549

Project Period: 08:10 – 08:12

James McCalley, Principal Investigator

515-294-4844 (v)

jdm@iastate.edu

Iowa State University, Ames, Iowa 50011

November 13, 2012

Acknowledgment: This report is based upon work supported by the U. S. Department of Energy under Award No. DE-EE0003549. The below individuals are Iowa State University faculty who contributed to development of the Wind Energy Minor.

Dionysios Aliprantis, Electrical Engineering, 515-294-7387, dali@iastate.edu
Jeramy Ashlock, Civil Engineering, 515-294-6176, jashlock@iastate.edu
Lisa Brasche, Nondestructive Evaluation, 515-294-5227, lbrasche@iastate.edu
Konstantina (Nadia) Gkritza, Civil Engineering, 515-294-2343, nadia@iastate.edu
Mike Kessler, Material Science Engineering, 515-294-3101, mkessler@iastate.edu
James McCalley, Electrical Engineering, 515-294-4844, jdm@iastate.edu
Shashi Nambisan, Civil Engineering, 515-294-5209, shashi@iastate.edu
Frank Peters, Industrial Engineering, 515-294-3855, fpeters@iastate.edu
Ganesh Rajagopalan, Aerospace Engineering, 515-294-6796, rajagopa@iastate.edu
Vern Schaefer, Civil Engineering, 515-294-9540, vern@iastate.edu
Sri Sritharan, Civil Engineering, 515-294-5238, sri@iastate.edu
Gene Takle, Geological and Atmospheric Sciences, 515-294-9871, gstakle@iastate.edu

Disclaimer: Any findings, opinions, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

Table of Contents

Executive summary	3
1. Introduction	3
2. ISU Wind Energy Minor Program	4
3. Program impact	6
3.1 Students in the Wind Energy Minor program	6
3.2 Student enrollment in key Wind Energy Minor courses	6
3.3 Industry comments on the program	6
APPENDIX A: TOPICAL SUMMARIES OF COURSES	8
APPENDIX B: COMMENTS FROM PROGRAM REVIEWERS	16

Final Report An Undergraduate Minor in Wind Energy at Iowa State University

Executive summary

This report describes an undergraduate minor program in wind energy that has been developed at Iowa State University. The minor program targets engineering and meteorology students and was developed to provide interested students with focused technical expertise in wind energy science and engineering, to increase their employability and ultimate effectiveness in this growing industry. The report describes the requirements of the minor program and courses that fulfill those requirements. Five new courses directly addressing wind energy have been developed. Topical descriptions for these five courses are provided in this report. Six industry experts in various aspects of wind energy science and engineering reviewed the wind energy minor program and provided detailed comments on the program structure, the content of the courses, and the employability in the wind energy industry of students who complete the program. The general consensus is that the program is well structured, the course content is highly relevant, and students who complete it will be highly employable in the wind energy industry. The detailed comments of the reviewers are included in the report.

1. Introduction

As stated by the DOE Wind Program (www1.eere.energy.gov/wind/outreach_education.html), "...the nation will continue to need skilled scientists and engineers who can develop the next generation of wind power technologies." However, wind energy science, engineering and policy at many schools around the nation is only found, if at all, as components of other courses. The complexity of wind energy demands provision of more dedicated and refined attention in the undergraduate and graduate curricula in order to meet the needs of this dramatically growing industry. In addition, students need structure to help them select courses exposing them to wind energy, and they need a designator to clearly market their expertise. We have directly addressed these needs in this project.

The objective of this project was to develop an undergraduate minor in wind energy at Iowa State University (ISU). This objective, which was accomplished, makes available a wide selection of coursework to undergraduate students positioning them to fully engage in the evolution of wind farm financing, turbine/tower/blade design/analysis, construction, manufacturing & supply chain, operation, reliability, maintenance, grid interface, turbine-grid interactions, transmission, and policy.

In this final report, we describe the ISU Wind Energy Minor program in Section 2. Section 3 provides information on program evaluation including statistics on student participation to date and comments from industry reviewers.

2. ISU Wind Energy Minor Program

Central attributes of the ISU Wind Energy Minor Program include:

1. Oversight committee: The required course or courses in the Wind Energy Minor are developed, owned, maintained, and staffed under the guidance of a Wind Energy Minor Program Oversight Committee. The chair of this committee is Professor Frank Peters.
2. Accessibility: The Wind Energy Minor was developed to minimize additional pre-requisite courses for students of the following departments: Aerospace Engineering, Agricultural and Biosystems Engineering, Agronomy, Chemical and Biological Systems Engineering, Civil, Construction, and Environmental Engineering, Electrical and Computer Engineering, Geological and Atmospheric Science, Industrial and Manufacturing Systems Engineering, Material Science Engineering, and Mechanical Engineering. Representatives from each of these listed departments have membership on the Wind Energy Minor Program Oversight Committee.
3. Wind Energy Minor Content: The Wind Energy Minor was developed so that students satisfying its requirements would be exposed to core basics of wind energy while obtaining depth of expertise in at least one area. The Minor requires 15 credits (5 courses). Of these, 6 credits are focused wind-energy courses while the remaining 9 credits provide additional depth in one or more wind energy areas.

