

Table of Contents

For

Jacobson, M.Z., *Still No Miracles Needed: How Today's Technology Can Save Our Climate and Clean Our Air*, Cambridge University Press, Cambridge, 2026

<https://web.stanford.edu/group/efmh/jacobson/WWStilINMN/StilINMN.html>

June 12, 2025

Contact: Jacobson@stanford.edu

Table of Contents

Preface

Chapter 1

What Problems Are We Trying to Solve?

1.1 The Air Pollution Tragedy

1.2. Global Warming

1.2.1. The Natural Greenhouse Effect

1.2.2. Global Warming

1.2.3. Causes of Global Warming

1.2.3.1. Anthropogenic Greenhouse Gas Emissions

1.2.3.2. Anthropogenic Warming Particle Emissions

1.2.3.3. Anthropogenic Heat Emissions

1.2.3.4. The Urban Heat Island Effect

1.2.3.5. Cooling Particle Emissions

1.2.4. Impacts of Global Warming

1.2.5. Strategies for Reducing Air Pollution and Global Warming Together

1.3. Energy Insecurity

1.3.1. Energy Insecurity due to Diminishing Availability of Fossil Fuels and Uranium

1.3.2. Energy Insecurity due to Reliance on Centralized Power Plants and Refineries

1.3.3. Energy Insecurity due to Reliance on Fuel Supplies Subject to Human Intervention

1.3.4. Energy Insecurity due to Fuels That Have Mining, Pollution, or Catastrophic Risk

Chapter 2

WWS Solutions For Electricity Generation

2.1. Components of a WWS System

2.2. Onshore and Offshore Wind Electricity

2.3. Wave Electricity

2.4. Geothermal Electricity and Heat

2.5. Hydroelectricity

2.6. Tidal and Ocean Current Electricity

2.7. Solar Photovoltaic Electricity

2.8. Concentrated Solar Power

Chapter 3

WWS Solutions For Electricity Storage

- 3.1. Hydroelectricity Reservoir Storage**
- 3.2. Pumped Hydropower Storage**
- 3.3. Stationary Batteries**
- 3.4. Concentrated Solar Power With Storage**
- 3.5. Flywheels**
- 3.6. Compressed-Air Energy Storage**
- 3.7. Gravitational Storage With Solid Masses**
- 3.8 Green-hydrogen storage**

Chapter 4

WWS Solutions For Transportation

- 4.1. Battery-Electric Vehicles**
 - 4.1.1. Efficiency of Battery-Electric Vehicles**
 - 4.1.2. History of Battery-Electric Transportation**
 - 4.1.2.1. Ground Vehicles*
 - 4.1.2.2. Marine Vessels*
 - 4.1.2.3. Aircraft*
 - 4.1.3. Lithium and Neodymium Mining**
 - 4.1.4. Battery Fires**
- 4.2. Hydrogen-Fuel-Cell-Electric Vehicles**
 - 4.2.1. Green Hydrogen Production**
 - 4.2.2. Hydrogen Storage**
 - 4.2.3. Hydrogen Fuel Cells**
 - 4.2.4. History of Hydrogen-Fuel-Cell-Electric Vehicles**
 - 4.2.4.1. Ground Vehicles*
 - 4.2.4.2. Marine Vessels*
 - 4.2.4.3. Aircraft*
 - 4.2.5. Platinum for Hydrogen-Fuel-Cell-Electric Vehicles**

Chapter 5

WWS Solutions For Buildings

- 5.1. District Heating and Cooling**
 - 5.1.1. Hot and Cold Storage in Water Tanks**
 - 5.1.2. Cold Storage in Ice**
 - 5.1.3. Underground Heat and Cold Storage**
 - 5.1.3.1. Borehole-Thermal-Energy Storage*
 - 5.1.3.2. Pit-Thermal-Energy Storage*
 - 5.1.3.3. Aquifer-Thermal-Energy Storage*
 - 5.1.4. Stanford University 100 Percent Renewable Electricity, Heat, and Cold Storage System**
- 5.2. Individual Heating and Cooling Units in Buildings**
 - 5.2.1. Rooftop Solar Water Heaters**
 - 5.2.2. Heat Pumps**
 - 5.2.3. Passive Heating and Cooling in Buildings**
 - 5.2.3.1. Insulation*
 - 5.2.3.2. Thermal-Mass Materials*
 - 5.2.3.3. Ventilated Façades*

