Approaches, Background, and Resources for Teaching Energy in Environmental Studies

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Abstract

Production and use of energy have figured prominently in environmental studies and sciences (ESS) for many years, and it is particularly relevant to enduring themes, such as climate change, environmental justice, ecosystem disruption, and the study of natural resources. Despite its acknowledged centrality, relatively few ESS courses have delved into the intricacies of energy in a broad interdisciplinary framework. This paper encourages the development and improvement of such courses but recognizes that ESS faculty will have to select topics and resources to match their own abilities and interests and the needs of their students. The paper (a) proposes a framework for conceptual content and (b) suggests numerous resources organized in 5 categories and 17 subcategories. Each subcategory has an explanation of its role in the larger picture about energy, and each resource has a brief annotation about its content and utility. Future work on energy in ESS should address pedagogical techniques, different ways of integrating perspectives from different disciplines, and the needs of specific subsets of ESS courses and programs.

Energy used by humanity to run its machines and generate its electricity has two important links to environmental studies and sciences (ESS). First, primary energy sources are natural resources, i.e. physical components of the environment that humans extract, refine, and use. Second, production and use of primary energy sources inevitably changes the biophysical properties of the earth, sometimes benefiting people and sometimes harming them or other species and ecosystems. ESS has always had a dual focus on natural resources and damages resulting from habitat destruction and pollution.

Events in the past 55 years make incorporation of energy topics into ESS imperative. During that time, global population rose from 3.3 billion (1965) to 7.7 billion (2019), while at the same time increasing numbers of people lived in modern, urban societies, which are built on intensive use of energy. Primary energy consumption increased globally by a factor of 3.7, from 155 to 583 EJ; and average per capita annual energy use increased from 47.0 GJ to 75.7 GJ per person (BP, 2021b). (Joules (J), gigajoules (GJ), and exajoules (EJ) are units of energy; Jaffe and Taylor (2018), Perkins (2017), and Smil (2017) introduce energy units for those who have not previously worked with them.

Clearly, the increase in energy use per capita has created a better life for most of the world's population, and comparable energy inputs must continue to support humanity in the future. Nevertheless, the physical limits of this increase and its environmental impacts are severe and deserve a prominent place in the ESS curriculum. It's especially important for ESS to teach and research the comparative environmental strengths and weaknesses of the primary energy sources currently used.

To promote and improve the teaching of energy within ESS, we offer this selection of resources and encourage ESS faculty and students to increase their attention to energy issues. We also encourage ESS programs and departments to form or improve degree or certificate programs on energy as it relates to ESS. In addition, we encourage students and faculty to focus research efforts on energy. Many of the resources are background and reference materials intended to help faculty improve their knowledge and ability to incorporate energy into existing or new courses. They are far beyond materials needed by students, especially undergraduates. Other resources may be valuable both for faculty development and for use by students in class. We leave the question of selecting the uses of resources to readers.

The paper emphasizes key concepts linking energy with environmental issues. ESS faculty must recognize the breadth of concerns indicated in these issues. As they organize courses, programs, and research topics, however, they must choose concepts for emphasis and pedagogical techniques, based on their own and their students' objectives, skills, and interests. Full incorporation of energy in ESS will always require teamwork and collaboration, but it helps teams if all members have a sense of the field's breadth. The paper is not an exhaustive or critical review of the literature on energy and ESS, but it will have met its purpose if it contributes to expanded attention to energy in the ESS academy.

Objectives and status: energy and environmental education

Our assessment of energy and environmental education rests on two building blocks. First, environmental education in its current form reflects concerns about environmental and health hazards that burst into view in the 1950s and 1960s. Epitomized by Rachel Carson's *Silent Spring* (1962) and other books, the public and governments became aware that the burgeoning benefits of the industrial revolution also came with serious downsides in damages to human health and safety. Some extremely dangerous hazards had subtle causes requiring new perspectives and expertise to detect and reduce or eliminate. Educators, especially after 1970, built new research, teaching, and degree programs to tackle these new types of problems, which spread into many institutions of higher education.

Second, after 1990, concerns about climate change, and the connections of energy from fossil fuels to climate change, steadily increased among the public and governments. Educators working in environmental education built these concerns into their teaching and research efforts. The Global Council for Science and the Environment (2021), formerly the National Council for Science and the Environment (NCSE) organized in 1990, began to assess the status of environmental education, including effects from energy, and found a steady increase in attention to these subjects in 2012 and 2016 (Table 1). Nevertheless, the assessments also showed gaps needing remedy. Below, we summarize the major features of each of these building blocks.

<u>Building block number 1: foundations of environmental education</u>. William Stapp and his colleagues at the University of Michigan articulated an influential definition of environmental education:

> *Environmental education is aimed at producing a citizenry that is knowledgeable concerning the biophysical environment and its associated problems, aware of how to help solve these problems, and motivated to work toward their solution.* (Stapp, *et al.,* 1969)

In this definition, Stapp and his colleagues explicitly recognized the profound demographic shift that had occurred in 20th century United States: the migration of rural people to urban environments stemming largely from the industrial revolution and the mechanization of agriculture. Mechanization reduced the need for farm labor, and urban industries developed new job opportunities. People were either pulled or pushed out of rural areas, and many people therefore lost everyday contact and knowledge of natural resources. Earlier educational programs in conservation had focused on resources such as soils, agriculture, fisheries, and forests, which rural people knew intimately. Conservation education, however, did not focus on issues such as pollution that affected both rural and urban residents; nor did it cover the critical roles played by primary energy sources in powering both farm mechanization and urban industry.

Based on these contextual factors, Stapp and his colleagues (Stapp, *et al*., 1969, p. 31) saw the need for a new type of environmental education, emphasizing four axioms:

- Understand humanity as an inseparable part of natural systems, with a need for citizens to understand both the biophysical environment and culture. Students needed to gain knowledge of ". . .social, political, economic, technological processes, institutional arrangements, and aesthetic considerations. . ." that affected use of resources from the biophysical environment.

- Understand the role of resources from the biophysical environment in shaping contemporary society.
- Understand resulting problems from using resources and how these problems might be solved.
- Develop attitudes that ". . .motivate citizens to participate. . . in problem solving."

Inclusion of problem solving, placed environmental education firmly in the tradition of the "liberal arts," which was to prepare students for action and decision-making as citizens (Association of American Colleges and Universities, 2021). From a different perspective, however, education for problem solving could lead to charges of "politicizing education." This was particularly a problem for ESS, because partisan divisions have always haunted democratic decision-making on both energy and environmental protection (Mayer, 2019).

This paper embraces the principle that ESS should help students learn about and prepare for problem-solving and decision-making about environmental issues including energy. Many of our suggestions focus on climate change, because we believe this is the most serious of the environmental problems of energy, caused primarily by venting carbon dioxide from combustion of fossil fuels to the atmosphere (Perkins, 2017, p. 115).

We also include other consequences of the production and use of energy resources. Human health and the health of other species, for example, is adversely affected by producing, refining, transporting, and using primary energy sources. In addition, geopolitical tensions have arisen due to the production, use, and dependency on primary energy sources, especially petroleum and uranium (nuclear power).

Reductions of harmful consequences, particularly climate change, rests on reduction of uses of fossil fuels (coal, petroleum, natural gas). Fossil fuels, however, provide over 80 percent of the energy currently used by humanity. Mitigation of climate change requires a swift "energy transition"—in the next one to two decades—away from fossil fuels to other primary energy sources. Such a rapid energy transition, however, will not be easy. The difficulty can be seen in US dependency on fossil fuels which has taken 10 years to drop from 86% in 2005 to 81% in 2015 (U.S. Energy Information Administration, 2021). It's important to note, however, that technology changes in the last 15 years have opened new possibilities for renewable energy with no or few emissions of greenhouse gases.

<u>Building block number 2: assessments of environmental and energy education</u>. In 2008, 2012, and 2016, the National Council for Science and the Environment (NCSE) conducted censuses of baccalaureate and graduate programs in environment, sustainability, and energy. The 2012 census identified environmental (Vincent, Bunn, and Stevens, 2012), sustainability (Vincent, Bunn, and Stevens, 2013), and non-traditional, broad energy (NTBE) education programs (Vincent, Blockstein, Bunn, and Stevens, 2013). [1] The last emphasized renewable energy sources ("non-traditional") and "broad" concerns, such as policy, law, management, and planning. NTBE programs differed from those based on the physical sciences and engineering and focused on building and running commercial energy systems using fossil fuels, uranium, and hydropower.

The first report from the 2016 census focused on the broad spectrum of Interdisciplinary Environmental, Sustainability, and Energy (IESE) programs at the baccalaureate and graduate levels in 1,690 US colleges and universities in eleven categories of the Carnegie Classification system (Vincent, Rao, Fu, Gu, *et al*., 2017). A second report building on this data dealt with the number of NTBE energy programs in the 1690 institutions (Luzadis, Hirsch, and Huang, 2018).[2]

The NCSE reports demonstrated that American higher education had incorporated—in varied ways—the perceptions, frameworks, and objectives developed fifty years ago by Stapp and his colleagues. Moreover, the efforts increased from 2008 to 2016, measured by numbers of institutions, degree programs, and certificate- and minor-programs.

These censuses demonstrated the establishment of educational opportunities in environmental and sustainability education in a majority (52 percent) of the major educational institutions of the United States, a remarkable change from the situation Stapp and his colleagues faced in 1969. Also clearly demonstrated is the fact that only a small minority (9 percent) of US, four-year institutions have energy education of the type addressed in this paper (Table 1).

PLACE TABLE 1 HERE

The paucity of NTBE education programs bolsters our judgment that more programs in ESS should consider beginning or improving energy education linked to environmental and sustainability concerns. This conclusion also draws strength from two related sources. First, climate science projects dire risks for increases in global mean temperatures above 2°C; reduction of emissions of greenhouse gases is a key route to preventing such increases (IPCC, 2018). Second, according to 100 well known economists, governments must, within decades, end the "carbon economy," i.e., end the fossil fuel industry (Stiglitz, Zucman, Reich, *et al*., 2020).

We do not, however, address the question of the format of improved energy education in ESS. Options range from material included in introductory classes and general education courses to capstone classes for graduating seniors to certificate or designated minors to formal degree programs at undergraduate and graduate levels. References used to build Table 1 provide more details on these various options. Resources needed for the options suggested clearly differ profoundly.

Framework for teaching and learning about energy within ESS

It's important to note two key subject matters underlying all proposals for solving climate change and other energy-related problems. Regardless of instructor backgrounds, we believe these two subjects must in some way appear in frameworks for energy classes, even if they are not the focus of the class.

First, the primary energy sources in use differ in their abilities to provide sustainable energy services in perpetuity to modern societies. Sustainability is discussed further below, but students need to recognize differences among primary energy sources. Some of the resources in Category 1 (Jaffe and Taylor, MacKay, Perkins) provide relevant background.

Second, energy and energy services always rely on investments in technology: if there are no investments, there is no technological infrastructure, no energy, and no energy services. Investment decisions have not typically played a role in ESS curricula and they need not be the focus of any ESS course. Nevertheless, the key role of investment decision-making needs recognition. Further, a decision to invest in a specific technology is simultaneously a decision to invest in a specific primary energy source. Infrastructures for using primary energy sources differ, and this point, too, needs recognition in energy education in ESS. Multiple scientific, technical, political, economic, and cultural factors affect investment decision-making, and comparative sustainability properties of primary energy sources also must factor into decision-making.

With the above background on the two key topics, we note the importance of the concepts, theories, and methods employed by academic disciplines. ESS is interdisciplinary and seeks holistic models and explanations of environmental factors that influence humans, other biological species, and ecosystems. ESS scholars and teachers generally characterize "the environment" based on their disciplinary education and training while also drawing attention to other disciplinary perspectives.

In this paper, we suggest the most relevant framework for interdisciplinary understanding of energy and its environmental effects rests on three components: (a) the dependence of modern societies on a perpetual flow of energy services, (b) the construction by modern societies of "energy systems," i.e. complexes of primary energy sources that undergo transformation and transport to supply energy services, and (c) the management of "wastes," materials that can poison organisms or disrupt physical processes on earth in ways that adversely affect organisms and ecosystems and that may have long residence times on earth once released.

