

Wiley Series on Energy

Alternative Energy and Shale Gas Encyclopedia

Edited by
Jay H. Lehr and Jack Keeley



WILEY

**ALTERNATIVE ENERGY AND SHALE
GAS ENCYCLOPEDIA**

ALTERNATIVE ENERGY AND SHALE GAS ENCYCLOPEDIA

Edited by

JAY H. LEHR

Editor-in-Chief

JACK KEELEY

Senior Editor

THOMAS B. KINGERY

Information Technology

WILEY SERIES ON ENERGY

WILEY

Copyright © 2016 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Alternative energy and shale gas encyclopedia / edited by Jay H. Lehr, editor-in-chief ; Jack Keeley, senior editor ; Thomas B Kingery, Information Technology.

pages cm

Includes index.

ISBN 978-0-470-89441-5 (cloth)

I. Renewable energy sources—Encyclopedias. 2. Shale gas—Encyclopedias. I. Lehr, Jay H., 1936- editor.
II. Keeley, J. W. (Jack W.), editor. III. Kingery, Thomas B., editor.

TJ807.4.E53 2015

621.04203—dc23

2014049361

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

CONTENTS

INTRODUCTION: ENERGY DRIVES <i>EVERYTHING</i>	
<i>Howard C. Hayden</i>	xi
LIST OF CONTRIBUTORS	xxv
PART I WIND	
1 Acceptance of Wind Power: An Introduction to Drivers and Solutions	3
<i>Jacob Ladenburg</i>	
2 Wind Power Forecasting Techniques	10
<i>Michael Negnevitsky</i>	
3 Maximizing the Loading in Wind Turbine Plants: (A) The Betz Limit, (B) Ducting the Turbine	20
<i>D. P. Georgiou and N. G. Theodoropoulos</i>	
4 Modeling Wind Turbine Wakes for Wind Farms	28
<i>Angus C. W. Creech and Wolf-Gerrit Früh</i>	
5 Fatigue Failure in Wind Turbine Blades	52
<i>Juan C. Marin, Alberto Barroso, Federico Paris, and Jose Canas</i>	
6 Floating Wind Turbines: The New Wave in Offshore Wind Power	69
<i>Antoine Peiffer and Dominique Roddier</i>	
7 Wind Power—Aeole Turns Marine	80
<i>Roger H. Charlier and Alexandre C. Thys</i>	
8 Impacts of Wind Farms on Weather and Climate at Local and Global Scales	88
<i>Justin J. Traiteur and Somnath Baidya Roy</i>	

9	Power Curves and Turbulent Flow Characteristics of Vertical Axis Wind Turbines	104
	<i>Kevin Pope and Greg F. Naterer</i>	
10	Windmill Brake State Models Used in Predicting Wind Turbine Performance	116
	<i>Panu Pratumnopharat and Pak Sing Leung</i>	
11	Lightning Protection of Wind Turbines and Associated Phenomena	120
	<i>Petar Sarajcev</i>	
12	Wind Turbine Wake Modeling—Possibilities with Actuator Line/Disc Approaches	141
	<i>Stefan Ivanell and Robert Mikkelsen</i>	
13	Random Cascade Model for Surface Wind Speed	153
	<i>R. Baile and J. F. Muzy</i>	
14	Wind Power Budget	163
	<i>Hugo Abi Karam</i>	
15	Identification of Wind Turbines in Closed-Loop Operation in the Presence of Three-Dimensional Turbulence Wind Speed: Torque Demand to Measured Generator Speed Loop	169
	<i>Mikel Iribas-Latour and Ion-Doré Landau</i>	
16	Identification in Closed-Loop Operation of Models for Collective Pitch Robust Controller Design	180
	<i>Mikel Iribas-Latour and Ion-Doré Landau</i>	
17	Wind Basics—Energy from Moving Air	194
	<i>Public Domain</i>	
18	Wind—Chronological Development	201
	<i>Public Domain</i>	
PART II SOLAR		
19	Solar Air Conditioning	205
	<i>Winston Garcia-Gabin and Darine Zambrano</i>	
20	Energy Performance of Hybrid Cogeneration Versus Side-by-Side Solar Water Heating and Photovoltaic for Subtropical Building Application	212
	<i>Tin-Tin Chow, Ka-Kui Tse, and Norman Tse</i>	
21	Polycrystalline Silicon for Thin Film Solar Cells	226
	<i>Nicolás Budini, Roberto D. Arce, Román H. Buitrago, and Javier A. Schmidt</i>	
22	Solar Basics – Energy from the Sun	233
	<i>Public Domain</i>	
23	NASA Armstrong Fact Sheet: Solar-Power Research	241
	<i>Public Domain</i>	

24	Solar Thermal – Chronological Development	247
	<i>Public Domain</i>	

25	Photovoltaic – Chronological Development	249
	<i>Public Domain</i>	

PART III GEOTHERMAL

26	Geothermal: History, Classification, and Utilization for Power Generation	253
	<i>Mathew C. Aneke and Mathew C. Menkiti</i>	

27	Enhanced Geothermal Systems	265
	<i>Rosemarie Mohais, Choashui Xu, Peter A. Dowd, and Martin Hand</i>	

28	Thermodynamic Analysis of Geothermal Power Plants	290
	<i>Mehmet Kanoglu and Ali Bolatturk</i>	

29	Sustainability Assessment of Geothermal Power Generation	301
	<i>Annette Evans, Vladimir Strezov, and Tim J. Evans</i>	

30	Geothermal Energy and Organic Rankine Cycle Machines	310
	<i>Bertrand F. Tchanche</i>	

31	Low Temperature Geothermal Energy: Geospatial and Economic Indicators	318
	<i>Alberto Gemelli, Adriano Mancini, and Sauro Longhi</i>	

32	Dry Cooling Towers for Geothermal Power Plants	333
	<i>Zhiqiang Guan, Kamel Hooman, and Hal Gurgenci</i>	

33	Thermal Storage	350
	<i>Marc A. Rosen</i>	

34	Shallow Geothermal Systems: Computational Challenges and Possibilities	368
	<i>Rafid Al-Khoury</i>	

35	Geothermal Basics—What is Geothermal Energy?	390
	<i>Public Domain</i>	

36	Geothermal—Chronologic Development	394
	<i>Public Domain</i>	

PART IV HYDROPOWER

37	Sustainability of Hydropower	399
	<i>Joerg Hartmann</i>	

38	Environmental Issues Related to Conventional Hydropower	404
	<i>Zhiqun Daniel Deng, Alison H. Colotelo, Richard S. Brown, and Thomas J. Carlson</i>	

39	Social Issues Related to Hydropower	410
	<i>Joerg Hartmann</i>	
40	Safety in Hydropower Development and Operation	413
	<i>Urban Kjellén</i>	
41	Pumped Hydroelectric Storage	423
	<i>John P. Deane and Brian O’Gallachoir</i>	
42	Greenhouse Gas Emissions from Hydroelectric Dams in Tropical Forests	426
	<i>Philip M. Fearnside</i>	
43	Physical and Multidimensional Numeric Hydraulic Modeling of Hydropower Systems and Rivers	437
	<i>Timothy C. Sassaman and Daniel Gessler</i>	
44	Experimental and Numerical Modeling Tools for Conventional Hydropower Systems	448
	<i>Zhiqun Daniel Deng, Thomas J. Carlson, Gene R. Ploskey, Richard S. Brown, Gary E. Johnson, and Alison H. A. Colotelo</i>	
45	The State of Art on Large Cavern Design for Underground Powerhouses and Some Long-Term Issues	465
	<i>Ömer Aydan</i>	
46	Hydroelectric Power for the Nation	488
	<i>Public Domain</i>	
47	Hydropower Basics—Energy from Moving Water	492
	<i>Public Domain</i>	
48	Hydropower—Chronologic Development	497
	<i>Public Domain</i>	
PART V BATTERIES AND FUEL CELLS		
49	Fuel Cell Control	501
	<i>Winston Garcia-Gabin and Darine Zambrano</i>	
50	Recent Trends in the Development of Proton Exchange Membrane Fuel Cell Systems	509
	<i>Amornchai Arpornwichanop and Suthida Authayanun</i>	
51	Integrated Solid Oxide Fuel Cell Systems for Electrical Power Generation—A Review	526
	<i>Suttichai Assabumrungrat, Amornchai Arpornwichanop, Vorachatra Sukwattanajaron, and Dang Saebea</i>	
52	Polymer Electrolytes for Lithium Secondary Batteries	547
	<i>Fiona M. Gray and Michael J. Smith</i>	

53	Recycling and Disposal of Battery Materials	566
	<i>Michael J. Smith and Fiona M. Gray</i>	

54	AC OR DC	578
	<i>M. Aram Azadpour</i>	

PART VI RENEWABLE ENERGY CONCEPTS

55	Will Renewables Cut Carbon Dioxide Emissions Substantially?	581
	<i>Herbert Inhaber</i>	

56	The Concept of Base-Load Power	585
	<i>Mark Diesendorf</i>	

57	Tidal Power Harnessing	590
	<i>Roger H. Charlier</i>	

58	The Loading of Water Current Turbines: The Betz Limit and Ducted Turbines	601
	<i>D. P. Georgiou and N. G. Theodoropoulos</i>	

59	Bottled Gas as Household Energy	606
	<i>Masami Kojima</i>	

60	Exergy Analysis: Theory and Applications	628
	<i>Marc A. Rosen</i>	

61	Global Transport Energy Consumption	651
	<i>Patrick Moriarty and Damon Honnery</i>	

62	Biomass: Renewable Energy from Plants and Animals	657
	<i>Public Domain</i>	

63	Planting and Managing Switchgrass as a Biomass Energy Crop	663
	<i>Public Domain</i>	

64	Municipal Solid Waste—Chronological Development	675
	<i>Public Domain</i>	

65	Ethanol—Chronological Development	677
	<i>Public Domain</i>	

66	Thermal Properties of Methane Hydrate by Experiment and Modeling and Impacts Upon Technology	680
	<i>Robert P. Warzinski, Isaac K. Gamwo, Eilis J. Rosenbaum, Evgeniy M. Myshakin, Hao Jiang, Kenneth D. Jordan, Niall J. English, and David W. Shaw (Public Domain)</i>	

