Energy: Supply and Demand

Focusing on trends in energy supply and demand, this text provides students with a comprehensive account of the subject and an understanding of how to use data analysis and modeling to make future projections and study climate impacts.

Developments in technology and policy are discussed in depth, including the role of coal, the fracking revolutions for oil and gas, the electricity grid, wind and solar power, battery storage, and biofuels. Trends in demand are also detailed, with analysis of electrical demands such as LEDs, air conditioning, heat pumps, and information technology, and the transportation demands of railroads, ships, and cars (including electric vehicles). The environmental impacts of the energy industry are considered throughout, and a full chapter is dedicated to climate change. Real-life case studies and examples add context, and over 400 full-color figures illustrate key concepts.

Accompanied by a package of online resources including solutions, video examples, sample data, and PowerPoint slides, this is an ideal text for courses on energy and is accessible to a range of students from engineering and related disciplines.

David B. Rutledge is the Tomiyasu Professor of Engineering, emeritus, at Caltech. He is a founder of the Wavestream Corporation (a manufacturer of transmitters for satellite uplinks) and his recent research has focused on modeling for projections of energy supply. He is a Fellow of the IEEE and a recipient of the Teaching Award of the Associated Students at Caltech.

Energy: Supply and Demand

David B. Rutledge
California Institute of Technology

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107031074
DOI: 10.1017/9781139381208

First published 2020

Printed in Singapore by Markono Print Media Pte Ltd. 2020

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Names: Rutledge, David B., 1952– author.
Title: Energy : supply and demand / David B. Rutledge, California Institute of Technology.
Description: Cambridge, United Kingdom ; New York, NY : Cambridge University Press, [2020] | Includes bibliographical references and index.
Identifiers: LCCN 2019015702 | ISBN 9781107031074 (hardback : alk. paper)
Subjects: LCSH: Fossil fuels.
Classification: LCC TP318 .R88 2020 | DDC 553.2–dc23
LC record available at https://lccn.loc.gov/2019015702

ISBN 978-1-107-03107-4 Hardback

Additional resources for this publication at www.cambridge.org/rutledge

To my wife

Dale

Contents

Preface *page* xv

1 Preliminaries 1

1.1 Plan of the Book 4
1.2 Units 5
1.2.1 Capacity Factors 8
1.2.2 Payback Times 9
1.3 Efficiency 10
1.3.1 Conservation and Efficiency 11
1.3.2 The Jevons Paradox 12
1.4 Energy Production 14
1.4.1 The Alternatives 15
1.4.2 Per-Person Consumption 16
1.5 Population 17
1.5.1 Doubling Times 18
1.5.2 The United Nations Projections 19
1.5.3 Growth-Rate Plots 21
1.6 Energy and the Economy 26
1.6.1 Oil Consumption and GDP 27
1.6.2 Electricity Generation and GDP 29
1.6.3 Electricity Access and Poverty 31
1.7 Agriculture 33
1.7.1 Life Expectancy and the Green Revolution 35
1.7.2 Thomas Malthus on Population 37
1.8 Fossil-Fuel Independence 38
1.8.1 Europe Turns toward the New Alternatives 40
1.8.2 Calculating Annualized Growth Rates 41
1.9 Carbon-Dioxide Emissions 42
1.9.1 The Kyoto Protocol and the Paris Agreement 43
1.9.2 Fossil-Fuel Production and Carbon-Dioxide Levels 45
Concepts to Review 47
Problems 47
Further Reading 48

2 Horses, Whales, and Wood 49
2.1 Horses 49
2.1.1 Horses and Mules at Work 53
2.1.2 The Transition from Horses and Mules to Tractors and Cars 55
2.2 Whales 57
2.2.1 Yankee Whalers 58
2.2.2 Whale Oil and Kerosene 59
2.2.3 A Logistic Model for Whale Oil Production 60
2.2.4 The Sperm Candle Lighting Efficacy Standard 62
2.3 Wood 63
2.3.1 Wood Fuel and Industrial Roundwood Production 63
2.3.2 Charcoal and Wood Gas 66
2.3.3 The Transition from Wood to Coal 68
2.3.4 Timber Density 72
2.4 The Norse Greenland Colony 73
2.4.1 The Greenland Colony and Climate 75
2.4.2 The Inuit in Greenland 76
Concepts to Review 77
Problems 77
Further Reading 78

