

*Nicola Armaroli and Vincenzo Balzani*

# **Energy for a Sustainable World**

From the Oil Age to a Sun-Powered Future



WILEY-VCH Verlag GmbH & Co. KGaA



*Nicola Armaroli and  
Vincenzo Balzani*

**Energy for a  
Sustainable World**

## ***Related Titles***

Olah, G. A., Goeppert, A., Prakash, G. K. S.

### **Beyond Oil and Gas: The Methanol Economy**

350 pages

2010

Softcover

ISBN: 978-3-527-32422-4

Paul, B.

### **Future Energy**

**How the New Oil Industry Will Change People, Politics and Portfolios**

approx. 240 pages

2007

Hardcover

ISBN: 978-0-470-09642-0

Cocks, F. H.

### **Energy Demand and Climate Change**

**Issues and Resolutions**

267 pages with 30 figures

2009

Softcover

ISBN: 978-3-527-32446-0

Kruger, P.

### **Alternative Energy Resources**

**The Quest for Sustainable Energy**

272 pages

2006

Hardcover

ISBN: 978-0-471-77208-8

Wengenmayr, R., Bührke, T. (eds.)

### **Renewable Energy**

**Sustainable Energy Concepts for the Future**

120 pages

2008

Hardcover

ISBN: 978-3-527-40804-7

Romm, J. J.

### **Der Wasserstoff-Boom**

**Wunsch und Wirklichkeit beim Wettlauf um den Klimaschutz**

219 pages with 3 figures

2006

Softcover

ISBN: 978-3-527-31570-3

Bührke, T., Wengenmayr, R. (eds.)

### **Erneuerbare Energie**

**Alternative Energiekonzepte für die Zukunft**

108 pages

2007

Hardcover

ISBN: 978-3-527-40727-9

*Nicola Armaroli and Vincenzo Balzani*

# **Energy for a Sustainable World**

From the Oil Age to a Sun-Powered Future



WILEY-VCH Verlag GmbH & Co. KGaA

## The Authors

### **Dr. Nicola Armaroli**

Ist. ISOF/CNR  
Molecular Photoscience Group  
Via Gobetti 101  
40129 Bologna  
Italy

### **Prof. Vincenzo Balzani**

Dept. of Chemistry G. Ciamician  
University of Bologna  
Via Selmi 2  
40126 Bologna  
Italy

## Cover idea:

**Fausto Puntoriero**

■ All books published by **Wiley-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

**Library of Congress Card No.:** applied for

## **British Library Cataloguing-in-Publication Data**

A catalogue record for this book is available from the British Library.

## **Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2011 Wiley-VCH Verlag & Co. KGaA,  
Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

**Cover** Formgeber, Eppelheim

**Typesetting** Toppan Best-set Premedia Limited, Hong Kong

**Printing and Binding** betz-druck GmbH, Darmstadt

Printed in the Federal Republic of Germany  
Printed on acid-free paper

**ISBN:** 978-3-527-32540-5

*To Claudia and Carla*





## Contents

<b>Preface</b>	XV
<b>Acknowledgments</b>	XVII
<b>Notation</b>	XIX

### Part One Living on Spaceship Earth 1

<b>1</b>	<b>The Energy Challenge</b>	3
1.1	Our Spaceship Earth	3
1.2	An Unsustainable Growth in an Unequal World	5
1.2.1	Population Growth and Carrying Capacity	5
1.2.2	Economic Growth and Ecologic Degradation	6
1.2.3	Inequalities	6
1.3	Energy and Climate Crisis	8
1.4	Dealing with Change	8
1.5	Unavoidable Questions	9
<b>2</b>	<b>Concepts and Misconcepts</b>	11
2.1	The Elusive Definition of Energy	11
2.2	A Taste of Basic Principles	12
2.3	Converting Primary Energy into Useful Energy	13
2.4	It Takes Energy to Make Energy: the EROI	14
2.5	Embodied Energy	14
2.6	Energy Units and Conversions	16
2.7	The Immense Energy and Power Scales	16
2.8	Some Energy Key Parameters	17
2.9	Energy Pervasiveness Versus Energy Illiteracy	19
2.10	Key Numbers: an Abacus for Energy Literacy	20
<b>3</b>	<b>Energy in History</b>	25
3.1	<i>Historia Magistra Vitae</i>	25
3.2	Animal Power	26
3.3	Human Slaves and Energy Slaves	28

