

100% Clean, Renewable Energy and Storage for Everything

Transitioning the world from fossil fuels to 100 percent clean, renewable energy and storage for everything is seen internationally as necessary to address global warming, air pollution, and energy insecurity.

This textbook lays out the science, technology, economics, policy, and social aspects of transitioning from fossil fuels to 100 percent clean, renewable energy sources for all energy purposes. It discusses the electricity- and heat-generating technologies needed; the electricity, heat, cold, and hydrogen storage technologies needed; how to keep the electric power grid stable; and how to address non-energy sources of emissions. It also describes how to develop science-based clean, renewable energy plans for cities, states, and countries, as well as the history of the 100 Percent Movement, which evolved from a collaboration among scientists, cultural leaders, businesspeople, and community leaders.

The text includes numerous worked-out example problems and Transition Highlight boxes that illustrate real-world successes. Online resources consist of lecture slides, answers to the end-of-chapter questions, and a list of extra resources.

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‘Engineering professors of the world: Are you teaching a course on climate change, or planning one? If you are, this is the textbook you should be adopting. Civil, mechanical, electrical, materials, and chemical engineering aspects of the energy transition are exhaustively addressed. And this book has soul: today’s engineering student feels the need to do something about climate change, and this book empowers them.’

Anthony R. Ingraffea, Department of Civil and Environmental Engineering, Cornell University

‘Mark Jacobson’s new book - *100% Clean, Renewable Energy and Storage for Everything* - provides the most authoritative look yet at the future of energy beyond fossil fuels. The text is clearly written, authoritative, and thoroughly referenced. This will make a great textbook for courses on energy and climate change, but is also a must read for all of us interested in the transition to a renewable future.’

Robert W. Howarth, Department of Ecology and Evolutionary Biology, Cornell University

‘Professor Jacobson’s work on the possibilities for renewable energy have opened eyes around the globe. Where people once saw barriers, increasingly they see possibilities and openings, and this book consolidates that new understanding.’

Bill McKibben, Middlebury College

‘A great book! It shows why problems of air pollution and global warming can be solved by using renewable energies. It explains very clearly all aspects of a secure and climate-friendly full supply of renewable energies, using comprehensive scientific facts and clear practical examples. It should be used as a standard textbook in all energy economics lectures, worldwide! It is highly relevant not only for students but for all those interested in energy economics in these times of unsolved challenges caused by climate change and pollution. A book that everyone should read!’

Claudia Kemfert, German Institute for Economic Research

‘The world’s major crises need radical and comprehensive solutions, with 100% clean renewable energy systems at the core of any health, climate, peace, or prosperity plan. Mark Jacobson shows in a brilliant and scientifically profound way why such a worldwide transformation is necessary and how it can be realized. A powerful work that leaves no more excuses for political inaction.’

Hans-Josef, Former German Parliamentarian and founder of German solar tariffs

‘Mark Jacobson shines a bright light illuminating the path forward, painstakingly detailing - with numbers and facts - how we can decarbonize our energy infrastructure, take action on climate, create a cleaner environment and sustain a healthy, green economy. At a time when there is far too much doom-and-gloom over our prospects for averting climate catastrophe, read this book, take action, and be part of the battle to preserve a healthy, livable planet.’

Michael E. Mann, Penn State University



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To Dionna, Daniel, and Jessica
and all others who will inherit the
Earth and everything that is in it

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Frontmatter
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CONTENTS