In this framework, "sustainability of energy services in perpetuity" is the key problem demanding solutions. We embrace the concept of sustainability articulated in 1986 by the World Commission on Environment and Development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (International Institute for Sustainable Development, n.d.)

The word "perpetuity" sounds demanding, and it is. Political leaders and policy makers have trouble planning government actions for longer than a few years, but we see no alternative to interpreting "perpetuity" as "forever." Laws and policies may not last forever, but modern societies cease to exist without modern energy services.

Summary of physical concepts fundamental for teaching energy

In this paper, we use "energy" in its scientific meaning, as summarized below in key points familiar to natural scientists and engineers but perhaps less so to those immersed in other disciplines.

- Energy can cannot be created or destroyed, only changed in form. As a result, no system can ever produce more work than the total input energy, no matter how clever or advanced the engineering (1st law of thermodynamics).

• Every time energy is converted from one form to another, some of the (primary) input energy cannot be converted into useful work and ends up in a much less useful form (e.g. waste heat). (2nd law of thermodynamics). This explains the 'rejected energy' in the Sanky diagrams of energy systems (see Category 7); the overall efficiency (defined as energy output divided by energy input) of converting all sources of primary energy into useful energy services in the US in 2019 was only 32.6%, mainly as the result of 2nd law of thermodynamics energy losses.

• The second law is especially restrictive when converting heat to mechanical energy (gasoline engines are less than 25% efficient and are unlikely to improve much, no matter how the technology advances). On the other hand, electrical energy conversions, for example electrical current to mechanical motion in a motor, are much less restricted by the second law (already 99% efficient in some cases).

• Fossil fuels, hydropower, wind, waves, and biomass are all indirect forms of solar radiation; hence solar energy is by far the largest source of energy available.

• Energy storage is a key component in using renewables. Storing energy involves conversion processes which always lose some energy because of the 2nd law.

• In 2018 transportation accounted for about 21% of global primary energy use, industry 45%, commercial buildings 29% and non-combustion (chemical feedstocks) 5% (BP, 2021a).

• Electricity, hydrogen, and ammonia are energy carriers, i.e. manufactured commodities and not primary sources of energy. They are all extremely useful, in different ways, but their production requires use of a primary energy source, i.e. a natural resource found in the environment.

• Energy Return on Energy Invested (abbreviated variously as EROI or EROEI) is useful for comparing potential fuel sources. EROI measures the amount of energy that must be used to produce a primary energy source, for example the energy needed to manufacture and service a windmill compared to the energy harvested by the windmill.

• Embodied energy, the energy needed to make a modern physical device or product, is often overlooked. For example, most of the energy involved in a car's lifetime is tied up in the fuel but most of the energy involved in a cell phone is in the manufacturing process. Aluminum is highly recyclable because it has high embodied energy (a lot of energy was used to make it in the first place); once made, recycling used aluminum takes very little energy compared to the amount needed to manufacture it.

Teaching resources

We have organized our many references as follows: Section A contains a few introductory materials to get you started, along with general essays. Section B contains categories that discuss the physical concept of energy and describes how the complex system of energy works in modern society. Section C broadens the discussion to investigate the social, political, and historic aspects of energy in society. Section D describes teaching resources for laboratories, field trips, and service-learning projects. Section E lists journals and websites useful for further exploration of these topics.

As noted earlier, many of these resources provide background and references for faculty development needed to better incorporate energy in their teaching and research. Accordingly, readers must select among the resources based on their own needs. Some of the resources may also be suitable for inclusion on syllabuses for students' reading. In addition, a few of these resources address issues of pedagogy, but the emphasis lies on conceptual issues.

Section A. Introduction

1. Getting started

For educators new to energy, the subject can appear daunting and off-putting. Environmental educators may be convinced about the importance of energy in ESS, but they may fear they lack the tools and experience to incorporate the subject into their teaching.

We don't mean to imply that energy is a snap to teach, because the subject truly does have some intricacies. Nevertheless, we are also convinced that an educator does not have to be a physicist, chemist, or engineer to deal intelligently with energy. Moreover, we are absolutely convinced that students in ESS, often their only exposure to science, need and will welcome inclusion of this subject. They know, perhaps better than the faculty, that energy and climate change will affect their lives, and they want to know more. In this section we list a few resources as good launching pads for educators and students just getting started.

Heinberg, Richard, and David Fridley, *Our Renewable Future: Laying the Path for 100% Clean Energy* (Washington: Island Press, 2016), 226 pp.

> Non-technical introduction to energy principles, electrical energy, transportation, and other sectors. Includes roles of government and society in the fair distribution of energy between developing and developed economies, and the prospects of moving to renewable energy.

Jaffee, Robert L. and Washington Taylor, *Physics of Energy* (New York: Cambridge University Press, 2018), 874 pp.

> Physicists provide a through overview of energy physics; useful technical reference for faculty who plan to bring energy into environmental science courses. Though not aimed exclusively at physics majors, this book does require calculus.

MacKay, David J. C., *Sustainable Energy- Without the Hot Air* (UIT Cambridge Ltd., 2009), 366 pp.; free download, https://withouthotair.com/ , accessed Dec. 27, 2020.

> Physicist analyzes energy sources (fossil fuels, nuclear, wind, solar, etc.) and feasibility of making major changes to global energy supplies. Heavy emphasis on United Kingdom. Math (algebra) in appendix but otherwise non-technical.

Perkins, John H, *Changing Energy: The Transition to a Sustainable Future* (Oakland, University of California Press, 2017), 343 pp.

> ESS educator uses "energy transitions" to trace scientific and political history of energy from pre-historic to modern era. Analytic schemes presented for assessing strengths and weaknesses of energy sources in commercial use. Low use of mathematics. Emphasizes climate change as driver of a necessary and feasible energy transition, currently underway.

Smil, Vaclav, *Energy: A Beginner's Guide*, 2nd edition (London: Oneworld, 2017), 219 pp.

> Geographer-physical scientist reviews physical nature of energy, its role in the ancient and modern worlds, and the numerous choices facing uses of energy in the future. Non-mathematical other than emphasis on scales of energy use.

Toosi, Reza, *Energy and the Environment; Choices and Challenges in a Changing World*, 4th ed. (Columbia: Global Digital Press, 2017), 564 pp.

> Basic physics: energy conversion, thermodynamics, renewable, transportation and sustainability. Two chapters on the economics. Non-mathematical except for a "Digging Deeper" section at the end of each chapter.

Wolfson, Richard, *Energy, Environment, and Climate*, 3rd ed. (W. W. Norton & Co., 2017), 528 pp.

> Physics textbook focused on energy and climate, useful for environmental science classes, with mathematics limited to algebra and simple equations, not calculus.

2. General texts and essays

Introductory texts and essays can help faculty gain frameworks for presentations of materials and serve as reference texts. These materials may also serve as reading assignments for students in all types of ESS classes.

Cunningham, William P. and Mary Ann Cunningham, *Environmental Science: A Global Concern*, 13th ed. (New York: McGraw-Hill Education, 2015), 614 pp.

> Introductory textbook for ESS. Emphasizes ecology with chapters on energy, climate change, conventional energy, and renewable energy.

Hobson, Art, "Physics and society: Energy," *American Journal of Physics* vol. 75 No. 4 April (2007): 294 (Resource Letter PSEn-1).

> A list of available resources related to energy used by society from a physics perspective. Updated and expanded by Forinash and Whitten below (Category 3).

Kemp, W. H., *Renewable Energy Handbook: The Updated Comprehensive Guide to Renewable Energy and Independent Living* (Amazon, 2015).

> A practical guide for powering your home using renewable energy. Includes explanations of home efficiency, off-the-grid living, solar, wind and micro-hydro energy sources. Several existing energy self-sufficient homes are used as examples.

Lovins, Amory B., *Soft Energy Paths: Toward a Durable Peace* (New York: Harper & Row, 1979), 231 pp.

> Physicist Lovins prepared the first comprehensive argument that it was possible and necessary to move humanity away from fossil fuels and uranium (nuclear power) to renewable energy used efficiently.

Miller, G Tyler and Scott. E. Spoolman, *Environmental Science*, 15th ed. (Boston: Cengage Learning, 2016), 483 pp.

> Textbook for introductory ESS courses. Includes energy and sustainability, energy resources, air pollution including climate change.

Muller, Richard A., *Energy for Future Presidents* (W. W, Norton Company, NY, 2012), 350 pp.

> Physicist assesses use of energy and energy disasters (Fukushima and the Deepwater Horizon spill). The author is sharply skeptical of some proposed energy solutions (e.g. electric cars, large scale solar, paper recycling, etc.

Oreskes, Naomi, and Erik Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (Bloomsbury Press, NY, NY, 2010), 355 pp.

> Historians argue that conservative ideologues favoring free markets with minimal government regulations sowed doubt on scientific findings about acid rain, the ozone hole, tobacco smoke, climate change, and toxicity of pesticides. Section on climate change makes book relevant to energy in ESS. Good for provoking student discussions about multiple environmental topics.

Richter, Burton, *Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century* 2nd ed. (Cambridge University Press, Cambridge, UK, 2014), 226 pp.

> A succinct and well-organized presentation of the current status of human caused climate change for the general public. Fossil fuels and the difficulties in switching to renewable and nuclear energy are included.

World Commission on Environment and Development, *Our Common Future* (New York: Oxford University Press, 1987), 383 pp.

> Original report outlining concepts of sustainability.

Section B: Energy Systems

3. Physical science and energy

ESS faculty teaching science majors will need resources that address energy science in detail. These resources generally have more mathematical treatments than those in Category 1.

Binder, P. M., T. P. Collins, and K. Blacksmith (2020), Development of an energy science curriculum, *The Physics Teacher* 58: 405, https://doi.org/10.1119/10.0001838

> Pedagogical description of the development of a three-year certificate program in energy science. ESS faculty will benefit from the experiences assessed in a closely related field.

Brown, Robert C., *Biorenewable Resources: Engineering New Products from Agriculture* (Ames: Blackwell Publishing, 2003), 286 pp.

> Engineer presents scientific underpinnings of biomass as a primary energy source. Includes agronomic dimensions of producing it, engineering aspects of changing raw biomass into useful products, and environmental and economic features of a bioeconomy.

Ehrlich, Robert, *Renewable Energy: A First Course* (Boca Raton, CRC Press, 2013), 442 pp.

> For physical science majors. Covers all renewable primary sources of energy plus uranium (nuclear power) and fossil fuels. Also covers energy efficiency, energy storage and transmission, and climate change.

Flanagan, G., G. Kulynych, and C. Parks, The Future of Nuclear Power, *Am. J. Phys.* **78** (2010): 981, Resource Letter FuNP-1: https://doi.org/10.1119/1.3446850.

> A list of references, some technical, some not, regarding nuclear power.

Forinash, Kyle, A few ideas for teaching environmental physics, *Physics Education* 51 (2016), 065024. DOI: 10.1088/0031-9120/51/6/065024

> A brief, non-technical review of concepts which could be covered in an introductory course for science students on environmental issues.

Forinash, Kyle, *Physics and the Environment* (IOP Press, London UK, 2017).

> Brief overview of topics that could be included in an environmental physics course. Uses some calculus.

Forinash, Kyle, and Barbara Whitten, Resources for teaching environmental physics, *American Journal of Physics* 87 (7) (2019):421, 'Resource Letter EP-1.

A resource guide for physics teachers and students. This is an update and expansion of Hobson, above (Category 2)

Lamarsh, J. R., and A. J. Baratta, *Introduction to Nuclear Engineering*, 4th ed. (Prentice Hall, NJ, 2017), 816 pp.

Physics textbook for science majors and engineers. Includes less technical and more accessible (to non-physicists) discussions on reactor types and accidents, including Fukushima.

