A Multidisciplinary Undergraduate Alternative Energy Engineering Course

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Abstract*—*Contribution: **A novel multidisciplinary undergraduate course on alternative energy (AE) engineering that addresses gaps in current AE education, provides hands on skills, and matches topical coverage with societal needs.**

Background: **Resource depletion and emissions associated with burning fossil fuels have led to growing worldwide interest in electricity production from non-fossil fuel, or alternative, energy sources. Recently there has been rapid growth of AE sources such as wind and solar photovoltaics. Societal and economic factors contribute to this continuing trend. Recent research has shown the urgent need for structured AE course curricula; engineering education in this multidisciplinary field is essential to support continued growth in this field.**

Intended Outcomes: **A new approach to AE engineering education at the undergraduate level. Specifically, a comprehensive multidisciplinary approach that fills identified gaps in AE education.**

Application Design: **The design of the course includes lectures, laboratories, and a hybrid power system design project focusing on economic integration of AE in power systems. Topics include principles of energy conversion, energy storage, and integration of solar thermal, solar photovoltaic, wind, hydroelectric and fuel cell AE sources into power systems. Societal needs are addressed through focus on industry structure, technology, economics and policies pertaining to AE.**

Findings: **Learning outcome assessment demonstrate the validity of the proposed course for multidisciplinary alternative energy engineering education.**

***Index Terms*—Alternative energy, electrical engineering, higher education, laboratory, multidisciplinary, solar energy, wind energy.**

I. Introduction

INSTALLED capacity of alternative sources of energy has recently been exhibiting exponential growth. A corresponding development of education in this field is occurring [1]–[11]. Motivation includes the renewable nature of these energy sources and reduction of greenhouse gas emissions. There are also many global and regional initiatives supporting growth in non-fossil fuel based sources. For example, in 2012 the U.S. Department of Defense (DoD) announced a $7 billion renewable and alternative energy power program through a Multiple Award Task Order Contract (MATOC) [12], and a U.S. Department of the Army net-zero energy program has been developed [13]. In support of these efforts and motivations a senior-level undergraduate multidisciplinary engineering course on alternative energy (AE) engineering was created.

A global status review on renewable energy education has recently identified twelve recommendations for improvement [14]. Those pertinent to university-level education programs helped guide design decisions in this work. It was noted in [14] that there is an urgent need for development and implementation of structured course curricula, a mix of academic and hands-on skills (laboratory experiments, software, site visits), and the matching of topical coverage with societal needs. The main contribution of this work is a novel undergraduate multidisciplinary AE engineering course, suitable for a wide range of engineering disciplines, that address these needs. Course content is available upon request.

Table I compares existing undergraduate (U) and graduate (G) university-level courses [1], [4]–[11] to this work (XE442). Significant depth of topical coverage is indicated (e.g., power electronic (PE) converters and their controllers are designed and simulated in [4]). In XE442, coverage of PE converters and control includes higher-level functionality and system design. Some courses require electrical engineering background (El), are lower-level general education courses (G), or are part of an energy engineering program (E). XE442 is differentiated by a focus on a breadth of AE sources, the multidisciplinary (MD) nature of the course, and coverage of pertinent policies, economics, and integration of AE sources into power systems. The work in [1] is the closest in comparison, but lacks a lab component, is a graduate-level electrical engineering course, and lacks the comprehensiveness of XE442.

The topic of AE engineering is inherently multidisciplinary. The effectiveness, and the necessity, of such a multidisciplinary approach to an AE topic is discussed in [1]–[4] and [15]. For example, in teaching the functionality and integration of fuel cells in a combined heat and power application, topical coverage must include power electronics, power systems, controls, chemistry, thermodynamics and economics. Policies and policy makers also play an important role in AE, as discussed in [15], and should be included in a comprehensive AE course.

This paper is divided into five sections. Section II discusses course objectives and topics, followed by Section III discussing specific learning tasks and assessment. Section IV reports and discusses the assessment of learning outcomes, and Section V makes concluding remarks.