Preface	page xiii		
1			
What Problems Are We Trying to Solve?	1		
1.1 The Air Pollution Tragedy	1		
1.1.1 Health Risks from Air Pollution	1		
1.1.2 Sources of Air Pollution	1		
1.1.3 How Transitioning the Energy Infrastructure Can Address the Air Pollution Tragedy	2		
1.2 Global Warming	2		
1.2.1 The Natural Greenhouse Effect	3		
1.2.2 Global Warming	3		
1.2.3 Anthropogenic Greenhouse Gases	4		
1.2.3.1 Carbon Dioxide, Methane, and Nitrous Oxide	4		
1.2.3.2 Ozone	5		
1.2.3.3 Halogens	5		
1.2.3.4 Lifetimes and Global Warming Potentials	6		
1.2.3.5 Carbon Dioxide Equivalent Emissions	8		
1.2.3.6 Anthropogenic Water Vapor	9		
1.2.2 Anthropogenic Absorbing Aerosol Particle Components	9		
1.2.3 Anthropogenic Heat Emissions	10		
1.2.4 The Urban Heat Island Effect	10		
1.2.5 Impacts of Global Warming	10		
1.3 Energy Insecurity	11		
1.3.1 Energy Insecurity due to Diminishing Availability of Fossil Fuels and Uranium	11		
1.3.2 Energy Insecurity due to Reliance on Centralized Power Plants and Oil Refineries	11		
1.3.3 Energy Insecurity due to Reliance on Energy from Outside a Country	12		
1.3.4 Energy Insecurity due to Fuels That Have Mining, Pollution, Waste, Meltdown, and/or Weapons Risk	13		
1.4 Summary	13		
Further Reading	13		
1.5 Problems and Exercises	14		
2			
Wind-Water-Solar (WWS) and Storage Solution	17		
2.1 WWS Electricity-Generating Technologies	18		
2.1.1 Onshore and Offshore Wind	18		
2.1.2 Wave	19		
2.1.3 Geothermal	20		
2.1.4 Hydroelectric	21		
2.1.5 Tidal and Ocean Currents	25		
2.1.6 Solar Photovoltaics	25		
2.1.7 Concentrated Solar Power	27		
2.2 WWS Transportation Technologies	28		
2.2.1 Battery-Electric Vehicles	28		
2.2.2 Hydrogen Fuel Cell Vehicles	29		
2.2.2.1 Mechanisms of Hydrogen Production	31		
2.2.2.2 Hydrogen Fuel Cells	32		
2.2.2.3 Is Platinum a Limitation If Hydrogen Fuel Cells Are Adopted on a Large Scale?	34		
2.2.3 Comparing Masses and Volumes among BE, HFC, and ICE Vehicles	34		
2.3 WWS Building Heating and Cooling Technologies	38		
2.3.1 District Heating and Cooling	38		
2.3.2 Rooftop Solar Water Heaters	39		
2.3.3 Heat Pumps	39		
2.4 WWS High-Temperature Industrial Heat Technologies	42		
2.4.1 Electric Arc Furnaces	42		
2.4.2 Induction Furnaces	43		
2.4.3 Electric Resistance Furnaces	44		
2.4.4 Dielectric Heaters	44		
2.4.5 Electron Beam Heaters	44		
2.4.6 Steam Production from Heat Pumps and CSP	45		
2.4.7 Steel Manufacturing	45		
2.4.7.1 Reducing Carbon Emissions with Hydrogen Direct Reduction	46		
2.4.7.2 Reducing Carbon Emissions with Molten Oxide Electrolysis	46		
2.4.8 Concrete Manufacturing	47		
2.4.8.1 A Type of Concrete That Emits No CO ₂	47		
2.4.8.2 Sequestering CO ₂ in Concrete	47		
2.4.8.3 Concrete Recycling	48		
2.5 WWS Electric Substitutes for Fossil-Fuel Appliances and Machines	48		
2.5.1 Electric Induction Cookers	48		
2.5.2 Electric Fireplaces	48		
2.5.3 Electric Leaf Blowers	49		
2.5.4 Electric Lawnmowers	49		
2.5.5 Other Appliances and Technologies	49		