- 3.4 Waterwheels and Windwheels 28
- 3.5 From Wood to Coal 30
- 3.6 Steam-Powered Machines 31
- 3.7 Road Vehicles 32
- 3.8 Aircraft 33
  - 3.8.1 Conventional Engines 33
  - 3.8.2 Jet Engines 34
- 3.9 Electricity 35
  - 3.9.1 Early Development 35
  - 3.9.2 From Wayfarers to ICT 35

## **Part Two Fossil Fuels 39**

- 4 Oil 41**
  - 4.1 What is Oil 41
  - 4.2 Oil History, Exploration, Drilling, Production 42
    - 4.2.1 History 42
    - 4.2.2 Exploration 43
    - 4.2.3 Drilling 43
    - 4.2.4 Production 45
  - 4.3 Oil Transportation 47
    - 4.3.1 Pipelines 47
    - 4.3.2 Tankers 48
  - 4.4 Oil Refining 49
  - 4.5 Oil Storage 50
  - 4.6 Unconventional Oil 51
  - 4.7 Petrochemicals 53
  - 4.8 Oil as a Fuel 54
    - 4.8.1 World Picture 54
    - 4.8.2 US and Developed Countries 55
    - 4.8.3 China and India 56
  - 4.9 America's Addiction to Oil 57
  - 4.10 Oil Price 61
  - 4.11 Oil Peak and Reserves 63
    - 4.11.1 A Non-renewable Resource 63
    - 4.11.2 Oil Reserves 63
    - 4.11.3 Oil Peak 64
- 5 Natural Gas 69**
  - 5.1 What is Natural Gas and Where It Comes From 69
  - 5.2 Gas Properties and Definitions 70
  - 5.3 Brief Historical Notes on Gas Exploitation 71
  - 5.4 Gas Production, Consumption, and Reserves 71
  - 5.5 Liquefied Natural Gas (LNG) 73
  - 5.6 Natural Gas Processing 75

5.7	Transport, Storage, and Distribution	76
5.7.1	Transport	76
5.7.2	Storage	78
5.7.3	Distribution	78
5.8	Gas Uses: Energy and Feedstock	79
5.8.1	Energy Use	79
5.8.2	Natural Gas as a Feedstock	80
5.9	Unconventional Gas	81
<b>6</b>	<b>Coal</b>	<b>85</b>
6.1	What is Coal	85
6.2	Coal Extraction	86
6.3	Coal Transportation and Industrial Uses	87
6.4	Coal Gasification	88
6.5	Coal Production, Consumption, and Reserves	89
6.6	Carbon Capture and Sequestration (CCS)	90
6.7	Integrated Gasification Combined Cycle (IGCC)	93
<b>7</b>	<b>Fossil Legacy</b>	<b>97</b>
7.1	The Energy Dark Sides	97
7.1.1	Inequalities and Externalities	97
7.1.2	Monetizing Costs	98
7.1.3	Indirect Effects	98
7.2	Alteration of the Carbon Cycle by Fossil Fuel Combustion	99
7.2.1	Carbon Reservoirs and Fluxes	99
7.2.2	CO <sub>2</sub> Rise and Its Measurement	100
7.2.3	The Greenhouse Effect	101
7.3	Anthropogenic Climate Change	102
7.3.1	The Path to Present Understanding	102
7.3.2	Melting of Ice Sheets	103
7.3.3	Interference with Ocean Currents	104
7.3.4	Ocean Acidification	104
7.3.5	Permafrost Melting	105
7.3.6	Effects on Weather and Ecosystems	106
7.4	Air Pollution and Global Warming	106
7.4.1	Globalizing Smog	106
7.4.2	Aerosols and Black Carbon	107
7.4.3	Ozone, Ozone Depleting Substances and N <sub>2</sub> O	108
7.4.4	A Complicated Picture	108
7.5	Counterbalancing our Climate Influence	109
7.6	Putting a Limit to CO <sub>2</sub>	111
7.6.1	Regulatory Efforts to Curb Greenhouse Emissions	111
7.6.2	ppm or Teratons?	113
7.7	Air Pollution and Human Health	114
7.7.1	A Complex Atmospheric Mix	114