Meredith, D. and N. Ruzycki, Introduction to the energy theme issue, *American Journal of Physics* 87: 493, https://doi.org/10.1119/1.5110871

Introduction to a special issue on teaching energy which includes 13 articles and two book reviews about teaching energy concepts to both science and non-science majors. This is an important issue pervading the natural sciences, and ESS faculty can benefit from experiences of faculty in physics.

Outlaw, Joe L., Keith J. Collins, and James A. Duffield, *Agriculture as Producer and Consumer of Energy* (Cambridge, MA, CABI Publishing, 2005), 345 pp.

Technical discussion of energy use in agriculture and energy output obtainable from biomass as a primary energy source.

Rez, P., *The Simple Physics of Energy Use* (Oxford University Press, Oxford UK 2017), 304 pp.

Practical orientation of solutions to questions about energy needs for buildings, transportation, embodied energy in manufacturing, and agriculture. Includes nuclear energy and nuclear waste from a non-technical perspective. Focuses on the US.

Schwartz, S. E., The Greenhouse Effect and Climate Change: Earth's Natural Greenhouse Effect**,** *Am. J. Phys.* 86 (2018): 565, Resource Letter GECC-1, https://doi.org/10.1119/1.5045574

Schwartz, S. E., The Greenhouse Effect and Climate Change: The Intensified Greenhouse Effect, *Am. J. Phys*. 86 (2018): 645, Resource Letter GECC-2, https://doi.org/10.1119/1.5045577

Physicist explains the models of the "natural" or pre-industrial greenhouse effect and the intensified greenhouse effect caused by human-related releases of greenhouse gases, mostly from fossil fuels in the last 250 years. These gases will likely increase the surface temperature of the earth significantly, by about 1 percent. Useful articles for physical science courses, and they help non-physicists see the reasoning of climate-change science.

4. Energy efficiency, EROI (Energy Return on Energy Invested), and NE (Net Energy)

First, some simple definitions: Both EROI and NE compare two figures characterizing the production and use of energy. As noted by Odum nearly 50 years ago, production of an energy source, a fuel, requires energy. For example, pulling oil from the ground requires pumps, pipes, personnel, and other inputs, all of which themselves require energy to make and transport to the oil field. Thus, "$Energy_{out}$" represents the energy in the oil pulled from the ground, and "$Energy_{in}$" is the energy required to pull the oil to the surface and make it available as a resource (Odum, 1973).

EROI is a proportion: ($Energy_{out}/Energy_{in}$); when multiplied by 100, EROI is a percent. This number compares the relative amounts of $Energy_{out}$ and $Energy_{in}$. NE is ($Energy_{out} – Energy_{in}$). It indicates the amounts of new energy made available by using already produced energy, both measured in the same energy units (joules, abbreviated J, named in honor of James Prescott Joule, a 19th century English scientist).

Modern societies depend upon steady supplies of energy for their existence, and they typically obtain energy with EROI values around 20 and above. When EROI falls beneath 10, the amount of NE made available for purposes other than procuring new energy drops precipitously. Perkins (Category 1) has general discussions of the central importance of EROI in historical and current times (Perkins, 2017, pp. 97 – 99, 160 – 165, 168 – 171, 237 – 238).

A low EROI from a primary energy source can therefore imperil the prosperity and security of a society. An EROI below one means more energy is used to extract the energy than is gained in the obtained fuel, a net energy loss. This can only be justified if the product is used in a process which is otherwise not possible to complete. Electrical energy illustrates this principal: electricity is extremely versatile in delivering energy services, and modern societies routinely expend more energy ($Energy_{in}$) than is contained in the electrical energy ($Energy_{out}$). Electricity is a manufactured form of energy, often called an "energy carrier" or "secondary energy source." Similarly, oil refineries routinely produce gasoline and jet fuel from crude oil, even though oil refining means E_{out} is less than E_{in}; the refined fuels, however, are more valuable as manufactured commodities than is the crude oil.

Teaching resources in this section delve into a cluster of related concepts and topics, all of which derive their environmental significance from the proposition, "Minimizing production and use of energy is the best way to minimize adverse environmental consequences." In other words, "efficiency" in general is "good." The problem with the term "efficiency," however, lies in its exact meaning.

All measures of "efficiency" have the form of "efficiency = (output of something/input of something) x 100, which makes the efficiency metric a percent value. Faculty and students need to be constantly mindful of the exact meaning of "something," because different disciplines often rely on a specific meaning, not always made explicit. Consider the following examples:

- Physicists generally measure "energy efficiency" as (output in joules/input in joules).
- Economists generally measure "economic efficiency" as (output in $/input in $).
- Measurement of "efficiency" of energy services may have multiple formulations:
    - "Efficiency of energy production" might be in (output in joules, kg, m^3, or $/inputs in joules or $). If the efficiency is (output in joules/input in joules), it's a measure of EROI or Energy Return on (Energy) Invested. If efficiency is (output in joules/input in $), it measures the economic efficiency of producing energy; if

efficiency is (output in \$/input in \$), it measures the potential profitability of producing energy.

- "Efficiency of mobility" might be "(output in km, vehicle-km, m^3, or kg-km/input in joules, \$, or hours-of-travel; any of the four output metric can be divided by any of the three input metrics to yield a total of 12 different efficiency measurements. Each of the 12 efficiency values would assess a different aspect of mobility. E.g. "m^3/hours-of-travel" could measure the time efficiency of transporting natural gas, H_2 or NH_3 in a pipeline.)
- "Efficiency of agricultural production" might be (output in kg, food-nutrients, joules, or \$/input in fertilizer-nutrients, joules, \$, or hours-of-labor)

Berg, Weston, Shruti Vaidyanathan, Eric Junga, Emma Cooper, Chris Perry, Grace Relf, Andrew Whitlock, Marianne DiMascio, Corri Waters, and Nadia Cortez, *The 2019 State Energy Efficiency Scorecard* (Washington: American Council for an Energy-Efficient Economy, Report U1908, October 2019), 211 pp. Available at https://aceee.org/sites/default/files/publications/researchreports/u1908.pdf, accessed Dec. 27, 2020.

> Develops a ranking method for evaluating each of the States on their promotion and achievements in energy efficiency.

Brockway, Paul E., Anne Owen, Lina I. Brand-Correa, and Lucas Hardt, Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources, *Nature Energy* 4 (July, 2019): 612 – 621.

> Assesses argument that renewable energy has far lower EROI values than fossil fuels. Authors maintain that EROI of refined fossil fuels has declined since 1995, due to extraction of harder to reach deposits, and that these EROI values are now close to those of renewable energy.

Castro-Alvarez, Fernando, Shruti Vaidyanathan, Hannah Bastian, and Jen King, *The 2018 International Energy Efficiency Scorecard*, (Washington: American Council for an Energy-Efficient Economy, Report I1801, June, 2018), 139 pp. Available http://www.aceee.org/sites/default/files/publications/researchreports/i1801.pdf, , accessed Dec. 27, 2020.

> Develops a ranking method for all countries on their promotion and achievements in energy efficiency.

Hall, C. A. S., Lambert, J. G., Balogh, S. B., "EROI of different fuels and the implications for society" *Energy Policy* 64 (2014): 141–152.

> Explains methodological challenges in calculating EROI data and argues that EROI values for many deposits of fossil fuels have declined over last two decades, to levels much closer to EROI values calculated for renewable energy and, in some cases, lower.

Lambert, Jessica G., Charles A. S. Hall, Stephen Balogh, Ajay Gupta, and Michelle Arnold, Energy, EROI and quality of life, *Energy Policy* 64 (2014): 153 – 167.

Analysis showing that as EROI drops, quality of life may also drop.

Laitner, John A. "Skip," Steven Nadel, R. Neal Elliott, *et al*., The long-term energy efficiency potential: what the evidence suggests (Washington: American Council for an Energy-Efficient Economy, Report E121, January, 2012), 88 pp. Available https://aceee.org/research-report/e121, accessed Dec. 27, 2020.

Comprehensive report on the potential for energy efficiency to reduce consumption of energy without compromising standards of living, from leading NGO on energy efficiency.

Murphy, David J., The implications of the declining energy return on investment of oil production, *Philosophical Transactions of the Royal Society A* 372 (2014): 20130126. http://dx.doi.org/10.1098/rsta.2013.0126

Review of literature on EROI of oil production indicates decline, and low EROI means higher costs to extract crude oil. Provides a metabolic model of why EROI values below 10 pose a challenge to the prosperity of modern societies.

Raugei, Marco, Net energy analysis must not compare apples and oranges, *Nature Energy* 4 (February 2019): 86 – 88.

Demonstrates importance of system boundaries when calculating values of EROI and net energy.

5. Energy units and their conversions

Some faculty and students interested in energy have considerable flair for and facility with quantitative and mathematical reasoning, but others do not. We don't believe that understanding energy within an ESS context necessarily requires well developed skills in mathematics, but it is important to understand that understanding energy requires dealing with the units by which energy is measured. In addition, it is essential to understand the scales covering the uses of energy by individuals, communities, nations, and the global community. The latter requires dealing with small numbers to big ones and skills with arithmetic and proportions. This Category points to resources that can help gain familiarity with energy units and converting from one unit to another.

Energy is the ability to do work, and introductory physics textbooks define work as "a force displacing a mass through a distance." In the 18th century, the steam-engine made work and energy, without those modern names, important things to measure in science, technology, and commerce. The increasing substitution of coal for firewood in England launched efforts to develop units for work and energy, and in 1875 the system was unified globally by creating the International System of Units (SI units) (Perkins, 2017, pp. 291 – 296).

The *Bureau International des Poids et Mesures* (BIPM, International Bureau of Weights and Measures) in Paris became the global center for negotiations establishing and periodically updating SI units. Few people have much cause to study the detailed standards for SI units, but BIPM's latest summary is listed below. Most scientists and commercial people use SI units at a far lower level of accuracy, but the formal standards set the stage for measuring energy, work, and power. The multitude of units used to express energy is an indication of its ubiquity in science, commerce, and ESS.

ESS students will need to learn the meanings of SI units for energy (joule, J) and power (watt = joules/second); in the United States they will also see the unit for heat energy (British thermal unit, BTU) in commercial statistics and the measure of calorie for food. More important, students who delve into commercial statistics will quickly discover they need to understand units such as "barrels of oil," "million tons of oil," "therms," and many others. They will also need to become familiar with (a) the prefixes and SI units used to express very small and very large amounts of energy, work, and power, and (b) the ability to convert between commercial and scientific units. Many websites provide easy conversions, but they are best used after a student learns what the SI units mean.

Once the units of energy, work, and power are well in mind, students will confront the concept of "energy density," measured in different ways. Energy density measures how much weight or space a fuel occupies. Low energy density may indicate a physical problem in obtaining enough energy to provide an energy service, i.e. the work valued by people. In some cases, low energy density fuels are more expensive, but not always. High energy density can be an advantage economically, but it might also be a measure of risk or danger, such as unintended fires or explosions.

Energy density can be expressed as joules/volume (volumetric density) or joules/mass (gravimetric density). These measures often characterize non-renewable sources like coal or uranium. Renewable energy such as solar radiation and wind have densities measured by joules/area, reflecting the areas required to produce a certain number of joules.

Converting units from one to another is often aggravating, but practice and websites ease the burden. One useful site is https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php, courtesy of the U.S. Energy Information Administration (accessed Dec. 27, 2020). The resources below will provide more depth.

Bureau International des Poids et Mesures, *The International System of Units*, 9th edition (Paris: Bureau International des Poids et Mesures, 2019), 216 pp.

> Contains authoritative French language version as well as English translation. At https://www.bipm.org/utils/common/pdf/si-brochure/SI-Brochure-9.pdf, accessed Dec. 27, 2020.

Hofstrand, Don, *Energy Measurements and Conversions* (Ames: Iowa State University, 2007), 8 pp.

Excellent source for conversions between SI units and many commercial units. At https://www.extension.iastate.edu/agdm/wholefarm/html/c6-86.html, accessed Dec. 27, 2020.

Zimmerman, Neil M., A primer on electrical units in the Système International, *American Journal of Physics* 66 (4) (1998): 324 – 331.