PART VII SHALE GAS

67	Shale Gas Will Rock the World	689
	<i>Amy Myers Jaffe</i>	

68	What is Shale Gas?	692
	<i>Energy Information Administration (Public Domain)</i>	
69	Directional and Horizontal Drilling in Oil and Gas Wells	695
	<i>Public Domain</i>	
70	Hydraulic Fracturing of Oil and Gas Wells Drilled in Shale	697
	<i>Public Domain</i>	
71	Hydraulic Fracturing: A Game-Changer for Energy and Economies	700
	<i>Isaac Orr</i>	
72	Zero Discharge Water Management for Horizontal Shale Gas Well Development	720
	<i>West Virginia Water Research Institute (Public Domain)</i>	
73	About Oil Shale—What is Oil Shale?	723
	<i>Public Domain</i>	
74	Natural Gas Basics—How Was Natural Gas Formed?	725
	<i>Public Domain</i>	
75	Natural Gas—Chronological Development	732
	<i>Public Domain</i>	
76	Energy Mineral Division of the American Association of Petroleum Geologists, Shale Gas and Liquids Committee Annual Report, FY 2014	734
	<i>Neil S. Fishman, Chair</i>	
	INDEX	857

INTRODUCTION: ENERGY DRIVES *EVERYTHING*

HOWARD C. HAYDEN

INTRODUCTION

Everything we make, bend, heat, cool, cut, fasten, grow, harvest, move, or shape requires energy. That is, when we do *anything* to *anything*, we use energy. If we do it by hand, the energy source is the sun which produces the food we eat. The human labor part of the energy picture, however, is minuscule. Let me elaborate. The best coupling between man and machine is to put a person on a bicycle seat to use the strong leg muscles to push the pedals (which in turn might turn an electric generator). Whereas a good athlete might produce a few hundred watts—perhaps as much as a thousand watts—over a short period, it is a real chore to produce 100 W on a continuous basis for hours at a time. If we produce 100 W for a 10-hour period, the amount of electrical energy produced is $100 \text{ W} \times 10 \text{ hours}$, which is 1000 Wh, or 1 kilowatt-hour (kWh), for which the average price in the United States is about a dime. Not many people would be willing to work that hard, that long, for a mere 10 cents. For another comparison, a 2000-Calorie¹ daily diet is equivalent to about 100 W.

To expand that perspective just a bit, let us look at the amount of energy—over 100 exajoules²—used in the United States every year. Averaged over the 31.6 million seconds in the year, and over the roughly 315 million US citizens, our rate of energy consumption is about 11,000 W *per capita*, about 110 times as much power as the average human produces in the form of heat, or our athlete produces while on the bicycle seat. Alternatively, one may think of our energy consumption as being equivalent to having 110 servants tending

to our needs night and day. This is why we can accurately say that human labor is a minuscule part of the energy picture.

Over 90% of our energy comes from petroleum, natural gas, coal, and uranium. Of the 9% contribution from renewable energy sources, the venerable ones—hydro and biomass—provide over 80%.

The electricity that powers our appliances is not primary energy, but rather a *carrier* of energy. In a coal-fired power plant, for example, the fire boils water into high-pressure, high-temperature steam that turns a turbine that turns an electricity-producing generator. The generator energizes electrons, and our lights and machines in turn become energized by those electrons. The important detail is simply that the electrical power does not come from the socket, but rather from some primary source like coal or natural gas.

Scientists *began* to understand things pertaining to electricity at about the time of the American Revolution. It was not until 1882 that the first hydropower station produced commercial electrical power. So useful is electricity that, by now, a full 40% of our primary energy in the United States goes into the production of electricity.

SOME FUNDAMENTALS

Energy is somewhat hard to define. There is no instrument that directly measures energy. By and large, you cannot see it or touch it. *Work*, on the other hand, is fairly easy to define. Work is the equivalent of lifting a weight to some height above the starting point; indeed, it is the product of the weight and the vertical distance the weight moves.

Now we come to the definition: Energy is the *capacity* to do work. (That does not mean the *ability* to do work.) In other words, energy is numerically the same as the work it could do at an impossible 100% efficiency. In broadest terms, there

¹One food Calorie (capitalized) is one kilocalorie.

²We will say more about this unit further on.

is energy due to position—called *potential energy*—such as the energy of an object that has been lifted. There is also energy due to motion—called *kinetic energy*—such as that of a falling ball. The two kinds of energy can appear together, such that of a ball dropped from a 20-story high building as it passes (say) the 12th floor, where it has potential energy with respect to the ground and also has kinetic energy due to its speed.

Chemical energy is potential energy. It is not due to gravity, but to the positions of the atoms and molecules with respect to one another. For example, when heptane molecules (the most common ones in gasoline) encounter oxygen molecules in air under conditions of high temperature (such as that created by a spark in a gasoline engine), the energy released as chemical bonds are broken and formed is thermal energy, often called heat.³ Heat is a special kind of energy to which special rules apply. Energy (PE and KE) can be converted to heat with 100% efficiency. Heat can be converted to energy, but with an efficiency that is less than 100%.

Electromagnetic energy travels at the speed of light, but light is a minuscule part of the spectrum. The term *light* usually refers to visible light, but usually not to ultraviolet radiation, x-rays, gamma radiation, infrared, and radio waves, although the only meaningful distinction is that we can *see* light. The generic term is *electromagnetic radiation*.

ENERGY IS NOT POWER AND POWER IS NOT ENERGY

The distinction between *power* and *energy* is the same as the distinction between speed and location. Everybody understands that going 45 miles/h is not the same as being at 4th and Main. Similarly, everybody understands that 250 horsepower is not the same as the chemical energy in a liter of gasoline. But too many people fail to distinguish between *kilowatts* (a unit of power) and *kilowatt-hours* (a unit of energy).

Power is a term that has a well-defined technical meaning and several ill-defined meanings in common parlance (such as “political power,” a “powerful idea,” or “the power of the purse”). In common parlance, *power* means something related to the electrical socket. Indeed, power is provided by the grid, but electrical power is only one kind. For example, it takes power to run your car—the term *horsepower* is commonly used. But using *watts* for electrical power, horsepower for automobiles, and British Thermal Unit (BTU)/hour for a furnace is somewhat akin to measuring sugar in pounds, coal

³Thermodynamicists usually use the term *heat* to refer to thermal energy in transit, such as when a hot body is placed in contact with a cold one: heat flows from the hot one to the cold one. There are good reasons for doing so, but they need not concern us here.

in tons, and diamonds in carats. Why do that, when they are all weights? Similarly, power needs only one unit of measurement. By international agreement, that unit is the watt.

Let us begin with something simple. Suppose we have a cupful of gasoline. We can burn up that gasoline very slowly or we can burn it up in a hurry, possibly even in an explosion. In both cases, the same amount of energy is released, because that cup of gasoline has just so much energy, no more, no less. When the fuel is burned slowly, that is low power. When it is burned rapidly, that is high power.

For a very dramatic example, consider the electrical energy from a single large coal-fired power plant operating for one half of a day. The energy is used for heating, refrigeration, lighting, manufacturing, and many other useful ventures. But if that amount of energy were expended in a small area in about a microsecond, it would be an explosion like that of the atomic bombs that fell on Hiroshima and Nagasaki. That is extremely high *power*.

In all cases to which the term *power* applies, energy is being converted from one form to another. The faster the energy is converted, the higher the power.

Technically, then, $\text{power} = \text{energy converted} \div \text{the time interval}$.

Alternatively, $\text{energy converted} = \text{power} \times \text{the time interval}$.

The electrical meter on your house measures power consumption, second by second, and keeps a running tally in units of kilowatt-hours.

UNITS OF MEASUREMENT

Energy has historically been measured in many units, including foot-pounds, ergs, joules, calories, kilocalories, and BTUs. There are also units that pertain to fuels: the gallon of gasoline, the barrel of oil, the therm, the cubic foot of natural gas, the heat content of a cord of white oak, and the ton of coal, to name a few.

Since power is energy per unit time, we need to consider common units for time: the second, the minute, the hour, the day, the summer, the winter, the year, and so forth. Using just the 12 listed units for energy and the 8 listed units of time, we can construct 96 units of power (such as kilocalories per month). A table of factors to convert from any one of them to any one of the others would have 96 by 96 entries, of 9216 entries. It is largely because of the vast profusion of units that most casual readers find the topic of energy confusing: how can you compare the things said in one book with those said in another?

The only sane thing to do is to insist on *one* unit for energy, *one* unit for time, and *one* unit for power. Then the attached numbers can tell their story. The units used *internationally*

(as well as *officially* by the US, though almost never by US agencies) are those in the *Le Système International d'unités* (abbreviated SI):

- Energy: the *joule*. Abbreviation: J, uppercase
- Time: the *second*. Abbreviation: s, lowercase
- Power: the *joule per second*, otherwise known as the *watt*. Abbreviation: W, uppercase

For many Americans, the term *joule* is unfamiliar. How big is it? For one, it is the energy expended by 1 W during 1 second: a *joule is a watt-second*. Think of the energy expended by a flashlight during 1 second. Alternatively, it is approximately the energy expended in lifting a 1-L bottle of soda 10 cm (about 4 inches, the “hand” known to horseman). Most importantly, even if the term *joule* is strange and unfamiliar, *it is a trivial matter to compare the amounts of energy if the same international unit is used for all applications*.