7.7.2	NO <sub>x</sub>	115
7.7.3	Ozone	115
7.7.4	Particulate Matter	116
7.7.5	Carbon Monoxide (CO)	117
7.7.6	Sulfur Dioxide (SO <sub>2</sub> ) and Acidic Precipitations	117
7.7.7	Heavy Metals	118
7.8	Land and Water Degradation	119
7.8.1	Oil Spills	119
7.8.2	Coal Combustion Residues (CCRs)	120
7.9	So, What?	122

### **Part Three Nuclear Energy 123**

<b>8</b>	<b>Nuclear Energy</b>	<b>125</b>
8.1	Principles of Nuclear Fission and Fusion	125
8.1.1	Radioactivity, Mass and Energy	125
8.1.2	Structure of Matter	126
8.1.3	Nuclear Fission	128
8.1.4	Controlled and Uncontrolled Chain Fission Reactions	129
8.1.5	Nuclear Fusion	130
8.2	Power from Nuclear Fission	130
8.2.1	Past and Present	130
8.2.2	Nuclear Fuel	132
8.2.3	Uranium Supply	133
8.2.4	Nuclear Reactor Technologies	135
8.2.5	Cost and Time Issues	137
8.2.6	Proliferation	139
8.2.7	Safety and Security	140
8.2.8	Waste Management	141
8.2.9	Decommissioning and Dismantling	142
8.2.10	Other Limiting Factors	144
8.2.11	Perspectives	145
8.2.12	Nuclear Industry Renaissance?	147
8.3	Civilian Use of Nuclear Fusion?	148
8.3.1	A Difficult Problem	148
8.3.2	Magnetic Confinement Approach	149
8.3.3	Inertial Confinement Approach	150
8.3.4	Wishful Thinking	150

### **Part Four Renewable Energies 155**

<b>9</b>	<b>Solar Energy Basics</b>	<b>157</b>
9.1	The Origin of Sunshine	157

9.2	Solar Radiation and Attenuation	159
9.3	Abundant, Fairly Distributed, Vital	161
9.4	Sun's Limits: Dilution and Intermittency	162
9.5	The Conversion of Solar Energy: Heat, Fuels, Electricity	163
<b>10</b>	<b>Solar Heat and Electricity</b>	<b>167</b>
10.1	Passive Solar Harnessing in Buildings	167
10.2	Thermal Conversion: Unconcentrated Solar Flux	168
10.2.1	Solar Thermal Panels	168
10.2.1.1	Collectors	168
10.2.1.2	Water Management	169
10.2.1.3	Sun Exposure	170
10.2.2	Current Deployment and Trends of Solar Thermal Panels	170
10.2.3	Earth Energy Systems (EES)	172
10.2.4	Solar Thermoelectrics	173
10.3	Thermal Conversion: Concentrated Solar Flux	176
10.3.1	Concentrating Solar Power (CSP)	176
10.3.2	Parabolic Trough Collectors	178
10.3.3	Solar Towers	180
10.3.4	Dish Collectors with Stirling Engines	181
10.3.5	Solar Updraft Towers (Chimneys)	181
10.3.6	Cost Considerations and Carbon Footprint of Solar Thermal Electricity	182
10.3.7	Solar Thermochemical Conversion	183
10.4	The Birth and Rise of Photovoltaics	185
10.5	Inorganic Photovoltaics: Key Principles	186
10.6	Silicon Solar Cells	188
10.6.1	Manufacturing of Poly- and Single-crystalline Silicon Cells	189
10.6.2	Material Requirements, Life-cycle Impacts and Cost	190
10.6.3	Amorphous Thin Film Silicon Cells	191
10.7	Thin Film Solar Cells	192
10.8	Organic Solar Cells	193
10.9	Concentrated Photovoltaics and Other Innovative Concepts	196
10.10	Photovoltaics: Global Installation and Market Trends	197
10.11	Solar Energy: Sustainable and Affordable	198
<b>11</b>	<b>Solar Fuels</b>	<b>203</b>
11.1	Introduction	203
11.2	Natural Photosynthesis	204
11.2.1	A Complex Process	204
11.2.2	Natural Antenna Systems	205
11.2.3	Natural Reaction Centers	205
11.2.4	Efficiency of Photosynthesis	208
11.3	Biomass and Biofuels	209
11.3.1	Biomass	209