Physicist explains history of SI units and their uses in electricity.

6. **Statistical data on energy**

Before the 1970s, statistics on energy resources, uses, and projections were limited, but the oil crises of that decade prompted the US government and other sources to expand data publicly available and update it frequently. The US Energy Information Administration (EIA) and the International Energy Agency of the Organization for Economic Cooperation and Development (IEA) are now two of the best sources of energy statistics. BP, the British international oil company, also produces useful annual reports. Oil is the world's foremost source of energy, used mostly for mobility. Thus, several resources allow tracking of mobility as a category of energy services.

BP Statistical Review of World energy: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html, accessed Dec. 27, 2020.

Revised annually, this web site maintains a compendium of historical data of global energy use and resources indexed by sector, end use, and many other categories.

Bureau of Transportation Statistics, https://www.bts.gov/, accessed Dec. 27, 2020.

A comprehensive, searchable database of transportation information in spreadsheet format for the US. Includes energy use, accident and fatality rates, fuel economy, CAFE (Corporate Average Fuel Economy) standards, car size, sales of all types of vehicles and similar data for other transportation modes (air, boat, rail).

International Energy Agency: https://www.iea.org/, accessed Dec. 27, 2020.

Comprehensive source of historical data of global energy use and resources including current and historical economic factors. Some information is free but the printed, annual report is not.

US Department of Energy, Energy Information Administration

Start with https://www.eia.gov/, accessed Dec. 27, 2020. Website has a search function that generally works well to find data relevant to users' interests. Many reports are available: by specific primary energy resources, electricity production, some on monthly basis and others on quarterly or annual schedules, by State in USA, by USA total, and by foreign countries.

7. Energy systems

Social and political debates about energy often focus on just one element. For example, "What is the effect on the surrounding ecosystem of using hydraulic fracturing (fracking) to produce gas?" Or, "What is the effect of building a dam to produce hydroelectricity?" For ESS teaching, however, such a limited focus is insufficient. Many problems require a "systems approach." All systems have four parts: (a) components, (b) relationships among the components, (c) outcomes of interest, and (d) boundaries. Secure prosperity and stability of the economy are generally of highest interest to most people, and those outcomes derive from the components of the energy system, i.e. the primary energy sources and all the technological infrastructure that delivers energy services.

Climate change, the most pressing unintended consequence of energy for ESS, calls for reduction or elimination of fossil fuels, major sources of greenhouse gases. Reductions of those energy sources without replacing the lost energy, however, diminishes or cripples the ability of the energy system to deliver services. Resolution of climate change requires understanding and altering the energy system underlying the economy.

The energy system of the United States, however, is big and complex, hard to grasp. Lawrence Livermore National Laboratory produces yearly energy flow charts (Figure 1, Sankey diagrams) summarizing the US energy system (https://flowcharts.llnl.gov/content/assets/images/charts/Energy/Energy_2019_United-States.png, accessed 8 January 2021).

In this diagram, the "energy system" consists of (a) the primary energy sources currently in commercial use, (b) the conversion of some of these sources to electricity, (c) the end users of each fuel and electricity categorized as Residential, Commercial, Industrial, and Transportation. Sankey diagrams usefully portray key components and their relationships, and (d) energy released as "waste heat" rather than useful work. The name, Sankey diagram, derives from an Irish engineer, Riall Sankey, who in 1898 used a diagram to illustrate the efficiency of a steam engine (Kennedy and Sankey, 1898). They are especially useful to explain complicated energy and material flows to non-experts and the public, but it takes practice in learning how to read the diagrams.

PLACE FIGURE 1 HERE

Figure 1. Sankey diagram of US energy flow, 2019

The width of each line is proportional to the energy provided by the energy source, measured in "quads" or 10^{15} (quadrillion) British thermal units (Btu). Thick lines indicate more energy flow than thin ones. One quad approximately equals 1 EJ. Boxes on the left side show the total Btu's derived from each source, and total energy used in the United States appears in the title.

Energy doing work (energy services) appears at the far right, along with energy released as heat that did no useful work ("rejected energy"). The US total energy system efficiency of 32.6%, mentioned in the introduction, comes from looking at the total input of primary energy (100.2 quads) compared to 32.7 quads of energy services and 67.5 quads of "rejected energy."

The diagram shows clearly that petroleum, gas, coal, and uranium (nuclear power) were the most important primary energy sources for the United States in 2019. Petroleum, gas, and coal total 80.2 quads, so their elimination to mitigate climate change or other hazards would severely reduce energy services. To avoid losses of energy services requires replacement of the lost energy by efficiency and/or renewable energy and/or uranium (nuclear power). Changes in behavior to reduce need for energy services can also help compensate for the losses of energy from fossil fuels.

Mitigation of climate change, therefore, rests on the exact pathway of replacement or reduction of need for energy, a topic on which no consensus currently exists. Finding acceptable pathways is the most important problem, and the Sankey diagrams illustrate the components of the energy system that must change.

Lawrence Livermore National Laboratory also prepared Sankey diagrams of the energy supply system of each State in 2008 (Simon and Belles, 2011), but unfortunately these diagrams have not been updated as of 2021. Current State profiles of energy use, however, can be found at https://www.eia.gov/state/ These data and the older diagrams illustrate the challenges facing each State, and comparisons of multiple States quickly reveal that States face different challenges. Different challenges make it difficult for the US Congress to craft laws guiding US reductions in emissions of greenhouse gases.

8. Materials and energy systems

Delivery of energy services always involves materials: fuels and the components of devices that produce, transport, and use energy. Materials don't constitute a "problem" if they are widely available across the earth, require little energy to prepare, generate little or no toxic release, and don't destroy habitat.

Unfortunately, production and use of all energy sources, including renewable energy, create problems. Manufacturing photovoltaic devices uses toxic chemicals needing careful management. Rare earth metals that have had little or no previous use have become key minerals. Wind-generated electricity, for example, benefits greatly from steel alloys containing niobium (Nb), a rare earth listed as a "strategic mineral" for the United States, 100 percent of which is currently imported (U.S. Department of Commerce, 2019). These alloys have exceptional strength, which allows construction of higher wind turbines with lower weight steels, thus reducing costs of electricity generated (Patel and Jansto, 2012). Similarly, neodymium (Nd) alloyed with iron and boron makes exceptionally strong permanent magnets for the generators in wind turbines (Marx, *et al*., 2018).

The sparsity of general teaching resources for a broadly accessible understanding of energy-related materials may hinder a transition to renewable energy. This deficiency provides an opportunity for potential research topics for ESS students and faculty. The resources below serve as a starting point.

Ashby, M. F., *Materials and the Environment; Eco-Informed Material Choice*, 2nd ed. (Butterworth-Heinemann, 2012).

A thought-provoking description of the embodied energy of manufacturing materials plus explanations of energy life cycles, eco-audits, and recycling.

Cheisson, Thibault, and Eric J. Schelter, Rare earth elements: Mendeleev's bane, modern marvels, *Science* 363 (1 February 2019): 489 – 493.

Heavy on chemical methods of isolating rare earth elements, but the introduction and conclusions are generally accessible.

Guyonnet, Dominique, Gaétan Lefebvre & Nourredine Menad, Rare earth elements and high-tech products. Found at https://www.cec4europe.eu/wp-content/uploads/2018/09/Chapter_3_3_Guyonnet_et_al_Rare_earth_elements_and_high_tech_products.pdf, accessed Dec. 27, 2020.

General discussion of rare earth metals from viewpoint of the European Union. Easily accessible for all readers.

9. Electrification: electric grids and intermittency

As displayed in the Sankey diagram in Category 7, Energy Systems, the transformation of primary energy into electricity is a major component of the energy system that delivers energy services to consumers. No mystery surrounds this key fact: electricity is an exceedingly useful form of energy that can provide a multitude of services, including heat, light, motion, data management, and communications. Economically, it has proven inexpensive to produce compared to the conveniences and high economic values of the services provided. Moreover, properly installed it is usually quite safe to handle, and it produces no pollutants in the immediate vicinity of use.

Electricity also plays a key role in reducing the risks of climate change, which requires a substantial or complete substitution of renewable energy for fossil fuels. Solar radiation, wind, and hydropower are renewable, primary energy sources made useful by transformation to electricity. The other two, major renewable primary energy resources—biomass and geothermal heat—are generally used either directly as heat or by transformation to electricity. As noted in Category 4, all transformations to electricity involve losses of energy in the transformation from primary source to electrical energy (2nd law), i.e. the EROI is less than 1, a loss tolerated because of electricity's high versatility and value.

Electrification of energy services with two of the most important sources of renewable energy, however, has an Achilles heel: intermittency due to variability of energy supply. Solar radiation has highly predictable variation due to time of day and time of year, but changing cloud cover is less predictable. Wind varies in speed (energy content), but forecasts can predict some of these changes.

Despite increasingly accurate forecasts in these two sources, variability in solar and wind energy supply will always interfere, because stability of voltage in a wire transporting the power does not tolerate much variation. Electrical engineers seek to limit variations in frequency and voltage within small ranges. The production of the voltage energizing the grid and its transmission are inseparable, and methods to stabilize it are mandatory.

Solving intermittency with renewable energy involves either storing renewable electricity or combining power generated by solar and wind with renewable sources that can produce electricity on demand, e.g. hydropower, geothermal heat, or biomass. Uranium (nuclear power) can also solve intermittency, but it is not it is not ideal for this purpose, and it is not a renewable energy source. Uranium also has other environmental challenges (e.g. Cooke, Category 13).

In addition to solving intermittency of solar and wind power by combining it with electricity from other primary sources of energy, engineers are also turning to storage mechanisms. Teaching resources in this Category focus on kinds of storage: chemicals, particularly hydrogen (H_2) and ammonia (NH_3), batteries of various kinds including flow batteries, and many other devices.

Hydrogen can be used to produce electricity, both by combustion and by fuel cells. It can also be used to produce hydrocarbon fuels by reacting it under appropriate conditions with carbon dioxide. Virtually all hydrogen now manufactured relies on natural gas (mostly methane, CH_4) as the source of hydrogen and heat to drive the processes, which releases carbon dioxide and fugitive methane, both greenhouse gases. The utility of hydrogen as part of mitigating climate change lies in commercializing its synthesis with electricity from renewable energy without emissions of greenhouse gases. Some resources in this section detail the status of efforts to commercialize hydrogen production from renewable energy sources.

Ammonia can be used as a fuel in combustion and in fuel cells to make heat and electricity, respectively. It, too, has long been produced in large quantities around the world with fossil fuels, for example to make fertilizers. Ammonia, however, can also be made with electricity from renewable sources. These processes are not yet commercially viable compared to ammonia made with fossil fuels. Efforts are underway to change ammonia into a chemical for storing renewable electricity, and some resources in this section summarize the current status.

Both hydrogen and ammonia have one more extremely valuable feature. They can be transported by pipelines or vehicles from place of synthesis to place of use. Efficient, low cost transport of one or both from renewable energy sources makes them valuable in building economies based on renewable energy without fossil fuels.

Variable production levels of solar radiation and wind create challenges for grid operators, and energy storage is now a key item of research, development, and deployment. For the most part, these challenges are of necessity in the domain of engineers, due to their demands for precision and highly specialized expertise. For ESS faculty and students interested in the multiple methods of storing energy, comprehensive reviews are available (Koohi-Fayegh and Rosen, 2020).

In addition to intermittency, using solar radiation and wind to generate electricity has introduced other problems in managing electric grids. Fossil fuels currently generate most electricity, and the grid transmits power from a relatively small number of large power plants. Public policy and falling prices, however, have promoted electrical generation from many relatively small sources of wind and solar radiation. The grid, therefore, must change to accommodate “distributed energy resources,” a process now underway.

The resources below can provide a basic understanding of the status of dealing with electrification.

Bakke, Gretchen, *The Grid: The Fraying Wires between Americans and Our Energy Future* (New York: Bloomsbury, 2016), 352 pp.

> Cultural anthropologist unpacks the people, laws, politics, economics, and technology of transmitting electricity at a time when the means of generating, selling, and trading electricity have sharply shifted. Useful review in *Science* 353 (22 July 2016): 355, doi: 10.1126/science.aaf9323.