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TABLE I
RENEWABLE/ALTERNATIVE ENERGY COURSE COMPARISON

	XE442	[1]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
Level	U	G	G	U	U	U	U	U	U	G
Focus	MD	El	El	El	El	G	E	El	G	El
Wind Power	✓	✓	✓		✓	✓	✓			✓
Solar PV	✓	✓		✓	✓		✓	✓	✓	✓
Solar Thermal	✓					✓				
Fuel Cells	✓	✓		✓		✓				
Hydro	✓	✓								
Control			✓	✓				✓		✓
Power Electronics			✓					✓		✓
Policy	✓	✓	✓							
Economics	✓		✓							
Grid Integration	✓	✓	✓		✓		✓			✓
Lab Component	✓						✓	✓	✓	✓
Design Project	✓	✓			✓			✓		✓

TABLE II
COURSE CONTENT AND STRUCTURE

Description	Lecture/Lab Hours	Assignments and Exams
Introduction to Alternative Energy and Power Systems	5/0	-Circuits & Power Review -Homework 1
Fuel Cells and Combined Heat and Power	4/2	-Homework 2 -Exam 1 -Lab 1
Solar Energy	10/4	-Homework 3 and 4 -Exams 1 and 2 -Lab 2 and 3
Wind Energy	7/0	-Homework 5 -Exam 2
Hydroelectric, wave/tidal and geothermal energy	3/0	None
Alternative Energy Power System Integration	8/0	-Software tutorial -Design project

II. COURSE OBJECTIVES AND TOPICS

The Alternative Energy Engineering course (XE442) was developed as an undergraduate senior-level, multidisciplinary engineering course at the United States Military Academy (USMA). XE442 is an elective which requires courses in fundamental physics, differential equations, chemistry and introductory electrical engineering (EE) (covering AC and DC circuit analysis) as prerequisites. Most engineering curricula include these courses, and XE442 has been taken by electrical, mechanical, chemical, nuclear, and environmental engineering students. XE442, required for students selecting the AE-focused depth option in the EE curriculum, is a developmental course supporting student research in AE. Recent research has shown that proper education in AE "includes a study of technology, resources, system design, economics, industry structure and policies in an integrated package" [2]. Given this, and the renewable energy education recommendations in [14], key design decisions when developing XE442 were to include:

- A multidisciplinary focus supporting numerous undergraduate engineering majors.
- Hands on laboratory components and site visits.
- A focus on integration of AE into power systems to include a software based design project.
- A focus on political, societal, and economic factors pertaining to AE.

The course's intended learning outcomes, used for assessment purposes, are that students should:

1) demonstrate knowledge of energy conversion, economic analysis, and policy impacts pertaining to fuel cell, solar photovoltaic, and wind energy systems.
2) construct appropriate models, and estimate the energy production, of solar thermal, solar photovoltaic, fuel cells, wind power, hydroelectric, and geothermal energy sources.
3) demonstrate problem-solving skills by developing a high-level design for integration of intermittent solar- and/or wind-based alternative energy sources.
4) execute laboratories, that include model development and validation, with fuel cells, photovoltaic cells, photovoltaic panels and the associated energy conversion circuits.
5) demonstrate effective oral and written communication skills through laboratory reports and a design project report and presentation.

The course content and structure is shown in Table II. XE442 is a three-credit hour, single-semester course, comprised of lectures (55 minutes in length), in and out of class exercises, laboratory exercises (120 minutes in length), a final design project, and a Term End Exam (TEE). Site visits to AE installations are also included. An instruction methodology of learning (readings and in class instruction), practicing (in and out of class problems and homework assignments), and demonstration (labs, exams, final project) is employed. Outcomes are assessed in the demonstration phase (culminating events for a block, or the entire course).

