What makes a solar engineer?

Abstract

The international response to climate change has driven growing demand for engineers trained to design solar energy systems and integrate them into electricity infrastructure. There is a need for some guidance as to what training is necessary for future engineers to meet this demand. This study gathers data from literature, industry perspectives and current educational practice to help establish suitable learning objectives for training undergraduate engineers to be prepared for solar project development. In general, results suggest that students be trained to understand the complete workflow of concepts related to design of photovoltaic systems including solar positioning, the solar resource and irradiance data sources, design of a photovoltaic system from both a solar resource and an electrical perspective and performing calculations to model or support validation of photovoltaic systems. Professionals also highlighted the importance of discussing various types of typical financing structures for solar energy systems, though these were less common in existing courses. The paper summarizes these outcomes with a proposed set of learning objectives that encompasses these highlight areas and that could form the backbone of an undergraduate course on solar energy engineering.

Introduction

Climate change poses a serious threat to the status quo of human activity on the planet. Changes to typical weather patterns and the frequency of severe weather events that already occur are being attributed to climate change [1]. Evidence points to human production of greenhouse gases as the primary cause of these changes [1]. In response to these issues, governments have developed action plans that aim to reduce the utilization of fossil fuels, and transition toward long-term sustainable sources of energy generation, including renewables such as solar and wind. The United States' stated goal is to reach net-zero greenhouse gas emissions by 2050 [2]. It is estimated that in order to meet these goals, the energy workforce will need to grow substantially during that time period. The rate of solar photovoltaics (PV) deployment is projected to need to quadruple to meet these goals [3] and job growth related to solar deployment has already begun [2].

As solar PV represents an intermittent, distributed energy resource, it poses unique challenges to the operation of legacy energy systems including the electricity grid. Mismatch between generation and demand for electricity associated with distributed generation can lead to bi-directional flows of electricity on short term basis. It can also pose a challenge for power quality and overall grid stability. A greater share of intermittent generation on the grid is expected to exacerbate these engineering concerns. Thus, a future workforce of engineers with the knowledge base that prepares them to address these challenges is needed to enable the transition towards renewables to take place. This article describes efforts at establishing what knowledge base engineers need to possess to work in the solar engineering industry, which can guide educators whose job it will be to train those future engineers.

Background

It may be useful to benchmark the activity in literature related to solar energy education. As of January 2023, there are 356,636 publications corresponding to the search term “Solar Energy” on the Web of Science platform, whereas the search term “Solar Energy Course” resulted in 2,086 publications. The annual number of “Solar Energy Course” publications are around 50 each year up to 2009, around 100 between 2009 and 2014. A peak value of 190 was reached in 2018. Since then, there are, on average, 130 publications per year related to the search term.

The reported literature shows that solar energy topics were integrated into renewable energy courses or other engineering courses in different universities [4]–[7]. For example, a renewable energy course developed at Drexel University was targeted for upper-level undergraduates and early graduate students interested in renewable energy [4]. The course mainly covers photovoltaic and solar power and wind power in depth, with additional coverage on fuel cells, hydrogen, energy storage, and more. Plans for integrating a renewable energy course into power and energy engineering minor program at Southern University were reported by Belu et al [4]. The four credit-hour integrated lecture-laboratory course includes all renewable energy sources, but wind and solar energy systems make up 60% of the course. Hertzog and Swart described the design and development of a renewable energy course covering solar photovoltaic, solar thermal, and small wind systems at Central University of Technology in 2017 [6]. Twelve solar-related modules were prepared, such as the power of solar energy, solar steam turbines and absorber materials. They suggested that these modules could be incorporated into chemical engineering, mechanical engineering and/or electrical engineering courses. Jiao described how three modules - solar radiation, solar cells, and solar energy harvesting- were integrated into electrical engineering classes and how one graduate course focusing on designing PV systems was created at Grand Valley University in 2018 [7].

