Embedding Sustainability Concepts into a Renewable Energy Course

Abstract:

Renewable Energy classes are taught around the world at both the undergraduate and postgraduate levels. The typical content of such classes includes the design of solar energy systems, wind energy systems, mini-grids, hydroelectric systems, and bioenergy systems. Yet many broader sustainability concepts that address a wide range of the UN Sustainable Development goals is often not included in these courses. In this paper we describe the implementation of a broader set of sustainability concepts into a renewable energy class. Through a combination of in-class lecture material and homework exercises, students actively engage in the learning of topics including materials challenges in photovoltaic technologies, acidification of oceans due to carbon emissions, and political factors influencing the implementation of renewable energy systems. This paper will describe these exercises as well as provide student reflections on these topics.

Keywords: renewable energy, sustainability concepts, materials considerations.

Introduction:

Clean energy technologies are of growing importance both for combating climate change but also because of their cost effectiveness in many applications. The last decade has seen an exponential growth in solar and wind deployment as can be seen in Figure 1. Figures 1a) and b) [1] show the growth in the deployment of solar and wind projects over the 2011-2021 decade. This exponential growth is not expected to slow down any time soon, especially since to meet the 1.5°C global temperature rise target requires a *tripling* of the deployment to 2030 and 2050 (see Figure 1c). Many renewable energy programs have emerged at both the undergraduate and graduate levels to provide students with the education needed to understand how to design such systems. I have been teaching a class on renewable energy system design for the last two decades. The class focuses on the design of electric power systems with special emphasis on the design of wind and solar electric systems. The class is open to both undergraduate and post-graduate students in electrical engineering, mechanical engineering, and sustainable engineering who have some background in electric circuits. It serves as an elective course for students taking the electrical energy systems track at the undergraduate level, an elective course for students pursuing the master's degree in electrical engineering with specialization in electric energy systems, and a core course for students pursuing the master's degree in sustainable engineering with a specialization in the alternative and renewable energy track.

In addition to the technical design, the class also covers the economic analysis of renewable power systems, calculation of carbon dioxide emissions from conventional fossil-fueled power plants, as well as governing policy issues around renewable energy deployment.

