The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #41892

Board 98: Engineering Education Curriculum Needs for Achieving Sustainable Energy and Decarbonize Economy

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Engineering Education Curriculum Needs for Achieving Sustainable Energy and Decarbonizing Economy

[AUTHORS]

Abstract:

The pressing demands of climate change require innovative and multidisciplinary approaches to training and equipping a new generation of engineers and physicists to be ready to solve the global challenge and transitioning to this new sustainable economy. It is imperative that academic institutions design appropriate curricula that prepare students to tackle the complex energy-related problems faced by society. Students need to understand existing technologies, such as cogeneration or combined heat and power (CHP), which reduces energy consumption, and it can be integrated with renewable energy sources. Weatherization of buildings, which consume more than 40% of the energy in the United States, is necessary to reduce energy consumption and strive to achieve net zero buildings. However, many mechanical engineering programs are not offering HVAC as a required or even as an elective course. In general, the courses should enable students to solve problems in the production, processing, storage, distribution, and efficient utilization of sustainable energy systems. Curricula should include such topics as: energy storage technologies, e.g., batteries, super capacitors, green hydrogen-generation; power transmission, including superconductivity and grid stabilization; electrochemistry and membrane technologies that are needed for innovative new power generation technologies such as fuel cells (FC) and salinity gradient energy (SGE) generation. The paper also provides evidence that topics such as Gibbs free energy, chemical potential and exergy analysis are going to be extremely important to be covered in mechanical engineering courses, as these new technologies will require a more fundamental, broader-based education, even at the undergraduate level.

1. Introduction:

The world needs to reduce carbon emissions to combat climate change. Decarbonization of the economy, shifting to electricity produced with low-carbon energy sources and building up adequate capacity of renewable energy will take time. The events of 2022 caused ongoing energy security and crises in Europe. Additionally, at the COP28 UAE United Nation Climate Change

Conference, in which two hundred countries participated, there was a failure to mandate "phase-out" of fossil fuel; instead, they merely promised to transition away from fossil fuel. Realistically, there will be an even longer transition period than any optimistic environmentalist anticipated.

Some key factors that are required to manage climate change include: efficiency of converting energy from one form to another, energy required to transport or transmit energy, energy storage, and energy conservation [1]. According to Pacala and Socolow [2] and the report by the Carbon Mitigation Initiative (CMI) at the High Meadows Environmental Institute of Princeton University [3], to get on track to avoid dramatic climate change by limiting global warming to 1.5 degrees Celsius above pre-industrial levels, the world must avoid emitting about 200 billion tons of carbon, which has been broken into eight 25-billion-ton wedges over the next 50 years in Figure 1. Since no one particular approach can sufficiently curb these emissions, fifteen (15) different strategies, each of which has the potential to reduce global carbon emission by at least 1 billion tons per year by 2060, thereby enabling the triangle to be segmented into wedges, were proposed.

In February 2023, the ASME Board of Governors ratified a statement on climate change that sets out ASME's role in finding these solutions. They concluded that "engineers are natural problem solvers with the tools and training needed to find and implement sustainable climate action for the benefit of all humanity" [4]. Therefore, it is incumbent upon academic institutions to provide these tools and train a new generation of engineers and physicists equipped to combat the climate crisis and to build a sustainable future. Courses should enable students to have knowledge and skills to solve problems in the production, processing, storage, distribution, and efficient utilization of sustainable energy systems.