The reported literature also shows there are standalone graduate and undergraduate courses focusing on solar energy only. Some of these courses cover the chemistry, policy and material science aspects of solar energy. Pullen and Brinkert described a graduate course on solar energy and its integration into chemistry education curriculum [8]. The course included 7 modules covering solar policy, applied solar research and research perspectives. The course included lectures given by invited experts from different universities, governmental and non-governmental (industry) institutions. In addition, reading assignments including scientific articles were assigned. Discussion seminars and laboratory exercises were also included. Ciriminna et al. described a multidisciplinary solar energy graduate course that involved elements of science and energy engineering, as well as elements of economy, social, environmental and management science [9]. The student enrollment was limited to fifteen, and the basic knowledge of science was a prerequisite for the course. Different quality learning materials were utilized for the course: slides, multimedia resources including videos and webinars, technical reports, five different books on solar energy, hand on activities, tutorials on energy modeling using software such as HOMER, Helioscope and AutoCAD, and projects and field trips. Ramos et al. described an undergraduate solar course focusing solar resource calculations [10]. Seven learning activities were developed using solar irradiation data from the National Renewable Energy Lab (NREL) and MATLAB programming. It was reported that the participants had a positive class experience and learned how to use engineering principles to design a solar facility. Additionally, the literature revealed that there are descriptions of courses focusing on how to utilize programs such as TRNSYS and MATLAB, or lab experiments for solar energy analysis [11]–[13].

Besides programs for university students, there are also programs dedicated to educating the public and encouraging sustainable energy solutions. For example, an Engineering Research Center for Quantum Energy and Sustainable Solar Technologies program aims to advance photovoltaic science, technology and education through a Research Experience for Teachers program. It also hopes to promote broader solar energy education by developing an extensive set of K-12 curriculum materials on solar energy and PV engineering education [14].

In 2014, Kandpal and Broman provided a review on renewable energy education and training at university, school and professional levels. The authors concluded that one of the main challenges for renewable energy education is unavailability of well-structured energy curricula [15]. A formal survey on energy education was conducted in 2021 by CREATE Energy Center [16]. The survey was sent to over 700 faculty ranging from middle school to university level along with 150 industry representatives to examine energy industry trends and educational programming needs for the next decade. Solar photovoltaics was the top choice for growth and technological change. The survey showed that "support faculty and programs to meet workforce needs" was listed as the top priority that the CREATE program should pursue.

Methods

In order to identify coverage of topics related to solar energy in current university courses, we collected data on practices from sources within the field. Data about the importance of various topics within solar engineering education was collected by collecting and reviewing existing university course syllabi, and by conducting a survey professional and faculty perspectives.

Syllabus Reviews

Universities' course offerings related to solar energy engineering courses were investigated based on the results of an informal internet search. For each of the hits, we gathered course titles and descriptions from the universities' public websites and bulletins, specifically looking for course titles and descriptions that indicated a primary course focus on solar energy engineering. Courses that surveyed many renewable technologies and courses that discussed solar energy from a non-technical perspective were excluded. A list of 26 courses meeting these criteria was produced.

We collected syllabi for as many of these courses as possible by two methods. First, we performed internet searches for public resources on the web (e.g. faculty or course websites with posted syllabi). In the event that no published syllabus was available for a course, we contacted listed course instructors via email. Combined, this allowed us to obtain 17 course syllabi that were reviewed and analyzed in the results. A summary of all course offerings we identified, along with those that had syllabi available can be found in the Appendix.

Survey

An anonymous online survey was conducted to assess perspectives of instructors and professionals on the importance of several common topics. The survey collected simple demographics about area of work within solar and years of experience in the field. The survey then asked participants to rank several topics (as generated from a prior version of the authors' course syllabus) on a 5 point scale (0-Not at all important, 1-Low Importance, 2-Neutral, 3-Very Important, 4-Extremely Important). Open ended responses were provided for respondents to list any unlisted topics that they believed were important.