2.6	Reducing Energy Use and Increasing Energy Efficiency	50	3.2.1	Air Pollution Increases and Only Modest Lifecycle CO ₂ e Decreases due to Carbon Capture	91
2.7	WWS Electricity Storage Technologies	51	3.2.2	Total CO ₂ e Emissions of Energy Technologies	92
2.7.1	Concentrated Solar Power with Storage	51	3.2.2.1	Opportunity Cost Emissions	93
2.7.2	Hydroelectric Power Dam Storage	53	3.2.2.2	Anthropogenic Heat Emissions	94
2.7.3	Pumped Hydropower Storage	53	3.2.2.3	Anthropogenic Water Vapor Emissions	98
2.7.4	Stationary Batteries	54	3.2.2.4	Leaks of CO ₂ Sequestered Underground	101
2.7.5	Flywheels	58	3.2.2.5	Emissions from Covering Land or Clearing Vegetation	102
2.7.6	Compressed Air Energy Storage	58	3.2.2.6	Comparison of Coal and Natural Gas with Carbon Capture with Other Energy Technologies	102
2.7.7	Gravitational Storage with Solid Masses	59	3.2.3	Carbon Capture Projects	103
2.8	WWS Heat, Cold, and Hydrogen Storage Technologies	59	3.3	Why Nuclear Power Represents an Opportunity Cost	109
2.8.1	Heat and Cold Storage in Water Tanks	59	3.3.1	Risks Affecting the Ability of Nuclear Power to Address Global Warming and Air Pollution	111
2.8.2	District Heating Systems	60	3.3.1.1	Delays between Planning and Operation and due to Refurbishing Reactors	112
2.8.3	Underground Thermal Energy Storage	61	3.3.1.2	Air Pollution and Global Warming Relevant Emissions from Nuclear	114
2.8.3.1	Borehole Thermal Energy Storage	61	3.3.1.3	Nuclear Costs	114
2.8.3.2	Pit Thermal Energy Storage	64	3.3.2	Risks Affecting the Ability of Nuclear Power to Address Energy and Environmental Security	115
2.8.3.3	Aquifer Thermal Energy Storage	65	3.3.2.1	Weapons Proliferation Risk	115
2.8.4	Passive Heating and Cooling in Buildings	67	3.3.2.2	Meltdown Risk	117
2.8.4.1	Thermal Mass	67	3.3.2.3	Radioactive Waste Risks	118
2.8.4.2	Ventilated Façades	68	3.3.2.4	Uranium Mining Health Risks and Land Degradation	118
2.8.4.3	Window Blinds	68	3.4	Why Not Biomass for Electricity or Heat?	120
2.8.4.4	Window Film	69	3.4.1	Biomass without Carbon Capture	120
2.8.4.5	Night Ventilation	69	3.4.2	Biomass with Carbon Capture	121
2.8.5	Cold Storage in Ice	69	3.5	Why Not Liquid Biofuels for Transportation?	122
2.8.6	Hydrogen Storage	69	3.6	Why Not Synthetic Direct Air Carbon Capture and Storage?	124
2.8.7	Stanford University 100 Percent Renewable Electricity, Heat, and Cold Energy System	70	3.6.1	Discovery of Chemical Removal of CO ₂ from the Air	125
2.8.8	Electrified Home with Battery Storage and Heat Pumps	71	3.6.2	Reaction of CO ₂ with Alkali and Alkaline Earth Metal Oxides and Hydroxides	127
2.9	Controlling Non-Energy Air Pollution and Climate-Relevant Emissions	77	3.6.3	Reaction of CO ₂ with Organic-Inorganic Sorbents Consisting of Amines	128
2.9.1	Open Biomass Burning and Waste Burning	77	3.6.4	Opportunity Cost of SDACCS/U	128
2.9.2	Methane from Agriculture and Waste	78	3.7	Why Not Geoengineering?	131
2.9.3	Halogen Emissions	79	3.8	Summary	133
2.9.4	Nitrous Oxide and Ammonia Emissions from Fertilizers	79	Further Reading	133	
2.10	Summary	80	3.9	Problems and Exercises	134
Further Reading	80		4		
2.11	Problems and Exercises	81	Electricity Basics	139	
3			4.1	Static Electricity, Lightning, and Wired Electricity	139
Why Some Technologies Are Not Included	85				
3.1	Why Not Use Natural Gas as a Bridge Fuel?	86			
3.1.1	Climate Impacts of Natural Gas versus Other Fossil Fuels	87			
3.1.2	Air Pollution Impacts of Natural Gas versus Coal and Renewables	88			
3.1.3	Using Natural Gas for Peaking or Load Following	89			
3.1.4	Land Required for Natural Gas Infrastructure	89			
3.2	Why Not Use Natural Gas or Coal with Carbon Capture?	91			

4.1.1	Static Electricity	139
4.1.2	Lightning	139
4.1.3	Wired Electricity	140
4.2	Voltage and Kirchoff's Laws	142
4.3	Power and Resistance	143
4.4	Resistors in Series and Parallel	144
4.5	Capacitors	145
4.6	Electromagnetism	147
4.7	AC Electricity and Inductors	148
4.8	Single-Phase and Three-Phase AC Electricity and Generators	151
4.9	Real versus Reactive Power	152
4.10	Transmission, Transformers, and the Battle of DC versus AC	153
4.11	Summary	155
	Further Reading	155
4.12	Problems and Exercises	156