There were two 3-credit courses created under the funding for this project. These courses were AER E 381 and ENGR 340. The university catalog descriptions for these two courses are given below, and topical summaries for these two courses are provided in Appendix A.

AER E 381. Introduction to Wind Energy. (3-0) Cr. 3. S. Prereq: MATH 166, PHYS 221
Basic introduction to the fundamentals of Wind Energy and Wind Energy conversion systems. Topics include but not limited to various types of wind energy conversion systems and the aerodynamics, blade and tower structural loads, kinematics of the blades and meteorology. Nonmajor graduate credit.

ENGR 340. Introduction to Wind Energy: System Design & Delivery. (3-0) Cr. 3. F. Prereq: MATH 166, PHYS 222. Introduction to wind energy. Economic analysis related to wind energy. Electrical power generation, transmission, and grid operations. Tower, blade and nacelle materials and manufacturing. Tower design. Construction, transportation, supply chain and life cycle analysis for wind turbine components.

Each of the above two courses are required by students wishing to obtain the Wind Energy Minor. In addition, three elective courses (9 credits) are required, and students may select those elective credits from the following list.

- ☐ AER E 422: Aeroelasticity
- ☐ AER E 423: Composite Flight Structures
- ☐ AER E 470: Wind Engineering
- ☐ AER E 481: Advanced Wind Energy- Technology & Design
- ☐ C E 460: Foundation Design
- ☐ C E 541: Dynamic Analysis of Structures
- ☐ I E 443: Wind Energy Manufacturing

- ☐ MAT E 362: Introduction to Nondestructive Evaluation
- ☐ E E 452: Electrical Machines and Power Electronic Devices
- ☐ E E 457: Power System Analysis II
- ☐ E E 459: Electromechanical Wind Energy Conversion and Grid Integration
- ☐ M E 325: Machine Design
- ☐ M E 411: Automatic Controls
- ☐ M E 417: Advanced Machine Design
- ☐ M E 421: System Dynamics and Controls
- ☐ MTEOR 405/AGRON 405/ENVSCI 405: Environmental Biophysics
- ☐ MTEOR 407/AGRON 407/ENVSCI 407: Mesoscale Meteorology
- ☐ MTEOR 411: Synoptic Meteorology
- ☐ MTEOR 417: Mesoscale Forecasting Laboratory
- ☐ MTEOR432: Instrumentation and Measurement

Of the above Wind Energy Minor elective courses, three of them directly address wind energy and though they were developed using other resources, are expected to be frequently elected by students obtaining the wind energy minor and therefore will significantly strengthen the minor program. These three courses were AER E 481, E E 459, and I E 443. University catalog descriptions for these three courses follow:

E E 459. Electromechanical Wind Energy Conversion and Grid Integration. (Dual-listed with 559). (3-0) Cr. 3. Prereq: Credit or enrollment in E E 452, E E 456. Summary of industry status and expected growth; power extraction from the air stream; operation and modeling of electric machines, and power electronics topologies for wind energy conversion; analysis of machine-grid power electronic circuits, controller interface, and collector (distribution) networks; treatment of harmonics, flicker, over/under-voltages, filters, low-voltage ride-through, and reactive compensation; relaying; effects on transmission expansion, planning and grid operation and coordination including variability, frequency control, reserves, and electricity markets; overview of storage technologies and hybrid configurations. Nonmajor graduate credit.

AER E 481. Advanced Wind Energy: Technology and Design. (3-0) Cr. 3. F. Prereq: AER E 381 or senior classification in engineering or junior in engineering with a course in fluid mechanics. Advanced topics in wind energy, emphasis on current practices. Theoretical foundations for horizontal and vertical axis wind turbine. Design codes for energy conversion systems design, aerodynamic and structural load estimation, wind resource characterization wind farm design, optimization. Nonmajor graduate credit.

IE 443. Wind Energy Manufacturing. (Dual-listed with 543). (3-0) Cr. 3. Prereq: Credit or enrollment in I E 448. Materials, processes and systems required to produce the major components (blades, towers, nacelles) of megawatt scale wind turbines. Transportation, manufacturing siting and procurement decisions as it relates to these large components in an expanding industry.

3. Program impact

This section provides information indicating program impact to date. However, this information should be perceived as preliminary; because the Wind Energy Minor program is so new, it is not possible to fully assess its impact at this point.

3.1 Students in the Wind Energy Minor program

There are 20 students presently enrolled in the Wind Energy Minor program. The program just became available on campus as of September 2012, and so this number may not be a good indication of interest in the program.

3.2 Student enrollment in key Wind Energy Minor courses

Data characterizing student enrollment in the five courses described above is a good measure of the impact associated with the efforts of this project. These data are provided in Table 1 below.

Table 1: Course enrollments

Course	Enrollment		
	First offering	Second Offering	Third offering
AER E 381	60 (Spring 2010)	55 (Spring 2011)	35 (Spring 2012)
ENGR 340	27 (Fall 2011)	21 (Fall 2012)	
AER E 481	20 (Fall 2010)	10 (Fall 2012)	
EE 459/559	17 (Spring 2009)	20 (Fall 2010)	24 (Spring 2012)
I E 443/543	24 (Spring 2010)	11 (Spring 2012)	

3.3 Industry comments on the program

The description of the Wind Energy Minor program as given in Section 2, including the course syllabi in the appendix, and the data presented in Sections 3.1 and 3.2, were provided to industry personnel familiar with wind energy. These individuals were asked to answer the following questions.