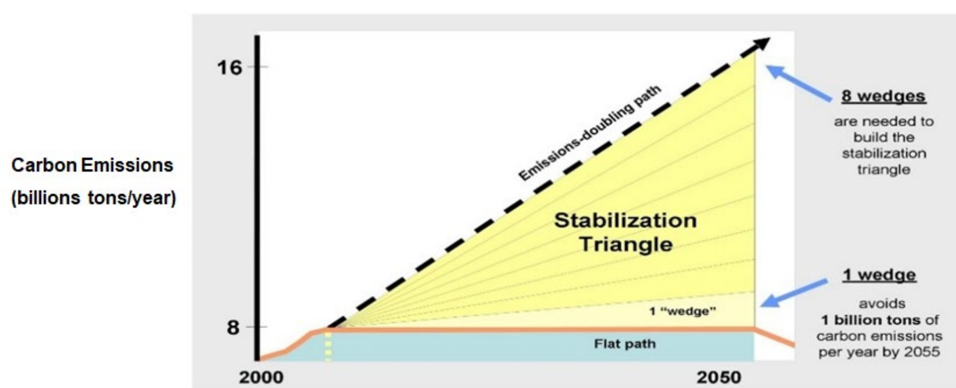

Figure 1. Two possible carbon emission levels (billion tons per year) define the "stabilization triangle" broken into 8 wedges [1].

In the following sections of this paper some of the strategies to combat the climate crisis are addressed followed by a summary of the topics and courses that should be included in the undergraduate engineering curricula. This strategy will better prepare students and equip them with the knowledge and skills to build innovative technology-based solutions towards carbon neutrality.

2. Decarbonization of Buildings

Decarbonizing buildings using the most efficient practices in all residential and commercial buildings is one of the stabilizing strategies suggested by the group at Princeton [2,3]. According to the U.S. EIA, the operation of buildings, both residential and commercial, currently represents about 38% of the energy consumption in the United States and about 30% of global energy consumption [5, 6]. The combination of weatherization of the buildings, by using insulation and conservation to reduce energy consumption, and the addition of photovoltaic (PV) panels to provide renewable energy will enable the target of "net zero energy" buildings to be achieved.

2.1 HVAC

To reduce the energy consumption of buildings, building designers and engineers need to have knowledge of heating, ventilation, and air conditioning (HVAC). Since there are many different climate zones, there is not one solution to fit all buildings [7]. The importance of maintaining healthy indoor air quality (IAQ) within buildings is another important requirement for HVAC systems. Supplying conditioned spaces with outdoor air more than the minimum requirements (i.e., over ventilation) and use of high efficiency HEPA filters, electrostatic precipitators or plasma air purification along with maintaining relative humidity between 40-60% could have reduced the spread and severity of outbreaks of recent COVID-19 around the world [8-10]. In addition, building managers and engineers must become more familiar and knowledgeable with IAQ, air purification, ventilation, infiltration, and control of air leakage into and out of a space by creating negative and positive pressure environments which are among the topics that are discussed in a HVAC course.

2.2 Combined Heat and Power (CHP)

Combined heat and power (CHP) systems satisfy both electrical power and thermal loads, which consists of heating, cooling, and hot water (DHW), in buildings. The average efficiency in electricity production is about 33%, and the waste energy, which consists of low-grade heat which is rejected during processes [1], is about 60%. Cogeneration is common in Europe with Denmark leading the way by producing 55% of their electricity by cogeneration and heating 60% of its homes through "district heating' provided by cogeneration [11], whereas in the United States, only 8% of homes are heated via cogeneration. There is also a strong synergy between cogeneration or CHP and renewables for reducing carbon emission and improving security of energy supply during the transition period towards decarbonization [12,13].

2.3 Electrification

Electrification of end-use services in the transportation, building and industrial sectors coupled with decarbonization of electricity generation has been identified as one of the key pathways to achieve a low-carbon future in the United States. Building electrification is a key strategy for achieving net-zero emissions by 2050 and addressing the climate crisis [14,15]. Zero emission construction is being discussed by legislators in a few states. New York is the first state in the U.S. to ban natural gas and other fossil fuels in most new buildings statewide. Besides heating systems and hot water (DHW), gas stoves must be electric too, which also helps to improve indoor air quality (IAQ). Methane (CH_4), the main component of natural gas, has a global warming potential (GWP) of 27-30 times greater than CO_2 over 100 years.