5

Photovoltaics and Solar Radiation		159
5.1	Solar Photovoltaics	159
5.1.1	Conduction, Forbidden, and Filled Bands	159
5.1.2	Maximum Possible PV Cell Efficiency	161
5.1.3	Creating Electric Fields and Electricity in a PV Cell	161
5.1.4	Types of and Materials in PV Cells	163
5.1.5	PV Panels and Arrays	164
5.1.6	PV Panel Efficiencies	165
5.1.7	Correction of PV Output for Cell Temperature and Other Processes	167
5.1.7.1	Correction for Cell Temperature	167
5.1.7.2	Corrections for Additional Processes	168
5.1.8	Solar Zenith Angles and Fluxes and How They Vary with Tilted or Tracked Solar Panels	169
5.1.8.1	Solar Zenith Angle	170
5.1.8.2	Current Solar Flux to Horizontal Panels	172
5.1.8.3	Current Solar Flux to Tilted or Tracked Panels	173
5.1.8.4	Optimal Tilt Angles	174
5.1.8.5	Impacts of Tilting and Tracking versus Horizontal Panels	175
5.2	Solar Resources	175
5.3	Calculating Direct and Diffuse Fluxes of Solar Radiation	177
5.3.1	Radiation Spectra	177
5.3.2	Solar Radiation Reaching the Top of Earth's Atmosphere	180
5.3.3	Angles on a Sphere	182
5.3.4	Radiance and Irradiance	182
5.3.5	Optical Depth	183

5.3.6	The Radiative Transfer Equation	184
5.3.7	Phase Function and Asymmetry Parameter	185
5.3.8	Solutions to the Radiative Transfer Equation	187
5.4	Summary	189
	Further Reading	190
5.5	Problems and Exercises	190

6

Onshore and Offshore Wind Energy		193
6.1	Brief History of Windmills and Wind Turbines	193
6.2	Types of Wind Turbines	194
6.3	Wind Turbine Parts	195
6.4	Wind Turbine Mechanics	196
6.5	Wind Turbine Generators	198
6.6	Power in the Wind and Wind Turbine Power Output	200
6.6.1	Wind Turbine Power Curve	200
6.6.2	Rayleigh and Weibull Frequency Distributions	201
6.6.3	Power in the Wind	203
6.6.3.1	Impacts of the Variation of Day and Night Wind Speed with Altitude on Power in the Wind	203
6.6.3.2	Impacts of the Variation in Air Density and Pressure with Altitude on Power in the Wind	206
6.6.4	Betz Limit	208
6.6.5	Wind Turbine Energy Output and Capacity Factor	209
6.6.6	Factors Reducing Wind Turbine Gross Annual Energy Output	212
6.6.6.1	Transmission and Distribution Losses	212
6.6.6.2	Downtime Losses	216
6.6.6.3	Curtailement Losses	216
6.6.6.4	Array Losses due to Competition among Wind Turbines for Available Kinetic Energy	216
6.6.6.5	Overall Loss of Wind Energy Output	217
6.7	Wind Turbine Footprint and Spacing Areas	218
6.7.1	Defining Wind Farm Spacing Area	218
6.7.2	Estimates of Wind Farm Spacing Areas	221
6.7.3	Application of Spacing Area	221
6.8	Wind Physics and Resources	222
6.8.1	Forces Acting on the Air	223
6.8.1.1	Pressure Gradient Force	223
6.8.1.2	Apparent Coriolis Force	223
6.8.1.3	Friction Force	224
6.8.1.4	Apparent Centrifugal Force	224
6.8.2	How Winds Form	224
6.8.2.1	Geostrophic Wind	224
6.8.2.2	Surface Winds along Straight Isobars	225