- A. Individual course assessment: For the following courses, what modifications would you make in terms of coverage, under the assumption that no material can be added to a course without eliminating some existing material?
 1. Required courses:
 - a. AER E 381
 - b. ENGR 340
 2. Elective courses:
 - a. AER E 481
 - b. E E 459
 - c. I E 443
- B. Overall program:

1. Do you believe students who complete this minor program will be attractive employment candidates for organizations involved in wind energy?
2. Are there particular types of wind energy-related organizations for which students completing this minor program are well-prepared for employment? If yes, can you identify or characterize the types of organizations you feel students completing this program would be well-prepared for employment?
3. Are there particular types of wind energy-related organizations for which students completing this minor program would not be well-prepared for employment? If yes, can you identify or characterize the types of organizations you feel students completing this program would not be well-prepared for employment?

A summary of the comments received from these industry reviewers is compiled in Appendix B. Respondents included the following individuals:

- Mark Ahlstrom, CEO, WindLogics.
- Tom Daft, Manager, Wind Development & Administration, MidAmerican Energy Company
- Jason MacDowell, Principal Engineer, Energy Consulting, GE Infrastructure, Energy.
- J Charles Smith, Executive Director, Utility Variable Generation Integration Group (UVIG).
- Paul Veers, Chief Engineer, NREL's National Wind Technology Center.
- Tom Wind, President, Wind Utility Consulting.

Comments were generally very positive, but some reviewers raised issues about certain topics. These issues will be addressed during the next year.

**APPENDIX A: TOPICAL SUMMARIES OF COURSES
AER E 381, ENGR 340, AER E 481, E E 459, I E 443**

Topical Summary of AER E 381, Introduction to Wind Energy

1. History

- a. Early History
 - i. 1-900AD
- b. Medieval History
- c. Age of the Industrial Revolution – Water Pumping
 - i. Halladay
 - ii. Thomas Perry
 - iii. Laverne Noyes
- d. Wind Power and Electric Generation
 - i. First turbines
- e. VAWT development
- f. Wind farm development
- g. Closing comments
 - i. Power generation from wind
 - ii. Types

2. Wind and Meteorology

- a. Nature of the wind
- b. Atmospheric boundary layer (ABL) for wind energy application

3. Wind and Energy Potential

- a. Work, Energy and Power
 - i. Kinetic Energy
 - ii. Work
 - iii. Power
 - iv. Wind Power
 - v. Power Density
- b. Measurements and instrumentation
 - i. Wind speed/direction sensors
- c. Describing the vertical variation of wind speed
 - i. The log profile
 - ii. Power law
- d. Resource Assessment and Wind Resource Maps
- e. Energy potential of wind in the US

4. Review of Fluid Mechanics

- a. Units and basic definitions

5. Conservation Equations

- a. Methods of describing fluid motion
 - i. Lagrangian approach
 - ii. Eulerian approach
- b. Conservation of mass
- c. Conservation of momentum
- d. Streamlines and pathlines
- e. Simplifications to conservation equations
 - i. Steady flow
 - ii. One-, two-, and three-dimensional flows
 - iii. Axisymmetric flow
- f. Bernoulli's equation

6. Aerodynamics and Airfoils

- a. Aerodynamic forces and moments
- b. Airfoil nomenclature
 - i. NACA series
- c. Lift, drag and stall characteristics
- d. Flow similarity
 - i. Geometric similarity
 - ii. Dynamic similarity
- e. Airfoil characteristics
- f. Reynolds number effects on airfoil characteristics
- g. Mach number effects

7. Wind Turbine Aerodynamics

- a. Axial momentum theory
- b. Momentum analysis
 - i. Assumptions
- c. Betz limit
- d. Induction factors
- e. Non-dimensional coefficients
 - i. Power and thrust
 - ii. Solidity, taper ratio and tip speed ratio
 - iii. Effect of non-dimensional parameters on performance
- f. Parameters of interest at a blade section
- g. Losses due to swirl
- h. Summary

Topical Summary of AER E 381, Introduction to Wind Energy (Continued)

8. Performance of Wind Energy Conv Systems
 - a. Introduction
 - b. Power curve and power coefficient curve
 - c. Energy estimation
 - d. Wind speed variation with time & height
 - e. Method of bins
 - f. Wind speed histogram
 - g. Probability density function
 - h. Cumulative distribution function
 - i. Wind speed duration curve
 - j. Power duration curve
 - k. Statistical quantities from meth of bins
 - l. Mean wind speed
 - m. Standard deviation
 - n. Energy pattern factor
 - o. Wind turbine operation
 - p. Capacity factor
 - q. Availability factor
 - r. Spectrum averaged power
 - s. Turbulence in wind energy applications
9. Anatomy of a Modern Wind Energy Conversion System (WECS)
 - a. Basic definitions
 - b. Rotor
 - c. Drive/gear train, including high-speed and low-speed shafts
 - d. Generator
 - e. Nacelle
 - f. Yaw drive
 - g. Tower
 - h. Power electronics and control units
10. Wind Turbines and Gears
 - a. Operation of gears
 - b. Parallel gears: Rotation of a rigid body and speed ratio
 - c. Planetary gears and speed ratio
 - d. Examples of gear trains used in modern wind turbines, including planetary gears
 - e. Polar moment of area (J)
 - f. Polar moment of inertia (I)
 - i. Parallel axis theorem
 - ii. Radius of gyration
 - g. Polar moments of area, inertia
 - h. Angular momentum