We pay the utility for the electrical energy we use, and the unit of measurement the utility uses is the kilowatt-hour (kWh). How much is that in joules? 1 kWh is 1000 W multiplied by the number of seconds in an hour ($60 \times 60 = 3600$), or 3,600,000 J.

No matter what units might be used, there would be an enormous range of numbers between (say) the energy consumed by walking up a flight of stairs and the energy consumed in the United States during an entire year. For example, in 2011, the annual energy consumption in the United States was 103,000,000,000,000,000 J. It is tedious work to keep track of all those zeroes, so we have shorthand methods. We write it as 1.03×10^{20} J (scientific notation), 103×10^{18} J (engineering notation, with exponents in multiples of 3), or 103 exajoules (abbreviated EJ).

The metric prefixes are given in Table I.1.

Many units have been defined for energy. Table I.2 presents conversion factors. Note that the BTU is actually defined in terms of the joule by a 12-digit conversion factor.

Often used informally as energy units are the heat contents of fuels. For example, we endlessly hear of nuclear weapon

TABLE I.1 Metric prefixes.

E (exa)	10^{18}
P (peta)	10^{15}
T (tera)	10^{12}
G (giga)	10^9
M (mega)	10^6
k (kilo)	10^3
m (milli)	10^{-3}
μ (micro)	10^{-6}
n (nano)	10^{-9}
p (pico)	10^{-12}
f (femto)	10^{-15}
a (atto)	10^{-18}

TABLE I.2 Energy conversion factors.

Multiply number of ↓	By ↓ to get joules
Watt-seconds	1
British Thermal Units (BTU)	1055.05585262
Quadrillion BTUs (quads)	1.055×10^{18}
Kilowatt-hours (kWh)	3.6×10^6
Horsepower-hours	2.69×10^6
Kilocalories (kcal)	4186.8
Calories (cal)	4.187
Therms ($=10^5$ BTU)	1.055×10^8
Foot-pounds	1.36
Ergs	1×10^{-7}
Watt-years	3.16×10^7

yields expressed in tons of TNT. Or, people will say that such-and-such project will displace a million tons of coal. Table I.3 gives heat contents of fuels by mass, and Table I.4 gives the heat content by volume. One kilogram of petroleum has a heat content of about 45 MJ/kg, and the same number holds approximately for all petroleum products. However, they have different densities. A gallon of propane weighs less than a gallon of gasoline, and therefore it has less heat content.

Combustion of fuels produces carbon dioxide and water vapor. Sometimes (for reasons of precision) it is important to distinguish between the higher heat value (HHV) and the lower heat value (LHV), the difference between them due to the heat of vaporization of water. Under almost all circumstances, either in heat engines or fuel cells, water *vapor* escapes, carrying with it the energy that converted the water to steam in the first place. The higher heat value (HHV) is the total energy per kilogram that is produced by the oxidation of the fuel; the lower heat value (LHV), is the HHV minus the energy of vaporization. The tables of the Energy Information Administration (EIA) give HHVs and some LHVs.

The most extreme case is that of hydrogen, for which the only by-product is water vapor. The HHV of hydrogen is 142 MJ/kg, but the LHV is 120 MJ/kg, some 15% less. From Table I.3, the difference between HHV and LHV is about 10% for both methane and methanol, and about 6% for petroleum fuels.

US Energy Usage

The best source of information about how we produce, consume, import, and export energy in the United States is the *Annual Energy Review (AER)*, produced by the EIA of the Department of Energy (DOE). Through 2011, the EIA produced a PDF file of the *AER* that could be downloaded (<http://www.eia.gov/totalenergy/data/annual>). The EIA’s website is now interactive and actually has more information than before; however, they no longer produce a single PDF of *AER*. A major failing of the *AER* is their use

TABLE I.3 Heat contents of fuels (by mass).

Multiply number of ↓	By ↓ to get joules (HHV)	By ↓ to get joules (LHV)
Kilogram of crude petroleum	$42.5\text{--}45.4 \times 10^6$	41.2×10^6
Kilogram of gasoline	47.5×10^6	44.5×10^6
Kilogram of diesel fuel	44.8×10^6	42.5×10^6
Kilogram of coal	15×10^6 to 30×10^6	
Kilogram of coal (US average)	24.1×10^6	
Kilogram of drymatter (biomass)	15×10^6	
Kilogram of hydrogen(Not a source of energy!)	141.9×10^6	119.9×10^6
Kilogram of methane (CH ₄)	55.5×10^6	50.0×10^6
Kilogram of methanol (CH ₃ OH)	20.0×10^6	18.0×10^6
Kilogram of ethanol (EtOH)	30×10^6	
Kilogram of propane	50.4×10^6	45.6×10^6
Pound of coal (average)	10.9×10^6	
Ton of coal (average)	21.9×10^9	
Kilogram of TNT	2.1×10^6	

of arcane units: quadrillion BTU (a.k.a. quads) for primary energy, kilowatt-hours for electrical energy, BTU per kWh for reciprocal efficiency, barrels of oil, cubic feet of natural gas, tons of coal, *metric* tons of carbon, and so forth.

Because energy is eventually degraded to heat, there is some method to the EIA’s madness. They refer to *primary* energy in heat units (quadrillion BTU), but to *electrical* energy in kilowatt-hours. This topic will be discussed further in our brief discussion of hydropower, but for now we simply point out that the EIA would be able to make the same distinction by using the subscripts “t” for *thermal*, and “e” for *electrical*. For example, many engineers now use the abbreviation W_t for thermal watts and W_e for electrical watts. In other words, the EIA should start using sensible units and get into the 20th century before the rest of us get out of the 21st.

As noted above, the United States used 103 EJ in 2011. But that factoid by itself does not tell us what our history of energy consumption is, how much energy is used for what purposes, or how much energy we get from what sources. Figure I.1 shows the history of US energy consumption from various sources. Notice that each horizontal line represents 10

TABLE I.4 Heat contents of fuels (by volume).

Multiply number of ↓	By ↓ to get joules HHV
Barrels of crude oil	6.12×10^9
Barrels of aviation gasoline	5.326×10^9
Barrels of motor gasoline	5.542×10^9
Barrels of propane	4.047×10^9
Barrels of kerosene	5.982×10^9
Gallon (US) of gasoline	0.131×10^9
Gallon of ethanol (EtOH)	0.095×10^9
Cubic feet of natural gas	0.001092×10^9
Ton of TNT	4.2×10^9
Cords of wood (white oak)	$31. \times 10^9$

times the value of the next-lower one. Roughly speaking, we use 100,000 times as much energy annually as our ancestors did in the middle 1600s. At that time, the energy source was almost exclusively firewood. Two centuries later, coal was making inroads, and petroleum was beginning to replace whale oil for lamps. Natural gas and hydropower made their debuts in the late 1800s, and nuclear power began producing electricity around 1960.

Figure I.1 shows a very dramatic increase in the US annual consumption of energy, but might leave the impression that we Americans are individually using a vast amount of energy compared to our forebears. Bear in mind, however, that the population in 1700 was fewer than 250,000; today it is about 1300 times as large at 315 million. It is interesting to calculate the energy consumption *per capita* in the US history. Figure I.2 shows that the *per-capita* energy consumption from

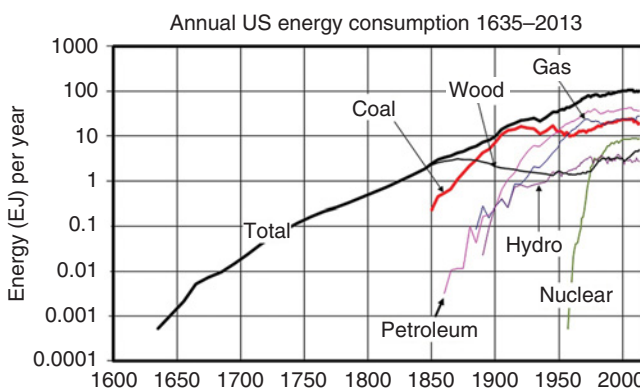


FIGURE I.1 Energy consumption in the United States since 1635, showing energy sources. The predominant source until about 1850 was firewood; since then its consumption has remained relatively constant. Notice that the vertical scale is logarithmic: each horizontal line represents a factor of 10 more than the line beneath it.

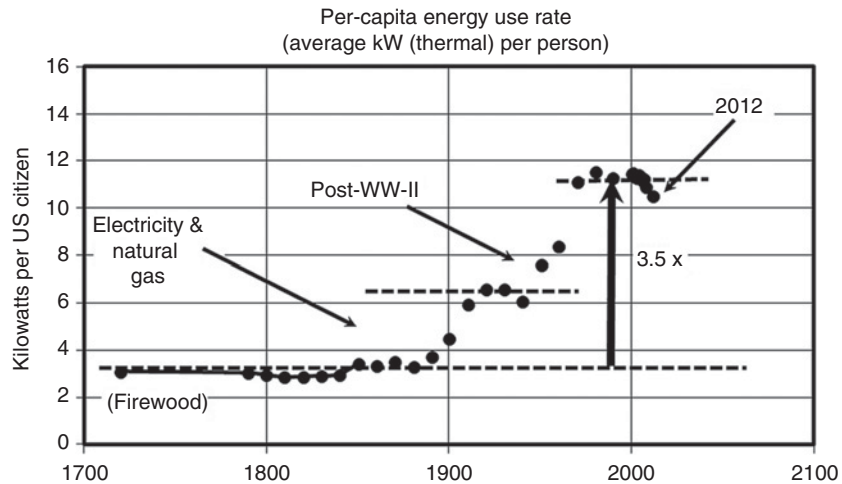


FIGURE I.2 Historical *per-capita* energy consumption in the United States. From the early 1700s, when firewood was the main energy source to the present, when we have automobiles, jet planes, satellites, GPS, elevators, electric lights, television, refrigeration, air conditioning, and fast internet, we have only tripled out *per-capita* energy consumption.

the early 1700s until the late 1800s was about 3.1 kW *per capita*, whereas it is now about 11 kW *per capita*. In other words, the overwhelming cause of our increase in energy consumption is due to increasing population; the *per-capita* growth during the last three centuries is a factor of 3.5. The reason for this low figure is that we have vastly improved our energy efficiency.