5.2.3.4. *Window Blinds, Awnings, and Films*

5.2.3.5. *Night Ventilation*

5.3. WWS Electric Appliances and Machines

5.3.1. Electric-Induction Cooker

5.3.2. Electric Fireplaces

5.3.3. Electric Leaf blower

5.3.4. Electric Lawnmower

5.3.5. Other Appliances and Technologies

5.4. Increasing Energy Efficiency and Reducing Energy Use

5.5. All-Electric Home

5.6. Microgrids

Chapter 6

WWS Solutions For Industry

6.1. Current Energy Sources For Industry

6.2. Arc Furnaces

6.3. Induction Furnaces

6.4. Resistance Furnaces, Kilns, and Boilers

6.5. Electric Crackers

6.6. Electron-Beam Heaters

6.7. Dielectric Heaters

6.8. Electric Heat Pumps and Solar Heaters

6.9. Firebrick Storage

6.10. Steel Manufacturing

6.10.1. Reducing Carbon Emissions with Hydrogen Direct Reduction

6.10.2. Reducing Carbon Emissions with Lasers

6.10.3. Reducing Carbon Emissions with Molten Oxide Electrolysis

6.11. Concrete Manufacturing

6.10.1. Basalt-Based Concrete

6.11.2. Geopolymer Concrete

6.11.3. Ferrock

6.11.4. Concrete Recycling

6.11.5. Sequestering Carbon Dioxide in Concrete

6.12. Silicon Purification

6.13. Ammonia Manufacturing

Chapter 7

Solutions for NonEnergy Emissions

7.1. Open Biomass Burning and Waste Burning

7.2. Methane from Agriculture and Waste

7.3. Halogens

7.4. Nitrous Oxide

Chapter 8

What Doesn't Help

8.1. Brief History of Fossil Fuels

8.1.1. Wood and Coal Burning Before the Industrial Revolution

- 8.1.2. The Industrial Revolution and the Growth of Coal
- 8.1.3. The History of Fossil Gas
- 8.1.4. Discovery of Oil
- 8.2. Comparison of Energy Technologies**
 - 8.2.1. Lifecycle Emissions
 - 8.2.2. Opportunity-Cost Emissions
 - 8.2.3. Anthropogenic-Heat Emissions
 - 8.2.4. Anthropogenic-Water-Vapor Emissions
 - 8.2.5. Leaks of Carbon Dioxide Sequestered Underground
 - 8.2.6. Emissions from Covering Land or Clearing Vegetation
 - 8.2.7. Total CO₂-Equivalent Emissions
- 8.3. Why Not Fossil Gas as a Bridge Fuel?**
 - 8.3.1. Climate Impacts of Fossil Gas versus Coal
 - 8.3.2. Air Pollution Impacts of Fossil Gas versus Coal and Renewables
 - 8.3.3. Fossil Gas in Not Needed for Peaking or Load Following
 - 8.3.4. Land Required for Fossil Gas Infrastructure
- 8.4. Why Not Carbon Capture With Fossil Gas and Coal?**
 - 8.4.1. Air-Pollution and Climate Impacts of Fossil Sources With Carbon Capture
 - 8.4.2. Carbon Capture Projects
 - 8.4.2.1. *Boundary Dam Project*
 - 8.4.2.2. *Petra Nova Project*
 - 8.4.2.3. *Gorgon Project*
- 8.5. Why Not Gray, Blue, or Brown Hydrogen?**
 - 8.5.1. Steam Methane Reforming
 - 8.5.2. Autothermal Reforming
 - 8.5.3. Methane Pyrolysis
 - 8.5.4. Coal Gasification
- 8.6. Why Not Synthetic Direct Air Carbon Capture?**
 - 8.6.1. How Does Air Capture Remove Carbon Dioxide from the Air
 - 8.6.2. Opportunity Cost of Direct Air Capture
- 8.7. Why Not Nonhydrogen Electro-Fuels?**
- 8.8. Why Not Biomass or Biogas for Electricity or Heat?**
 - 8.8.1. Biomass and Biogas Combustion Without Carbon Capture
 - 8.8.2. Biomass and Biogas Combustion with Carbon Capture
- 8.9. Why Not Liquid Biofuels for Transportation?**
 - 8.9.1. Ethanol Refined Without Carbon Capture
 - 8.9.2. Ethanol Refined With Carbon Capture
- 8.10. Why Not Nuclear Electricity?**
 - 8.10.1. Risks Affecting Nuclear's Ability to Address Global Warming and Air Pollution**
 - 8.10.1.1. *Delays Between Planning and Operation and due to Refurbishing Reactors*
 - 8.10.1.2. *Air Pollution and Global Warming Relevant Emissions from Nuclear*
 - 8.10.1.3. *Nuclear Costs*
 - 8.10.2. Risks Affecting Nuclear's Ability to Address Environmental Security**
 - 8.10.2.1. *Weapons Proliferation Risk*
 - 8.10.2.2. *Meltdown Risk*
 - 8.10.2.3. *Radioactive Waste Risks*