11.3.2	Biofuels Today	209
11.3.3	Second-generation Biofuels	213
11.3.4	Biofuel Perspectives	214
11.4	Future Options for Transportation Fuels	215
11.5	Artificial Photosynthesis	216
11.5.1	The Need for Solar Fuels	216
11.5.2	Choosing the Right Type of Photoreaction	219
11.5.3	Choosing the Right Chemical Substrate	220
11.5.4	Components of an Artificial Photosynthetic System	222
11.5.5	Coupling Artificial Antenna and Reaction Center	222
11.5.6	The Problem of Multi-electron Redox Processes	224
11.5.7	Water Splitting by Semiconductor Photocatalysis	225
11.6	Dye-sensitized Solar Cells	227
11.7	The Solar Fuel Challenge	228
<b>12</b>	<b>Other Renewables</b>	<b>231</b>
12.1	Hydroelectric Energy	231
12.1.1	The Rise of Hydropower	231
12.1.2	Potential, Current Deployment, and Use	232
12.1.3	Advantages, Disadvantages, and Environmental Impact	233
12.1.4	Hydropower Future	234
12.2	Wind Energy	235
12.2.1	Brief Historical Notes	235
12.2.2	Wind Power Technology	235
12.2.3	The Huge Potential of Wind Power	238
12.2.4	Current Deployment and Trends	239
12.2.5	Environmental Impact	241
12.2.6	The Cost of Wind Power	242
12.3	Ocean Energies	242
12.3.1	Tidal Energy	242
12.3.2	Wave Energy	244
12.3.3	Ocean Thermal Energy	245
12.4	Geothermal Energy	246
12.4.1	The Geothermal Resource	246
12.4.2	Electricity Production	247
12.4.3	Heat for Direct Use	248
12.4.4	Advantages, Disadvantages, and Perspectives	249
12.4.5	The Next Frontier: Going Deeper	249

## Part Five Energy Carriers 251

<b>13</b>	<b>Electricity</b>	<b>253</b>
13.1	Basic Concepts	253
13.2	Illumination	255

13.3	Traditional Power Generation	256
13.3.1	Demand and Supply	256
13.3.2	Thermal Power Plants Based on Fossil Fuels	259
13.3.2.1	Coal-fired Power Plants	259
13.3.2.2	Oil or Gas Power Plants	259
13.3.3	Hydroelectric Power Plants	260
13.3.4	Nuclear Power Plants	261
13.3.5	Contribution by Other Energy Sources	261
13.4	Traditional Electricity Grid	261
13.5	Power Generation from New Renewables	264
13.5.1	Intermittency and Fluctuation	264
13.5.2	Electricity from Wind	265
13.5.3	Electricity from Solar Energy Conversion	265
13.6	Energy Storage for Electricity Supply Networks	266
13.6.1	Role of Storage	266
13.6.2	Pumped Hydro	267
13.6.3	Compressed Air Energy Storage (CAES)	268
13.6.4	Flywheels	268
13.6.5	Superconducting Magnetic Energy Storage (SMES)	269
13.6.6	Electrostatic Energy Storage (Capacitors)	270
13.6.7	Batteries	270
13.6.7.1	Battery Requirements	270
13.6.8	Electrolytic Hydrogen	273
13.7	Plugging-in Transportation	273
13.7.1	Hybrid and Full Electric Vehicles	273
13.7.2	Infrastructure	275
13.8	Smart Grid	275
13.9	Towards an Electricity Powered World	277
<b>14</b>	<b>Hydrogen</b>	<b>279</b>
14.1	Introduction	279
14.2	Properties and Industrial Uses	280
14.3	Hydrogen as an Energy Carrier: The Scale of the Task	281
14.4	Methods for Producing Hydrogen	282
14.4.1	“Clean Coal” Technology	282
14.4.2	Biomass	282
14.4.3	Water Electrolysis	283
14.4.3.1	General Concepts	283
14.4.3.2	Hydroelectric Power	284
14.4.3.3	Wind Electric Power	285
14.4.3.4	Solar Photovoltaic and Photoelectrochemical Electricity	285
14.4.3.5	Solar Thermal Electricity	285
14.4.4	Photoelectrochemical and Photochemical Water Splitting	286
14.4.5	Nuclear Energy	286
14.5	Hydrogen Storage	287