Buchmann, I., *Batteries in a Portable World: A Handbook on Rechargeable Batteries for Non-Engineers*, 4th ed. (Cadex Electronics, 2017).

> Comprehensive, non-technical discussion of the history, specifications, composition, terminology and current use of various types of commercially available batteries, including flow batteries. A published version of information at http://batteryuniversity.com/, accessed Dec. 27, 2020.

Huggins, R., *Energy Storage: Fundamentals, Materials and Applications* 2nd ed. (Springer, Berlin, Germany, 2016).

> Advanced theoretical elucidation of energy storage (thermal, reversible chemical, organic fuels, mechanical, electromagnetic, electrochemical). Some practical applications are included. The treatment of basic thermodynamics and electrochemical processes as related to energy conversion is more in-depth than what is usually found in an introductory physics text.

International Energy Agency, *The Future of Hydrogen: Seizing Today’s Opportunities* (International Energy Agency, 2019), 199 pp.

> Technical report outlines the challenges still facing creation of a hydrogen-production industry based on renewable energy. For physical scientists and engineers.

Koerth-Baker, Maggie, *Before the Lights Go Out: Conquering the Energy Crisis before It Conquers Us* (Hoboken: John Wiley & Sons, 2012), 290 pp.

> Journalist explains electrical generation, transmission, and distribution at a time of rapid technological change. Now somewhat dated due to rapid changes in renewable energy technology, but still useful for easy, non-technical language.

Lazard, *Levelized Cost of Energy Analysis, Version 14.0 and Levelized Cost of Storage Analysis, Version 6.0*, https://www.lazard.com/perspective/lcoe2020, accessed Jan. 8, 2021.

Cost of electricity varies among different sources, and cost always influences willingness to employ the source. The levelized cost of electricity (LCOE) seeks to compare the costs of electricity from different sources, and this annual report provides frequent updates. Use of LCOE data, however, requires care, because the types of costs included and the assumptions used to calculate them differ among analysts.

Malloy, Patrick, and LeeAnn Baronett, The truth about hydrogen, found at https://rmi.org/the-truth-about-hydrogen/, accessed Dec. 27, 2020.

Non-technical summary of current situation of global H_2 production industry and the need for more H_2 in the future. Authors believe production of green hydrogen, from renewable energy, will become cost competitive.

Rufer, Alfred, *Energy Storage: Systems and Components* (CRC Press, Taylor and Francis, Oxforshire UK, 2018).

Systematic discussion of most existing large- and small-scale energy storage systems including pumped hydro, compressed air, flywheels, superconducting magnets, capacitors, supercapacitors, fuel cells, batteries, and flow batteries. Algebra and some chemistry; Ragone plots, cycle efficiency, power density, specific power, battery aging, and conversion processes are also treated.

Thompson, William L., *Living on the Grid: The Fundamentals of the North American Electric Grid in Simple Language* (Bloomington: iUniverse, 2016), 199 pp.

Electrical engineer, who worked in electric power industry, explains the transmission of electrical energy (power) on a grid, from source of generation to transmission lines to distribution lines back to the source. Non-mathematical.

U.S. Department of Energy, Sustainable Ammonia Synthesis**:** Exploring the scientific challenges associated with discovering alternative, sustainable processes for ammonia production (Washington: U.S. Department of Energy, 2016), 23 pp. Available at https://www.osti.gov/servlets/purl/1283146, accessed Dec. 27, 2020.

Chemists ponder the challenge of synthesizing NH_3 commercially with electricity from renewable energy. Introductory material understandable without chemistry.

Zito, R., *Energy Storage: A New Approach* (Wiley/Scrivener, NY, 2010).

Energy requirements of various applications for energy use are treated first. Focus is on batteries (flow or redox batteries included) but other energy storage such as mechanical energy, capacitors and compressed gas also are discussed. Uses basic physics, calculus, and differential equations.

10. Energy transitions

To avoid potential catastrophes from climate change, the world must reduce carbon emissions to as close to zero as possible as quickly as possible. Such reductions must begin with recognizing fossil fuels as the source of most of the world's energy. These energy sources are deeply embedded in all political economic systems, and the technologies for finding, producing, and using them are widely familiar. Changing, therefore, requires shifts in technology, political economic, and cultural relationships. Some people, companies, and countries may benefit without much disruption, but others will not. Any practical scheme for transition must include all these elements of a "sociotechnical system" on which prosperity, security, and survival depend. Resources for teaching and learning about transitions are plentiful, and the list below barely scratches the surface.

Aklin, Michaël, and Johannes Urpelainen, *Renewables: The Politics of a Global Energy Transition* (Cambridge: The MIT Press, 2018), 330 pp.

> Political scientists present a model explaining how energy crises enabled renewable energy sources to join the energy systems of some countries.

Araújo, Kathleen M., *Low Carbon Energy Transitions: Turning Points in National Policy and Innovation* (New York: Oxford University Press, 2017), 384 pp.

> Public policy specialist analyzes four case studies on countries that embraced importance of developing low-carbon sources of energy: Iceland (geothermal heat), France (nuclear power), Brazil (biomass (ethanol)), and Denmark (wind power). For advanced students in public policy.

Arent, Douglan, Channing Arndt, Mackay Miller, Finn Tarp, and Owen Zinaman, eds., *The Political Economy of Clean Energy Transitions* (Oxford: Oxford University Press, 2017), 594 pp.

> Explanation of political and economic factors that have changed and will need to further change if world is to make a transition to renewable energy fast enough to prevent global average temperature from rising above 1.5 °C.

Beveridge, Ross, and Kristine Kern, The *Energiewende* in Germany: Background, Developments and Future Challenges, *Renewable Energy Law and Policy Review* 3 (2013): 3 – 12.

> Examination of exceptional features that led the German federal government to craft laws promoting energy transition, and assessment of the German experience for lessons applicable elsewhere. The US does not yet have comparable federal laws, but states such as California, New York, and others are increasingly adding comprehensive legislation that mimics the German example.

Davis, Steven J., Nathan S. Lewis, Matthew Shaner, *et al.*, Net-zero emissions energy systems, *Science* 360 (29 June 2018): 10 pp. (summary + full article). Full article available https://science.sciencemag.org/content/360/6396/eaas9793, accessed Dec. 27, 2020.

Systems analysts summarize ways of providing essential energy services without greenhouse gas emissions. Their projections use renewable energy and nuclear power to produce H_2 and NH_3 as well as synthetic hydrocarbon fuel. Includes comparative cost data. For science faculty and advanced science students.

European Commission, *A Clean Planet for All* (Brussels: European Commission, COM(2018) 773 final), 25 pp. Available https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN, accessed Dec. 27, 2020.

Blueprint for EU to achieve net-zero carbon emissions by 2050 through eight specific actions.

Farmer, J. D., C. Hepburn, M. C. Ives, *et al.*, Sensitive intervention points in the post-carbon transition, *Science* 364 (12 April 2019): 132 – 134. DOI: 10.1126/science.aaw7287

UK policy analysts propose key actions to promote transition. Good, short piece to promote discussion by students.

Geri, Laurance R., and David E. McNabb, *Energy Policy in the U.S.: Politics, Challenges, and Prospects for Change* (Boca Raton: CRC Press, 2011), 290 pp.

Public administration scholars provide comprehensive discussion of the challenges of crafting energy policy in the US federal government and the mechanisms adopted to promote a transition to renewable energy. A disciplined approach that strives to be neither prescriptive nor proscriptive.

Helm, Dieter, *Burn Out: The Endgame for Fossil Fuels* (New Haven: Yale University Press, 2017), 281 pp.

Economist argues that technological innovations can and will make fossil fuels obsolete.

Jacobson, Mark Z., Delucchi, Mark A., Bauer, Zack A.F., *et al.*, 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World, *Joule*, 1, (6) (September 2017): 108-121. http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf accessed Dec. 27, 2020.

The cost, logistics and economic issues involved in moving 139 countries around the globe to all renewable energy using existing technology are presented. A similar report by some of the same authors exists for each of the 50 states in the US.

Intergovernmental Panel on Climate Change (IPCC), *Special Report on Renewable Energy and Climate Mitigation* (2012): https://archive.ipcc.ch/report/srren/ accessed Dec. 27, 2020.

A comprehensive study of current renewable energy technology and possible routes to implementation. A discussion of the costs and policy issues impacting the switch from fossil fuels to renewables is included. Now dated in terms of technology and costs, but still a useful, comprehensive treatment.

Lambert, Martin, and Gbemi Oluleye, A mountain to climb? Tracking progress in scaling up renewable gas production in Europe (Oxford: Oxford Institute for Energy Studies & Sustainable Gas Institute, London, OIES Paper: NG 153, 2019), 36 pp. Available free at https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/10/A-mountain-to-climb-Tracking-progress-in-scaling-up-renewable-gas-production-in-Europe-NG-153.pdf?v=7516fd43adaa, accessed Dec. 27, 2020.

For advanced students in engineering, resource economics, and environment. It tackles the problem of scaling up facilities that could manufacture methane from carbon dioxide, water, and renewable electricity.

Linquiti, Peter, and Nathan Cogswell, The Carbon Ask: effects of climate policy on the value of fossil fuel resources and the implications for technological innovation, *Journal of Environmental Studies and Science* 6 (2016): 662 – 676, DOI 10.1007/s13412-016-0397-2.

Public policy scholars estimate the current value of fossil fuel deposits—that cannot be produced without causing climate warming above 2°C—as $185 trillion, a loss of about 63 percent of their current value. The value of "stranded assets" equals over two years' value of the world's annual GDP. Economic dislocations of this magnitude are almost certain to meet political opposition.

Lovins, Amory B., *Reinventing Fire: Bold Business Solutions for the New Energy Era* (White River Junction: Chelsea Green Publishers, 2011), 334 pp.

Physicist-futurist argues that energy efficiency and renewable energy sources will be a more profitable and prosperous energy economy than one based on the "hard" sources of energy (fossil fuels and uranium).

McElroy, Michael B., *Energy and Climate: Vision for the Future* (New York: Oxford University Press, 2016), 266 pp.

An analysis, heavy on economic considerations, of a future energy system without much carbon emissions.

Moore, Sharlissa, *Sustainable Energy Transformations, Power, and Politics: Morocco and the Mediterranean* (London: Routledge, 2018), 260 pp.

Science, technology, and society scholar assesses the plan to link mammoth production of electricity by solar and wind sources in Morocco for the European Union and North Africa. Emphasizes interactions among technology, society, and culture.

Morris, Craig, and Arne Jungjohan, *Energy Democracy: Germany's Energiewende to Renewables* (Switzerland: Palgrave Macmillan-Springer Nature, 2016), 437 pp.

A journalist and political scientist argue that community actions are essential to move government policies to support transition to renewable energy. Heavy emphasis on Germany's *Energiewende* (energy transition).

Mulvaney, Dustin, *Solar Power: Innovation, Sustainability, and Environmental Justice* (Oakland: University of California Press, 2019), 329 pp.

ESS scholar advocates transition to renewable energy, especially solar radiation, and offers reforms needed to ensure environmental justice and protection of ecosystems.

Princen, Thomas, Jack P. Manno, and Pamela L. Martin, eds., *Ending the Fossil Fuel Era* (Cambridge: The MIT Press, 2015), 374 pp.

Selection of papers, including six case studies on events in specific countries, illustrate editors' argument that a new ecological politics must emerge to delegitimize the extraction and use of fossil fuels. Market-based policies alone can't accomplish ending uses of fossil fuels.

Quitzow, Leslie, Weert Canzler, Philipp Grundmann, *et al*., The German *Energiewende*: What's happening? Introducing the special issue, *Utilities Policy* 41 (2016): 163 – 171. http://dx.doi.org/10.1016/j.jup.2016.03.002

A good, short summary in non-technical language of the background to Germany's decision to transition its energy system away from fossil fuels and uranium (nuclear power).