Building decarbonization is greatly dependent on the local electricity grid. If an entire building system is electrical, a net zero energy building that uses photovoltaics to offset all electrical energy consumption is achievable. Unfortunately, not all buildings can generate enough on-site electricity due to different constraints [16]. However, many electric grids are moving in the direction of 100% carbon-free electricity.

2.4 Heat Pump and Geothermal Energy

For the decarbonization of buildings, current typical HVAC systems can be replaced with alternative energy systems that use heat pumps, instead of gas heaters and boilers, for both heating in winter and cooling in summer, while also providing domestic hot water. Heat pump water heaters (HPWH) are also continuing to gain the attention of energy providers and policy makers as an alternative to traditional equipment for the residential market such as gas and electric water heaters. Heat pumps use a refrigeration cycle incorporating a compressor and refrigerant to absorb heat from a cold space and release it to a warmer one. The compressor requires electricity to operate which will increase the electricity demand load in the winter. A solar thermal collector combined with a heat pump could independently supply energy for space heating or DHW (parallel configuration), or the collector could act as a source for the heat pump either as an exclusive source or as additional source (series configuration).

The uniform energy factor (UEF) is the efficiency rating metric in the U.S. and Canada that measures the efficiency under a standard draw pattern and set of environmental conditions. A UEF value of 3.55 is achievable with HPWH, whereas the best 50-gallon electric resistance water heater has a corresponding value of only 0.93 [17].

Eversource, a utility company, is building a networked geothermal pilot system that will heat and cool 37 residential and commercial buildings in Framingham, MA [18]. These types of projects by gas and utility companies are spread all over the country and will provide future jobs and projects for students that are enrolled in engineering programs.

3. General Topics

In addition to decarbonization of buildings, other general topics need to be considered to achieve energy sustainability. Some of these topics will be addressed in this section, including renewable energy, energy storage, hydrogen technology, small modular nuclear reactors and additional innovative technologies.

3.1 Renewable Energy

Existing renewable energy technologies, such as solar, wind, hydroelectric, geothermal, and biomass have several issues, including their intermittent nature, inability to follow load, spatial variation, water use, food vs. fuel, material, and rare earth mineral shortages.

Wind and solar electricity generation have been steadily increasing across the United States and around the world. The DOE reported that wind power accounted for over 10% of U.S. electricity generation in recent years and solar installations have also been growing both in residential and utility-scale applications to about 3.4%.

Solar thermal panels are more efficient than solar power (PV) panels; however, the quality of the energy output, as far as the second law of thermodynamics is concerned, is lower. Nevertheless, in residential applications, solar thermal and thermal storage should be used in buildings to meet heating and cooling thermal load and to make hot water, as opposed to using electricity stored in a battery, as is required for PV panels. Even in colder regions, evacuated-tube solar water heater collectors, that eliminate conductive and convective thermal losses, could be used to achieve high efficiency. Obviously, the percentage of available south-facing roof area or area adjacent to the building that should be dedicated to thermal panels versus the PV panels depends on the location and other energy and economic analysis. There are hybrid solar panels that are known as photovoltaic-thermal (PVT) systems. PVT systems have a layer of photovoltaic cells to produce electricity from sunlight while running a heat exchange fluid through the panels to absorb excess heat generated by the PV cells. PVT has not gained much traction, and it might be more complex and costlier compared to stand-alone PV or solar thermal systems.

3.2 Energy Storage

Wind, solar, tidal and wave energy are primary energy forms, but they are storable only after a transformation into a secondary energy form like electricity or thermal energy. Some secondary forms of energy like hydrogen, gasoline and diesel can be easily stored in large tanks. Gasoline is a form of energy storage for transportation with an energy density of 12.9 kWh/kg, as opposed to an upper limit of only ~0.27 kWh/kg for lithium-ion and ~0.4 kWh/kg for solid-state electric batteries; therefore, current generation electric vehicles are significantly heavier than their gasoline-powered counterparts [1,18].