11. Principles of Generators
 - b. Magnetic flux
 - c. Faradays law
 - d. Electromagnetism
 - i. Power
 - ii. DC and AC circuits
 - iii. Rms values of current and voltage in AC ccts
 - iv. Kirchhoff's rules
 - v. Purely resistive AC ccts
 - vi. Inductance
 - vii. Time variation of current and voltage in an inductive circuit
 - viii. Pure inductor circuit
 - ix. Resistor-inductor circuit
 - x. Power factor
 - e. Wind electric generation
 - i. Electrical machines
 - ii. AC generator
 - f. Synchronous generators
 - g. Asynchronous generators
 - i. Induction generators
 - h. Power quality and control
12. Wind Turbine Control
 - a. Yaw mechanism
 - b. Control system and rated power
 - c. Passive stall regulation
 - d. Pitch regulation (active stall)
 - e. Yaw control (small turbines)
 - f. Yaw error
13. Economics of Wind Electric Generation
 - a. Operations and maintenance
 - i. Scheduled maint
 - ii. Unscheduled maint
 - b. Energy economics
 - i. Example
 - ii. Energy economics
 - iii. Metering
 - c. Annual energy production
 - d. Economic analysis
 - e. Economy of scale
 - f. Economy of mass production
 - g. Total cost of project
 - i. Power purchase agreement
 - ii. Project economic merit

Topical Summary of ENGR 340, Introduction to Wind Energy: System Design & Delivery

1. Introduction to wind energy a. Power, energy, capacity factor b. Background on wind power growth worldwide, nationally, region, state, manufacturer and owner c. Wind farm size d. Policy issues: RPS, PTC, ITC e. Wind energy potential f. Windenergy relative to other enrgy frms g. Overview of GHG emissions h. Future scenarios i. Grand challenge for energy j. Grand challenges for wind energy: i. Moving wind energy ii. Variability and uncertainty iii. Wind turbine & wind farm economics iv. Effects on wildlife, visual and noise impact, effects on agriculture 2. Overview of electric power systems a. Organizations comprising ElectPwr Ind b. Historical perspective c. Energy cntrl cnters/balancing authorities d. Electricity markets i. LMPS ii. Internet-based two-sided auctions iii. Two-settlement structure e. Participation of wind in elect markets 3. Wind power variability and the grid a. Grid-power balance requirement b. Characterizing wind power production c. Power extracted from the wind d. Wind stream speed ratio e. Performance coefficient and Betz limit f. Control of performance g. Power curve h. Power system control i. Primary control ii. Secondary control: AGC iii. Dispatch - real-time/day-ahead mrkt i. Wind energy effect on variability: i. Regulation via moving avg ii. Variance as measure of regulation j. Solutions to increased variability i. Fast-ramping generation ii. Demand-side control iii. Storage iv. Geo-diversity, hvdc for vrbly transfer	4. Electric delivery system a. Turbine transformers b. Collection cct/substation design c. Windfarm to backbone transmission d. Interregional transmission e. Offshore collection & transmission 5. Turbine generators a. Induction generators b. Double-fed induction generators and speed-torque control methods c. Permanent magnet sync generators d. Converter configurations e. Magnetic materials 6. Manufacturing and blades a. Blade anatomy/components b. Blade objectives c. Blade materials d. Polymer matrix composites & processes e. Fiber reinforced polymer composites f. Compositing composites: open mold process, filament winding, pultrusion g. Reusable silicon bag technology h. Quality issues i. Assembly variation j. Future automation systems k. Options for larger blades 7. Manufacturing and towers a. Transportation constraint to height b. Materials c. Weldment: fusion zone, HAZ, base metal d. Types of weld: gas-metal, flux-core, self-shielded flux core, submerged arc e. Residual stress f. Cost-reduction savings in welding g. Longitudinal & circumferential welding h. Integrated systems strategy/productivity i. Subarc welding 8. Materials and blades a. Material requirements: stiffness, density, fatigue-life b. Constituent materials used in blades: fibers, polymer mix, and composites c. Characterizing materials and cure d. Blade design and construction e. Mech properties and damage modes

Topical Summary of ENGR 340, Introduction to Wind Energy: System Design & Delivery
(continued)