Sivaram, Varum, *Taming the Sun: Innovations to Harness Solar Energy and Power the Planet* (Cambridge: The MIT Press, 2018), 371 pp.

Materials scientist-policy analyst believes solar power can power the earth, but further innovations required to elicit investments needed.

Smil, Vaclav, *Energy Transitions: Global and National Perspectives*, 2nd edition (Santa Barbara: Praeger, 2017), 282 pp.

Geographer-physical scientist synthesizes vast literature on past energy transitions and emphasizes the scales of changes needed in infrastructure and materials. Special treatment given to especially challenging reductions in uses of fossil fuels in making iron-steel, cement, ammonia, and plastics.

Sovacool, Benjamin K., *Visions of Energy Futures: Imagining and Innovating Low-Carbon Transitions* (New York: Routledge, 2019), 256 pp.

Sociologist- policy analyst summarizes and assesses multi-disciplinary literature on the role of vision and imagination driving technological innovation and deployment related to a future with low carbon emissions.

Stokes, Leah Cardamore, *Short Circuiting Policy: Interest Groups and the Battle over Clean Energy and Climate Policy in the American States* (New York: Oxford University Press, 2020), 318 pp.

> Political scientist demonstrates that interest groups delayed and blocked policies to promote renewable energy sources in generation of electricity.

Tester, J. W., E. M. Drake, M. J. Driscoll, M. W. Golay, and W. A. Peters, *Sustainable Energy: Choosing Among Options* (MIT Press, Cambridge, MA 2012).

> Technical analysis (calculations using calculus of levelized costs, externalities, economic decision trees, etc.) of current energy technology. Historical contexts, geopolitical and sociological factors are included. Useful for gaining a social and economic perspective of renewable energy implementation.

Warburg, Philip, *Harness the Sun: America's Quest for a Solar-Powered Future* (Boston: Beacon Press, 2015), 241 pp.

> Lawyer describes the beginnings of solar power as a practical substitute for fossil fuels and suggests ways to promote its continued expansion. Reviewed in *Science* 350 (9 October 2015): 169.

11. Geoengineering

Some analysts have concluded (a) the risks of climate change are too large and (b) the pace of abandoning fossil fuels and other sources of greenhouse gases is too slow. Consequently, they argue, humanity must embark on a project of breathtaking complexity: to "engineer" the earth's climate to lower the risks of climate change. The mechanisms included include solar radiation management (SRM), carbon dioxide removal (CDR), carbon capture and sequestration (CCS), and negative carbon emissions (NCE).

Geoengineering's challenges to ESS reside in the fact that (a) the engineering techniques are at best in their infancy and (b) each suggested engineering practice has unknown challenges in governance and ethics. Moreover, the unknowns tend to generate sharp debates and—in the judgment of this paper's authors—potentially interfere with the task of promoting a transition to renewable energy.

The resources here will help start further thinking and debate among faculty and students. The topic of geoengineering is excellent for stimulating classroom discussions and prompting students to examine the issues carefully.

Bastin, Jean-Francois, Yelena Finegold, Claude Garcia, *et al.*, The global tree restoration potential, *Science* 365 (5 July 2019): 76 – 79.

> Ecologists argue that reforestation of approximately 1 billion hectares could be humanity's best investment, at an engineering scale, in removing carbon from the atmosphere. Paper prompted considerable debate.

National Research Council, *Climate Intervention: Reflecting Sunlight to Cool Earth* (Washington, D.C.: The National Academies Press, 2015). https://doi.org/10.17226/18988, accessed Dec. 27, 2020.

Report evaluating risks and benefits of geoengineering, with recommendations.

Preston, Christopher J., "Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal," WIREs Clim Change 2013, 4:23–37. doi: 10.1002/wcc.198.

Philosopher reviews ethical issues raised by various forms of geoengineering. Focuses on modifications of the earth's albedo but touches on carbon dioxide removal as well.

Section C: Energy and Society

12. Energy history

Faculty who emphasize either physical science or environmental history may wish to incorporate a richer understanding of the scientific and technological history underlying the conceptual and the practical dimensions of energy. Energy as a concept or phenomenon was not "discovered," but instead natural philosophers (precursor to the modern word "scientist") developed it as a mathematical, calculated factor that proved immensely useful in understanding, predicting, and controlling physical transformations. The concept quickly migrated to all physical sciences (physics, chemistry, biology, geosciences) and the engineering disciplines.

For some science students, understanding the historical origins of the concept helps them learn its nature and utility. In addition, some of the developers of energy as a concept, plus modern philosophers, have explored the epistemological links between energy as a scientific phenomenon and its metaphysical, cosmological, theological, and political dimensions. Perkins (Category 1) has material that briefly summarizes some of these issues, particularly the technological precursors in engines and electricity that preceded the development of thermodynamics as a mathematical science (Perkins, 2017, pp. 4 – 75).

Coopersmith, Jennifer, *Energy, the Subtle Concept: The Discovery of Feynman's Blocks from Leibniz to Einstein* (New York: Oxford University Press, 2010), 400 pp.

Historian emphasizes physical science in the 18^{th} and 19^{th} centuries in Europe. She connects the work of artisans (technology) with work of the natural philosophers-scientists.

Daggett, Cara New, *The Birth of Energy: Fossil Fuels, Thermodynamics, & the Politics of Work* (Durham: Duke University Press, 2019), 268 pp.

Political scientist argues that religious and political beliefs of Scottish scientists interacted with thermodynamics, a science they helped develop in the 19^{th} century. Reform efforts to prevent climate change, she argues, must incorporate perspectives from

ecofeminism and environmental justice if efforts to eliminate fossil fuels are to succeed. For advanced students in philosophy of science and in political theory.

Hughes, Thomas P., *Networks of Power: Electrification in Western Society, 1880 – 1930* (Baltimore: Johns Hopkins University Press, 1983), 474 pp.

Historian of technology compares the initial electrification in the US, Germany, and the UK. Explains how electrical energy began as a curiosity in limited areas but grew to networks that fully modernized countries.

Mitchell, Timothy, *Carbon Democracy: Political Power in the Age of Oil* (New York: Verso, 2013), 292 pp.

Historian links rise of democracy in the West to the rise of carbon economies, first based on coal, then oil. Insists on primacy of following the labor forces of industries assembled to supply carbon fuels, not the flow of money to the companies. Compare with Yergin (below).

Smil, Vaclav, *Energy and Civilization: A History* (Cambridge: MIT Press, 2017), 552 pp.

Geographer-physical scientist synthesizes changes in human uses of energy from pre-historic to modern times, with emphasis on physical dimensions of energy and the challenges of reducing the uses of fossil fuels, a necessity he acknowledges and on which he expresses highly cautious optimism.

Smith, Crosbie, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* (Chicago: The University of Chicago Press, 1998), 404 pp.

Historian emphasizes work in Britain, especially Scotland, which placed the concept of energy as a center piece in the physical sciences. Smith also explores the theological and commercial ties of Scottish scientists affecting their thinking.

Weart, Spencer R., *The Discovery of Global Warming* (Cambridge: Harvard University Press, 2008), 230 pp. Available on-line: https://history.aip.org/climate/index.htm accessed Dec. 27, 2020.

History of the discovery of human-caused climate change. Non-technical with some technical references included.

Wrigley, E.A., *The Path to Sustained Growth: England's Transition from an Organic Economy to an Industrial Revolution* (Cambridge: Cambridge University Press, 2016), 219 pp.

Economic historian traces the first substitution of coal for firewood, in England, 1500s through 1800s, which opened the possibility of economic growth without a commensurate growth in farmland. Coal powered Britain's transformative industrial revolution and its transition to the first modern nation. Updated with expanded scope of an earlier book (2010),

Yergin, Daniel, *The Prize: The Epic Quest for Oil, Money & Power* (New York: Simon & Schuster, 1991), 877 pp.

> Historian/energy industry consultant portrays development of the modern oil industry, based on following the money sought, not the labor forces enabling production. Compare to Mitchell (above).

13. Energy: environment, health, geopolitics, society, and culture

Modern societies developed based on energy services from, primarily, fossil fuels and hydropower. The knowledge to produce and control these energy sources and energy services lies in the physical sciences and engineering but just as importantly modern energy services profoundly affected both societies and the biophysical environment. Energy services affected lives, work, behavior, thinking, expectations, and ethical norms.

Climate change may wreak havoc on modern societies and stems largely from greenhouse gases emitted from fossil fuels. Mitigating its risks requires abandonment of what were here-to-fore the foundations of modern life, those same fossil fuels. Other environmental and social effects stemming from modern energy services may be somewhat less consequential, but they, too, argue powerfully for mitigation and curtailment of fossil fuels.

Renewable energy sources will be essential for abandoning the fossil fuels, but they, too, can produce negative environmental and social effects. In short, despite the essential requirement for energy for modern life, any use of energy may produce negative effects, and some can cause potentially catastrophic consequences.

Potential negative effects of energy occur in all three phases of delivering energy sources and services. "Upstream" processes mine or collect primary energy sources, i.e. raw natural resources. "Midstream" processes refine and transport primary sources and fuels to refiners and users. "Downstream" processes turn energy or fuel into the energy services.

ESS focuses on the environmental effects or consequences accompanying all three steps involved with both primary and secondary energy sources, such as electricity. The effects are many, and multiple methods have evolved to assess their nature and magnitudes, the risks or destruction caused, the changes in the visual landscape induced by energy technologies, and the social-economic-political-cultural upheavals that have affected individuals and communities near the steps involved.

For example, crude oil is a primary energy source found by geologists and extracted from the earth by petroleum engineers, the upstream processes. Crude oil is transported to oil refineries that change the raw material into a fuel ready to use, e.g. gasoline or diesel fuel, the midstream processes. Finally, the fuel is transported to users who burn it with an internal combustion engine to produce an energy service, mobility, which is the downstream process. Only the energy service, e.g. mobility, is desired, but having mobility intrinsically requires the upstream and midstream processes.

Another example: drivers may be aware of the downstream environmental impacts of mobility, such as air pollution and the landscape changes required to build roads, but often the effects of upstream and midstream processes go unnoticed. People and other organisms near the mining, refining, and transport processes are at risk, however, even if they don't enjoy the mobility enjoyed by automobile owners.

Consider also the potential negative effects of a wind turbine producing electricity used to produce hydrogen. Then, midstream processes may transport and refine the hydrogen into a convenient chemical fuel in a chemical factory with negative side effects. Transport may again be essential for taking the fuel to its downstream site of use, e.g. an automobile powered by synthetic gasoline made in the chemical factory. Alternatively, the hydrogen may be transported to a fueling station dispensing hydrogen to auto drivers with a fuel-cell powered electric car. The downstream "clean car" may still have negative upstream and midstream effects.

Health effects require toxicological studies to identify the effects of chemical and physical entities on people and other organisms. Knowledge and methods of chemistry, physics, and biology all play critical roles in toxicological analysis. Anthropologists, sociologists, and economists assess the changes in communities and lifestyles. Landscape architects assess changes in visual landscapes. Ecologists study the effects on communities of organisms spread over small and large areas of terrestrial and aquatic habitats. Lawyers and policy analysts use laws, e.g. the National Environmental Policy Act (NEPA), to assess, regulate, and mitigate the activities of the energy and transport industries. ESS faculty and students with many different interests and skills, therefore, have important roles to play in all steps of the energy economy.

Environmental educators must recognize both the undeniable benefits of energy and the potential negative effects. Authors in this Category come from ESS, anthropology, economics, history, landscape architecture, medical sciences, philosophy, psychology, risk assessment, sociology, and urban-regional planning.

The social sciences play an essential role in this arena, especially those that developed STS perspectives and methods. STS ("science and technology studies," sometimes "science, technology and society") recognized technology was not based solely on expertise that was objectively and universally "true." Instead, it has multiple ties to the sociocultural and political dimensions of human society. Examples include issues of gender, race, class, visions of the future, health, geopolitics, and ethical-moral standards. See especially Hess and Sovacool (2020) and Sovacool, *et al*. (2020) below. Many ESS faculty are well positioned to use and contribute to insights developed in STS.