On the other hand, storing electricity requires another substance, called an “energy carrier” which is required to store the energy and return it when needed. For renewable energy to be dispatchable in utility scale applications, a vast amount of energy storage must be added to both sides of electric meters [19]. Electrical and thermal energy storage devices make renewable energy dispatchable and help capacity-constrained electrical grids by shifting peak demand period.

Battery storage in buildings could allow renewable energy to help with decarbonization, if the battery systems are charged at low-carbon hours on the grid using renewable generation and discharged during high carbon hours, which are usually dominated by fossil fuel generation [19]. Small-scale rechargeable energy storage such as lithium-ion, nickel-metal hydride, lead-acid, and solid-state batteries (SSBs) are suitable for cordless power tools, electrification of buildings, and transportation.

According to the International Energy Agency (IEA), we need 10,000 GWh of available energy storage worldwide by 2040; that is fifty times more than the size of the current energy storage market. Utility-scale hydroelectric energy storage systems pump water uphill to store excess energy and then retrieve that stored energy when needed by allowing the water to flow downhill through turbines. Even though pumped hydro-turbine storage systems are among the most widespread and effective methods of grid-scale energy storage, their implementation depends on geographical locations for reservoirs and environmental and infrastructure cost considerations.

A flow battery, which stores energy in liquid electrolytes contained in separate tanks, can be scaled up easily to store large amounts of energy, making it suitable for utility-scale energy storage applications. A flow battery includes two electrolyte solutions that are stored in separate tanks and are separated by a membrane and two electrodes, typically graphite. The membrane allows ions to pass through while preventing the mixing of the two electrolytes, enabling the electrochemical reactions to take place at the electrodes that generate electricity [20].

Thermal energy storage can be used for shifting the peak demand loads and for the peak shaving, for example, for cooling and air conditioning applications. This can be achieved, for example, by running the chiller at night when electricity is more available and less expensive, or when there is excess renewable energy and storing the chilled water. Then the stored chilled water could be pumped to air handling units during the peak demand period instead of running the chiller compressor. Hot water storage tanks allow for smaller, more efficient electric heat pumps to produce the hot water required over a much longer period, lowering the demand, and increasing the efficiency [19].

Another consideration is that the national power grid is already operating at its maximum rated capacity during periods of high demand, such as heat waves or extreme cold spells [21], and, as more electric vehicles are used, this situation will only grow worse, especially if larger vehicles, such as large trucks, boats, and trains, are also electrified through that same electricity grid. In addition, there is virtually no energy storage capacity on the national power grid.

Considering the challenges of energy storage and distribution, renewable energy sources may best be utilized to decarbonize the heavy transportation sector, especially since this sector lends itself to centralized fleet vehicle implementation, as opposed to individually owned electric cars which require electrification at home or along highly dispersed traffic routes. Trucks, trains and boats, however, which are used in the shipping and transportation industries, operate on specified routes out of centralized hubs; this is known as "co-locating" energy sources with transportation [1]. Therefore, it is easier and perhaps more productive to target renewable energy sources to power this sector of the economy as depicted in Figure 2.