To meet current societal needs, there is a large focus on fuel cells, solar energy and wind energy, as these are the most prevalent AE sources, have recently exhibited the most growth, and show the most promise for use in the immediate future. Each block focusing on an AE source consists of an introductory lesson(s) on recent trends, policy impacts, and quantification of available resources (e.g., solar radiation). This is followed by lessons on energy conversion from fundamental principles, system modeling, integration into power systems, and economic analysis of these technologies.

A. Introduction to Alternative Energy and Power Systems

The objective of this block is to provide the context of existing power systems for the purpose of integrating AE sources, and the tools to analyze policy impacts and economics of AE. The block contains an introduction to AE engineering that covers fundamental definitions, trends in AE, electric power industry, and comparisons to traditional fossil fuel-based energy sources. A review of electrical power and power systems concepts is included. Lastly, a detailed coverage of electrical energy economics and energy policies is provided. Focus is placed on energy/demand balance and on how a portfolio of energy sources provide for electric demand in an economic, market-based fashion. The concept of levelized cost of energy (LCOE) is introduced, and applied to traditional energy sources, to allow for equitable economic comparisons between traditional sources of electrical energy (e.g., coal power plants) which have high operating (fuel) costs, and AE sources which have high capital costs and low operating costs. Economic analysis of utility-owned AE (to augment or replace traditional sources) and customer-owned AE (net-metered, time-of-use, tariff rate structures) are covered in depth. An overview of generation scheduling and energy markets, in the context of high AE penetration and curtailment impacts to LCOE, is included.

B. Fuel Cells and Combined Heat and Power

The fuel cell block has four lessons and a laboratory. The first lesson focuses on energy conversion from first principles (chemical reaction and catalysts) and sources of fuel for fuel cells (type and production). The next two lessons discuss electrical characteristics, derive a detailed non-linear fuel cell model and a simplified linear model, and examine fuel cell types and applications. The final lesson is a case study of integration of fuel cells in both standalone and combined heat and power applications, with a focus on high-level system design, evaluating LCOE, and economic and technical comparison to traditional heating and electrical systems.

C. Solar Energy

The solar energy block is comprised of two labs and ten lessons; it starts with an introduction to the topic, and the measurement and quantification of solar resources in terms of solar irradiance spectrum and energy density (W/m^2). The fundamental energy conversion principles of photovoltaics (PV), including a study of PV materials and cell structure are covered, and extended to the construction and configuration of PV modules. Detailed models are developed for PV cells and PV modules; these are extended to high-level PV system design and the estimation energy production based on installation location and solar resources. PV system economics is evaluated based on LCOE and long term energy production estimation (e.g., 25 years). The block ends with the design of an off-grid PV system incorporating energy storage.

D. Wind Energy

The wind energy block consists of seven lessons, the first of which gives an introduction to the topic and quantifies power and energy density within wind. This is followed by a lesson on wind turbine structure and energy conversion based on fluid dynamics. Specifically wind energy is converted to mechanical energy which is then converted to electrical energy. Later lessons focus on studying and quantifying wind regimes, estimating wind turbine and wind farm energy production over time, and evaluating the economics (LCOE) of wind turbines. The final lesson examines a wind energy case study at USMA that is based on real collected wind data.

E. Other Alternative Energy Sources and Integration of Alternative Energy Sources

A three-lesson block studying emerging AE sources (concentrating solar, geothermal and micro hydroelectric) is followed by eight lessons on AE integration in power systems, which cover smart grid technology, demand side management concepts applied to the integration of AE (e.g., cost/benefit analysis of adding AE generation and/or reducing energy demand), and further economic analysis (net-metering, feed-in tariffs, renewable energy credits, and carbon taxation impacts) including sensitivity analysis. The course concludes with an AE design project and presentation.