9. Turbine/blade nondestructive evaluation a. What is NDE, why and when is it usedb. Types of NDE: visual inspection, liquid penetrant inspection, magnetic particle inspection, ultrasonic inspection, eddy current inspection, radiographic testing, thermal inspectionc. Applications to wind turbine components10. Life cycle analysis: a. Economics analysis: levelized cost of energyb. Expected lifetime and retirementc. Materials in blades/towers: disposal methods11. Transportation: a. Safetyb. Legal aspects: laws & regulationsc. Turbine size and truck sizingd. Wind turbine haulinge. Escort regulationsf. Operational issues and logisticsg. Time and costh. Vehicle performancei. Highway design standards12. Turbine tower design a. What is designb. Design vs. constructionc. Understanding the constraintsd. Conceptual designs: lattice towers, tubular towers, concrete options, offshoree. Focus on utility scale/steel tubular designsf. Tower mass vs. powerg. Future designs for increased heights: concrete and concrete/steel hybrid; cast-in-place optionsi. Design approach: define loads, perform analysis, derive dimensionsh. Example calculations13. Foundations a. Design requirementsb. Foundation typesc. Geotechnical engineering: overview: Soil mechanics, site investigations, in-situ tests, laboratory tests.d. Design example14. Construction a. Construction process: idea→plan→scheduleb. Constraintsc. Critical pathd. Duration, lag, and delays	

Topical Summary of AER 481. Advanced Wind Energy: Technology and Design

1. Aerodynamic Loads
 - a. Power in the wind (PW)
 - b. (Ideal) Power extracted by the rotor (PR)
 - c. Control volume approach (momentum based)
 - d. Induction Factor
 - e. Individual blade
 - f. Combining momentum and blade element theory
 - g. Optimum turbine design
2. Dynamics and control
 - a. Control system and rated power
 - b. Passive stall regulation (constant pitch)
 - c. Pitch regulation (active stall)
 - d. Yaw control (small turbines)
 - e. Yaw error
 - f. Control subsystem
3. Structural loads and deflection
 - a. Types of loads (HAWT)
 - b. Source of loads
 - c. Blade loads and bending moments
 - d. Fluctuating loads
4. Electrical generator and load matching
5. Statistical analysis using skew functions
 - a. Determination of Weibull parameters k and c
6. Macro and Micro Siting
 - a. Energy Potential
 - b. Statistical characterization
7. Design Choices
 - a. Turbine components
8. Advanced Topics
 - a. Acoustics
 - b. Modern trends in design
 - c. Forecasting
 - d. Permitting
 - e. Radar interference
 - f. Avian issues
 - g. Legislation

Topical Summary of EE 459. Electromechanical Wind Energy Conversion & Grid Integration

2. Introduction a. Industry status, expected national growth and transmission needs b. Wind energy technology c. Levelized cost of wind energy d. Capacity factor vs. capacity credit 3. Overview of wind energy components & concepts: towers, rotors, gearboxes, generators, blades, collector ccts, meteorological principles 4. Types of electric gens: fixed speed induction, double-fed induction, permanent magnet direct-drive synch 5. Fixed-speed squirrel-cage induction generator (SCIG): equivalent circuit and analysis 6. Variable-speed SCIG 7. Double-fed induction generators – steady-state a. Basic concepts b. Equivalent circuit, per-phase steady-state model c. Referring quantities d. Voltage equations e. Power relations f. Torque expressions g. Torque-slip characteristic h. Airgap and slip power i. Power balance j. Generator modes k. Phasor diagrams l. Efficiency m. Wind turbine control levels i. Rotor and grid-side control to regulate power flow between grid & generator ii. To control the amount of energy extracted from wind by wind turbine rotor iii. Responds to wind-farm or grid-central control commands for MW dispatch, voltage, frequency, or inertial control n. DFIG with non-unity power facts 8. Double-fed induction generators – machine model a. Voltage equations b. Flux equations c. Application of d-q-0 transformation d. Rotor circuit transformation 9. DFIG dynamic analysis a. Space vectors b. Reference frame transformations: i. α-β transformation ii. d-q-0 transformation	a. Torque in abc quantities b. Torque in d-q-0 frame c. Power in d-q-0 frame d. Stator voltage-oriented control e. Cntrl relations in terms of torque & pwr f. Sequence control of rotor-side converter g. Function of grid-side converter 9. Voltage source converter a. Basic topology b. Grid-side converter (GSC) design c. Harmonic analysis of GSC switching d. α-β components of voltages e. Space-vector diagram f. Dwell-time calculation g. Switching sequence h. Space vector from switching sequence 10. Transient freq perf & wind penetration a. Potential for inertia decrease b. Power balance-frequency analysis c. Frequency performance analysis d. Impact of low transient freq dips 11. Regulation/load following & wind pentrtn a. Automatic generation control: dynamic and steady-state formulations/analysis b. Wind's effects on cntrl perf standards c. Based point calculation via RT markets 12. Handling wind pwr variability/uncertainty a. Basic problems, potential solutions b. Wind power from the air stream c. Net load variability d. System control, solutions (incl storage) 13. Wind and markets a. Basics of electricity markets b. Wind and markets c. Dispatchable intermittent resources 14. Wind & expansion planning: capacity credit via effective load carrying capacity 15. Collection circuits a. Topologies b. Underground design: soil thermal prop, cable temperatures, thermal backfill, conductor sizes, ampacity calculations c. Equivalent collector systems 16. Interregional transmission design 17. Offshore technologies 18. Power quality issues and protective relaying