14.5.1	A Difficult Problem	287
14.5.2	Liquid Hydrogen	288
14.5.3	Compressed Hydrogen	288
14.5.4	Metal Hydrides	288
14.5.5	Other Systems	289
14.6	Hydrogen Transportation and Distribution	290
14.6.1	Centralized Distribution	290
14.6.2	Decentralized Distribution	291
14.7	End Uses of Hydrogen Fuel	291
14.7.1	Fuel Cells: General Concepts	291
14.7.2	Proton Exchange Membrane (PEM) Hydrogen Fuel Cells	292
14.7.3	Other Types of Hydrogen Fuel Cells	293
14.7.4	Reformed Methanol Fuel Cells	294
14.7.5	Direct Methanol Fuel Cells	295
14.8	Hydrogen Powered Vehicles	296
14.9	Towards a Hydrogen Economy?	298

## **Part Six Scenarios for a Sustainable Future 301**

<b>15</b>	<b>The Challenge Ahead</b>	<b>303</b>
15.1	Reflection on the State of Our Planet: Now We Know	303
15.2	Energy Demand and Supply	304
15.3	Energy and the Quality of Life	305
15.3.1	A Focusing Illusion	305
15.3.2	Energy, Obesity, Iniquity	306
15.4	Saving the Climate	306
15.5	Phasing Out Fossil Fuels	307
15.6	Avoiding Nuclear Energy	307
15.7	Ecological Sustainability	308
15.7.1	Natural Capital	308
15.7.2	Learning to Say Enough	309
15.8	Why We Need to Develop Renewable Energies	310
15.9	Conclusion	312

## **Appendix – Did You Know That ... ? 315**

### **References 321**

### **Index 353**



## Preface

“With no foresight into the future  
one is bound to find troubles at hand.”

Ancient saying

In recent decades, by observing the Earth from space, we have fully realized that we live in a spaceship that cannot land and cannot dock anywhere to be refueled or repaired. We travel alone in the Universe and we can only rely on the resources available on the surface or in the hold of our planet, and on the energy coming from the Sun. We have also realized that the Earth is a system of intricately connected parts and that human activities can affect biogeochemical cycles. In fact, our 4.5 billion year old planet has entered a new epoch, Anthropocene, characterized by a dramatic increase of the size of human ecological footprint.

Energy is embedded in any type of goods and is needed to produce any kind of service. What makes the modern life of affluent people apparently so easy compared to that of our ancestors, or even to that of billions of individuals still living in poverty, is a steady flux of cheap and plentiful energy in the form of fossil fuels. We know, however, that these resources will not last forever and we have also learnt that their use has caused, and is still causing, severe damage to the Earth's atmosphere. Furthermore, fossil fuels have indirectly contributed to establish disparities and iniquities in human society: almost half of the total primary energy supply is consumed by about 10% of the population living in rich countries, while the poorest 25% of mankind consumes less than 3% of global energy.