III. Learning Tasks and Assessment

A learn, practice, demonstrate methodology is employed in XE442 to educate the students and achieve the learning outcomes. Initial learning consists of individual reading, lectures, sample problems, and individual instruction on an as-needed basis. The practice phase follows by engaging students with in class exercises, culminating case studies, and homework assignments. Lastly, students demonstrate learning, and have their achievement of learning outcomes assessed, through labs, a final design project and the term end exam.

A. Laboratory Assignments

Three labs are included in XE442; their objective is to augment and validate classroom theory, and to provide hands-on experiences. Students characterize the behavior of the AE source, develop and validate models for these sources and analyze the integration of these sources into power systems, or as a stand-alone system. Each lab has a dedicated station with associated hardware, software, data acquisition equipment and experiments. There is one station dedicated to fuel cells, one for PV cells, and for PV array. Each lab is worth 60 points, allocated to having a prelab assignment to be completed prior to the lab (20 points), a laboratory experimentation component, and a formal written report (40 points). Labs are used to help assess outcomes 2 (prelim modeling and analysis), 4 (prelim modeling and report model refinement and validation) and 5 (report clarity and format). The labs have 180 points (3×60) in total, or 18% of the overall course grade (1000 points total).

1) Fuel Cell Laboratory: The prelab exercise for the fuel cell lab familiarizes the students with the lab station and the performance of the fuel cell. The lab station contains a 50W proton exchange membrane fuel cell, hydrogen tank, electric loads, and a DC to DC converter to provide a regulated DC output to a load. Additionally, students are tasked with analyzing the fuel cell specifications and estimating V-I and efficiency-I curves (10 points) and developing a model of the fuel cell (10 points). Three models are covered in the course (ideal, non-linear, and linearized models) and two methodologies are presented (derived from electrical specifications or from chemical reaction theory and stack construction). The modeling question is posed in an open-ended fashion, for which students must apply an appropriate model/modeling approach and justify their decisions. The nonlinear model is based on the equivalent circuit shown in Fig. 1, consisting of an ideal voltage source behind three resistive components. R_{act} and R_{conc} are nonlinear components modeling the activation and concentration losses respectively and R_{ohmic} is a linear

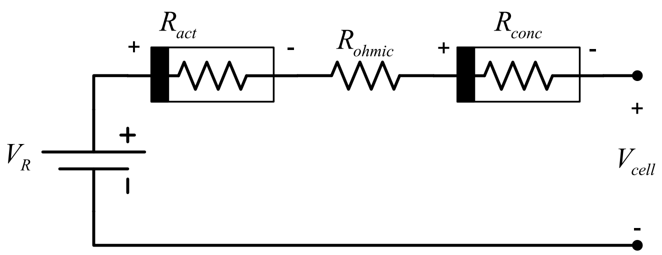

Fig. 1. Fuel Cell Equivalent Circuit.

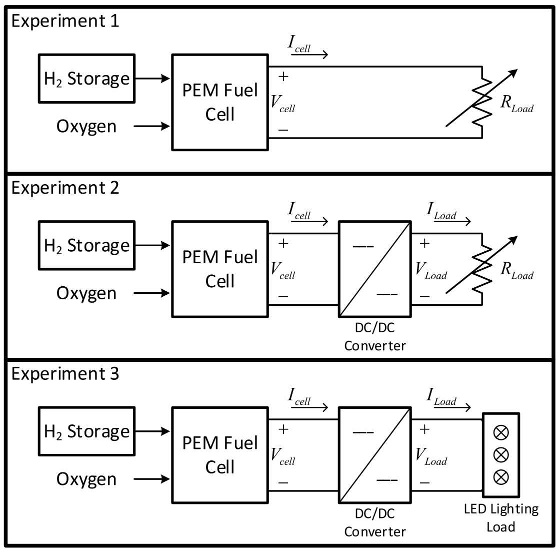

Fig. 2. Proton Exchange Membrane (PEM) Fuel Cell Experiments.

resistor modeling the ohmic losses. The model is [16]:

$$V_{cell} = V_R - ir - B\ln(i) - m \cdot e^{ni} \tag{1}$$

where:

$i \triangleq$ fuel cell current density $\left(mA/cm^2\right)$

$r \triangleq$ area specific resistance $\left(k\Omega\ cm^2\right)$

$B \triangleq$ constant modeling electrochemical reaction speed

$m, n \triangleq$ constants modeling concentration losses

The linearized model can be derived by linearizing the nonlinear terms in (1). The laboratory exercise consists of three experiments shown schematically in Fig. 2.