Topical Summary of I E 443. Wind Energy Manufacturing

- Engineering Economy: set economic stage upon which most of the design and manufacturing decisions must be made upon
- Blades:
 - Materials: glass, carbon fiber, resins, bond paste, balsa vs. foam
 - Processes: layup methods, vacuum infusion, automation methods and needs, alternative manufacturing methods, painting and finishing operations
 - Quality requirements: waves and other defects, measuring waves dry and infused, testing, surface finishes
- Towers:
 - Materials: steel vs. composite vs. concrete
 - Processes: welding, rolling, forming,
 - Quality requirements: creating door opening; welding process requirements, minimizing stress concentrations
- Nacelles:
 - Materials: steel vs. iron for large castings, gearbox vs. direct drive
 - Processes: assembly processes, metalcasting processes
 - Quality requirements: assembly variation, casting quality and design for casting
- Product specifications and standards
- Supply chain decision making
 - What is driving domestic vs. import decisions
- Transportation:
 - Cost and constraints
 - Options as components get larger
- Sustainability
 - End of life disposition decisions for all components
 - Economic impact of recycling or not
 - Alternative solutions for blades, thermoplastic vs. thermoset resins; beneficial reuse options for the materials.

APPENDIX B: COMMENTS FROM PROGRAM REVIEWERS

General Comments:

- As a general comment, I am very impressed and I believe you and your team have done a great job. You have accomplished a great deal within the span of just two years. This no doubt reflects my own personal interests and concerns, but my only general observation is to wonder if building a relationship with the College of Business or the Public Policy program would also be useful down the road. Admittedly, this is beyond the scope of your DOE project and may be more appropriate at the graduate level, and perhaps it is best done through guest lectures or special conferences, but I do see a growing need for graduates who understand the policy and power market issues around renewable energy and especially as it relates to grid integration. Some of this is touched on in ENGR 340 and EE 459, but perhaps the lectures about power system operations, power markets, grid integration of wind energy, and policy could also be used in a more policy- and business-focused class, thereby making them available to students who may be put off by the engineering aspects of the current classes. Just an idea for the future...
- The report describes a program at Iowa State University for development of an undergraduate minor in wind energy. This Wind Energy Minor consists of two mandatory courses that are wind energy specific and 9 credits of elective courses. The electives can be selected from a set of 20 preapproved courses that have a strong relationship to one part of wind energy or another. Three of these courses are wind energy specific. The prospective Wind Energy Minor candidate would need to have their selected coursework approved by the Wind Energy Minor Oversight Committee. The approved courses that are not wind energy specific will have only a tangential relationship to wind energy so the oversight Committee will need to be careful to guide the students into a suite of courses that fill in important aspects of wind energy technology. All of the requirements of the major course of study will remain intact. It is important that the Wind Energy Minor not be interpreted to replace any elements of the core coursework in the major area, since the future success of the student will depend more critically on having built a solid foundation in a major area than in having been exposed to wind energy through the broadening experience of the minor degree.
- Regarding the final report:
 - I believe it would add value to list the departmental affiliations of the ISU project team that developed the program. I expect it will show that all of the departments who will be represented on the oversight committee participated in the development. If there was a chair or vice chair, they should be indicated here as well (your name on the top of list is indicative that you lead the group, but I'd make it explicit). That would make it easier to follow-up with a team leader, rather than just guessing at whom to follow-up with.
 - In Section 1, there is a rather extensive list of the areas a student might participate in. One area I noticed missing from the list is construction.
 - Point three of section 2 (ISU Wind Energy Minor Program) indicates that students will have breadth in multiple areas and depth in at least one area. I didn't see where the curriculum included any requirements to achieve depth in a single area. I believe depth in an area would be an advantage when pursuing work in that specific area of wind. Providing some insight into which electives support which career areas would be helpful for students.

- As a nit, the cover page of the Appendix lists AER E 341 as having a topical summary included, I believe this should indicate AER E 381.
- A couple of topics that I didn't see covered in the various courses were Safety and Balance of Plant. Balance of plant is intended to address the electrical collection system, and SCADA system and any other components not included within the turbine itself, but key to a successful wind farm. Safety as a topic speaks for itself.

Answers to questions:

A. Individual course assessment: For the following courses, what modifications would you make in terms of coverage, under the assumption that no material can be added to a course without eliminating some existing material?

1. Required courses:

a. AER E 381

- Looks good as an overview class. While the meteorology topic doesn't show much detail in the outline, I assume that you have a lecture on the basics of boundary layer meteorology and that seems adequate for this type of class.
- No specific mention of Doubly-Fed or Perm. Magnet/Full conversion technologies in the syllabus. Is this covered under sections e, f, or g? If not, should there be high level discussion of conversion technologies in this course?
- Leave as is.
- This appears to be a well-structured overview of wind energy technology encompassing history, resource, fluids, mechanics, and aerodynamics. Depending on how the individual instructor fills out the outline, it has the potential to provide a well-rounded and general background. One curiosity is where "Losses due to swirl" is noted. This is not a major source of inefficiency, but there are other sources that are critically important to understanding why turbines are put together the way they are. There should be a section devoted specifically to losses that discusses tip losses, optimal twist and taper (and why it is never employed), drag losses, and the issues around tracking the peak efficiency operating point (peak CP) in variable speed operation. It would also be very useful to include a section on the market and manufacturing differences between small and large turbines, reflecting on the differences between configurations of each that are proving successful. In the way of removing material, it seems more in depth than necessary to describe the details of Eulerian vs. Lagrangian approaches, or Reynolds and Mach number effects. These seem inconsistent with the sweeping overview of the rest of the course. Also, many of the items listed under Performance of Wind Energy Systems are not commonly used in wind circles to my knowledge, including wind speed duration curve, power duration curve, energy pattern factor, and spectrum averaged power. The discussion of gearbox moments of inertia seems too much in the weeds, as do some of the discussions within the area of the generator. It will be difficult to teach Kirchhoff analysis and to find a practical use for it within the time constraints of this