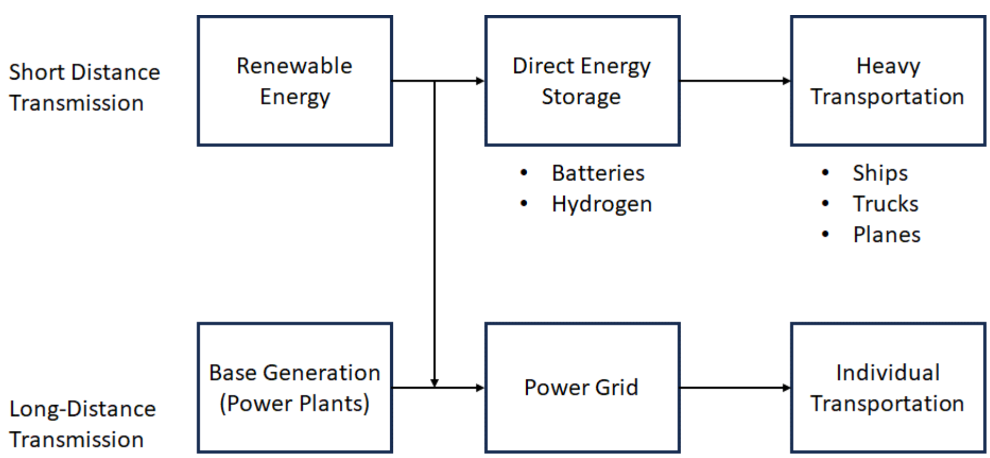

Figure 2. Use of renewable energy combined with short-distance transmission and energy storage to power the heavy transportation industry.

As an example, consider a large solar farm in the Nevada desert. With the existing paradigm, planners are focused on converting the DC solar electricity to AC power so that the voltage can be stepped-up using transformers for long-distance transmission. The initial AC-DC conversion and the subsequent long-distance transmission have associated energy losses. Instead, consider a scenario as shown in Figure 2, whereby the DC power is not converted but rather used locally to charge batteries on locomotive cars, which can then be picked up by passing trains to give it an electric assist for part of its journey. This concept could be called a renewable energy assist (REA).

In another scenario, let us consider windfarms. Wind generators usually use AC generators to produce electrical power which can be synched with power electronics to the power grid. However, if we consider the paradigm shift of Figure 2, we could consider using DC generators, such as Faraday homopolar generators, to make low-voltage DC power for electrolysis of either the surrounding sea water or fresh water sources to produce hydrogen. Hydrogen could be stored locally and used for passing trucks, or shipping vessels, once again giving them a renewable energy assist (REA) for at least part of their journey.

3.3 Hydrogen Technology

Hydrogen (H_2) is gaining attention as an energy carrier with a low carbon footprint, but a more hydrogen-centered economy may also increase the amount of H_2 in the atmosphere, causing indirect global warming effects (e.g., increasing methane lifetime). Hydrogen is an energy carrier rather than a source and is only as environmentally friendly as the method of producing it. Most of the current hydrogen used worldwide, mainly for oil refining and ammonia production, is produced via steam reforming of methane (SRM) and it is referred to as "gray" hydrogen [22]. Capturing the CO_2 generated through steam reforming and sequestering is referred to as "blue" hydrogen. Electrolysis using electricity that is produced through renewables or non-fossil fuel means is a way to produce "green" hydrogen and could be used as an alternative to batteries for storing renewable energy. Unfortunately, the electrolytic production of hydrogen is too expensive compared to SRM. Steam-reformed biomass is another way to produce carbon-neutral hydrogen.

Ammonia (NH_3), a main component of many fertilizers, could play a key role in a carbon-free fuel system as a convenient way to transport and store clean hydrogen. Ammonia is a gas at standard pressure and temperature but can be liquified without much effort, as it has a much higher boiling point of 240K (or -33°C), as compared to that of liquid hydrogen, which boils at 20K (or -253°C). NH_3 can also itself be burned as a zero-carbon fuel. However, even though ammonia may not be a source of carbon pollution, its widespread use in the energy sector could pose a grave risk to the nitrogen cycle and climate without proper engineering precautions [23].

Green hydrogen production and its applications in fuel cells or other power generation devices should be integrated in the engineering curriculum.

3.4 Small Modular Nuclear Reactor (SMR)

Plant Vogtle's Unit 3, near Waynesboro, GA, with capacity of 1215 MW that went online on July 2023, is the only addition of nuclear power to the North American grid since 1990 when Seabrook Nuclear Power Plant with capacity of 2200 MW went online in New Hampshire. Plant Vogtle's Unit 4 is scheduled to go online in 2024. At the present time, there is no other conventional light water nuclear reactor, which often takes between 5-10 years to build and can cost multi-billion dollars, under construction in the United States.