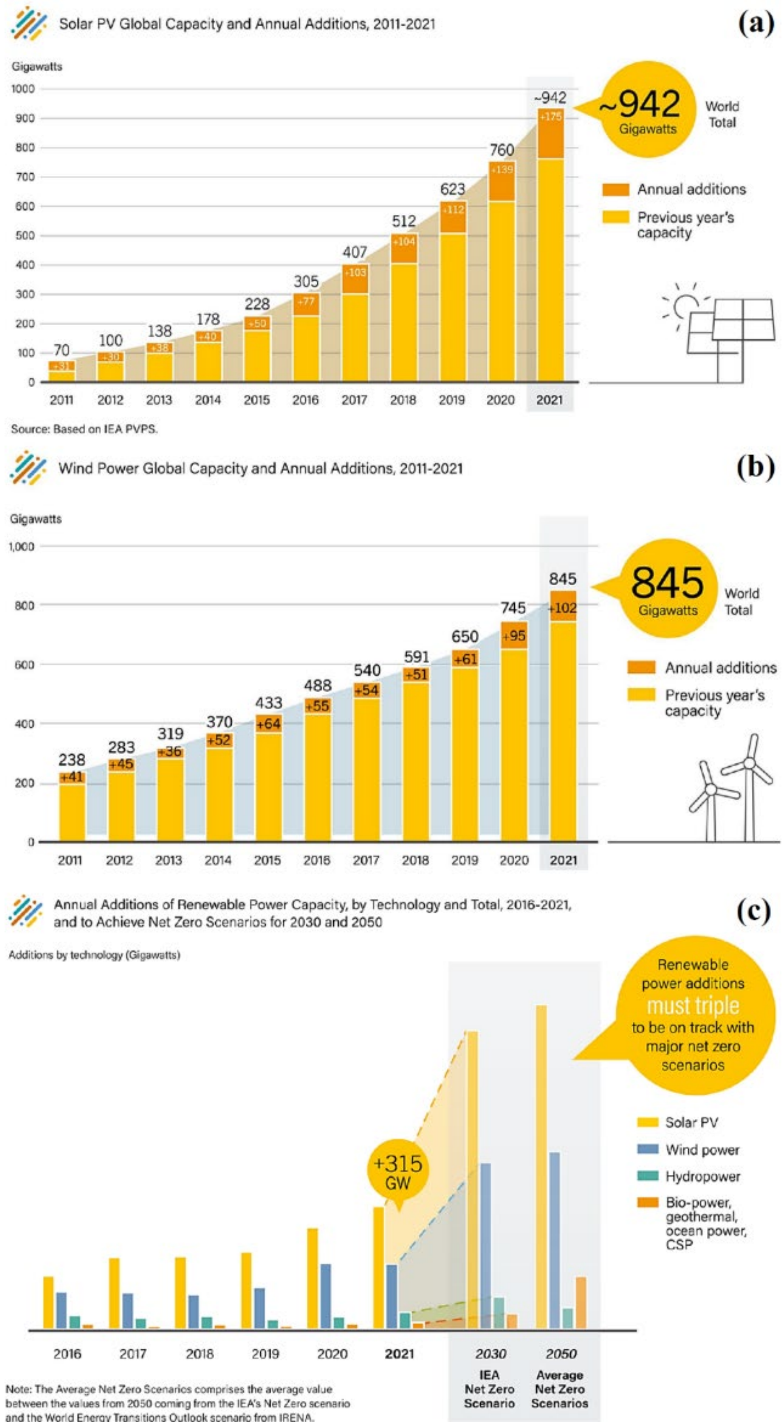


Figure 1 Deployment of (a) solar PV systems and (b) wind power globally in 2011-2021. (c) Renewable Energy Deployments to reach Net Zero Goals [1].

In May 2023, the author took the “Engineering for One Planet” workshop [2] and was exposed to a broader set of considerations related to the UN Sustainable Development goals and sustainability concepts and has since incorporated some of those learnings into the class. This paper begins with a description of the course and the earlier version without sustainability content enhancements. This is then followed by a description of the broader sustainability concepts now introduced into the course. A description of a qualitative assessment of the students’ response to these course additions concludes the paper.

Course Syllabus:

The Renewable Energy Systems class (ECE 7800) is offered at the senior/first year postgraduate level and may be taken by engineering students with a minimal electrical engineering background. The course syllabus is shown in Table 1. The textbook used for the course is Gilbert M. Masters and Kevin Hsu’s, "*Renewable and Efficient Electric Power Systems*”, 3rd Edition, IEEE Press/John Wiley, 2023 [3]

Table 1: Course Timetable for Renewable Energy Systems Class (ECE 7800)

Date	Topic	Textbook Pages
Jan. 13	Present US/World Energy Mix; Global Warming	
Jan. 20	*No class; Martin Luther King holiday*	
Jan. 27	Electric Utility Industry Today; Power Generation with Fossil Fuels; Social and Environmental Considerations	1-32; 32-58; 617-623
Feb. 3	Power Systems Background	117-185
Feb. 10	Solar Insolation	193-255
Feb. 17	Basics of Photovoltaics	263-280
Feb. 24	Photovoltaic Technologies	281-315
March 3	*No class; Spring Break*	
March 10	Grid-Connected Photovoltaic System Design	331-359
March 17	Off-Grid PV System Design	727-751;751-763
March 24	PV System Economics;	357-378;
March 31	Wind Power Fundamentals	389-435
April 7	Wind power system design	435-473
April 14	Tidal, Wave, Bioenergy, Microhydropower, and Geothermal Systems	512-555
April 21	*No class; Easter Break*	
April 28	Project Presentations	
May 3	Final Project Report Due	
May 6	Final Exam Due	

The course begins with an overview of the present US/World energy mix using resources from the International Energy Agency [4], US Energy Information Administration [5], and from REN21[6]. Additionally, the IPCC reports [7] are reviewed with regards to the influence of carbon dioxide levels and their impact on natural systems. These topics are then followed by coverage of the electric utility industry today including a description of fossil fueled power plants. A review of basic electric power concepts then follows. The topic of solar energy and solar resources is covered next followed by a description of photovoltaic technologies and the basic concepts regarding solar panel performance under different environmental conditions. This is followed by the topic of how to design solar electric systems. The course then shifts to the topic of wind energy, starting with the basics of the wind resource and the operating principles of wind turbines. This is then followed by the design of wind energy systems. How to calculate the economic viability of renewable energy systems follows and then the course concludes with the topic of small scale (<100kW) hydroelectric systems. These concepts are narrowly focused on engineering concepts and renewable energy system design with little coverage of broader sustainability concepts. The next section describes some broader sustainability concepts that have been added to the class along with a qualitative assessment of students' responses to these additions.