The first experiment isolates the fuel cell for characterization and modeling under various temperatures (28°C and 40°C). Students obtain I-V and P-I curves, and hydrogen-current (H-I) curves, evaluate the effects of temperature on operation, fuel cell efficiency, then refine and validate their model developed from the prelab. The following experiments investigate fuel cell integration. Experiment two integrates a DC to DC converter to regulate the load voltage. Specifically, voltage regulation and efficiency of the fuel cell system with a boost converter is investigated over a range of load levels. The third experiment incorporates a variable LED lighting load. The purpose of this experiment is to analyze hydrogen fuel requirements and efficiency for long term operation. The results are summarized in a laboratory report (theory and modeling is worth 10 points, lab procedure 5 points, and the results, analysis, and model refinement/validation 25 points).

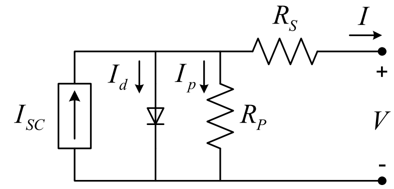

Fig. 3. PV Cell Model.

2) Photovoltaic Cell Laboratory: The PV lab station provides the capability of testing PV cells with a close approximation of the solar spectrum seen on earth. Key components include a class AAA solar simulator with variable solar irradiation output, a source-meter to load the PV cell and measure current and voltage, and software to operate the system and log data. The students were tasked with developing a PV cell model (10 points), and evaluating maximum power point, fill factor and efficiency from a sample I-V curve (10 points) in the prelab exercise. The model for the PV cell, shown schematically in Fig. 3, is [17]:

$$I = I_{SC} - I_0\left[e^{\left(\frac{q(V+I\cdot R_S)}{kT}\right)} - 1\right] - \left(\frac{V + I \cdot R_S}{R_P}\right) \tag{2}$$

where:

$R_p \triangleq$ resistance modeling leakage current at cell edges

$R_s \triangleq$ resistance modeling losses across PN junction and wiring

$I_0, I_d, I_{SC} \triangleq$ reverse satuation, diode, and short circuit currents

$k, q \triangleq$ Boltzmann's constant, electron charge

$T \triangleq$ junction temperature (K)

$V, I \triangleq$ PV cell outptut voltage, current

The first experiment consists of I-V curve testing on the reference PV cell at various irradiance levels between 400-1000 W/m^2. I-V and P-V curves are plotted for each irradiance level. These results are compared to theoretical expectations from the prelab exercise. An equivalent circuit model, maximum power point, cell efficiency, and cell fill factor are determined for each irradiance level. The second experiment investigates PV cell performance at various shading levels (25%, 50% and 75% of surface area shaded). The results are summarized in a laboratory report (theory and modeling is worth 10 points, lab procedure 5 points, and the results, analysis, and model refinement/validation 25 points).

3) Photovoltaic Integration Laboratory: The third lab focuses on modeling and grid integration of a 1.1kW PV array. The prelab familiarizes students with the system, PV panel performance analysis (5 points), PV array design (10 points), and development of a test plan for I-V characterization of the PV array (5 points). The first experiment isolates the PV array for modeling and characterization. Subsequent experiments have the student tie the array to the grid and analyze the short term performance (during the lab) and long-term performance (over the period of one year, with total energy production, capacity factor, seasonal variation, etc.) and compare these figures to the theoretical energy production estimate. For the

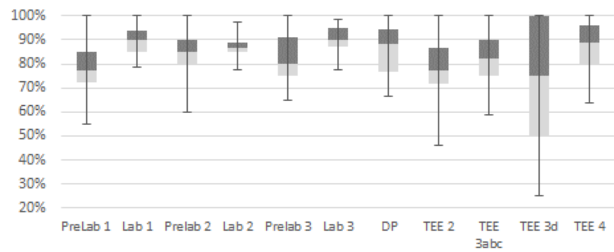

Fig. 4. Student performance for graded events tied to learning outcomes (36 students).

long-term performance analysis, students are provided with previously logged data.