Feminist theorists, for example, have analyzed environmental issues from the perspective of gender and developed some of the most profound insights into the relationship between people and their environment. Environmental historian Carolyn Merchant pioneered this topic.

Class and race issues have appeared most strongly in issues of environmental justice, pioneered by Robert Bullard. Analyzing energy with systems analysis and statistics alone may ignore important differences between different groups. For example, poor and minority countries and communities have contributed the least to negative effects of energy use, but they suffer the most from the effects of pollution and climate change.

Grassroots activist groups are engaged in many local environmental struggles centered on drilling, fracking, pipelines, and other dimensions of producing fossil fuels. It might be useful to assign a research project, asking your students to describe an environmental issue local to their home. Be sure to ask them to look for authoritative sources, and to describe both sides of the issue. The resources by Funes and Shinn, plus others below, lend themselves well to such an exercise.

The resources below provide a few insights into this multitude of subjects, but we emphasize they are only a few of the resources available. Faculty and students can use key words in Google Scholar or other search engines to find a treasure trove of literature in this Category.

Apostol, Dean, James Palmer, Martin Pasqualetti, Richard Smardon, and Robert Sullivan, *The Renewable Energy Landscape: Preserving Scenic Values in Our Sustainable Future* (New York: Routledge, 2017), 286 pp.

> Landscape architects and urban planners present comparative methods of assessing the visual landscape changes due to adoption of renewable energy. Material from Australia, United Kingdom, USA, and elsewhere. For advanced students.

Bauhardt, Christine, Solutions to the crisis? The Green New Deal, Degrowth, and the Solidarity Economy: Alternatives to the capitalist growth economy from an ecofeminist economics perspective, *Ecological Economics* 102 (2014): 60 – 68. http://dx.doi.org/10.1016/j.ecolecon.2014.03.015 accessed Dec. 27, 2020.

> German economist and ecofeminist links need to replace fossil fuels with renewable energy to establishment of a non-growth economy and valuation of women's labor. Probably one of many European precursors to proposal for a Green New Deal in the US.

Bullard, Robert, *Dumping In Dixie: Race, Class, And Environmental Quality,* Third Edition, (Boulder: Westview Press, 2000), 234 pp.

> Pathbreaking sociologist pioneered field of environmental justice. Argued that racism was more important than income as an indicator of who suffered from environmental pollution.

Bullard, Robert, Confronting Environmental Racism in the 21st Century, in Alison H. Deming and Lauret E. Savoy, eds., *The Colors of Nature: Culture, Identity, and the Natural World* (Minneapolis: Milkweed Editions, 2011), 337 pp.

> Succinct summary of the argument for environmental justice.

Busenberg, George J., *Oil and Wilderness in Alaska: Natural Resources, Environmental Protection, and National Policy Dynamics* (Washington: Georgetown University Press, 2013), 168 pp.

Environmental policy analyst explains the relationships among extraction of oil in Alaska, its transport to market, land claims by Native Americans, wilderness protection, and pollution control from oil spills. Excellent case study for students.

Coleman, James W., Beyond the pipeline wars: reforming environmental assessment of energy transport infrastructure, *Utah Law Review* 2018 (1) (2018): 119 – 168.

Legal assessment of environment and transport energy from sources (“upstream”) to sites of use (“downstream”), including pipelines, port infrastructure, transmission lines, and other infrastructure. Emphasizes National Environmental Policy Act (NEPA) review of Keystone XL pipeline. For advanced students.

Cooke, Stephanie, *In Mortal Hands: A Cautionary History of the Nuclear Age* (New York: Bloomsbury, 2009), 491 pp.

Journalist specializing in nuclear industry provides broad overview of the development of nuclear weapons and nuclear power, and the relationships between the two. Thought provoking critique relevant to the potential of uranium and plutonium to provide mitigation for climate change. International in its scope, highly readable.

Deutch, J. M. and R. K. Lestor, *Making Technology Work; Applications in Energy and the Environment* (Cambridge University Press, Cambridge UK, 2004).

Examples of economic analysis of the implementation of renewable energy, non-renewable energy, and nuclear energy. A brief discussion of risk analysis is also included. Technical details are relegated to end of chapter sections.

Epstein, Alex, *The Moral Case for Fossil Fuels* (New York: Portfolio/Penguin, 2014), 248 pp.

Philosopher-business consultant argues that continued and expanded uses of fossil fuels are essential. We do not accept his argument, but it represents an intellectual and political viewpoint for ESS. Good resource for stimulating debate among students.

Funes, Yessenia, “North Dakota's First Solar Farm Opens on Standing Rock Tribal Land,” Dec. 27, 2020 https://earther.gizmodo.com/north-dakotas-first-solar-farm-opens-on-standing-rock-t-1836732750, 25 December 2020.

Favorable press report on a new solar farm involving Native Americans

Gardiner, Stephen M., Ethics and global climate change, *Ethics, 114,* (2004), pp. 555-600.

Philosopher reviews the ethical issues raised by climate change, along with effective explanations of the objections of climate skeptics.

GenderCC: Women for Climate Justice, https://www.gendercc.net/home.html, accessed Dec. 27, 2020.

International coalition of activist groups advocating for gender justice in climate issues.

Gibbs, Lois Marie, *Love Canal: My Story* (Albany: State University of New York Press, 1982), 174 pp.

Classic story of environmental justice, by the activist who organized resistance to chemical pollution.

Hess, David J. and Benjamin K. Sovacool, Sociotechnical matters: reviewing and integrating science and technology studies with energy social science, *Energy Research and Social Science* 65 (2020): 101462, https://doi.org/10.1016/j.erss.2020.101462

STS scholars review an extensive sample of social science literature to show examples and utility of STS approaches in studying the social dimensions of energy systems and technology.

Klein, Naomi, *This Changes Everything: Capitalism vs. the Climate* (Simon and Schuster: New York, NY, 2014).

Journalist argues for changes in our economic system to respond to the climate crisis.

LaDuke, Winona, Black snake and the pipeline chronicles: Northern Gateway, Keystone, and the Enbridge Great Lakes Lines, in Sean Aaron Cruz, ed., *The Winona LaDuke Chronicles: Stories from the Front Lines in the Battle for Environmental Justice* (Halifax: Fernwood Publishing, 2016), 299 pp.

Native American activist describes movements involving pipelines constructed on tribal land.

Lockwood, Alan H., *The Silent Epidemic: Coal and the Hidden Threat to Health* (Cambridge: MIT Press, 2012), 229 pp.

A physician collates the health effects for all stages in the use of coal as an energy source. For all levels.

Martinez-Alier, Joan, *The Environmentalism of the Poor: A Study of Ecological Conflicts and Valuation* (New York: Oxford University Press, 2005), 312 pp.

Analysis of environmental conflicts using the lenses of environmental economics and political ecology, with a focus on environmental justice. International perspective.

Merchant, Carolyn, *Autonomous Nature: Problems of Prediction and Control from Ancient Times to the Scientific Revolution* (New York: Routledge, 2016), 196 pp.

Environmental historian originally trained in the physical sciences describes tension between the scientific prediction of natural laws and the chaos and complexity of the

natural world. See particularly introduction, “Can Nature Be Controlled?” and epilogue, “Rambunctious Nature in the Twenty-first Century.”

Nader, Laura, ed., *The Energy Reader* (Malden: Wiley-Blackwell, 2010), 548 pp.

Useful anthology of many articles on cultural, historical, and political economic dimensions of energy. Somewhat dated in terms of technologies available to discuss, but the social dimensions affected are less time sensitive.

National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, National Research Council, 2010), https://www.nap.edu/catalog/12794/hidden-costs-of-energy-unpriced-consequences-of-energy-production-and accessed Dec. 27, 2020.

The hidden costs (externalities) of various types of energy resources are analyzed from an economic perspective.

Perkins, John H., Energy transitions: linking energy and climate change, in Walter Leal Filho and Sarah L. Hemstock, eds., *Climate Change and the Role of Education* (Switzerland, Springer Nature, 2019), Chapter 6, pp. 87 – 106.

Conflict over policy about fracking for natural gas pitted the national government of the UK against Lancashire County and illustrates contentious politics affecting efforts to mitigate climate change and protect the local environment. The case study illustrates (a) importance of scale in energy issues, (b) relative strengths and weaknesses of primary energy sources, and (c) constraints affecting efforts to decrease uses of fossil fuels.

Prud’homme, Alex, *Hydrofracking: What Everyone Needs to Know* (New York: Oxford University Press, 2014), 184 pp.

Journalist explains both sides of debates about hydraulic fracturing for gas and oil. Accessible, a book that could be used to stimulate student discussions.

Robinson, Mary, *Climate Justice: Hope, Resilience, and the Fight for a Sustainable Future* (New York: Bloomsbury Publishing, 2018), 162 pp.

Stories of indigenous climate activists from around the world, written by a former President of the Republic of Ireland.

Roth, I. F. and L. L. Ambs, Incorporating externalities into a full cost approach to electric power generation life-cycle costing, *Energy* 29 (12-15) (2004): 2125.

Somewhat dated but gives excellent detailed calculations of the cost of specific externalities for various fossil fuels and compares them to existing renewable energy technology.

Seager, Joni, Changing the Climate, *Arrows for Change, 15: 1* (2009).

Succinct argument that climate change is a feminist issue.

Shinn, Lora, "As the DOE Abandons a Toxic Mess Threatening the Columbia River, the Yakama Nation Fights Back," https://www.nrdc.org/stories/doe-abandons-toxic-mess-threatening-columbia-river-yakama-nation-fights-back, accessed Dec. 27, 2020.

An example of a grassroots environmental issue; there are many on the web.

Sovacool, Benjamin K., David J. Hess, Sulfikar Amir, *et al.*, Sociotechnical agendas: reviewing future directions for energy and climate research, *Energy Research and Social Science* 70 (2020): 101617, https://doi.org/10.1016/j.erss.2020.101617

STS scholars identify a wide range of STS research needed to improve formation and implementation of policies fostering a transition away from fossil fuels.

Thompson, Andrea, Air inequality, *Scientific American*, June 2019, pp. 10-12.

U.S. racial minorities are exposed to more air pollution than white people yet cause less of it.

Wells, Jennifer, and Carolyn Merchant, Melting Ice: Climate Change and the Humanities, *Confluence, 14:*2 (Spring 2009).

Authors explore questions of ethics, justice, and philosophy that can be addressed by scholars in the humanities.

Section D: Teaching Resources

14. Laboratory exercises and site-specific measurements/demonstrations/designs

Many science instructors employ lab exercises to illustrate, to the students' eyes, the reality of physical changes discussed in books. Such active learning also has a place in ESS classes, and the resources here provide suggestions of possibilities.

Home Energy Saver, http://hes.lbl.gov/consumer/ accessed Dec. 27, 2020.

One of many online home use energy and carbon footprint calculators. Shows how individuals can save energy and reduce carbon emissions.

The GREET model, https://greet.es.anl.gov/ accessed Dec. 27, 2020.

A free, downloadable spreadsheet that allows the user to calculate the well-to-wheels energy use and greenhouse gas emissions of various transportation choices, both existing and hypothetical. For example, existing internal combustion gasoline hybrid systems can be compared with hypothetical diesel hybrid cars. This resource is useful for student projects at the upper undergraduate student level.

Nathan, S. A. and Loxsom, F., "A Sustainable Energy Laboratory Course for Non-Science Majors" *The Physics Teacher* 54, 420 (2016).

> Thirteen laboratory exercises, like introductory undergraduate physics exercises, which focus on energy and energy flow. Includes activities on electricity, solar power, solar heat, R-value, lighting efficiency, wind power, CO_2 in the atmosphere.

Short, D., *Laboratory Experiments in Environmental Physics*, (CreateSpace Independent Publishing Platform, 2012).

> Stand-alone collection of 22 experiments on energy and the environment: force, heat, radiation, air pollution, electrical power, simple circuits, radioactivity, radon testing. Experiments may require special equipment such as a blower door (to pressurize a building or room to measure air leakage), infrared spectrometer, AC power meter, demonstration fuel cell, etc. Experiments are designed to be 2.5 hours in length.