Broader Sustainability Concepts Added to the Course

Three topics were added to the course to provide exposure to broader sustainability concepts in the course as follows:

1. UN Sustainable Development Goals
2. Materials availability related to solar panels/recycling of solar panels/circular economy
3. The importance of government policies
4. Calculation of CO_2 emissions from power plants

UN Sustainable Development Goals

As a part of the discussion of renewable energy in general, the topic of access to electricity is introduced along with the UN Sustainable Development Goals, particularly UN SDG 7 Access to Clean and Affordable Energy. However, in addition to the coverage of this particular goal, the other UN SDGs are introduced in the class so that the students have a broader picture of the environmental effects of fossil fueled energy. The SDGs that are particularly pertinent in this regard are:

- UN SDG 2: Zero Hunger
- UN SDG 8: Decent Work and Economic Growth

- UN SDG 9: Industry, Innovation and Infrastructure
- UN SDG 11: Sustainable Cities and Communities
- UN SDG 12: Sustainable Production and Consumption
- UN SDG 13: Climate Action
- UN SDG 14: Life Below Water
- UN SDG 15: Life on Land

Homework exercises are given to the students in their first homework set to reinforce the concepts for two of these goals (UN SDG 13 and UN SDG 14). The students are asked to answer the following two homework questions:

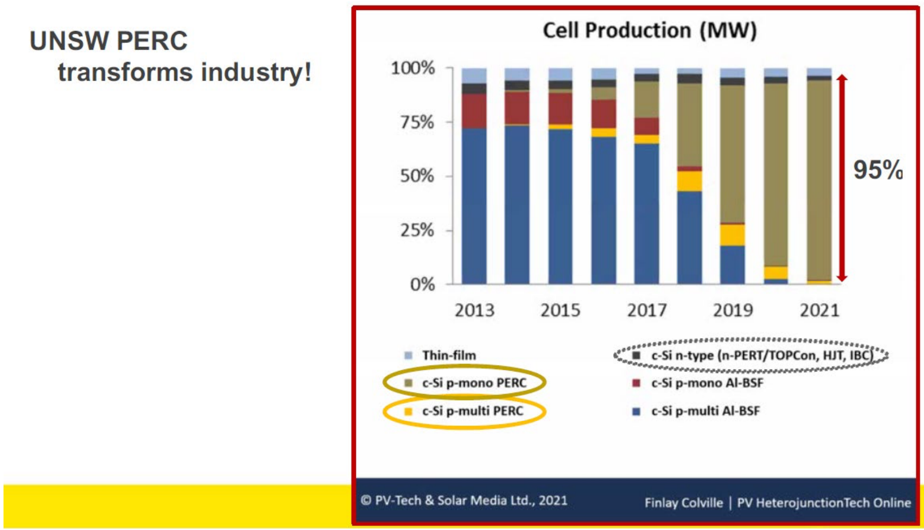
1. Read the IPCC's Sixth Assessment Report (Summary for Policymakers) on climate change and answer the following questions:
   a) By what rate has sea level risen (mm yr^{-1}) during the following periods: 1901-1971, 1971-2006 and 2006-2018. Comment on these changes.
   b) In recent days, we have seen the horrific damage done by forest fires on the west coast. Which of the Observed Changes and Impacts in section A.2 of the report (A2.1-A2.7) best describes the impact of the damage caused by these fires. Explain your answer.
   c) Describe which vulnerable populations are being most affected by climate change. Again, explain your answer.
   d) What mitigation strategies are needed to keep global warming temperatures to below 2°C? Explain what is expected to happen if business as usual continues.