Overwhelmingly, the sources of our energy are the so-called “fossil fuels,” coal, petroleum, and natural gas, as shown in Figure I.3. Almost all of our transportation is driven by petroleum, the main exception being electrically driven

commuter trains. Coal is used almost exclusively for producing electricity, as is nuclear energy. Natural gas is easier to use, so it is used not only for domestic heating, but also for producing electricity, as well as a negligible fraction of transportation. Contrary to the impression promoted by renewable energy enthusiasts, the great majority of our renewable energy is *not* wind and solar. Biomass (half being firewood, half being bio-liquids) and hydropower account for three-quarters of the renewable energy, as shown in Figure I.4. The bio-liquid component is primarily ethanol distilled from fermented corn and from (mostly Brazilian) sugar cane.

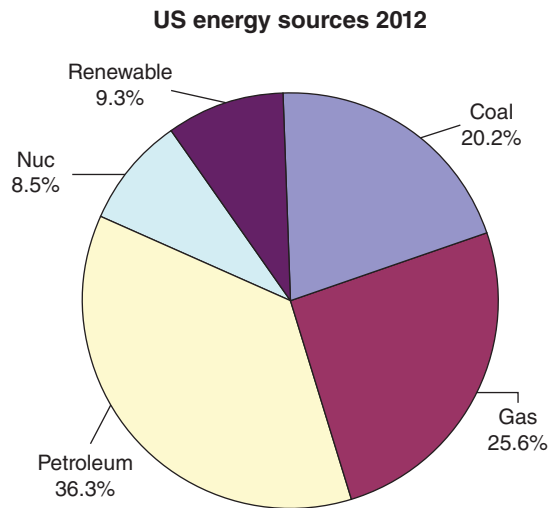


FIGURE I.3 The sources of the energy consumed in the United States in 2012. Renewable energy accounted for 9.3% of the energy, but the lion’s share was the venerable ones: hydro and biomass (half of which was firewood).

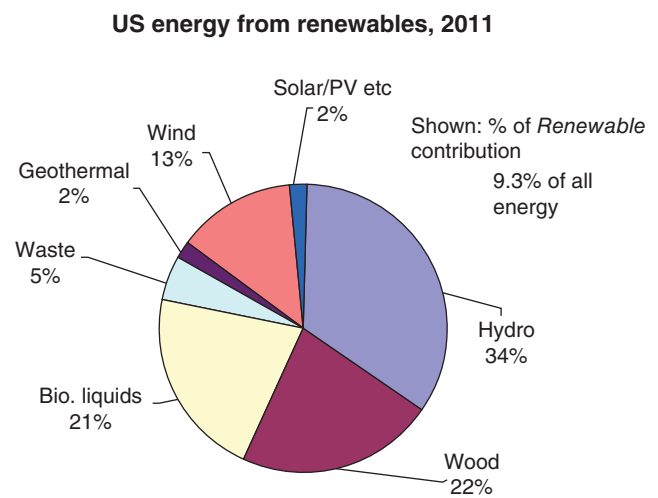


FIGURE I.4 The individual contributions of US renewable energy. All considered, they comprise 9.3% of all US energy consumption. The biological liquids are primarily corn ethanol added to gasoline.

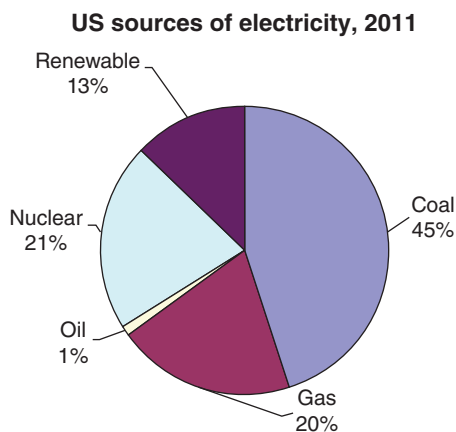


FIGURE I.5 Sources of US electricity, 2011. The coal fraction has diminished from 50% to 45% during the last few years, owing to the increasing availability of inexpensive natural gas and the EPA's strictures against coal.

As noted above, about 40% of our primary energy goes into the production of electricity. Figure I.5 shows how much each source contributes. Renewables account for 13% of our electricity, but again, the major fraction of the renewable contribution is from the venerable sources: firewood and hydro, as shown in Figure I.6. Owing to mandates (Renewable Portfolio Standards) and subsidies, wind has grown to produce 23% of our *renewable-source* electricity, or 3% of our electricity. Also notice that oil produces only about 1% of our electricity.

Physical Fundamentals

Fuels The earth has vast reserves of coal, oil, and natural gas. They are usually called *fossil fuels*—implying that they are the remains of long-dead trees and animals. While it is true that methane (the main component of natural gas) is

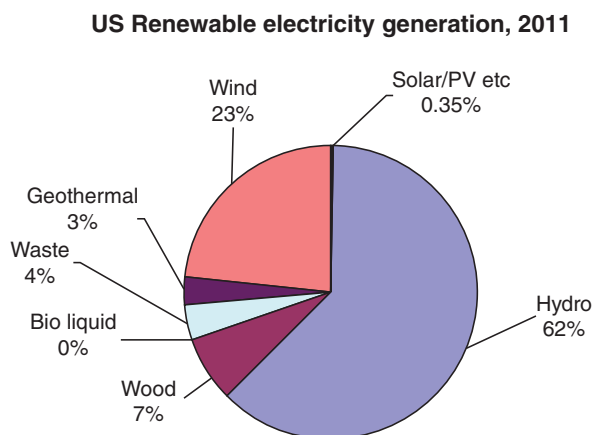


FIGURE I.6 Electrical production from renewables in 2011, as a percentage of total renewable kilowatt-hours.

produced in swamps and landfills, that explanation does not quite work for Titan, the largest moon of Saturn, where there are literally oceans of liquid methane. It seems likely that there may be some primordial methane trapped within the earth. It is controversial whether at least some of the earth's coal and oil are derived from that methane, but the question has relevance to the quantity of these fuels. That discussion, however, would take us too far afield.

Methane (CH_4) is chemically the simplest of the fuels and is a gas unless refrigerated to a very low temperature (approximately -162 C , or -260 F). As shown in Figure I.7, the methane molecule is a tetrahedral structure with a carbon atom in the center, and four hydrogen atoms at the vertices. When a methane molecule burns in air, the combustion produces one molecule of carbon dioxide (CO_2) and two molecules of water (H_2O).

Carbon has the property of forming long chains, side chains, hexagons, and many other complicated structures; without that property, petroleum—and for that matter DNA—would not exist. Figure I.8 shows the example of one petroleum molecule, pentane. It has 5 carbon atoms and 12 hydrogen atoms. As the number of carbon atoms increases, so does the number of hydrogen atoms. The ratio of their numbers—hydrogen to carbon—approaches 2. For example, nonane, the principal component of diesel fuel, has 9 carbon atoms and 20 hydrogens, so the ratio is 20:9, or 2.22. For this reason, we usually regard petroleum (which has both of these chemicals and *many* more) as being approximately CH_2 .⁴

There are two natural forms of carbon: graphite and diamond. Coal is neither of these; it is not pure carbon. Nor is all coal the same. The broad classifications—lignite, sub-bituminous, bituminous, and anthracite—do not even tell the story, because coal from different mines will have different compositions, different quantities of water (yes, coal has lots of water), as well as different quantities of silicates, sulfur, mercury, and other contaminants. This topic is best left to experts, but for our considerations, the combustible part of coal is chemically approximately CH : one atom of hydrogen for every one atom of carbon.

To summarize the above, the conventional fuels differ in the ratio of hydrogen atoms to carbon atoms: exactly 4-to-1 for methane; approximately 2-to-1 for petroleum and one-to-one for coal.

Methane, with a 4:1 ratio has an HHV of 52.2 MJ/kg.

The 2:1 hydrogen/carbon ratio of all petroleum chemicals means that the HHV is closely the same for all of them, namely about 45 MJ/kg \pm a few percent. The differences in the *volumetric* HHV values of the petroleum fuels are due to their differing densities. (The ethanol that is added to gasoline has only 72% as much energy on a per-liter or

⁴The long-chain molecules, known as *alkanes* have a generic formula $\text{C}_n\text{H}_{2n+2}$

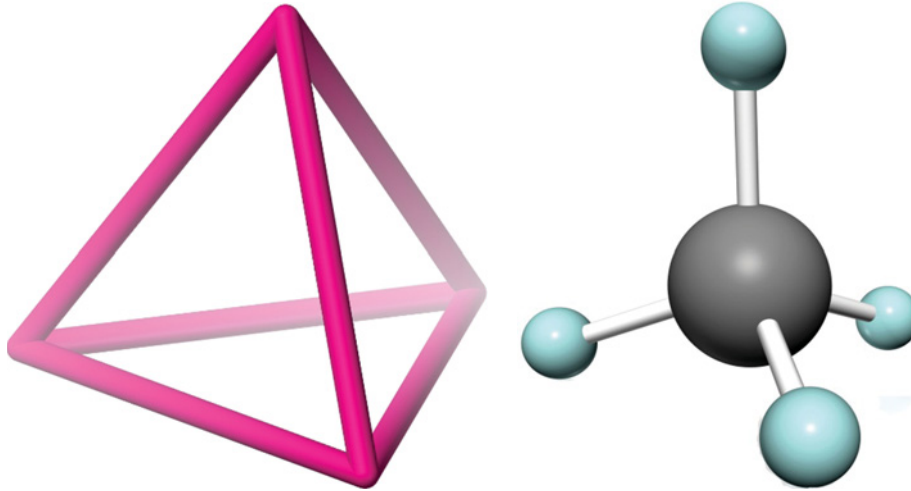


FIGURE I.7 Left, a regular tetrahedron. Place a carbon atom at the center and four hydrogen atoms at the vertices, and you get the structure of methane, the simplest of fuels.

per-gallon basis.) To get some perspective on the HHV, a car that gets 30 miles per gallon and is travelling at 60 miles per hour uses two gallons of gasoline per hour. Using the HHV for two gallons (262 MJ) and the 3600 seconds in an hour, we see that the fuel input power is 77 kW.