For all labs, student performance is quantified and assessed directly from grading prelab exercises and laboratory reports. The results are summarized in Fig. 4. The rubrics for these assignments were designed such that a score of 80% correlates to meeting learning expectations. This standard was achieved, except for a few outliers in individual graded events. All students exceeded the standard on a combined assessment of laboratory preliminaries and reports. The modeling aspect of the lab preliminaries proved to be challenging and was the primary issue for the three students performing below standard. However, all students demonstrated proficiency in modeling in the laboratory report.

B. Design Project

The design project tasks students with developing an optimal hybrid power system design for either a grid-tied residential application or an off-grid application with diesel generation. HOMER software is used for the project [18]. A lesson is dedicated to optimization theory and a software tutorial. The students develop a high-level design of the system, subject to a number of constraints. Guidance for the grid-tied scenario is:

1) Develop a model of the system to include grid interconnection, load profile, and renewable energy sources/supporting hardware (outcome 3).
2) Estimate and model renewable energy resources based on the location of your home town.
3) Incorporate economic analysis to include grid energy pricing, renewable energy installation costs, operation and maintenance costs, and determine LCOE for the system over a 25 year period (outcome 1).
4) Develop an optimal system design (minimize LCOE) for a system which provides at least 40% of energy from an alternative source.
5) Perform sensitivity analysis on grid energy pricing and renewable energy resources to refine and/or validate your system design (outcome 3).

Students are told the costs of system components (PV panels, wind turbines, batteries), and which specific components to study. The students formulate the structure of the hybrid system design, and incorporate modeling of solar/wind resources and economic modeling for the entire system. Economic modeling includes installation and operation costs, grid energy pricing and interconnection agreement (grid-tied application), and diesel fuel price (off-grid application). Local and federal policies related to AE integration and incentives (e.g., rebates, net-metering, etc.) must also be accounted for.

The deliverable for the project is a formal report and a presentation of the results (60 points). The design must include the components and technologies selected, specific component sizes, ratings, search space for optimization, and a thorough economic analysis of the system. The design should meet all specifications and provide evidence of sufficient sensitivity analysis on solar/wind resources and grid energy/diesel fuel pricing to refine and validate the design. Initial system design is worth 25 points, 15 points for economic/resource modeling, 10 points for sensitivity analysis, and 10 points for final design. Student performance was assessed on the combined score for the report and presentation of the design project, Fig. 4. All but one student met the standard. Defining a sufficiently wide search space and having a sufficient fidelity of design choices for sensitivity analysis proved to be challenging to the students. Most were not well versed in optimization theory. However, the vast majority of them performed extremely well on developing a system design that met specifications.

C. Term End Examination

The Term End Examination (TEE) is comprehensive and worth 250 points (25% of total course grade). 100 points were allocated to short answer/calculation and multiple choice problems, and 50 points each to detailed problems on solar, wind, and fuel cell topics. In the following typical TEE problem on solar photovoltaics (problem 3 in Table III), which includes technical calculations and economics, parts a, b, and c are used in outcome 2 assessment, and part d in outcome 1 assessment:

A grid-tied PV array consisting of twenty 250W PV modules is installed in Las Vegas, NV at latitude – 15° tilt. Assuming 90% inverter efficiency:

a) Calculate average cell temperature, and temperature adjusted array voltage and power output at 1 sun of insolation. (15 points)
b) Estimate a derate factor and the AC output power of the system at 1 sun of insolation. (10 points)
c) Estimate annual energy production and capacity factor of the PV installation. (15 points)
d) The installation cost is $2.00/watt and the system is paid for by a 5% 20 year loan. Assuming a lifespan of 20 years, calculate the levelized cost of energy. (10 points)

A datasheet from a commercially available 250W panel and solar insolation/temperature data is provided to students to help them solve the problem. Student performance on TEE problems is assessed in a similar fashion as that on the labs and the design project.