Results

The 17 syllabi collected were reviewed and summarized and an overview of the basic course characteristics is provided here. The majority of courses were at the undergraduate level (13) and the remainder were graduate courses (4). About half (9) of the courses were deemed to be more general courses geared towards design of solar systems, one third (6) focused on details of semiconductors, materials and fabrication of solar cells and the remainder dealt with unique topics (one focused on architectural passive solar and one on solar fuels). Only a few courses required prerequisites aside from a certain level of academic standing. The most common prerequisites among those courses that did specify them were Intro to Circuits or Heat Transfer, with fluid mechanics, thermodynamics and electro-magnetism (EM) physics also appearing. The use of required textbooks was uncommon; most textbooks that were listed were provided as reference materials. Some software tools were identified in the syllabi, including: EES: Engineering Equation Solver, PVWatts, Solar Pathfinder Assistant, System Advisor Model (SAM), Solmetric PV Designer and Helioscope.

Syllabi were reviewed by the investigators for topical coverage. The investigators first established a list of topics that were contained in the courses and then reviewed the syllabi to determine how many of the courses appeared to cover that topic, based upon lists of topics and/or course schedules. As all syllabi are different and different faculty may describe topics using different terminology, this process was somewhat subjective. A list of the frequency of topics is listed in Table 1.

The results of the survey are shown in Table 2. A total of 9 participants responded (8 professionals, 1 faculty), so results are based on a relatively small sample and should be interpreted with care. The respondents had varying levels of experience in the field (<2 years: 2, 2-5 years: 4, 10-15 years: 2, >15 years: 1). The topical Likert scale responses were converted to a numerical score. Based on the score of each level on the five-point scale (which ran from 0-4), a score of 2 would represent "Neutral" importance, with larger numbers indicating higher importance. The results show that topics related to design of PV systems, including at a detailed level, are perceived as most important by professionals. Topics dealing with understanding solar irradiance and data sources, sun charts and financing were also rated highly.

Table 1 - Frequency of Topics in Reviewed Syllabi

Topic	**# Syllabi**
Grid-tied PV Design	13
Solar Resource	10
PV Junction Model	10
Economics/Finance	7
Off-grid PV Design	6
Storage	5
Solar Thermal	5
Fabrication/Material Science of PV	5
Sun-Earth Geometry	4
Optical Properties of Surfaces	3
Policy	2
National Electric Code	2
Electrical Load	2
Site Survey	1
Architecture	1
Solar Fuels	1

Table 2 - Topic Importance Survey Results

Topic	Average Score
PV system design (strings, inverters, etc.)	3.7
PV electrical model	3.2
Working with irradiance data	2.9
Solar finance	2.9
Sun chart calculations	2.8
Types of solar irradiance	2.8
Clearness indices	1.9
Semiconductor physics	1.9
Solar thermal system design	1.9
Thermal radiation	1.4

The survey also provided space for open-ended responses about important any important topics that were not listed. Some replies were redundant with the rated list of topics, but a summary of topics identified in the open ended comments is as follows: power purchase agreements (PPAs) & community solar, codes & regulations, transposition models, geographic information system (GIS) tool skills, use of specific solar analysis software tools (PVSyst, SAM, pvlib, Aurora), forecasting of generation, integration of solar into buildings , additional plant hardware (transformers, switchgear, reclosers, relays, communications and controls), interpreting and validating modeled generation results, and storage.

Proposed Course Learning Objectives

Based upon the data collected, we have categorized three key units that could be used to make up a sample undergraduate engineering course focused on PV project development, along with learning objectives (following various Cognitive Domain levels of Bloom's Taxonomy) for each, shown in Table 3. One example course following this structure has been developed and offered for upper-division undergraduates at the authors' institution. Please note that these proposed areas are intended to be a summary of the knowledge collected from other workers that can serve as a starting point for expert faculty developing a course and should not be interpreted as a prescriptive, one-size-fits-all solution for all cases.

The primary areas that were commonly listed in the survey and syllabi that were not included in the proposed outline are design of solar thermal systems and fabrication/material science of PV as they were not indicated as critically related to PV project development. We do not in any way wish to minimize the importance of these topics, but suggest that they may be more suited for courses with a slightly different focus than that discussed here.