Nowadays, everybody wants to have more and more energy, an attitude that poses a variety of entangled problems. When a blackout takes place in a country for whatever reason, the solution proposed by politicians who are seeking to be (re)elected is that of making new power plants. Is it the right solution? Many economists seem to believe that well-being correlates with energy consumption, that energy prices reflect all significant costs and that any societal problems can be solved by enhanced economic growth. Is it true? Several scientists are convinced that technology will solve the energy problem as well as the problems that technology itself is creating. Can we trust them?

The aim of this book is to show that we live in a fragile world and that the world's fragility can be strongly reduced or increased depending on how the energy

problem is tackled. According to Stephen J. Gould, the fragility of the world is related to an intrinsic law of Nature that he called “the great asymmetry principle” (Gould, S.J., *Science*, 1998, 279, 812): “The essential human tragedy, and the true source of science’s potential misuse for destruction, lies in a great asymmetry in our universe of natural laws. We can only reach our pinnacles by laborious steps, but destruction can occur in a minute fraction of the building time, and can often be truly catastrophic. A day of fire destroyed a millennium of knowledge in the library of Alexandria and centuries of building in the city of London.” Within this general principle, the destruction force depends on place and time. Leaving aside the menace coming from nuclear weapons, presently the biggest danger for spaceship Earth comes from too much consumption of natural resources, too much waste generation and too many disparities among the passengers. Energy plays a key role in controlling Earth’s fragility because most of mankind’s problems, including food, water, health, wealth, climate, heating, lighting, cooling, transportation, communication, and, of course, wars are strictly related to the energy issue. The way out of the difficulties and disparities generated during the fossil fuel era is a global problem: the supply of secure, clean, sustainable energy to *all* of the passengers of spaceship Earth is the most important scientific and technological challenge of the twenty-first century.

Fortunately, the energy crisis is not only a tough challenge, but also an unprecedented opportunity. It offers a unique chance to become more concerned about the world in which we live and the society we have built up. Whereas it used to be axiomatic that civilization would always progress over time, because science and technology would have solved any problem, now we are no longer sure about that. Human progress is neither automatic nor inevitable. We have to take urgent and responsible decisions right now: tomorrow might be too late. The quest for ecological and social sustainability requires every single citizen to become aware that consuming resources above a threshold of his/her real needs does not help to create a better world. Earth is in our hands: are we wise enough to develop, with the help of science and technology, an ecological sustainable civilization capable of reducing disparity and creating a more peaceful world?

An old Italian proverb says that the only difference between an optimist and a pessimist is that the latter is better informed. A short-sighted optimism based on unawareness will not allow mankind to move toward a real progress. Pessimism, which arises from the consciousness of the gravity of the situation, is the right starting point: to propose solutions, we must acknowledge that there are problems and we must know them in any possible detail. There is a great need for spreading information about the unsafe conditions of our planet.

Finding a solution to the energy problem is a challenge of utmost difficulty, but also an extraordinary opportunity. Perhaps we are still in time to change and create an Anthropocene epoch based on resource conservation, waste reduction, human relationships, and global solidarity. To achieve this epochal result, we need to educate public opinion and to find visionary leaders capable of looking far, over the planet and into the future. Our generation will ultimately be defined by how we live up to the energy challenge.

## Acknowledgments

No book can be written in isolation and this one has, indeed, benefited from the work of the thousands of authors of books and articles that allowed us to gain a deeper understanding of the problems we have tried to illustrate and discuss comprehensively. We strived to acknowledge their work and we apologize beforehand if we have missed someone.

We are glad to thank the members of our research groups, including PhD students, for support, discussions, suggestions, and, even more, for their friendship. Special thanks are due to Gianluca Accorsi, Giacomo Bergamini, Francesco Barigelletti, Paola Ceroni, Sandra Monti John Mohanraj, and Margherita Venturi for their critical reading of several chapters of the manuscript. Public debates, many lectures in high schools and universities and intelligent questions by many students and colleagues have helped us to focus several topics better.

We also wish to thank Fausto Puntoriero for drawing the cover page of the book, Filippo Monti for preparing with great care and ability all the graphics and illustrations, and Andrea Listorti and Abdelhalim Belbakra for searching and gathering literature. We would also like to thank the staff of Wiley-VCH for their highly professional and valuable assistance.