6.8.2.3	Gradient Wind	225	7.5	Selecting a Mix of WWS Energy Generators to Meet Demand	259
6.8.2.4	Surface Winds along Curved Isobars	226	7.6	Estimating Avoided Energy, Air Pollution, and Climate Costs	272
6.8.3	Global Circulation of the Atmosphere	227	7.6.1	Avoided Energy Costs	272
6.8.3.1	Equatorial Low-Pressure Belt	227	7.6.2	Avoided Health Costs from Air Pollution	278
6.8.3.2	Winds Aloft in the Hadley Cells	229	7.6.3	Avoided Climate Change Damage Costs	294
6.8.3.3	Subtropical High-Pressure Belts	229	7.6.4	Summary of Avoided Energy, Health, and Climate Damage Costs	295
6.8.3.4	The Trade Winds	229	7.7	Summary	296
6.8.3.5	Subpolar Low-Pressure Belts	229		Further Reading	296
6.8.3.6	Westerly Winds Aloft at Midlatitudes	230	7.8	Problems and Exercises	297
6.8.3.7	Polar Easterlies	230			
6.8.4	Local Winds	230	8		
6.8.4.1	Sea/Land Breezes	230		Matching Electricity, Heat, Cold, and Hydrogen Demand Continuously with 100 Percent WWS Supply, Storage, and Demand Response	299
6.8.4.2	Gap Winds, Valley Breezes, and Mountain Breezes	232	8.1	Methods of Meeting Energy Demand Continuously	299
6.8.5	Global and Regional Wind Resources	232	8.1.1	Interconnecting Geographically Dispersed Generators	304
6.8.6	World Saturation Wind Power Potential	235	8.1.2	Determining Annual Average Demands and Sizing WWS Generation to Meet Them	306
6.9	Wind Turbine Impacts on Climate, Hurricanes, and Birds	238	8.1.3	Sizing Additional Generation, Storage, and Demand Response	308
6.9.1	Wind Turbine Impacts on Climate	238	8.1.3.1	Estimating Heat, Cold, Hydrogen, and Electricity Loads	308
6.9.2	Wind Turbine Impacts on Hurricanes	240	8.1.3.2	Estimating Loads Subject to Storage and Demand Response	311
6.9.3	Wind Turbine Impacts on Birds and Bats	244	8.1.3.3	Estimating Daily and Hourly Loads from Annual Loads	313
6.10	Summary	245	8.1.3.4	Sizing Storage and Additional Generation	315
	Further Reading	245	8.1.4	Solutions to Instantaneous Over and Under Generation	317
6.11	Problems and Exercises	246	8.1.4.1	Solutions When Instantaneous WWS Electricity or Heat Supply Exceeds Instantaneous Load	317
7			8.1.4.2	Solutions When Instantaneous Load Exceeds Instantaneous WWS Electricity or Heat Supply	317
	Steps in Developing 100 Percent All-Sector WWS and Storage Roadmaps	249	8.1.5	Measures Needed When Instantaneous Load Cannot Be Met with Instantaneous Supply or Storage	318
7.1	Projecting End-Use Energy Demand	249	8.1.5.1	Oversizing Wind, Water, and Sunlight Generation to Help Meet Demand	318
7.2	Transitioning Future Energy to WWS Technologies	250	8.1.5.2	Oversizing Storage to Help Meet Peaks in Demand	318
7.3	Calculating End-Use Energy Reductions due to a Transition	252	8.1.5.3	Increasing Transmission Nameplate Capacity to Help Meet Demand	318
7.3.1	Efficiency of Electricity and Electrolytic Hydrogen over Combustion for Transportation	252	8.1.5.4	Helping to Balance Demand with Vehicle-to-Grid	319
7.3.1.1	Efficiency of Battery-Electric Vehicles over Fossil-Fuel Vehicles	252			
7.3.1.2	Efficiency of Hydrogen Fuel Cell Vehicles over Fossil-Fuel Vehicles	253			
7.3.2	Efficiency of Electricity over Combustion for High-Temperature Heat	257			
7.3.3	Reducing Energy Use by Moving Heat with Electric Heat Pumps Instead of Creating Heat	257			
7.3.4	Eliminating Energy to Mine, Transport, and Process Fossil Fuels, Biofuels, Bioenergy, and Uranium	258			
7.3.5	Increasing Energy Efficiency and Reducing Energy Use beyond BAU	258			
7.3.6	Overall Reduction in End-Use Demand	258			
7.4	Performing a Resource Analysis	258			