2. Read the section from the "Sixth Extinction" [8] titled "The Sea Around Us" and write a reflection paragraph or two (~1/2-1 page) (single spaced, 1" margins, 12 pt. Times New Roman font) on the implications of this reading, particularly in view of recent findings of ocean warming/acidification and modeling as reported in the IPCC AR5 report. Also, include in your reflection the implications for biodiversity and especially about the UN Sustainable Development Goal #14 Life Below Water.

Materials availability related to solar panels/recycling of solar panels

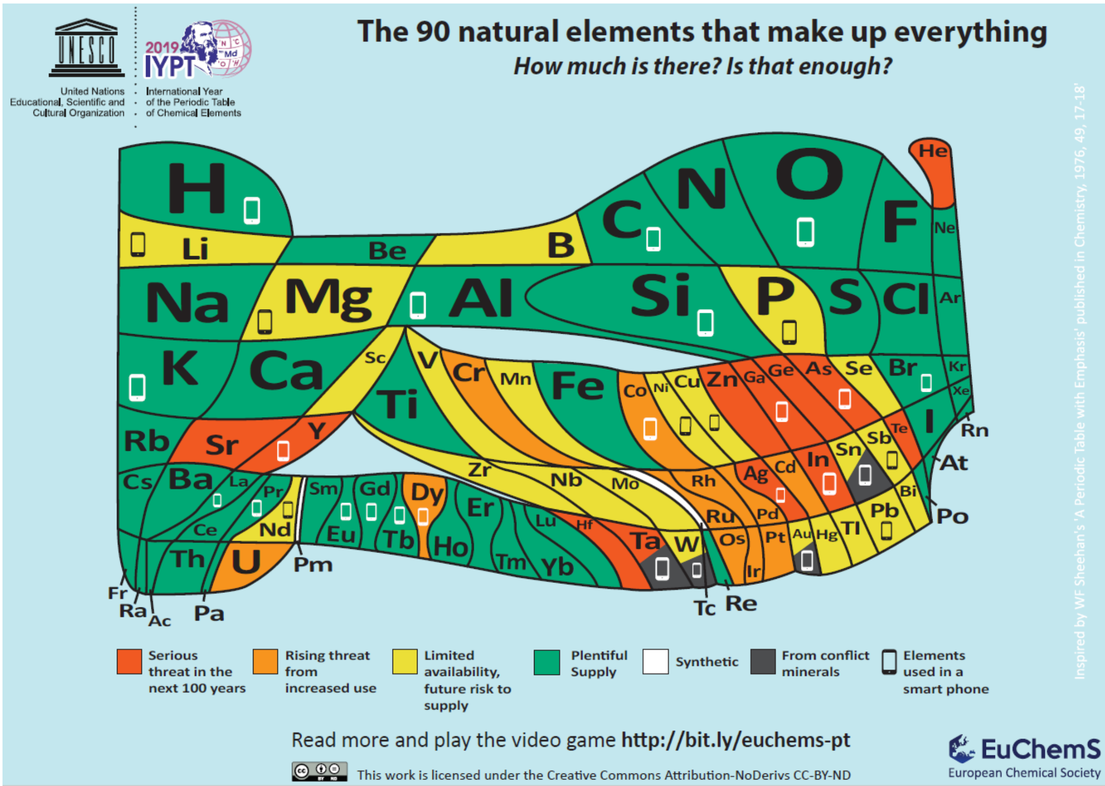
When the topic of solar panel technologies is discussed, materials considerations related to ramping up the scale of production to terrawatts/year is discussed. The European Chemical Society Materials version of the periodic table shown in Figure 2 is used to illustrate concerns about material supplies for solar panel production. This topic then leads to a discussion of recyclability of solar panels to reduce the need to mine for raw materials, such as silver used in the electrical contacts in solar panels. This also leads to the topic of the circular economy as well as the issue of harmful health effects of materials like cadmium, a known carcinogen, used in cadmium telluride solar panels. The following question on the final exam invites students to further explore the issue of materials availability:

1. In a recent presentation at the IEEE Latin American Electron Devices Conference, Dr. Martin Green of the University of New South Wales (UNSW) in Australia shared the below chart showing the transition from conventional crystalline/polycrystalline silicon technologies to domination by the PERC solar cell structure:



a) Describe the structure of the PERC solar cell developed at the University of New South Wales (UNSW).
b) How does its efficiency at the cell level (10cm. x 10cm.) compared to conventional c-Si solar cells? (You can consult the NREL solar cell efficiency chart in the notes).
c) He indicated that the thin film technologies, dominated by CdTe, are limited because of materials availability issues. Through research, determine the way that tellurium is mined and estimate how much tellurium would be needed per year if the production of 8 ft^2 CdTe modules would reach a rate of 100GW per year (assuming a 20% efficiency of the modules at 1kW/m^2 solar insolation). How does this compare with the annual production of tellurium?

Figure 2: European Chemical Society Materials Periodic Table Chart [9]

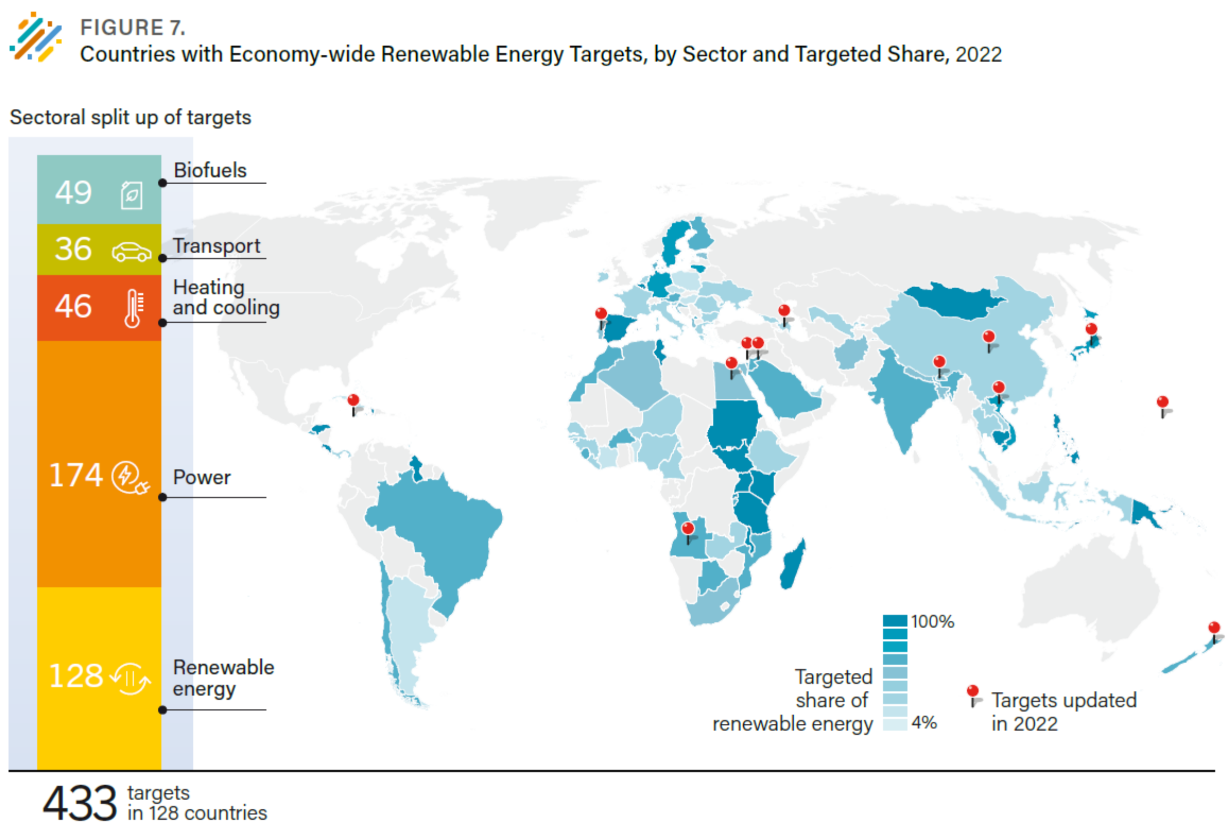


The importance of government policies

An important element in determining the uptake of renewable energy systems is government policies. Several topics are presented in the class including renewable energy policies from different countries around the world (as well as in the US) and deregulation of the electric grid in different countries. The renewable energy policies adopted by different countries is presented using the REN 21 report which includes a chart providing policies as shown in Figure 3. The deregulation of the electricity sector is described in the US, beginning with the chaotic initial efforts by the state of California and followed by smoother deregulation rollout adopted in other states (such as Pennsylvania). The students are then asked to explore this issue more closely in the following homework exercise:

1. Research the utility restructuring that has occurred in either the UK **or** New Zealand. Write a short report (2-3 pages using the same format as in question 1) indicating how the restructuring program in either of these countries has been successful compared to the California experience.

<u>Figure 3</u>: Countries with Renewable Energy Targets (REN 21 Global Status 2023 report) [1]



Calculation of CO_2 emissions from power plants

In order to understand the level of carbon dioxide emissions from fossil-fueled power plants, the following example of their calculation is presented in class:

Consider an average pulverized coal power plant with a heat rate of 10,340 Btu/kWh buring a typical US coal with a carbon content of 24.5kgC/GJ. About 15% of thermal losses are up the stack and the remaining 85% are taken away by cooling water.

a. Find the efficiency of the plant
b. Find the rate of carbon and carbon dioxide emissions from the plant in kg/kWh.

A similar problem is then assigned to the students as a homework problem. The problem that the students are asked to solve in their homework is as follows:

A combined cycle, natural gas power plant has an efficiency of 52%. Natural gas has an energy density of 55,340kJ/kg and about 77% of the fuel is carbon.

a. What is the heat rate of the plant expresses as kJ/kWh and Btu/kWh.

b. Find the emission rate of carbon (kgC/kWh) and carbon dioxide emissions ($kgCO_2/kWh$). Compare those with the average coal plant emission rates found in the class example.

This problem provides the opportunity for students to see that efficient, combined cycle, gas power plants can offer lower CO_2 emissions compared to coal plants.

Qualitative Assessment of Student Responses to Broader Sustainability Coverage

No formal quantitative assessment has been performed on the various exercises covered in class on these broader sustainability issues. Nevertheless, qualitative assessment has been performed through reflection components built into some of the questions as well as comments in the student course feedback.

The reflection piece on the chapter from Elizabeth Colbert's book was specifically designed to elicit a crafted response from the students. The most common response was that students were completely unaware of ocean acidification and the dramatic effect of carbon dioxide emissions on ocean ecosystems. They commented that the observations of decreasing underwater life under lower pH conditions were very interesting but also most of the students found the results of these observations very disturbing.

With regards to the potential effects of climate change through their reading of the IPCC reports and answering the homework questions, the students again reported how they had a better appreciation of the effects of climate change on humanity and biodiversity. They again expressed their concern about how they were unaware of these potential impacts.

They found it very enlightening to understand the scale of material usage in solar panels, particularly as production is scaled up to meet the Terrawatt challenge. It brought home very clearly the importance of recycling and the circular economy to meet the solar energy needs of the future. They were also horrified to learn about the limited supplies of helium that is widely used in applications such as MRI machines but is also wantonly wasted in helium balloons for parties!

Calculating the carbon dioxide emissions from coal-fired power plants at a rate of about 1kg/kWh of electricity generated was also enlightening to the students. Combining this realization together with the effects of CO_2 emissions on the environment, climate change, and biodiversity unified in their minds the importance of transitioning to clean, renewable energy.

Finally, through the coverage of government policies and their influence on development goals, the students reported an appreciation for the importance of government policies to motivate the integration of renewable energy into a country's energy generation infrastructure.

Conclusions and Next Steps

In this paper, we have described additional dimensions of sustainability concepts that have been integrated into a renewable energy course. These concepts have either been covered through explicit in-class exercises or through homework questions. These additional exercises have developed an understanding within the students of the importance of the broader dimensions related to renewable energy. They qualitatively report that they had no previous exposure to these concepts and found them to be both very interesting and very disturbing.

A limitation of the present work is not to have performed a more rigorous assessment of the development of the students' understanding of these broader sustainability concepts. This will be the next step in following up on this work as well as considering other potential broader sustainability topics to include in the course and how best to integrate them.

References

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