8.11. Why Not Geoengineering?

Chapter 9 Electricity Grids

- 9.1. Types of Electricity
- 9.2. Voltage
- 9.3. Power
- 9.4. Electromagnetism and AC Electricity
- 9.5. Capacitors and Inductors
- 9.6. The Battle of DC Versus AC Electricity
 - 9.6.1. Thomas Edison and the DC Grid
 - 9.6.2. Nikola Tesla
 - 9.6.3. Transformers
 - 9.6.4. George Westinghouse and the AC Electricity Grid
 - 9.6.5. The Fight Begins
 - 9.6.6. AC Rises Victoriously
- 9.7. Transmission and Distribution Losses

Chapter 10 Photovoltaics and Solar Radiation

- 10.1. Solar Photovoltaics
 - 10.1.1. Brief History of the Solar PV Cell
 - 10.1.2. How Silicon PV Cells Work
 - 10.1.3. Maximum Possible PV Cell Efficiency
 - 10.1.4. Creating Electricity in a PV Cell
 - 10.1.5. Types of PV Cells and Their Materials
 - 10.1.6. PV Panels and Arrays
 - 10.1.7. Utility versus Distributed PV
- 10.2. Solar Resources and How to Use Them Efficiently
 - 10.2.1. Solar Resources
 - 10.2.2. Sunlight Reaching Solar Panels
 - 10.2.3. Solar Panel Tilting and Tracking
 - 10.2.3.1. Optimal Tilt Angles
 - 10.2.3.2. Impacts of Tilting and Tracking Versus Horizontal Panels on Solar Output
- 10.2. Solar Resources

Chapter 11 Onshore and Offshore Wind Energy

- 11.1. Brief History of Windmills and Wind Turbines
- 11.2. Types of Wind Turbines
- 11.3. Wind Turbine Parts
- 11.4. Wind Turbine Mechanics
- 11.5. Wind Turbine Generators
- 11.6. Power in the Wind and Wind Turbine Power Output
 - 11.6.1. Wind Speed Frequency Distributions
 - 11.6.2. Betz Limit

- 11.6.3. Wind Turbine Power Curve
- 11.6.4. Wind Turbine Electricity Output and Capacity Factor
- 11.6.5. Factors Reducing Wind Turbine Gross Annual Electricity Output
 - 11.6.5.1. *Transmission and Distribution Losses*
 - 11.6.5.2. *Downtime Losses*
 - 11.6.5.3. *Curtailement Losses*
 - 11.6.5.4. *Array Losses*
 - 11.6.5.5. *Overall Loss*

11.7. Wind Turbine Footprint and Spacing Areas

- 11.7.1. Footprint Area
- 11.7.2. Spacing Area

11.8. Global and Land Wind Resources

11.9. Wind Turbine Impacts on Climate, Hurricanes, and Birds

- 11.9.1. Wind Turbine Impacts on Climate
- 11.9.2. Wind Turbine Impacts on Hurricanes
- 11.9.3. Wind Turbine Impacts on Birds and Bats

Chapter 12

Steps in Developing 100 Percent WWS Roadmaps

12.1. Projecting End-Use Energy Demand

12.2. Powering Future Energy With WWS

12.3. Changes in Energy Needed Upon a Transition to WWS

12.3.1. Efficiency of Electricity and Electrolytic Hydrogen over Combustion for Transportation

12.3.1.1. *Efficiency of Battery-Electric Vehicles over Fossil-Fuel Vehicles*

12.3.1.2. *Efficiency of Hydrogen-Fuel-Cell-Electric Vehicles over Fossil-Fuel Vehicles*