8.1.5.5	Using Weather Forecasts to Plan for and Reduce Backup Requirements	319	9.1.10	Effects of New York State Roadmap on New York Policies	356
8.1.6	Ancillary Services: Load Following, Regulation, Reserves, and Voltage Control	320	9.1.11	How the California Roadmap Led to Transitioning Towns and Cities	360
8.1.6.1	Load Following	320	9.1.12	The <i>Late Show with David Letterman</i>	361
8.1.6.2	Regulation	320	9.1.13	Impact of the California Roadmap on California Passing a 100 Percent Law	366
8.1.6.3	Frequency Regulation	321	9.1.14	50-State and 139-Country Roadmaps, New York Climate March, and Paris Climate Conference	368
8.1.6.4	Spinning, Supplemental, and Replacement Reserves and Voltage Control	321	9.1.15	Impacts of Roadmaps on U.S Policies, Public Opinion, and International Business Commitments	369
8.2	Case Study of Meeting Demand with 100 Percent WWS	322	9.2	Timeline for a Transition	375
8.2.1	Previous Studies of Matching Demand with or near 100 Percent WWS	322	9.2.1	Timelines for Individual Technologies to Transition	375
8.2.2	Types of Models for Meeting Demand	324	9.2.2	How the Proposed Timeline May Impact Global CO ₂ Levels into the Future	377
8.2.2.1	Power Flow or Load Flow Models	324	9.2.3	How the Proposed Timeline May Impact Global Temperatures into the Future	377
8.2.2.2	Optimization Models	324	9.3	Obstacles to Overcome for a Transition	379
8.2.2.3	Trial-and-Error Simulation Models	325	9.3.1	Vested Interests in the Current Energy Infrastructure.	379
8.2.3	Matching Demand with WWS Supply, Storage, and Demand Response in 24 World Regions	326	9.3.2	Zoning Issues (NIMBYism)	380
8.3	Estimating Footprint and Spacing Areas of WWS Generators	337	9.3.3	Countries Engaged in Conflict	381
8.4	Estimating Jobs Created and Lost as Part of a Transition	338	9.3.4	Countries with Substantial Poverty	381
8.5	Summary	342	9.3.5	Transitioning Long-Distance Aircraft and Long-Distance Ships	382
8.6	Problems and Exercises	343	9.3.6	Competition among Solutions	382
9			9.4	Policy Mechanisms	382
Evolution of the 100 Percent Movement and Policies Needed for a WWS Solution	347		9.4.1	Policy Options for a Transition	382
9.1	Personal Journey to 100 Percent WWS	347	9.4.2	Policy Options by Sector	384
9.1.1	First Exposure to Severe Air Pollution	347	9.4.2.1	Energy Efficiency and Building Energy Measures	384
9.1.2	Hungry for Knowledge	348	9.4.2.2	Energy Supply Measures	384
9.1.3	Lessons for Life	349	9.4.2.3	Utility Planning and Incentive Structures	384
9.1.4	Building a Coupled Regional Air Pollution–Weather Prediction Computer Model	349	9.4.2.4	Transportation Measures	385
9.1.5	Expanding from the Regional to the Global Scale	350	9.4.2.5	Industrial-Sector Measures	385
9.1.6	Black Carbon, the Kyoto Protocol, and Wind versus Coal	351	9.5	Conclusion: Where Do We Go from Here?	385
9.1.7	Wind Energy Analysis and Comparing Impacts of Energy Technologies	352	Further Reading	386	
9.1.8	100 Percent Wind-Water-Solar and the TED Debate	353	9.6	Problems and Exercises	387
9.1.9	The Solutions Project	354	Glossary of Acronyms	389	
			Appendix	391	
			References	395	
			Index	408	

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PREFACE

The world is on a path to transition away from fossil fuels to clean, renewable energy in order to address environmental pollution, global warming, and energy insecurity. However, unless such a transition occurs quickly, efficiently, and most everywhere, the world risks substantially increased mortality, warming, and economic instability compared with today. This textbook lays out the scientific, technological, economic, political, and social aspects of how to transition the world rapidly to entirely clean, renewable energy for all purposes.

Evolving out of a course I teach at Stanford University, this book includes a description of how to transition the world's current combustion-based energy to 100 percent clean, renewable **wind, water, and solar (WWS)** electricity and heat for all energy purposes; how to store electricity, heat, cold, and hydrogen; how to keep the electric power grid stable; and how to address non-energy sources of emissions.

Whereas many textbooks teach about clean, renewable technologies, this one also teaches about what is needed to transition towns, cities, states, provinces, and countries entirely to clean renewables and storage. It also describes how to develop science-based clean, renewable energy plans for cities, states, and countries. These plans have been used to justify 100 percent renewable and zero emissions laws and policies, including the Green New Deal, in many countries, states, and cities. They have also been used to justify 100 percent renewable commitments by many international companies. The textbook further discusses the history of the 100 Percent Movement, which evolved from a collaboration among scientists, cultural leaders, businesspeople, and community leaders. Finally, it discusses progress to date in transitioning to 100 percent WWS and policies needed to complete the transition.