Small modular reactors (SMRs)—that IAEA classified as reactors generating less than 300 MW—designed to be faster to build and easier to site, are conceived to make nuclear power simpler and less challenging to add to power grid [27].

Nuclear power plants have a carbon footprint comparable to renewable energy, such as solar and wind farms, are very often used for base load and are among the stabilizing wedge strategies. Resurgence of nuclear power, at least partly due to concerns over climate change, will require educated qualified nuclear personnel.

3.5 Additional Technologies

Decarbonizing the power sector will require the discovery of new clean energy sources and innovative technologies to replace the traditional fossil fuel combustion driven power cycles. The natural hydrological cycle offers a significant source of sustainable energy through salinity gradient energy (SGE) which was first demonstrated in 1954 [24] and is one of the main untapped clean energy sources. The energy produced from water salinity is a clean energy source that is non-polluting and free of CO_2 emissions with minimal environmental effects and is available on a continuous basis. There are different techniques for converting the salinity gradient energy to electricity making it an attractive research topic that should be included in today's energy curriculums, the fundamental theories necessary to prepare students for tomorrow's diverse energy supply should be covered in different course.

All salinity gradient energy technologies are essentially the reverse of energy-consuming desalinization processes. Some of the most promising methods and the most investigated membrane-based techniques include pressure-retarded osmosis (PRO), which is the opposite of the most common form of desalination; reverse osmosis (RO); and reverse electrodialysis (RED), which is the reverse of electrodialysis [25]. Other techniques that do not utilize membranes are electrode-based including capacitive mixing (CapMix), which is the opposite of capacitive deionization, and mixing entropy battery (MEB) technologies [26]. There are some advantages and disadvantages for conversion technologies of SGE in terms of generated power density, price, efficiency and the level of commercialization for these techniques.

The preceding description of SGE technologies has implications for the design of salt-based storage devices that would not have the recycling and end-of-life issues related to lithium-ion batteries.

4. Curriculum Need Summary

To better prepare students for these new technologies, it is imperative that mechanical engineering curricula be designed appropriately. In Table 1 a general assessment of the current state of engineering curricula to address the required technologies, along with some future recommendations, is provided.

While all these topics could be covered in a singular course on Renewable Energy, it is recommended that they first be integrated with other aspects of conventional undergraduate curriculum in order to give students a more comprehensive understanding of the required technologies. For example, in addition to covering some of these topics in a traditional mechanical engineering course on thermodynamics, some other topics may be addressed in existing undergraduate courses such as: physics, chemistry, electrical circuit theory, fluids and materials science.

The main technology topics that are required for this renewable energy-powered transition are as follows:

1. Renewable power—wind and solar
2. Power transmission—short-distance DC links
3. Energy storage—batteries and hydrogen
4. Power conversion—electric and hydrogen-powered motors

Based on the matrix presented in Table 2, the proposed Wentworth plan will be to design teaching materials, including presentations and homework or project assignments, which could be integrated into these existing courses. These materials will be given to the various course coordinators in an effort to have them introduced into their course materials. As these materials are integrated into existing courses, students' interest will be increased, and their ability to tackle a more comprehensive course on Renewable Energy, which is an existing technical elective, will be increased. If there is enough student interest, we will propose a new Renewable Energy minor at our school.

5. Conclusion

Unless a new viable source of renewable energy is discovered, implementation of small modular nuclear reactors (SMRs) in the energy portfolio mix is the only hope of achieving a net zero economy [28].

Topics such as Gibbs Free energy, chemical potential and exergy analysis are important in performance analysis of any energy systems that involves any chemical reactions. As an example, exergy analysis is the second law performance measure and allows process inefficiencies to be better pinpointed. The exergy balance is a tool that will be required for future engineers to design any new energy systems effectively and efficiently or for optimum integration of renewable energy and CHP system during the transition period.