3 Models 80
3.1 Introduction 80
3.1.1 Types of Statements about the Future 80
3.1.2 The R/P Ratio 81
3.2 The Decaying Exponential Model 82
3.2.1 The Prudhoe Bay Oil Field 82
3.2.2 The Laherrere Linearization for Prudhoe Bay 84
3.3 The Logistic Model 87
3.3.1 The Hubbert Linearization 87
3.3.2 The Logit Transform Linearization 90
3.4 Reserves, Resources, and Occurrences 94
3.4.1 Original Reserves 97
3.4.2 Oil Reserves History 99
3.4.3 Coal Resources History 100
3.5 An Economic Model 101
3.6 Statistical Formulas 103
Concepts to Review 104
Problems 104
Further Reading 105

4 Coal 106
4.1 Introduction 106
4.1.1 Coal consumption 106
4.1.2 Coal in Electricity Generation 109
4.2 Origins 112
4.2.1 Formation of Coal 112
4.2.2 Ranks of Coal 114
4.3 Mining Coal 116
4.3.1 Longwall Mining 116
4.3.2 Surface Mining 119
4.4 Impacts 121
4.4.1 The Aberfan Disaster 121
4.4.2 Air Pollution from Coal 124
4.5 British Coal 127
4.5.1 Stanley Jevons and *The Coal Question* 128
4.5.2 The Royal Commission on Coal Supplies 132
4.6 The Mature Regions 136
4.6.1 German Hard Coal 136
4.6.2 Pennsylvania Anthracite 139
4.6.3 Summary for the Mature Regions 142
4.7 The Active Regions 143
4.7.1 Western US Coal 146
4.7.2 Chinese Coal 149
4.7.3 Summary for the Active Regions 154
Concepts to Review 157
Problems 157
Further Reading 158

5 Hydrocarbons 159
5.1 Introduction 159
5.1.1 Edwin Drake and His Well 161
5.1.2 John D. Rockefeller and Standard Oil 163
5.1.3 Oil and War 166
5.1.4 The Texas Railroad Commission and OPEC 168
5.2 Origins 173
5.2.1 The Oil Window 174
5.2.2 Hydrocarbon Traps 177
5.2.3 Dad Joiner and the East Texas Oil Field 178
5.3 Drilling for Oil and Gas 184
5.3.1 Fracking Technology 186
5.3.2 Enhanced Oil Recovery (EOR) 188

5.4 Impacts 192
5.4.1 The First Gulf War 192
5.4.2 The Long Beach Subsidence 193
5.5 King Hubbert and Peak Oil 197
5.6 Natural Gas 202
5.6.1 George Mitchell and the Barnett Shale 202
5.6.2 American Shale Gas Production 206
5.6.3 Natural Gas Infrastructure 207
5.7 Projections 209
Concepts to Review 213
Problems 214
Further Reading 216

6 Farming and Fishing 217
6.1 Introduction 217
6.1.1 Norman Borlaug and the Green Revolution 217
6.1.2 The Role of Nitrogen in Agriculture 217
6.1.3 The Brazilian Cerrado 219
6.1.4 The Food Supply 221
6.1.5 Oil and Food 223
6.2 The Haber–Bosch Process 225
6.2.1 The Guano Islands 225
6.2.2 Fritz Haber and Ammonia Synthesis 227
6.2.3 Carl Bosch and Ammonia Production 229
6.3 Cereals 232
6.3.1 Corn 233
6.3.2 Regional Cereal Production 235
6.4 Livestock 239
6.5 Impacts 244
6.5.1 Agricultural Land 244
6.5.2 The Destruction of the Aral Sea 245
6.5.3 The American Endangered Species Act 247
6.5.4 Agriculture and Water 255
6.6 Fish 256
6.6.1 The Destruction of the Newfoundland Cod Fishery 260
6.6.2 The Pacific Sardine and the Pacific Decadal Oscillation (PDO) 263
6.6.3 Fish Farming 267
6.7 Biofuels 270
6.7.1 Gobar Gas 272
6.7.2 Liquid Biofuels Production History 273