Anthracite coal has an HHV of 32 MJ/kg. Bituminous coal varies from 17 to 23 MJ/kg. The coal used in the United States in 2011 had an average HHV of 22.8 MJ/kg. Hydrogen, by comparison, has a much higher HHV, namely 141.8 MJ/kg. This high number does not mean that hydrogen has a special affinity for oxygen. Rather, the value is due to the fact that hydrogen atoms have a mass unit of 1, compared to 12 for carbon; the mass is in the denominator.

By comparison, nuclear fuel yields about 80 TJ/kg, which is 1.8 million times as high as the HHV for petroleum.

Uses of fuels 1: Heat-to-work All useful fuel-driven engines work by the expansion of a gas that is heated directly or indirectly by the fuel. In a steam engine, for example, water is boiled under high-pressure conditions, and the resulting steam expands in the engine (which may be a piston- or turbine-type). A nuclear reactor works similarly, in that its job is just to boil water. In a gasoline or diesel engine, the

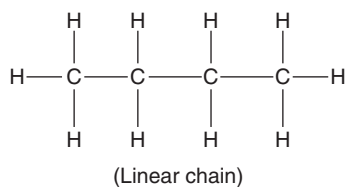


FIGURE I.8 A simple example of a carbon chain molecule, in this case, pentane.

expanding gas is none other than the combustion products, mostly CO₂ and H₂O.

In the abstract, the engine is a system into which you inject energy, and there are two outputs: work and waste heat. The efficiency is the work accomplished divided by the heat energy input (alternatively, the power produced divided by the input power). Averaged over the entire electrical supply, the efficiency of electricity generation is about 35%. This fact has implications for how the EIA regards hydro and wind.

The EIA has tables of annual energy consumption in the United States. For hydro, the 2011 value is 3.171 quadrillion BTU. The amount of electricity produced by hydro in 2011 was 325.1 billion kWh. If we make a simple conversion of units, we find that 3.171 quadrillion BTU is equivalent to 929.3 billion kWh, which is 2.858 times the actual electrical energy produced. For wind, the figures are 1.168 quadrillion BTU and 119.7 billion kWh, resulting in a ratio of 2.859. No dishonesty is intended. The purpose of the EIA tables is to show how much energy would have been required if the electricity had been produced by heat engines operating at 35% efficiency, instead of hydro.

Why is the efficiency so low for producing electricity from fuels? It is not a matter of failing to understand the basic principle, which is that the higher the temperature of the expanding gas, the higher the efficiency of the engine. But efficiency has much to do with the properties of materials. For example, the higher the temperature, the more corrosive steam becomes. *Combined-cycle* power plants, consisting of two heat engines operating their own generators, have become very efficient. The first engine is a gas turbine with specially made blades (ceramic-coated, or single-crystal titanium) that can withstand very high temperatures. The second engine is a conventional steam-turbine system that boils water with the hot gases exhausted from the gas turbine. Between the

two, they manage to convert up to 60% of the fuel energy to electricity.

Uses of fuels 2: Fuel cells Electrolysis is a method for separating water into hydrogen and oxygen. Basically, DC electricity is run through water containing an electrolyte, such as NaCl. Hydrogen is liberated at the cathode, and oxygen is liberated at the anode. A fuel cell is the opposite. Hydrogen is injected at the anode and oxygen (often just air) is injected at the cathode. The hydrogen ions (a.k.a. protons) permeate through a barrier to combine with oxygen to form water. The system acts like a battery with many cells, each of about 0.7 V, wired in series. In other words, it converts chemical energy to electrical energy without the use of expanding gases. The efficiency is up to 60%. Fuel cells are particularly sensitive to contaminants in the fuel, but less so with high-temperature ceramics as the barrier.

Hydro Hydropower turbines and wind turbines have one important thing in common. They convert mechanical energy into electricity by simply spinning a generator. For over a century, it has been possible to convert the mechanical energy of a rotating shaft into electricity with over 95% efficiency.

In the case of hydropower, the source of energy is *potential* energy of water stored behind a dam. (There are some low-power, inefficient devices—“undershot wheels”—that convert kinetic energy of a moving stream.) In the case of wind power, the source of energy is the *kinetic* energy of moving air. An important difference is that hydro energy is stored (by accumulating water in a lake behind a dam), whereas wind power is available only when the wind blows.

The power output of a hydro plant is proportional to the rate of flow of water and to the elevation of the water surface above the point where water is discharged into the river. Assuming a reasonable efficiency of 85%, the power is given by

$$P_{\text{out}}(\text{watts}) = 8330 \times h(\text{meters}) \times \frac{\Delta V}{\Delta t} (\text{cubic meters per second}) \quad (\text{I.1})$$

By and large, the flow rate $\Delta V/\Delta t$ is governed by the number of turbines being used. For example, Hoover Dam has 19 generators, each contributing about 5% of the 2.08 GW possible with all running. On yearly average, Hoover puts out about 480 MW. The annual capacity factor is therefore about 25% ($480 \text{ MW} \div 2080 \text{ MW}$). Hydro is rarely used for base-load power, but rather to handle the times during which the demand is high and/or fluctuating rapidly. Typically, hydropower plants have much more power available than the stream flow can handle on a long-term basis. High power is generated when needed, and that means high water flow, which reduces the water level. When demand drops and the water flow is shut off, the stream refills the lake.

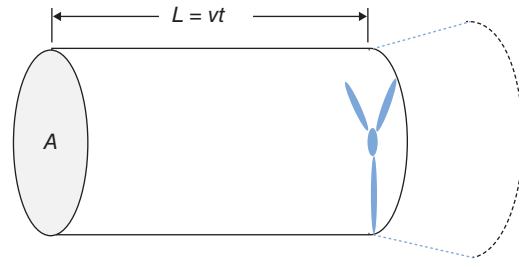


FIGURE I.9 A horizontal column of moving air reaches the wind turbine and expands as it slows down.

As hydropower is the easiest to use, it follows that the best dam sites are already in use. It produces about 8% of our electricity and is not likely to grow appreciably. No doubt, there are many rivers that can be dammed to produce (say) 50 MW, but just imagine having to write an Environmental Impact Statement — and having to fend off affected neighbors — for 20 of them, just to produce 1000 MW (enough for a city of 700,000).

Wind Imagine a horizontal circular column of moving air. Imagine a wind turbine of the same diameter facing into that column and extracting some of the kinetic energy (see Figure I.9). If the machine removed *all* of the energy, the column would stop, and no more energy would be available. In fact, the air has to keep moving, but at lower speed, because the wind turbine has slowed the air down. For the same amount of air to come in at high speed and leave at low speed, the slower air has to spread out to a larger diameter. This fact has implications for separating wind turbines from one-another. You do not want down-stream turbines to be in a low-speed area, and you do not want interference between side-by-side turbines. There is also the matter of turbulence, which can damage the machinery. Generally speaking, turbines are placed about 10 diameters apart in both directions.

The wind energy per unit time arriving at a wind turbine is proportional to the intercepted area (hence to R^2 , the square of the radius). It is also proportional to the cube of the wind speed, because the kinetic energy is proportional to the square of the wind speed, and the rate at which it arrives is proportional to the speed v . It is also proportional to the density of the air (about 1.3 kg/m^3), which varies with the elevation of the site. The wind turbine will convert a fraction (the *power coefficient*, for which we use a Greek η , eta) of that energy per unit time into useful power. If we represent the density by the Greek letter rho (ρ), the power output P_{out} is given by

$$P_{\text{out}} = (1/2)\eta\rho\pi R^2 v^3 \quad (\text{I.2})$$

Before proceeding to a discussion of real turbines, we take note of two very important facts. Consider using larger turbines instead of smaller ones. If we double the diameter, a turbine will produce four times as much power. On the other hand, we must space the turbines twice as far apart—in each direction—so that the gross amount of land devoted to the array of turbines is four times as large. Therefore, the amount of power *per unit of land area* is independent of the size of the wind turbines. A good rule of thumb is that a large array of wind turbines *in an excellent site* will produce about 12.5 kW per hectare (10,000 square meters) (5 kW/acre) on a year-round average basis.

To explain this further, wind sites are rated in terms of the power-per-unit-area⁵ carried in the wind, as shown in the following table from the Texas State Energy Conservation Office (NREL = National Renewable Energy Laboratory).

W/m ²	NREL class
<100	1–
100–200	1+
200–300	2
300–400	3
400–500	4
500–600	5
600–800	6
>800	7

A wind turbine presents an interception area A , which is proportional to the square of the diameter of the turbine, and the wind turbines are spaced typically 10–15 diameters apart in both directions, so the gross land area must be proportional to the interception area. For example, for a 10-diameter (20-radius) separation, the ratio of turbine area to gross land area is $\pi R^2 / \pi (20R)^2 = 1/400$. A 500-W/m² site would be exposed to about 1.2 W/m² (12 kW/hectare) average power, but produce less, because the wind turbine has its own power coefficient.