IV. Learning Outcome Assessment and Discussion

A challenge in developing this course was making it multidisciplinary and approachable to a wide range of disciplines while satisfying the learning outcomes. The outcomes required

TABLE III
STUDENT LEARNING OUTCOME MAPPING AND ASSESSMENT

	1	2	3	4	5
Indicator (weight)					
Lab 1 (20/40)		2.56		3.15	3.75
Lab 2 (20/40)		3.33		3.42	3.50
Lab 3 (20/40)		3.08		3.56	4.03
Design Project (70)	3.53		3.53		3.53
TEE Problem 2 (50)	2.64	2.64			
TEE Problem 3abc (40)		2.94			
TEE Problem 3d (10)	2.81				
TEE Problem 4 (50)		3.33			
Overall Assessment	**3.13**	**2.98**	**3.53**	**3.38**	**3.67**
Standard Deviation	0.96	0.82	1.28	0.67	0.68
95% Confidence high	3.46	3.26	3.96	3.60	3.90
95% Confidence low	2.81	2.70	3.10	3.15	3.44

substantial "depth" and engineering rigor. Learning outcomes were assessed based on student performance on indicators in labs, the design project, and the TEE. The mapping of these indicators to learning outcomes, and assessment of learning outcomes, from 36 students is shown in Table III. To enable generalized assessment with qualitative and quantitative measures across multiple courses, all indicators are mapped to a scale of 1-5. Rubrics and mapping of raw scores were designed so that a score of three is considered as meeting expectations. Presently, all XE442 indicators are quantitative. The percentage scores from students are mapped to the 1-5 scale. A score $\geq 93\%$ is a 5, $\geq 87\%$ and $< 93\%$ a 4, $\geq 80\%$ and $< 87\%$ a 3, $\geq 70\%$ and $< 80\%$ a 2, and a 1 for scores $< 70\%$. The overall assessment of each outcome is a weighted average based on the number of points assigned to each indicator. For labs, there were 20 points for the prelab and 40 points for the lab report. Outcome 2 used prelab scores, outcome 4 used prelab and lab scores, and outcome 5 used the lab report scores.

The vast majority of students met the learning outcomes. The standard of 3 was met across a 95% confidence interval for outcomes 3-5. Average values of outcomes 1 and 2 were met or were very close to standard (outcome 2 was 2.98) and viewed as acceptable. Outcome 2 was difficult for students as it the most in-depth and challenging objective. Complex economic concepts proved to be challenging upon assessing outcome 1. Case studies, which include topics of both outcomes at the practice stage of the instruction methodology, have been modified to better address outcomes 1 and 2.

V. CONCLUSION

This paper presents a novel multidisciplinary undergraduate course on alternative energy engineering with laboratory and design project components. A comprehensive approach was taken in designing the course, which includes the study of AE technology, industry structure, resources, system design and power system integration, economics and policy impacts on AE. This paper fills existing gaps in AE education by focusing on a multidisciplinary approach at the undergraduate level, including three laboratories, and a hybrid power system design project. The prerequisite structure enables a wide range of engineering majors to take the course. Course content and details of lab equipment are available upon request for those wishing to implement a similar course. HOMER software and laboratory equipment are required. (A free version of the HOMER software is available.) Assessment shows that course learning outcomes are being satisfied. Future work includes continued assessment and improvement, and integration of a wind energy lab.

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