Motivation for Transitioning

This book is motivated by the fact that air pollution, global warming, and energy security are three of the most significant problems facing the world today. Most scientists recognize that solutions to these problems must be

implemented rapidly. Every year that indoor and outdoor air pollution continues, 4 to 9 million more children and adults die from it. If at least 80 percent of emissions that cause global warming are not eliminated by 2030, and if 100 percent are not eliminated by 2050 or sooner, globally averaged temperatures will likely rise at least 1.5 °C above those in the early 1900s. This will likely trigger more glacier and sea-ice melting, sea level rise, coastal flooding, severe storminess, wildfires, air pollution mortality, heat-related mortality, drought, famine, agricultural shifts, climate migration, species extinction, coral reef damage, and more. In addition, if limited-resource fossil fuels are not replaced with sustainable clean, renewable energy, energy prices will probably rise dramatically, causing economic, social, and political instability worldwide.

The solution to these problems is to transition world energy in all energy sectors to 100 percent WWS electricity and heat, combined with storage, and to address non-energy sources of emissions.

The main idea behind the solution comes from the fact that air pollution health and climate problems result from the same source: combustion. That is, combustion of fossil fuels, biofuels, bioenergy, and open biomass. To solve the problems, it is necessary to move away from combustion by electrifying and providing direct heat without combustion. For the electricity and heat to remain clean and available for millennia to come while not creating other risks, they need to originate from clean, renewable, and sustainable sources – namely, WWS.

WWS includes energy from **wind** (onshore wind, offshore wind, and airborne wind electricity), **water** (hydro, tidal and ocean current, wave, and geothermal electricity and geothermal heat), and **sunlight** (solar photovoltaic [PV] electricity, concentrated solar power [CSP] electricity and heat, and captured solar heat [solar thermal]). WWS needs to power **all energy sectors**, which means electricity, transportation, building heating/cooling, industry, agriculture/forestry/fishing, and the military. Whereas human-designed energy systems cause about 95 percent of **anthropogenic** (human-produced) air

pollution and 75 percent of anthropogenic greenhouse gas emissions, this book also discusses methods to address non-energy anthropogenic emissions that affect air pollution and climate. The book additionally describes technologies available for electricity, heat, cold, and hydrogen storage.

Many solutions to date that have focused on the climate problem have included some technologies that are less helpful than WWS technologies. This book describes such technologies. The reason they are less helpful is that they raise costs to consumers and society, slow solutions to pollution and warming due to their long planning-to-operation times, increase emissions relative to WWS sources, and/or create risks that WWS sources don't have. Given the limited time and funding to solve pollution, climate, and security problems, it is essential to focus on known, effective solutions. Money spent on less-useful options will permit more damage to occur.

Some technologies that are clean and renewable are not discussed here because it seems they will not be commercially available in the next decade. One example is a technology that takes advantage of salinity and temperature gradients in the ocean to generate electricity. If such a technology does come to fruition, it could be included as a WWS resource.

Why 100 percent clean, renewable energy and storage for everything? Why not 50 percent, 80 percent, or 99 percent. The first reason is that the health plus climate cost of every tonne of air pollution, down to the last tonne, is so enormous that it outweighs other uses of the money required to remove the pollution. More important, one more person should not die or become ill from air pollution. Species extinction, global-warming-driven wildfires, supercharged hurricanes, and smog should no longer occur. Gas wells, coal mines, oil pipelines, gas stations, coal-fired power plants, gas storage reservoirs, diesel cars, jet fuel airplanes, and bunker fuel ships should no longer be needed. Nuclear power plant meltdowns and nuclear waste pileups should no longer occur. We don't want to drink chemicals in our water due to oil, gas, coal, or uranium mining leaks. We don't want to see more wars over fossil fuels. We don't want any more oil spills devastating the oceans, lakes, or rivers. Blackouts due to reliance on centralized power plants should be a thing of the past. Plus, we want to eliminate high energy prices that arise from fuel shortages and the need to transport fossil fuels long distances.

Aside from the fact that it is technically and economically possible to transition everything to 100 percent clean,

renewable energy and storage, 99 percent is not an ambitious goal to shoot for. Did Magellan aspire to circumnavigate 99 percent of his way around the Earth? Did the Apollo 11 crew aspire to reach 99 percent of its way to the moon? No. One hundred percent is the goal because that may be the best society can do and may result in the cleanest air and most stable climate for future generations. Societies often strive for the best and safest.

Can society reach the goal of 100 percent? This book examines the science, engineering, economic, social, and political aspects of transitioning towns, cities, states, countries, businesses, and the world to 100 percent clean, renewable WWS energy and storage for everything. Such a transition will address air pollution, global warming, and energy security simultaneously. The book also examines ways to reduce major types of non-energy emissions. It concludes that a transition among all energy and non-energy sectors worldwide is technically and economically possible. The main obstacles are social and political.