course. The wind turbine yaw control discussion includes active stall, which is almost never used any more. However, the important issues of control related to start up, shut down, and safety are not mentioned. Finally, the economics of the balance of station is not mentioned in the final section and must be included for a discussion of utility scale wind plants.

- In general, I am impressed with how much you include in the these two courses. I couldn't think of any significant area that was not covered.
- Item 1f – Wind Farm Development. A good topic, based on my experience it will need to include physical wind turbine siting, permitting requirements, land easements, transmission availability and the electrical interconnection requirements. All of these are fairly in-depth issues facing wind development.
- Item 13 – Economics of Wind Electric Generation. There are a couple of angles on wind turbine ownership and economics that may not be totally captured in sub-topics.
 - Wind turbines can be owned by utilities or non-utility entities. There are some significant differences between the two.
 - Revenues can be through utility rate base, power purchase agreements, or market prices. The impact of the investment tax credit and/or portfolio renewable energy standards cannot be over emphasized.

b. ENGR 340

- Coverage seems good to me.
- Nice comprehensive coverage. Should there be mention (albeit high level) of grid code requirements / performance requirements (like voltage regulation, fault ride through, frequency control, etc) mentioned somewhere in this course? Perhaps concurrent with the policy and/or design discussions?
- Add wind forecasting to grid operations; deemphasize construction, transportation and supply chain.
- This is a good overview of wind energy that gets into a higher level of technology than the AER E 381 can do. The two courses could make an excellent foundational pair, if the instructors are careful to avoid duplication, but use common topics to reinforce and build on content from the first course. The syllabus appears very optimistic in the level of detail that can be covered, but that is not my particular area of expertise. There are a couple minor points that could be revisited. Radar interference should be included among the Grand Challenges. I have never heard of a wind stream speed ratio. Filament winding of blades is never done (and is unlikely to ever be used in large blades) – perhaps fiber placement or tape laying is the intended topic. Materials discussions can be enhanced with a look at specific stiffness, i.e., the ratio of material modulus to density, which is remarkably constant over a wide range of material choices. The application of NDE to wind turbines is difficult given the size and number of machines used in a full wind plant, making the number of inspections

very large compared to comparable power levels of fossil plant. However, it is an area worth discussing as manufacturing QA will certainly depend on such methods more and more. The range listed looks like a text book table of contents – not all will be interesting in wind applications. Overall, this is a very comprehensive and well-constructed syllabus. Best of wishes fitting it all in.

- One term that I didn't quite understand in Course ENGR 340 was item 6f: "Compositing composites". I know what composites are, but I wasn't familiar with using it as a verb. Item 10 b has "Expected lifetime and retirement". Maybe you should include the term "refurbishment" because I think this will be a big and challenging field due to the favorable economics of keeping a turbine running longer. Item 12d has "Conceptual designs: lattice towers, tubular towers, concrete options, offshore." Another design is self-erecting towers.
- Item 1j – Grand Challenges for Wind. I'd add energy storage to the list. Once someone economically solves that issue, wind will look a lot more attractive.
- Item 14d – Construction, Duration, lag and delays. One item that needs to be included in this section is weather impacts. One of our biggest construction schedule challenges is excessive wind. In addition to wind, lightning keeps us out of the towers and prevents parts unloading, and excessive rains can make the rural roads we're using to get to turbine sites effectively impassable for the large turbine component trucks.

2. Elective courses:

a. AER E 481

- Less detail was provided, but it seems good. The "advanced topics" areas could cover a lot of ground.
- Looks great.
- Add turbulence and non-uniform flow; deemphasize vertical axis machines
- This course gets into the fundamental nuts and bolts of designing a wind turbine and would be great if matched with a design project. The coverage is good with a couple minor issues. Active stall is no longer used in large turbines. Statistical analysis is critically important to understand for wind systems where every aspect of the system is operating as a stochastic process. However, the use of skew functions seems to be an odd focus in wind energy applications. Perhaps more traditional analysis should be done by starting with the method of bins as a basis to introduce distribution functions which leads to understanding the distribution of total energy across wind speed. It might be more in line with the design aspects of the course to replace the advanced topics of permitting, radar, avian issues, and legislation with something like active controls, offshore fixed and floating systems, airborne wind, and other technological approaches.
- No comments.
- Nothing jumped out at me from the other course information you provided.