Conclusion

Results from a survey of professionals in the field suggest a need for engineering skills related to PV project development, with a deeper focus on skills needed to plan and analyze a proposed PV system both technically and economically. Many universities already offer courses that address these topics, though with a wide diversity in focus area and topical coverage. In this study, we have used collected data to describe commonalities in solar engineering education and to propose a common set of general units for an example solar development course, along with some candidate learning objectives. The three primary units proposed are Performing Calculations with Sunlight, Designing Solar Systems and Analyzing PV Systems. The learning objectives suggested for these course units are intended to highlight skills at different levels of Bloom's Taxonomy and to respond to the critical skills identified by professionals in the field. There is a significant need for engineers trained to work on solar energy systems in order to meet the needs of the future US energy transition and we hope that the present data can be a starting point for faculty preparing future engineers to achieve that goal.

Table 3 – Proposed Course Coverage Areas

Unit 1: Performing Sunlight Calculations - Describe interaction of solar irradiance with the atmosphere - Define the different types of solar irradiance commonly used in data sets - Describe the different sources of irradiance data including ground measurements and satellite derived data - Acquire irradiance data from available sources - Apply anisotropic transposition models to compute irradiance on a tilted surface - Compute a sun chart - Compute periods of shading based on a horizon - Describe different types of tracking
Unit 2: Designing Solar Systems - Compare and contrast common types of PV cells - Describe the operation of a PV junction - Explain PV cell I-V curve characteristics - Explain connections between modules and strings to form an array - Explain the role of inverters - Describe additional PV system components such (e.g. disconnects, combiner boxes) - Read data sheets for modules and inverters - Sketch single-line diagrams for different types of interconnections (e.g. with/without storage, grid tied) - Apply design tools to perform layout of a PV system (e.g. SAM, Helioscope) - Describe codes and standards that apply to PV system design
Unit 3: Analyzing Solar Systems - Simulate generation of a PV system - Differentiate different sources of losses - Compare generation to customer load - Describe different types of common PV financing - Explain different types of common solar incentives - Compute life cycle benefit of a PV system to a customer - Describe potential impacts of solar on the distribution network

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Appendix

List of Courses Reviewed

School	**Course**	**Course Title**	**Syllabus**
Alfred University	RNEW 432	Solar Energy Systems	X
California State University, Chico	MECH 433	Solar Energy Engineering	X
Columbia University	CHEN E4231	Solar Fuels	X
Georgia Tech	ECE 6456	Solar Cells	X
IIT Guwahati		Solar Energy Engineering and Technology	X
Missouri S&T	EE 5150	Photovoltaic Systems Engineering	X
MIT	EC.S07	Photovoltaic Solar Energy Systems	X
MIT	2-627	Fundamentals of Photovoltaics	X
Penn State University	EGEE 437	Design of Solar Energy Conversion Systems	X
Stanford University	EE 237	Solar Energy Conversion	X
Texas A&M University	ECEN 467	Harnessing Solar Energy: Optics Photovoltaics and Thermal Systems	X
UMass Lowell	MECH.5210	Solar Fundamentals	X
UMass Lowell	MECH.5270	Solar Energy Engineering	X
UMass Lowell	MECH.5250	Grid-Connected Solar Electric Systems	X
Umea University	5EN091	Solar Energy Engineering	X
University of Illinois	ECE 443	LEDs and Solar Cells	X
Uppsula University	1TE028	Solar Energy - Technology and Systems	X
Carnegie Mellon University	24-629	Direct Solar and Thermal Energy Conversion	
Missouri S&T	MECH ENG 5566	Solar Energy Technology	
Oregon Tech	REE 412	Photovoltaic Systems	
Oregon Tech	REE 348	Solar Thermal Energy Systems	
Texas A&M University	MEEN 439	Solar Energy Engineering	
UMass Lowell	MECH.5280	Photovoltaics Manufacturing	
UMass Lowell	MECH.5320	Off-Grid Solar Electric Systems	
University of California, Berkley	ELENG 134	Fundamentals of Photovoltaic Devices	
University of Southern California	ENGR 499	Alternative Energy Engineering	