The other important fact is the dramatic variation with wind speed. If the speed changes from 5 to 10 m/s, the power available becomes eight times as great. Alternatively, if the wind speed halves from 10 to 5 m/s, the power available drops by 87.5%. These rapid changes are unimportant when wind power is a small fraction of the power on the grid, but begin to be troublesome at about 10% penetration.

Capacity Factor for Wind Turbines For a given site with its winds, capacity factor is a matter of engineering design. We can nail down two ends of the curve with bits of nonsense. What if we built a wind turbine using a child’s pinwheel to

⁵Technically speaking, it is not power, because no conversion of one type of energy to another is involved. Pedantically, the term should be energy per unit area per unit time crossing an area perpendicular to the wind.

drive a 1-MW generator? We would get no energy at any time, and the power factor would be zero. What if we used a 50-m diameter turbine and had it drive a 1-W generator. Most likely, there would always be enough wind (or rotational energy in the rotor) to turn the generator for the full 8760 hours in a year. The capacity factor would be 100%.

In other words, the annual capacity factor (average power divided by nameplate power) depends on the size of the generator compared to the size of the turbine. For a couple of decades, wind turbines have been designed for an annual capacity factor of about 35%. In 2011, wind generated 120 billion kWh. At the end of 2010, the total wind nameplate power was 39.1 GW, and at the end of 2011 it was 45.2 GW. If we assume that the average nameplate power during 2011 was the average of the beginning and end capacities (42.15 GW), the wind turbines could have generated 369 billion constant high winds, so the capacity factor was $120 \div 369$, or 32%.

Actual Wind Machines At wind speeds below about 4 m/s, wind turbines produce no output at all. If they did, the amount of power would be trivially small in any case, owing to the v^3 dependence on wind speed (see Figure I.10). Then the power output rises dramatically until full power is achieved at about 16 m/s, after which the output is constant until 25 m/s when the machine shuts off to avoid damage.

The power coefficient η versus wind speed is shown in Figure I.11. It achieves a maximum value of about 40% at a wind speed of 8 m/s (29 km/h, 18 mph). The power coefficient is 25% or above for wind speeds from about 5 m/s (18 km/h,

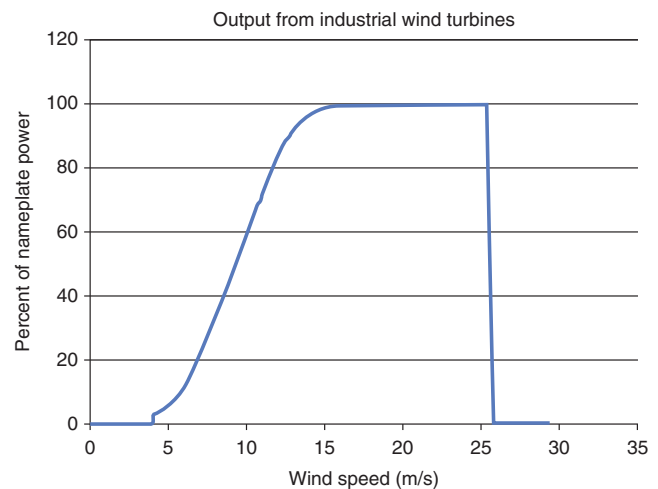


FIGURE I.10 The power output from a wind turbine, versus wind speed. Data from specification sheets of wind turbine manufacturers. The power rises abruptly, beginning at about 4 m/s until beginning to level off at around 13 m/s, reaching full power at 16 m/s. Above 25 m/s the machine must be shut down to avoid damage. Curves for major manufacturers are essentially identical.

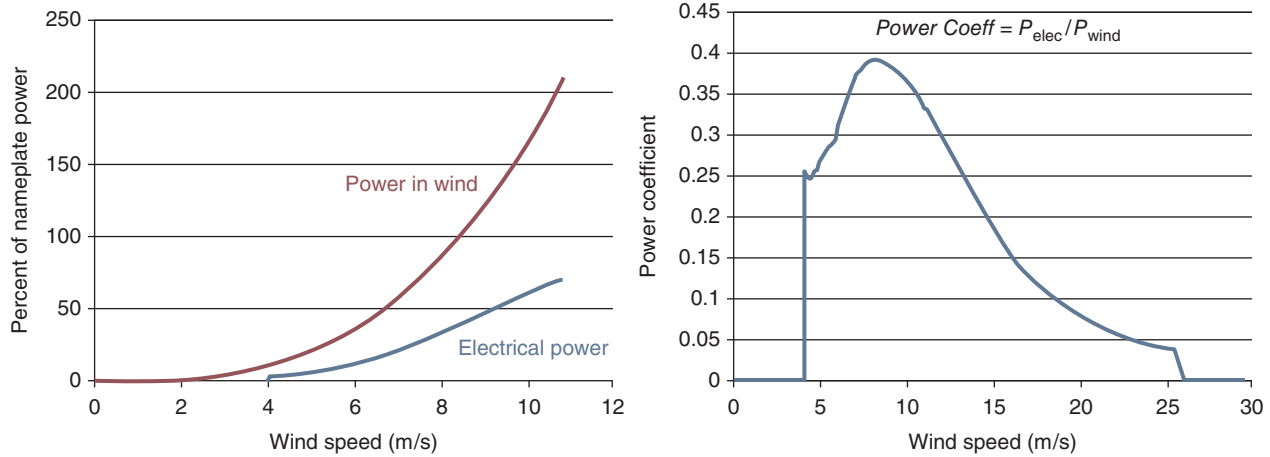


FIGURE I.11 Left: Wind turbine power and power in the wind, versus air speed. Right: The power coefficient, which is the ratio of generated power to wind power, versus wind speed. Data from specification sheets of wind turbine manufacturers.

11 mph) to about 13 m/s (47 km/h, 29 mph), which occurs about half the time.

The biggest machinery problem with industrial wind turbines has been the gear boxes. The larger the turbine diameter, the slower the rotation (but the tip speed remains at about seven times the wind speed, and can easily reach 80 m/s [200 miles per hour]). Typically they turn at 10–15 revolutions per minute, whereas the generator (depending on design) usually requires rotation rates in the high-hundreds to a few thousand RPM. The gear boxes are responsible for increasing the rotation rate, and they have very high stresses. It is possible, but expensive, to have direct-drive generators that use a large array of rare-earth permanent magnets around the periphery of the rotor, and coils appropriately placed on the stator.

The bases for wind turbines must be very substantial. Not only must the base have the strength to support the weight, but it must also deal with a tremendous torque (“twisting force”). For contemporary machines, it is equivalent to having a school bus out on the end of a plank the length of a football field. All in all, the generator, nacelle, support pipe, and base usually weigh over 1000 metric tons.

Geothermal Energy The term *geothermal* has a historical meaning and a new one. The historical one is the obvious one, referring to heat from deep (or not so deep) in the earth. The new meaning refers to the use of the earth a few meters down as a heat reservoir.

Outcroppings of heat (such as at the Geysers in California) are sometimes hot enough to run a steam turbine. In 2011, geothermal heat generated 0.04% (4 pennies out of 100 dollars) of US electricity. The high-temperature environment is frequently corrosive, but putting that issue aside, there are three other problems. The higher the temperature, the higher the efficiency can be for a heat engine (such as a

steam engine). The hot outcroppings, however, are not usually nearly as hot as the steam in a conventional steam plant, so the efficiency is lower. In the second place, extraction of heat from the ground necessarily cools the region where the heat is extracted, and that lowers the efficiency of the engine. One must limit the extraction of heat to the rate at which heat is conducted to the site through the surrounding rock. Finally, the number of such outcroppings is limited. On the other hand, if technology develops for drilling very deep into the mantle, the heat supply is enormous.

Refrigerators and Heat Pumps With regard to the new meaning of *geothermal*, it is necessary to take a brief look at refrigerators and heat pumps. A heat engine can be regarded in block form this way: It is a device into which you inject heat Q_{HIGH} , as shown schematically in Figure I.12. The device does some work W and rejects waste heat Q_{LOW} into the environment. Obviously, $Q_{HIGH} = Q_{LOW} + W$.

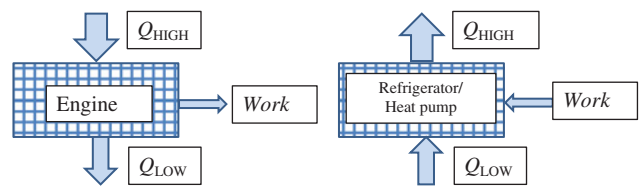


FIGURE I.12 Left: A schematic ideal engine. A quantity of heat Q_{HIGH} is fed into the engine from a high-temperature source. Work W is accomplished and waste heat Q_{LOW} is rejected to the low-temperature environment. The widths of the arrows represent amounts. Right: When work is put into the system (say by the serpentine belt of an automobile, or by an electric motor), the directions of the heat flow are reversed. Heat pumps and refrigerators are essentially identical. The only difference is the purpose. Refrigeration is concerned with the heat removed Q_{LOW} . Heat pumps are concerned with the heat delivered Q_{HIGH} .

In a more realistic scenario, the machine is cyclic with some average input power and average useful power produced, and average heat power rejected into the environment. For example, we might inject 10 kW of heat power from steam into an engine. The machine produces (say) 3 kW of useful electrical power and discards 7 kW of heat into the environment. Simple enough. Generally speaking, the higher the source temperature, the higher the efficiency.

Now imagine turning that engine around, as shown on the right side of Figure I.12. Under ideal conditions, we could put in 3 kW of electricity and extract 7 kW of heat from the environment. These days, that does not take a lot of imagination, because that is exactly what refrigerators and air conditioners do. Yes, we do extract more heat energy from the refrigerated environment than we put in as electricity. Importantly, the 3 kW plus the 7 kW add up to 10 kW that is delivered back to the “hot” area, namely the room or the outdoors.