b. EE 459

- This class looks to have very good coverage for the Electrical Engineering-oriented student. Do students get enough background on power system operations (or already have it from other EE classes) to appreciate the issues around wind integration and markets?
- Same comment regarding codes/standards requirements for ENGR340, perhaps a more detailed coverage of the issues regarding compliance and performance (?)
- Expand electricity market design and operation; deemphasize storage technologies and hybrid configurations.
- This is another well-constructed course. The only comment here is that it seems odd to put the topic of controlling the amount of energy extracted from the wind as a sub-sub topic under Double-fed induction generators. This should be a major section of its own in which the subject of the need to regulate maximum power output in high winds. The electromechanical combination of pitch controlled blades in combination with the choice of generator type and power electronics design will determine the effectiveness of keeping everything together while maintaining rated power in high winds. The transition from Region 2 to Region 3 operation (below to above rated wind speed) is also an important subject to address.
- No comments.

c. IE 443

- Coverage seems good to me.
- Looks great.
- Provide context for course with review of global wind turbine manufacturing capabilities and resource availability.
- This course also has the potential to be an excellent overview of the kinds of manufacturing processes used for the various parts of the wind turbine system. My only comment is that the term “Nacelles” is sometimes confused, since the cover that houses the mechanical systems at the tower top is sometimes called the “Nacelle”, not referring to any of the mechanical systems within. It would be better to call out drive train, generator, and supporting structure specifically.
- No comments.

B. Overall program:

- a. Do you believe students who complete this minor program will be attractive employment candidates for organizations involved in wind energy?
- Yes, I believe that this minor would make them more attractive to companies and organizations involved with wind energy.
 - Yes. The program gives relatively comprehensive coverage of the relevant topics facing the wind industry today.
 - Yes.
 - The students will be attractive employment candidates IF the wind energy minor is combined with sound fundamentals in the area of their major. The greatest disappointment I have had in working with those who have wind energy related degrees is in those rare cases where the focus on wind

has detracted from their fundamental understanding of the physics of the system or their ability to conduct engineering evaluations of such systems. This is rare, but will always speak poorly of the institution that granted the degree.

- They should be. These provide an excellent background.
 - I recently completed the interview process for an Engineer 1 – Wind in my group. If any candidates had completed the wind energy minor program, I would have taken a closer look at their qualifications and they would have had an increased likelihood of getting a telephone interview. It's clearly a differentiating item, but it's only one of a variety of factors influencing a hiring decision.
- b. Are there particular types of wind energy-related organizations for which students completing this minor program are well-prepared for employment? If yes, can you identify or characterize the types of organizations you feel students completing this program would be well-prepared for employment?
- They would be particularly well prepared for engineering positions in turbine, blade and component design and manufacturing companies. It is difficult for me to judge from the materials provided, especially since I do not know the other classes that typical students may already take in their majors, but it would be very useful for power engineers to be exposed to these classes before they join electric utilities or power system operators. In fact, exposure to the material covered in this minor would be useful for many engineers to have before they join the work force even if they won't be directly employed in a renewable energy company.
 - 1)Wind Manufacturers 2)Project owners/developers 3)Policy Makers (FERC, NERC) 4) Investment firms (specializing in renewable energy) 5)Power Utility Companies (non-engineering)
 - Yes. Wind turbine design firms, wind plant design and development firms, owners, and operators.
 - My background has been exclusively in research and development where bachelor level degrees have a limited value. The interesting question to me is therefore how this program might prepare and inspire students to enter graduate school with the intent of gaining the necessary tools for wind energy related R&D. I think this is an outstanding program on which talented and motivated students can build toward a graduate program that is well informed of the nature and needs of the wind energy community. The students should be encouraged to make contact with faculty at ISU who are engaged in more advanced wind energy research, and linked to other universities with opportunities for graduate-level study.
 - Companies that develop wind farms could use people with this type of broad background. I believe wind turbine manufacturers would also see these students as being ready to "start work".
 - I think the determining factor on which types of wind energy related organizations will find students attractive will depend in part on the wind energy electives they select, as well as how it fits in with the rest of their coursework.

- c. Are there particular types of wind energy-related organizations for which students completing this minor program would not be well-prepared for employment? If yes, can you identify or characterize the types of organizations you feel students completing this program would not be well-prepared for employment?
- As noted in my general comments above, combining some portions of these classes with broader understanding of electricity policy, power system operations, power markets, grid integration, and business could be a good future step, as I see a role for generalists who can cross the boundaries between engineering, policy and business. But this is difficult to pull together and probably is more appropriate at the graduate level.
 - Short Answer: NO. However, concerning 1) Power Engineering Consulting 2) Power Utility Companies 3) Manufacturers -- I believe consulting organizations and power companies seek to employ graduate level students, particularly for their engineering and operations staff. This undergrad program provides an excellent base for students to ascend to graduate level work in this field. I believe a combination of undergrad and grad work in these topic areas would be highly attractive to power engineering consulting companies as well as more advanced engineering positions within manufacturing companies and power companies.
 - Yes. ISO/RTOs in the field of market design and operation.
 - See above.
 - The only areas of employment where these courses might not produce a graduate with enough experience might be research labs that work on specific areas, perhaps dealing with material sciences or advanced electrical design. These areas would likely require masters or PHD candidates anyway.
 - Coursework only takes students so far. If you look at the history of where the people working in wind have come from, my experience is that most of us have come from related industries, very few have only worked in wind. A few years experience in a related industry may be required before a student will be able to transition into a wind related job.