12.3.2. Efficiency of Electric Heat Pumps for Buildings

12.3.3. Efficiency of Electricity over Combustion for High-Temperature Heat

12.3.4. Eliminating Energy to Mine, Transport, and Process Conventional Fuels

12.3.5. Increasing Energy Efficiency and Reducing Energy Use

12.3.6. Overall Reduction in End-Use Demand

12.4. Performing a Resource Analysis

12.5. Selecting a Mix of WWS Generators to Meet Demand

12.6. Estimating Avoided Energy, Air Pollution, and Climate Costs

12.6.1. Private Energy Cost

12.6.2. Avoided Health Costs from Air Pollution

12.6.3. Avoided Climate Change Damage Costs

12.6.4. Summary of Avoided Energy, Health, and Climate Damage Costs

Chapter 13

Keeping the Grid Stable With 100 Percent WWS

13.1. Variable versus Intermittent Resources

13.1.1. Risk of Grid Failure with the Current Grid

13.1.2. Countries, States, and Regions with 100 Percent WWS and a Stable Grid

13.1.2.1. *Countries and Regions with 100 Percent WWS grids*

13.1.2.2. *US States with Close to 100 Percent WWS grids*

13.1.2.3. *100 Percent WWS in California*

13.1.3. Effects of Climate Change on the Reliability of Conventional and WWS Resources

13.2. Methods of Meeting Energy Demand Continuously

- 13.2.1. Steps in Creating an Infrastructure for Providing All Energy with WWS**
- 13.2.2. Steps for Matching Demand with Supply, Storage, and Demand Response**
- 13.2.3. Specify WWS Generator Requirements to Meet Continuous Demand**
- 13.2.4. Specify Storage and Demand Response Requirements to Meet Continuous Demand**
- 13.2.5. Procedures for Matching Demand with Supply in Cases of Over- and Under-Generation**
 - 13.2.5.1. Steps When Instantaneous WWS Electricity or Heat Supply Exceeds Instantaneous Demand*
 - 13.2.5.2. Steps When Instantaneous Demand Exceeds Instantaneous WWS Electricity or Heat Supply*
- 13.2.6. Measures Needed When Instantaneous Demand Cannot Be Met with Current Supply or Storage**
 - 13.2.6.1. Oversizing Wind, Water, and Solar Generation to Help Meet Demand*
 - 13.2.6.2. Oversizing Storage to Help Meet Peaks in Demand*
 - 13.2.6.3. Increasing Transmission Nameplate Capacity to Help Meet Demand*
 - 13.2.6.4. Helping to Balance Demand with Vehicle-to-Grid*
 - 13.2.6.5. Using Weather Forecasts to Plan for and Reduce Backup Requirements*
- 13.2.7. Ancillary Services: Load Following, Regulation, Reserves, and Voltage Control**
 - 13.2.7.1. Load Following*
 - 13.2.7.2. Regulation*
 - 13.2.7.3. Frequency Regulation*
 - 13.2.7.4. Spinning, Supplemental, and Replacement Reserves and Voltage Control*
- 13.3. Studies on Meeting Demand with 100 Percent WWS**
 - 13.3.1. Previous Studies of Matching Demand with or near 100 Percent WWS**
 - 13.3.2. Matching Demand with WWS Supply, Storage, and Demand Response: Case Study**
- 13.4. Estimating Footprint and Spacing Areas of WWS Generators**
- 13.5. Job Creation and Loss Due to a Transition**

Chapter 14

Timeline and Policies Needed to Transition

- 14.1. Transition Timeline**
 - 14.1.1. Transition Timelines for Individual Technologies**
 - 14.1.2. How the Proposed Timeline May Impact Carbon Dioxide Levels and Temperatures**
- 14.2. Obstacles to Overcome for a Transition**
 - 14.2.1. Vested Interests in the Current Energy Infrastructure**
 - 14.2.2. Zoning Issues (NIMBYism)**
 - 14.2.3. Countries Engaged in Conflict**
 - 14.2.4. Countries with Substantial Poverty**
 - 14.2.5. Transitioning Long-Distance Aircraft and Long-Distance Ships**
 - 14.2.6. Competition among Solutions**
 - 14.2.7. Slow Progress**
- 14.3. What Can Individuals Do?**
 - 14.3.1. New Home Construction**
 - 14.3.2. Home Retrofits**
 - 14.3.3. Renting**
 - 14.3.4. Transportation**
 - 14.3.5. Consumer Choices**
- 14.4. Policies**
 - 14.4.1. Policy Options for a Transition**
 - 14.4.2. Policy Options by Sector**
 - 14.4.2.1. Energy Efficiency and Building-Energy Measures*
 - 14.4.2.2. Energy-Supply Measures*
 - 14.4.2.3. Utility Planning and Incentive Structures*

- 14.4.2.4. Transportation Measures*
- 14.4.2.5. Industrial Sector Measures*
- 14.4.3. US Inflation Reduction Act**

Chapter 15

My Journey

- 15.1. First Exposure to Severe Air Pollution**
- 15.2. Hungry for Knowledge**
- 15.3. Lessons for Life**
- 15.4. Modeling Regional Pollution and the Weather**
- 15.5. Modeling Global Pollution and Climate**
- 15.6. Black Carbon, the Kyoto Protocol, and Wind versus Coal**
- 15.7. Analyzing Wind and Other WWS Technologies**
- 15.8. 100 Percent Wind-Water-Solar and the TED Debate**
- 15.9. The Solutions Project**
- 15.10. Effects of New York State Roadmap on Policy**
- 15.11. Effect of California Roadmap on City Policies**
- 15.12. The Letterman Show**
- 15.13. Impact of California Roadmap on California Law**
- 15.14. State and Country Roadmaps and Paris Conference**
- 15.15. Impacts of Roadmaps on US and Business Policies**
- 15.16. Climate Lawsuits**
- 15.17. Conclusion: Where Do We Go from Here?**