Intended Audience, Level, and Scope

This book is written to be accessible to everyone concerned with renewable energy and storage, including those studying Renewable Energy, Sustainability, Environmental Sciences and Engineering, Earth Sciences, Climate Sciences, Atmospheric Sciences, Electrical Engineering, Mechanical Engineering, Geography, Health Sciences, Economics, Business, and Policy departments as well as researchers, professionals, policymakers, advocates, and interested readers in many areas.

The book assumes no prior knowledge of, yet provides, needed information about, energy systems, electromagnetism, thermodynamics, dynamical meteorology, radiation transfer, mechanical engineering, aerodynamics, economics, weather, climate, and air pollution. Readers will therefore be able to understand the operations of the following: wind turbines, solar photovoltaics, concentrated solar power systems, hydropower systems, pumped hydropower storage systems, batteries, flywheels, gravitational mass electricity storage, underground thermal energy storage systems, thermal mass storage in buildings, generators, hydrogen fuel cells, heat pumps, electric vehicles, hydrogen fuel cell vehicles, arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, and transmission/distribution systems.

The book also gives information about how to determine wind and solar resources, the maximum wind and solar potentials of the world, the impacts of wind turbines

on global temperatures and hurricanes, the effects of tilting and tracking solar panels on electricity output, the efficiencies of wind turbines and solar photovoltaics, and the rates at which different electricity storage technologies can ramp up.

By the end of the book, readers will understand why all the technologies covered throughout the book will help to solve the air pollution, climate, and energy security problems we face and why other technologies are not so useful.

Readers will be able to calculate the private (business) and economic (social) costs of energy technologies and of energy systems. They will understand the methods of matching electricity, heat, cold, and hydrogen demand with clean, renewable supply and storage over time at low cost. Finally, they will understand the origin of the 100 percent clean, renewable energy movement, the progress made to date in transitioning the world to 100 percent, and the policies needed to complete the transition.

Structure

The book is structured in the order that I teach the material in a course. It starts by defining the air pollution, global warming, and energy insecurity problems we seek to solve (Chapter 1). Chapter 2 discusses WWS electricity- and heat-generating technologies; transportation technologies; building heating and cooling technologies; high-temperature industrial heat technologies; and appliances and machines needed for a transition. It further discusses energy efficiency measures, electricity storage, heat and cold storage, and hydrogen storage. Finally, it discusses methods of addressing non-energy sources of greenhouse gas and aerosol particle pollution. Chapter 3 goes into depth about why we don't need natural gas as a bridge fuel, fossil fuels with carbon capture, nuclear power, biomass (with or without carbon capture), biofuels, synthetic direct air capture, or geoengineering.

Because a 100 percent WWS world is mostly electrified, Chapter 4 focuses on electricity basics. Because solar photovoltaics (PV) and wind power will likely comprise the largest share of energy generation in a WWS world, Chapter 5 discusses solar PV and solar radiation, and Chapter 6 discusses onshore and offshore wind. Chapter 7 moves on to discuss steps in developing a 100 percent WWS roadmap for a country, state, or city. Chapter 8 explains how to match power demand with 100 percent WWS supply plus storage.

Finally, Chapter 9 outlines my personal journey toward 100 percent; the 100 Percent Movement that has arisen around the WWS roadmaps; laws and commitments that have been implemented to date due to them; and the policies needed in the future to finally solve the problems of air pollution, global warming, and energy in security.

Pedagogical Features

The book is supported by a comprehensive set of pedagogical features:

- A short introduction to each chapter and an end-of-chapter Summary to clarify each chapter's objectives and to ensure understanding of the material discussed
- Highlighted key terms and clear definitions throughout the book
- Numerical examples in each chapter that explain how to apply important equations
- Abundant tables, diagrams, and photographs that illustrate important and interesting aspects of the field
- Problems and Exercises in the Further Resources section that consolidate and extend student understanding
- A list of Recommended Readings in the Further Resources section at the end of each chapter
- A Glossary of Acronyms and a list of conversion constants and units in the Appendices

In order to assist with teaching information in the textbook, teaching materials have been developed to accompany the course and are available online. Such materials include a teaching guide, a model syllabus, lecture slides for each chapter, a solution manual, and a test bank.

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