A heat pump is simply a refrigerator used for a different purpose. In this case, we are concerned with delivering heat from a cooler place to a hotter place. In our example, the 3-kW of electricity refrigerates one place to the tune of 7 kW and heats another place to the tune of 10 kW.

In actual practice, we can use an air conditioner in the summer to extract heat from the house and inject it into the comparatively cool ground which serves as a heat reservoir. That produces cooling more efficiently than rejecting heat into the hot summer air. By the same token, we can reverse the valves in the winter so as to refrigerate the relatively warm ground (compared to the outside air) and deliver the heat into the house. The use of the ground as a heat sink or source is what has led to the term *geothermal heat*, which many people would confuse with high-temperature heat in places like Yellowstone National Park.

The Seasonal Energy Efficiency Ratio (SEER) is the ratio of the seasonal heat extracted (for air conditioners) or delivered (for heat pumps) to the electrical energy input for commercial devices; however, there is a different unit in the numerator (BTUs) than in the denominator (Wh), and manufacturers usually do not bother telling customers that the units are BTU/Wh. To make a more understandable number, note that 1 BTU = 3.412 Wh. Commercial heat pumps and refrigerators have SEERs that run from about 10 BTU/Wh to as high as 18 BTU/Wh, corresponding to simple ratios of 2.93 (=10 BTU/Wh ÷ 3.412 BTU/Wh) to 5.86. In other words, one unit of energy from the electrical grid will deliver 2.93–5.86 units of heat. Engineers refer to these dimensionless ratios as the *coefficient of performance* (COP). A glance at Figure I.12 will reveal that the COP for a heat pump must be greater than that for the same device used as a refrigerator, because the heat delivered Q_{HIGH} must always exceed the heat Q_{LOW} removed from the cold reservoir. In fact, $\text{COP}_{\text{heatpump}} = \text{COP}_{\text{A.C.}} + 1$.

Solar Energy Solar energy has many forms, including biomass, solar heat, photovoltaics, wind energy, and hydropower. It is useful to distinguish between broad types. Biomass and solar devices (like heat collectors and photovoltaic cells) produce usable energy because of very local sunlight. In these cases, the solar energy is collected where, and only where, our devices capture sunlight.

By contrast, the winds blow in one place because of sunlight somewhere else, and hydropower produced at a dam is due to water that evaporates far away and rains out somewhere upstream. In these cases, the solar energy is captured *naturally*, carried elsewhere by air and water, and converted into a useful form by machinery. Hydro and wind are therefore discussed separately from other forms of solar energy.

Our magnificent sun is located 150 million kilometers away, is powered by hydrogen fusion, and has a surface temperature of about 5800 K. A one square-meter panel facing the sun at the location of the earth intercepts about 1400 W [thermal, W_t] of sunlight. Much sunlight is reflected by the atmosphere (clouds, water vapor . . .), and some is absorbed by the atmosphere, so that the sunlight reaching a square-meter panel at the surface and facing the sun intercepts about 950 W_t under clear-sky conditions at noon. The year-round average sunlight intensity ($\langle I_H \rangle$ known as *insolation*) on a *horizontal* surface in the United States, averaged over all of the lower-48 is 200 W/m², with ±20% place-to-place variations covering about 2/3 of the lower-48. For example, Hartford, CT, gets about 160 W/m², and Albuquerque, NM, gets about 240 W/m².

There is, therefore, a certain simplicity to energy obtained by direct sunlight. A given parcel of land of area A (unit: square meters (m²), using some apparatus, produces a certain quantity of useful energy E (S.I. unit: joules), during the year ($t = 31.6$ million seconds). The *useful* average power intensity $\langle I_U \rangle$ produced per unit area is therefore $\langle I_U \rangle = \frac{E/t}{A}$. Of course, the energy produced on the parcel of land is less than the solar energy that illuminated the parcel. We can define the overall efficiency η as the ratio of the two. We have

$$\langle I_U \rangle = \eta \langle I_H \rangle. \quad (\text{I.3})$$

The simplicity of equation (3) is that all we need to know to place solar energy in the broad context of energy production is the overall efficiency of the processes that convert solar energy into useful energy. This fact holds for photovoltaics, solar heat, growth of plants, and all other cases where sunlight is directly converted to energy.

Bio-fuels A relatively recent paper in *Chemical and Engineering News* "Chasing cheap feedstocks" (*C&EN*, Aug. 12, 2013, page 11) rated numerous energy fuels in terms of production, but in units that are not very illuminating. The *best* crops (well watered, well fertilized) produce about 10 tons



FIGURE I.13 Solar/thermal/electric generating systems in the Mojave Desert, California. Left: SEGS unit at Kramer Junction, California (2005); Right: Ivanpah installation (2013). Both systems use concentrating mirrors to produce super-heated steam to turn turbines.

of drymatter per acre per year. A little arithmetic with conversion factors (acre = 4047 m²; ton = 907 kg; year = 3.16 × 10⁷ s; heat content of drymatter ≈ 15 MJ/kg) brings the result that these fuels are produced at the rate of about 1.2 W/m² on year-round average basis. (Untended hardwood forests produce firewood at about 0.12 W/m².) Compared to sunlight at 200 W/m², this amounts to a solar efficiency of 0.06%. What we are discussing here is the heat energy that could be released if the drymatter were simply burned in place. Anything whatsoever that is done (such as mere collection and delivery) results in a lower efficiency yet.

There has been considerable debate about the amount of energy used in converting corn into ethanol, EtOH. The most optimistic estimates come from Shapouri, Duffield, and Wang.⁶ Using data from a 9-state survey, they produced the following figures, which we will translate to SI: Annual corn yield is 125 bushels/acre; each bushel produces 2.64 gallons of ethanol; and the HHV of ethanol is 83,961 BTU/gallon. We add that there are 4047 m² in an acre, 1055 J in a BTU, and 31.6 million seconds in a year. The result is that the *gross* production of ethanol amounts to 0.228 W/m², averaged over the year. The purpose of the Shapouri group's paper was to show that the production of ethanol is energy net-positive, *i.e.*, there is more energy in the ethanol than it takes to produce it. Their figures are that the *net* amount of energy in a gallon of ethanol is 6732 BTU/gallon, a mere 8% of the HHV. Expressed in SI units, it amounts to a very pathetic 0.018 net watts per square meter.

The area of all of the contiguous 48 states (including water area and huge tracts of non-arable land) is 9.8 × 10¹² m², and only 18% of the land (1.76 × 10¹² m²) is arable. The amount

of annual energy that could be produced by the best-tended best crops at 1.2 W/m² is about 67 EJ, only two-thirds of our consumption. The amount of *net* energy that could be produced using all arable land for production of ethanol (at 0.018 W/m²) is 1.0 EJ, which is only 1% of our energy requirement.

Solar Heat Any box covered with glass or transparent plastic facing the sun collects solar heat. Its efficiency at collection depends upon the interior color (preferably black), the shape (large window area compared to area of the sides), insulation, and the properties of the transparent cover (in some cases, double glazing helps). Most importantly, the interior and exterior temperatures play a huge role. The higher the temperature difference between the interior and the exterior, the more the heat lost through the walls and the glazing. All commercial solar heat units have graphs showing the efficiency dropping off as the outside temperature gets lower.

Solar/Thermal Electricity One way to produce electricity from sunlight is to use mirrors to concentrate sunlight so as to create a high temperature, make superheated steam, and then run a conventional steam-turbine/generator set. Figure I.13 shows two ways of accomplishing that task. The shiny parabolic trough system on the left reflects sunlight to heat a pipe containing a high-temperature oil pumped to a heat exchanger to boil water. The troughs slowly rotate during the day as the sun moves across the sky. It is not necessary to make seasonal adjustments.

On the right of Figure I.13 is a new installation near Ivanpah Dry Lake. One-hundred-seventy-thousand (170,000) independent computer-controlled heliostats, each with two 7.5 m² mirrors, reflect sunlight to the dark regions at the tops of the towers to boil water. They are spread out over 1416 hectares (3500 acres), and the peak power is 392 MW. The

⁶Hosein Shapouri, James A. Duffield, and Michael Wang. "The Energy Balance of Corn Ethanol: An Update;" U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses. Agricultural Economic, Report No. 813, 2002.

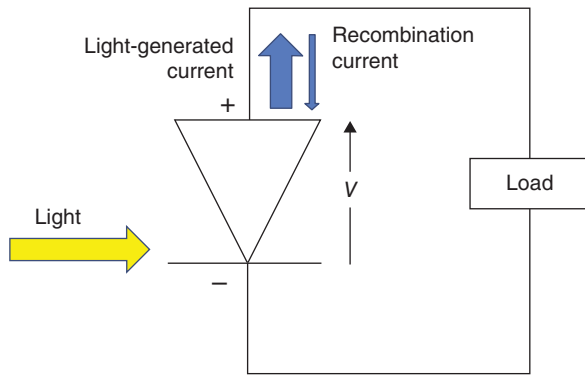


FIGURE I.14 Schematic photovoltaic cell. It is a diode (one-way valve for current), but the incident light makes the current go the opposite way from normal. As the voltage V rises, the recombination current rises dramatically, so it is necessary to draw sufficient current to keep the PV cell operating efficiently.

expected annual production is 1080 GWh, which amounts to an annual capacity factor of 31%. The system will generate year-round average power of 8.7 W/m^2 of land.

Photovoltaics (PV) Photocells convert light directly into electricity, as shown in the schematic drawing in Figure I.14. All PV cells are diodes (rectifiers) that normally conduct electricity in only one direction. This one-way phenomenon occurs because dissimilar materials are in contact. Incident light, however, produces a reverse current.

The problem that bedevils PV cells is that to boost an electron to cross the barrier requires a given amount of energy.