6.8 Prospects 277
Concepts to Review 278
Problems 278
Further Reading 280

7 Electricity and the Alternatives 281
7.1 Introduction 281
7.1.1 Thomas Edison and the Electrical Grid 282
7.1.2 Electricity Generation History 285
7.1.3 Daily Demand Curves 286
7.1.4 Capital Investments in Electricity Grids 290
7.1.5 European Residential Electricity 292
7.1.6 The Electricity Alternatives 294
7.2 Transmission Lines and Transformers 295
7.3 Electricity Generators 299
7.3.1 Three-Phase Systems 301
7.3.2 Fuel Costs in Fossil-Fuel Generation 302
7.4 Hydroelectric 304
7.4.1 Hydroelectric Generation History 304
7.4.2 The Pelton Wheel and Hydroelectric Power in California 305
7.4.3 The Francis Turbine and the Hoover Dam 310
7.5 Nuclear 314
7.5.1 The Atomic Bomb 314
7.5.2 Failed Dreams 317
7.5.3 Nuclear Generation History 318
7.5.4 The Chernobyl Disaster 320
7.5.5 The Great Tohoku Tsunami 321
7.6 Geothermal 323
7.6.1 The Geysers Field in California 324
7.6.2 Geothermal Heating in Iceland 326
7.6.3 The Japanese *Onsen* 327
7.7 Wind 328
7.7.1 Wind Resources 330
7.7.2 Wind Generation History 331
7.7.3 The Betz Limit 331
7.7.4 Wind Variability 336
7.8 Solar 338
7.8.1 Solar Resources 338
7.8.2 The Ivanpah Solar Thermal Plant 338
7.8.3 Solar Cell Efficiency 340

7.8.4 Solar Generation History 341
7.8.5 Solar Variability 342
7.9 Batteries 344
7.9.1 Battery Grid Storage 345
7.9.2 A Model Renewable Grid for California 346
7.10 Prospects 353
Concepts to Review 354
Problems 354
Further Reading 356

8 Stationary Demand 358
8.1 Introduction 358
8.1.1 Passive Cooling 359
8.1.2 Temperature and Mortality 361
8.1.3 OECD vs. Non-OECD Stationary Demand 363
8.2 Lighting 365
8.2.1 Nick Holonyak and His Light-Emitting Diode (LED) 367
8.2.2 LED Efficacy Limits 368
8.2.3 Prospects for LEDs 370
8.3 Electric Motors 372
8.3.1 The Universal Motor 373
8.3.2 Nikola Tesla and His Induction Motor 374
8.4 Heating and Cooling 379
8.4.1 The Comfort Zone 379
8.4.2 Heating with a Stove 380
8.4.3 Evaporative Coolers 382
8.4.4 Air Conditioners and Heat Pumps 383
8.4.5 Inline Water Heaters 386
8.4.6 Split-Zone Systems 388
8.5 Information Technology 389
8.5.1 The Jevons Paradox in Information Technology 389
8.5.2 Bitcoin Mining 391
8.6 The Rosenfeld Effect 393
8.6.1 Refrigerator Efficiency 393
8.6.2 A State Residential Efficiency Model 395
8.7 Trends in Residential Energy Demand 399
Concepts to Review 404
Problems 405
Further Reading 406