15. Field trips and service learning

Most students have never worked actively with energy issues or seen large energy infrastructures up close. Service-learning and field trips to nearby facilities add immensely to understanding. Issues of practicality and of size and scale become "real" when students cope with a house needing efficiency improvements or visit an energy installation. We have sponsored in our own classes either service-learning projects or field trips, for example to hydroelectric facilities, solar and wind installations, coal-fired power plants, coal strip mines, abandoned nuclear power plants that never operated, and the Chernobyl catastrophe in Ukraine. Exercises in active learning are particularly useful for raising issues of environmental justice.

We think ESS faculty who engage in these types of active learning should prepare written analyses of their experiences more often so that future classes may benefit. Such papers are excellent places to involve students in their preparation.

Morgenstern, Mark, Sally Meyer, Barbara Whitten, and Matt Reuer, "The Energy Retrofit of a Building: A Journey Through Bloom's Learning Domains," *Journal of College Science Teaching,* May/June, 2008, 7 pages.

> Description of a service-learning project, in which students audit and then retrofit an existing home.

Perkins, John H., Natalie Kopytko, and Kathleen M. Saul, Energy field trips: Chernobyl and the catastrophe with nuclear power, *Case Studies in the Environment*, 2019, pp. 1 – 13, electronic ISSN 2473-9510, DOI: https://doi.org/10.1525/cse.2018.001891.

> Assesses field trip to Chernobyl in Ukraine (2007). Also has background material on the pedagogical issues of planning field trips.

Section E: General information

16. Journals

Many peer-reviewed journals now publish extensively on scientific, engineering, and socio-cultural issues with energy. This list contains only some of the better-known ones.

Applied Energy (Elsevier)
Case Studies in the Environment (University of California Press)
Energy (Elsevier)
Energy and Fuels (ACS)
Energy Efficiency (Springer)
Energy Letters (ACS)
Energy Policy (Elsevier)
Energy Strategy Reviews (Elsevier)
Environmental History (Oxford University Press)
Environmental Research Letters (IOP Publishing)
Environmental Science and Technology (ACS- American Chemical Society),
Environmental Science and Technology Letters (ACS),
Geophysical Research Letters (American Geophysical Union)
Joule (CellPress)
Journal of Environmental Studies and Sciences (Association for Environmental Studies and Sciences)
Nature (Nature Publishing Group)
Nature Energy (Nature Publishing Group)
Nature Climate Change (Nature Publishing Group)
Physics Today (American Institute of Physics)
Renewable and Sustainable Energy Reviews (Elsevier)
Science (American Association for the Advancement of Science)
Scientific American (Springer Nature)

17. Websites

Websites providing information in agreement with vast majority of climate scientists

350.org

Environmental activists promote solutions to climate change by moving to renewable energy.

American Council for an Energy-Efficient Economy, https://aceee.org/, accessed Dec. 27, 2020.

Leading advocacy NGO for energy efficiency. Multiple publications and blog posts.

Electropaedia, The: https://www.mpoweruk.com/index.htm accessed Dec. 27, 2020.

A comprehensive battery web site with non-technical descriptions of various battery types.

Grist, *How to talk to a climate skeptic*: https://grist.org/series/skeptics/ accessed Dec. 27, 2020.

An exhaustive list of questions frequently raised by climate deniers with answers.

Institute for Carbon Removal Law and Policy, https://www.american.edu/sis/centers/carbon-removal/, accessed Dec. 27, 2020.

University research unit studying prospects and technology for removing existing greenhouse gases from the atmosphere, an important supplement to reducing new emissions.

Intergovernmental Panel on Climate Change: https://www.ipcc.ch/ accessed Dec. 27, 2020.

The most authoritative source for information on human caused climate change. The IPCC publishes periodic reviews in the form of reports on climate, renewable energy, mitigation and other climate related topics.

Lawrence Livermore National Laboratory, https://flowcharts.llnl.gov/commodities/energy, accessed Dec. 27, 2020.

Flow charts (Sankey diagrams) to portray energy-flow systems and carbon dioxide emissions associated with use of fossil fuels. Free to download. Useful to orient students to dimensions of energy systems.

Our Energy Policy: http://www.ourenergypolicy.org accessed Dec. 27, 2020.

Non-partisan clearinghouse of information and ongoing discussion by experts about US energy policy. Web page repository of white papers and a weekly email newsletter about current energy policy issues.

Oxford Institute for Energy Studies, https://www.oxfordenergy.org/?v=7516fd43adaa, accessed Dec. 27, 2020.

Many reports contain valuable analyses of energy situations in multiple countries, multiple energy industries, and involving multiple political economic factors, available for free download.

Real Climate: http://www.realclimate.org/ accessed Dec. 27, 2020.

Blog by climate scientists who discuss the most recent climate data and answer questions raised by climate change deniers and skeptics.

Rocky Mountain Institute, https://rmi.org/ accessed Dec. 27, 2020.

Consulting firm publishes studies and newsletters about issues of transition to renewable energy.

Skeptical Science, https://skepticalscience.com/ accessed Dec. 27, 2020.

Non-profit run by a professor using his own funds. Frequently contains useful scientific information answering skepticism about climate change.

Solutions Project, The, https://thesolutionsproject.org/ accessed Dec. 27, 2020.

Engineer Mark Jacobson (Category 10) and colleagues produce analyses on feasibility of energy economies based on 100 percent renewable energy.

Union of Concerned Scientists, https://www.ucsusa.org/ accessed Dec. 27, 2020.

Science activists have many studies on energy and climate change.

Yale Program on Climate Connections, https://www.yaleclimateconnections.org/ accessed Dec. 27, 2020.

Information about changing American opinions about climate change.

Websites containing information by climate change skeptics and deniers

Students will find contrarian web sites which purport to disprove climate change and/or other well-established scientific facts. They will find these websites on their own, but a useful exercise is to send them to these kinds of sources and have them compare the information produced by the scientific majority.

Center for Industrial Progress, https://industrialprogress.com/ accessed Dec. 27, 2020.

Alex Epstein accepts climate change science but believes risks will be minimal. Benefits of fossil fuels, however, are enormous and the world must continue using them. See Epstein entry, Category 13.

Heartland Institute, The, https://www.heartland.org/about-us/funding/index.html, accessed Dec. 27, 2020.

Primary source of skepticism about climate science, by the vanishingly small minority of scientists who remain skeptical of climate change as a serious problem. The Institute values free markets without significant regulation of energy by government. Source of many free publications on request.

Watts Up With That? https://wattsupwiththat.com/, accessed Dec. 27, 2020.

Retired TV meteorologist, Anthony Watt, is an enthusiast for renewable energy but doesn't accept climate science summarized by the IPCC.

Conclusions

Energy always has had an important place in ESS, because it involves natural resources, resource depletion, pollution, environmental justice, and the economic and social costs of energy technologies. Climate change and the need to sharply and quickly reduce emissions of carbon dioxide and methane, however, brought energy to a new and much higher level of significance for ESS.

The above discussion and suggested resources highlight two key points for ESS faculty seeking to improve existing courses or launch new courses and degree or certificate programs. First, the pervasiveness of fossil fuels in supporting modern societies and causing climate change means that the "energy problem" is far more than a local or single-issue affair. The ESS academy must approach energy as a "systems problem" with multiple hotspots and dilemmas surrounding every proposed remedy for dealing with climate change. The "systems dimension" of energy demands that ESS scholars delve into some new subjects and concepts and unite them with many existing perspectives and methods already embedded in the ESS canon of literature.

Climate science, for example, becomes a necessary but not sufficient topic for ESS students. Similarly, environmental justice issues require examination of social and cultural affairs but also the strengths and weaknesses of each proposal to resolve an issue of justice by changing primary sources of energy. Many other comparable problems also lie waiting for more comprehensive approaches in ESS.

Second, the approach here has focused on the broad conceptual areas needed to educate ESS students within a liberal arts context. Some students will go on to professional careers dealing with environmental problems, but many others may just take an ESS course for interest or to satisfy a distribution requirement. For the latter group, the ESS course may be the only time at university they heard a serious discussion about energy. Yet, no matter what their major at graduation, they will enter a world as citizens who must help constructively to find solutions to the imperative transition away from fossil fuels. ESS faculty, accordingly, have a key obligation to make their exposure to energy as understandable and memorable as possible. Awareness of key concepts lies at the heart of enabling future citizen-leaders to play constructive roles as generalists.

This paper cannot fully assess the difficulties involved in ending the carbon economy but suffice it to say that such a move involves ending many jobs and industries but also creating new ones; altering the economies and politics of many communities, states, and nations; upsetting many financial and monetary relations; and putting enormous responsibility on higher education to help citizens cope. It is truly an "all-hands-on-deck" situation, requiring teaching and research resources in every institution and state, thus enabling *every* student to have access to learning on this topic. Otherwise, one of two outcomes will develop: either (a) the United States will collaborate with the rest of the world in this task, or (b) the United States and every other country will suffer the ravages of climate change.

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Table 1

Table 1. Prevalence of IESE and NRBE programs in four-year institutions, 2016[2]

Category	Number	Percent of census	Number institutions without	Percent institutions without
Institutions with IESE degrees[2]	872	52	818	48
Institutions with NTBE degrees[2] [2]	156	9	1534	91
Institutions in census	1690	100		

[2] Table 1 was compiled from published reports by Vincent, *et al*., 2017; and Luzadis *et al*., 2018 (full references in footnotes below). An unpublished draft by Vincent, *et al*. provided most of the data in the published report by Luzadis, *et al*., 2018. Data and interpretations in the published 2018 report and the unpublished draft differ (Vincent, personal communication, 2020), but the differences do not affect the inferences we drew: to show that many institutions lack IESE degree programs and most lack NTBE degree programs. Universities and colleges are still in process of developing new programs, so future surveys will probably show growth in both categories of degree programs. Institutions without IESE and NTBE programs and percent values calculated by JHP.

[2] Vincent, S., Rao, S., Fu, Q., Gu, K., Huang, X., Lindaman, K., Mittleman, E., Nguyen, K., Rosenstein, R., Suh, Y. (2017). *Scope of Interdisciplinary Environmental, Sustainability, and Energy Baccalaureate and Graduate Education in the United States* (Washington, National Council for Science and the Environment), 46 pp. https://drive.google.com/file/d/1xmyXuP0za2hptOfQywLR33kvKUfXo-7a/view

[2] Luzadis, V.A., P.D. Hirsch, and X. Huang. (2018). Energy Programs in Higher Education in the United States: Assessing Trends Across Two Pathways To Knowledge Development. (Washington, National Council for Science and the Environment), 49 pp. https://drive.google.com/file/d/1Jt92wF9T8z7ixyd6mMtSVEyLWbxD52sU/view

[2] The number (156) included in Table 1 is a conservative estimate. Vincent (Unpublished, personal communication, 2021) found 46 institutions with NTBE degrees, and 119 institutions with NTBE specializations in other disciplines. Eight (8) institutions had both. Thus, this information estimates 157 institutions with NTBE degrees (46 + 119 – 8 = 157). Luzadis, *et al*., (footnote c) list 112 institutions with "Disciplinary/Professional Degree Programs" (Table 2, p. 10) and 44 "Interdisciplinary/General Degree Programs" (Table 3, p. 11). The sum of these two: 112 + 44 = 156. Luzadis, *et al*., however, do not analyze institutions with both kinds of degree programs. Based on their published information, therefore, the minimum number of institutions could be as low as 112. The unpublished material from Vincent, noted in footnote a, lists 208 institutions with "academic programs" classified as NTBE; this number, however, also includes minors and certificate programs, not full degree programs. Thus, the maximum number of institutions of 1690 could be 208, if minor and certificate programs are included. In any case, the total range of institutions with NTBE programs of some kind (112 to 208) means the percent with NTBE programs ranges between 7 and 12 percent, a decided minority. Our conclusion: this minority status is the problem, whatever its exact size may be. In Table 1, we used the published estimate, 156: 9 percent with and 91 percent without.