This job is supposed to be done by sunlight, with a wide spectrum of wavelengths, hence a wide array of energies to do the boosting. Some light does not have enough energy, and some has excess energy that is simply wasted as heat. There are some multiple band-gap (energy-step size) devices with efficiencies well above 30%, but they are laboratory-size devices made with expensive, exotic materials.

There is a trade-off between efficiency and size, and it hinges on economics. Comparing two PV cells, let us assume that one has twice the efficiency of the other. Then, for a given amount of power, we can get by with half the physical area. That might seem like the cost would be cut in half, but the better cells might cost 100 (or 50) times as much. In that case, economics dictates the use of the less efficient cells. Alternatively, the land may be horrendously expensive, in which case economics favors the more efficient cells.

In any case, experience with large PV arrays shows that the annual capacity factor is usually less than 20%.

SUMMARY

Sunlight is free, and so are wind, geothermal heat, and water at high elevation. For that matter, coal, oil, and natural gas are also free. So is uranium. The problems lie in efficient, inexpensive delivery to users who need energy on demand. Winds are capricious, sunlight is not available at night, and the biggest and best hydropower sites are already in use. We have long since passed the point where biomass can make any significant increase to our energy supply. The following chapters, written by energy technologists, address the details.

LIST OF CONTRIBUTORS

Rafid Al-Khoury Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Mathew C. Aneke Department of Chemical Engineering, Faculty of Science and Engineering, University of Hull, United Kingdom

Roberto D. Arce Physics Institute of Litoral (IFIS Litoral, UNL-CONICET), Santa Fe, Argentina; Facultad de Ingeniería Química, UNL, Santa Fe, Argentina

Amornchai Arpornwichanop Computational Process Engineering, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand

Suttichai Assabumrungrat Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand

Suthida Authayanun Department of Chemical Engineering, Faculty of Engineering, Srinakharinwirot University, Nakhon Nayok, Thailand

Ömer Aydan Department of Civil Engineering and Architecture, University of the Ryukyus, Nishihara, Japan

M. Aram Azadpour Engineer consultant in digital logic functional modeling and digital logic design verification, Grapevine, TX, USA

R. Baile UMR CNRS 6134, Université de Corse, Corte, France

A. Barroso School of Engineering, University of Seville, Seville, Spain

Ali Bolatturk Department of Mechanical Engineering, Suleyman Demirel University, Isparta, Turkey

Richard S. Brown Pacific Northwest National Laboratory, Richland, WA, USA

Nicolás Budini Physics Institute of Litoral (IFIS Litoral, UNL-CONICET), Santa Fe, Argentina

Román H. Buitrago Physics Institute of Litoral (IFIS Litoral, UNL-CONICET), Santa Fe, Argentina; Facultad de Ingeniería Química, UNL, Santa Fe, Argentina

J. Cañas School of Engineering, University of Seville, Seville, Spain

Thomas J. Carlson Pacific Northwest National Laboratory, Richland, WA, USA

Roger H. Charlier Vrije Universiteit Brussel—VUB, Free University of Brussels, Brussels, Belgium; Florida Atlantic University, Boca Raton, FL, USA

Tin-Tin Chow Building Energy and Environmental Technology Research Unit, Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Hong Kong

Alison H. Colotelo Pacific Northwest National Laboratory, Richland, WA, USA

Angus C. W. Creech Institute of Energy Systems, University of Edinburgh, Edinburgh, Scotland

John P. Deane Energy Policy and Modelling Group, Environmental Research Institute, University College Cork, Ireland

- Zhiqun (Daniel) Deng** Pacific Northwest National Laboratory, Richland, WA, USA
- Mark Diesendorf** Interdisciplinary Environmental Studies, University of New South Wales, Sydney, Australia
- Peter A. Dowd** School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia
- Annette Evans** Graduate School of the Environment, Macquarie University, Sydney, Australia
- Tim J. Evans** Graduate School of the Environment, Macquarie University, Sydney, Australia
- Philip M. Fearnside** National Institute for Research in Amazonia (INPA), Manaus, Brazil
- Wolf-Gerrit Früh** School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, Scotland
- Brian Ó Gallachóir** Energy Policy and Modelling Group, Environmental Research Institute, University College Cork, Ireland
- Winston Garcia-Gabin** ABB Corporate Research Center, Västerås, Sweden
- Alberto Gemelli** Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, Ancona, Italy
- D. P. Georgiou** Department of Mechanical Engineering and Aeronautics, Thermal Engines Lab, University of Patras, Rion-Patras, Greece
- Daniel Gessler** Alden Research Laboratory, Inc., Fort Collins, CO, USA
- Fiona M. Gray** School of Chemistry, University of St. Andrews, St. Andrews, UK
- Zhiqiang Guan** Queensland Geothermal Energy Centre of Excellence (QGECE), School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia
- Hal Gurgenci** Queensland Geothermal Energy Centre of Excellence (QGECE), School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia
- Martin Hand** Department of Earth Sciences, University of Adelaide, Australia
- Joerg Hartmann** Independent Sustainability Consultant, Estes Park, CO, USA
- Howard C. Hayden** University of Connecticut, Mansfield, CT, USA
- Herbert Inhaber** Risk Concepts, Las Vegas, NV, USA
- Damon Honnery** Department of Mechanical and Aerospace Engineering, Monash University—Clayton Campus, Melbourne, Australia
- Kamel Hooman** Queensland Geothermal Energy Centre of Excellence (QGECE), School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia
- Mikel Iribas-Latour** Wind Energy Department, Fundación CENER-CIEMAT, Sarriguren, Spain
- Stefan Ivanell** Uppsala University Campus Gotland, Section for Wind Energy, Visby, Sweden
- Gary E. Johnson** Pacific Northwest National Laboratory, Richland, WA, USA
- Mehmet Kanoglu** Department of Mechanical Engineering, University of Gaziantep, Gaziantep, Turkey
- Hugo Abi Karam** Department of Meteorology, Institute of Geosciences, Federal University of Rio de Janeiro, Brazil
- Thomas B. Kingery** Information Technology, Delaware, OH, USA
- Urban Kjellén** Norwegian University of Science and Technology, Trondheim, Norway; Statkraft, Oslo, Norway
- Masami Kojima** Energy and Extractives Global Practice, The World Bank, Washington, DC, USA
- Jacob Ladenburg** KORA, the Danish Institute for Local and Regional Government Research, Denmark
- Ion-Doré Landau** Automatic Control Department, GIPSA-LAB, Grenoble, France
- Jay H. Lehr** Editor-in-Chief, Science Director, Heartland Institute, Chicago, IL, USA
- Jack Keeley** Senior Editor, Former Chief of Ground Water Research, USEPA Kerr Water Research Laboratory, Ada, OK, USA
- Pak Sing Leung** Mechanical Engineering Division, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, United Kingdom
- Sauro Longhi** Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, Ancona, Italy
- Adriano Mancini** Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, Ancona, Italy
- J. C. Marín** School of Engineering, University of Seville, Seville, Spain

- Matthew C. Menkiti** Department of Chemical Engineering, Nnamdi Azikiwe University Awka, Nigeria
- Robert Mikkelsen** Department of Wind Energy, DTU, Lyngby, Denmark
- Rosemarie Mohais** School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia
- Patrick Moriarty** Department of Design, Monash University—Caulfield Campus, Melbourne, Australia
- J. F. Muzy** UMR CNRS 6134, Université de Corse, Corte, France
- Greg F. Naterer** Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada
- Michael Nagnevitsky** Centre for Renewable Energy and Power Systems, University of Tasmania, Australia
- Isaac Orr** The Heartland Institute, Chicago, IL, USA
- F. París** School of Engineering, University of Seville, Seville, Spain
- Antoine Peiffer** Principle Power Inc., Berkeley, CA, USA
- Gene R. Ploskey** Pacific Northwest National Laboratory, Richland, WA, USA
- Kevin Pope** Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada
- Panu Pratumnopharat** Mechanical Engineering Department, Faculty of Engineering, Rajamangala University of Technology, Thanyaburi, Pathumtani, Thailand
- Dominique Roddier** Principle Power Inc., Berkeley, CA, USA
- Marc A. Rosen** Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, Canada
- Somnath Baidya Roy** Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA
- Dang Saebea** Department of Chemical Engineering, Faculty of Engineering, Burapha University, Chonburi, Thailand
- Petar Sarajcev** Department of Power Systems, University of Split, FESB, Split, Croatia
- Timothy C. Sassaman** Alden Research Laboratory, Inc., Holden, MA, USA
- Javier A. Schmidt** Physics Institute of Litoral (IFIS Litoral, UNL-CONICET), Santa Fe, Argentina; Facultad de Ingeniería Química, UNL, Santa Fe, Argentina
- Michael J. Smith** Departamento de Química, Universidade do Minho, Braga, Portugal
- Vladimir Strezov** Graduate School of the Environment, Macquarie University, Sydney, Australia
- Vorachatra Sukwattanajaroorn** Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
- Bertrand F. Tchanche** Ecole Supérieure d'Ingénieurs en Electronique et Electrotechnique (ESIEE), Amiens, France 14, Quai de la Somme, 80000 Amiens
- N. G. Theodoropoulos** Department of Mechanical Engineering and Aeronautics, Thermal Engines Lab, University of Patras, Rion-Patras, Greece
- Alexandre C. Thys** Florida Atlantic University, Boca Raton, FL, USA
- Justin J. Traiteur** Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA
- Ka-Kui Tse** Building Energy and Environmental Technology Research Unit, Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Hong Kong
- Norman Tse** Building Energy and Environmental Technology Research Unit, Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Hong Kong
- Choashui Xu** School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia
- Darine Zambrano** Division of Systems and Control, Department of Information Technology, Uppsala University, Uppsala, Sweden