9 Transportation Demand 407
9.1 Introduction 407
9.1.1 Henry Ford and His Model T 408
9.1.2 Transportation Energy Demand 412
9.1.3 Electric Vehicles 414
9.1.4 Transportation Oil Demand 416
9.1.5 Commuting 416
9.1.6 Freight 420
9.2 Roads 422
9.2.1 The American Interstate Highway System 424
9.2.2 Vehicle Fuel Efficiency 426
9.3 Rails 429
9.3.1 The Japanese Shinkansen 429
9.3.2 American Rail Freight 431
9.4 Impacts 436
9.4.1 The Wreck of the MMA-002 Oil Train 436
9.4.2 "A Brown LA Haze" 441
9.4.3 The Volkswagen Diesel Scandal 445
9.5 By Sea 446
9.5.1 From Sails to Engines 446
9.5.2 Ocean Freight 447
9.6 By Air 449
9.6.1 Flight Range 450
9.6.2 Airline Passenger Travel 452
9.7 Prospects for Self-Driving Cars 454
Concepts to Review 456
Problems 457
Further Reading 459

10 Climate Change 461
10.1 Introduction 461
10.1.1 The Callendar Effect 461
10.1.2 California Forest Fires 464
10.2 Carbon Dioxide 465
10.3 Sea Level 468
10.4 Temperature Indexes 473
10.4.1 The Central England Temperature Index 476
10.4.2 The HadCRUT4 Index 478
10.4.3 Radiative Forcing and HadCRUT4 479
10.4.4 Summer Maximums and Winter Minimums in the United States 482

10.5 Projections 484
10.6 Summary 488
Concepts to Review 491
Problems 491
Further Reading 492

Index 493

Preface

Where does our energy come from? How do we use it? This book is an introduction to the fossil fuels and the alternatives, the electrical grid, energy use in buildings and transportation, agriculture, and climate-change policy for fossil fuels. Modeling is emphasized for understanding trends and for making projections. It is important to appreciate what models can tell us about how energy systems are evolving. Students should learn the distinction between physical laws that allow precise predictions and model projections that can be wrong. Models did not predict the shale gas revolution.

The material evolved from years of teaching classes to Caltech students at all levels. The students in the courses complete homework and laboratory exercises and they take tours of a natural gas power plant and a solar power station. At the end of the term, each student selects a topic to investigate and makes a presentation to the other students. After completing the course, students should be comfortable making energy calculations and developing models for energy systems. In addition, students should be able to critically assess articles, books, and films on energy. They should be familiar with the strengths and weaknesses of the arguments made by early writers like Stanley Jevons and King Hubbert. They should appreciate the potential of new energy technology. Finally, students should be able to recognize when government policies are working and when they are not.

Some homework problems involve locating energy databases online and downloading and analyzing the data. The online databases often provide their information in Excel format. Some students lack experience in Excel, and it is helpful for an instructor to demonstrate the functions that are used in the homework.

It is a pleasure to acknowledge people who have helped me in writing this book. Dale Yee took photographs and drew figures. Professor Joseph Shepherd at Caltech has been a collaborator in the classes. I have not found a question on combustion that he could not answer. Kent Potter at Caltech developed exercises and critiqued many of the ideas. Dr. Romeo Flores, formerly of the United States Geological Survey and the nation's foremost expert on coal, encouraged the work at the early stages. Jean Laherrere, formerly of the Total oil company, graciously provided production statistics. Jean taught many of us how to look at data. Several people read early drafts and made thoughtful suggestions, including the late Tom Tombrello, professor of physics at Caltech and erstwhile director of research at Schlumberger, Dr. Euan Mearns of Aberdeen, Scotland, founder of the blog Energy Matters, and

my brother John Rutledge, Vice-President and Water Resources Group Manager at Freese and Nichols, Inc., consulting civil engineers in Fort Worth, Texas. At the Cambridge University Press, I would like to thank Julie Lancashire, who has supported the project from the beginning, Nicola Chapman, who managed a challenging production process, and my wonderful editor, Heather Brolly.

Please let me know of errors by email at rutledge@caltech.edu.