Table 1. Curriculum assessment and needs summary.

Topic		Comment
2. Building Decarbonization		
2.1	**HVAC**	Out of 11 existing accredited programs in the US with sustainable, renewable, solar, or green energy in their names only one program, Energy Systems Engineering at Mass. Maritime Academy has HVAC as a required course and four (4) other programs—Penn State, Ohio University, U. Wyoming, and Oregon Institute of Tech.—offering as an elective course.
2.2	**Combined Heat and Power**	Cogeneration or combined heat and power (CHP) should be covered in Applied Thermodynamics or in Energy Systems, or Sustainable Energy course. CHP topic is not covered in any engineering programs and only barely mentioned in a few energy sustainability books.
2.3	**Electrification**	Electrification of buildings and transportation should be discussed in the curriculum.
2.4	**Heat Pump and Geothermal Energy**	Heat pumps and geothermal energy are barely discussed in current mechanical engineering programs. Air and water sources and geothermal heat pumps should be covered in more detail in mechanical engineering programs.
3. General Topics		
3.1	**Renewable Energy**	Renewables such as Solar Thermal and PV, Wind, and Geothermal energy should be incorporated in the engineering curriculum
3.2	**Energy Storage**	Topics like electrochemistry, batteries, super capacitor energy storage, membrane technologies, and thermal batteries should be covered in the curriculums. The battery characteristic requirements, such as: energy density, range, round trip efficiency (charging and discharging), charging speed, electrolyte type, material (liquid, gel, or solid), and cost and safety should be covered in the curriculum.
3.3	**Hydrogen Technology**	Green hydrogen production and applications in fuel cells or other power generation devices should be integrated in engineering curricula.
3.4	**Small Modular Nuclear Reactor**	Nuclear energy is an integral part of the decarbonization strategy and should be included in the engineering curriculum, Currently, most of the mechanical engineering programs are not offering nuclear energy even as an elective course.
3.5	**Additional Topics**	Topics like chemical potentials, solutions, and flow through membranes should be covered in the curriculum. Innovative technologies such as flow batteries, fuel cells, and SGE should be discussed and experimented with in the design projects.

Table 2. Existing courses which can incorporate elements of renewable energy curricula.

Topic	Subtopic	Freshman		Sophomore		Junior	
		Physics	Chem.	Applied Thermo-dynamics	Circuit Theory	Fluids	Material Science
Renewable	Wind power	X			X	X	
Power	Blade design					X	X
	Generator Design	X			X		
	Solar Power	X		X			X
	Geothermal	X		X		X	
Power	DC transmission				X		
Transmission	Superconductivity	X			X		X
Energy	Batteries		X	X			X
Storage	Hydrogen		X	X		X	X
	Electrolysis		X			X	
	Membranes		X			X	X
Power	Motor design	X			X		
Conversion	Fuel cells		X		X		X

While exergy analysis, Gibbs free energy and chemical potential are covered in most of the popular thermodynamics' textbooks, some of the new generation of thermodynamics instructors do not cover these topics in detail or omit these topics completely.

While standard thermodynamic power cycles, which are heavily covered in mechanical engineering courses, will continue to be a mature technology, moving toward newer technologies for power generation will require a more fundamental, broader-based education, even at the undergraduate level. Thermo-fluids courses should transition to covering chemical potentials, solutions, and flow-through membranes, including semi-permeable membranes that allow passage of certain ions or fluids but reject other molecules or ions, to analyze devices such as SGE devices such as proton exchange membrane (PEM), electrolyzers and fuel cells. Also, the introduction of more interdisciplinary programs needed to prepare the task force for decarbonizing buildings and energy producing systems should be developed.

We hope that this discussion will promote a more intense discussion of which core topics in engineering education can be de-emphasized and what critical topics should be included in a newly defined core curriculum in our undergraduate courses, and a more integrated approach of different disciplines that is consistent with sustainable energy technologies.

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