Last but not least we wish to thank our families, and in particular our wives Claudia and Carla, who have provided inspiration, sustained encouragement, and, definitely, a great deal of patience during the writing of this book.

Bologna, August 2010

*Nicola Armaroli and  
Vincenzo Balzani*



## Notation

### Prefixes

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

### Abbreviations

bbl	barrel of oil
Dwt	deadweight ton
ppm	part per million
toe	ton of oil equivalent
$W_{th}$	thermal watt
$W_p$	watt peak
$W_{el}$	electric watt

### Acronyms

AC	Alternating Current
AFC	Alkaline Fuel Cell
ASPO	Association for the Study of Peak Oil and Gas
ASTM	American Society for Testing and Materials

BHJ	Bulk Heterojunction
BP	British Petroleum
bpd	barrel per day
bpy	barrel per year
BTU	British Thermal Units
CAES	Compressed Air Energy Storage
CBM	Coalbed Methane
CCS	Carbon Capture and Sequestration
CFC	Chlorofluorocarbons
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CPV	Concentrated Photovoltaics
CR	Concentration Ratio (in CSP)
CSP	Concentrating Solar Power
DC	Direct Current
DME	Dimethyl Ether
DOD	US Department of Defense
DOE	US Department of Energy
DSSC	Dye-Sensitized Solar Cell
DU	Depleted Uranium
EEA	European Environment Agency
EES	Earth Energy Systems
EI	Energy Intensity
EIA	US Energy Information Administration
ENI	Ente Nazionale Idrocarburi (Italy)
EPA	US Environmental Protection Agency
EROI (EROEI)	Energy Return on Investment
EU	European Union
EUROSTAT	Statistical Office of the European Communities
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester
FIT	Feed-in Tariffs
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
IAEA	International Atomic Energy Agency
ICE	Internal Combustion Engine
ICF	Inertial Confinement Approach
ICT	Information and Communication Technology
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	International Panel on Climate Change
IR	Infrared (radiation)
KERS	Kinetic Energy Recovery Systems

LCA	Life-Cycle Analysis
LNG	Liquefied Natural Gas
LPG	Liquid Petroleum Gas
NASA	US National Aeronautics and Space Administration
NEA	Nuclear Energy Agency
NGO	Non-Governmental Organization
NIR	Near-Infrared (radiation)
NPT	Non-Proliferation Treaty
NREL	US National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development
OSC	Organic Solar Cell
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating Water Column
PCET	Proton-Coupled Electron Transfer
PEM	Proton Exchange Membrane
PM	Particulate Matter
PSII	Photosystem II
PV	Photovoltaic
QUAD	quadrillion BTU ( $10^{15}$ BTU)
RC	Reaction Center
RMFC	Reformed Methanol Fuel Cell
SEGS	Solar Energy Generating System
SHP	Small Hydropower
SI	International System of Units
SMES	Superconducting Magnetic Energy Storage
SUV	Sport Utility Vehicle
TPES	Total Primary Energy Supply
UCG	Underground Coal Gasification
UCTE	Union for the Coordination of the Transmission of Electricity
UNEP	United Nations Environment Programme
URFC	Unitized Regenerative Fuel Cell
USGS	US Geological Survey
UV	Ultraviolet (radiation)
Vis	Visible (radiation)
VOC	Volatile Organic Compound
WEC	World Energy Council
WHO	World Health Organization
WNA	World Nuclear Association
WWII	World War II





## **Part One**

### **Living on Spaceship Earth**



## 1

## The Energy Challenge

“Pay attention to the whispers,  
so you won’t have to listen to the screams.”

Cherokee Proverb

## 1.1

### Our Spaceship Earth

On Christmas Eve 1968, the astronauts of the Apollo 8 spacecraft, while in orbit around the Moon, had the astonishment to contemplate the Earthrise. William Anders, the crewmember who took what is considered one of the most influential photographs ever taken, commented: “We came all this way to explore the Moon, and the most important thing is that we discovered the Earth” [1] (Figure 1.1).

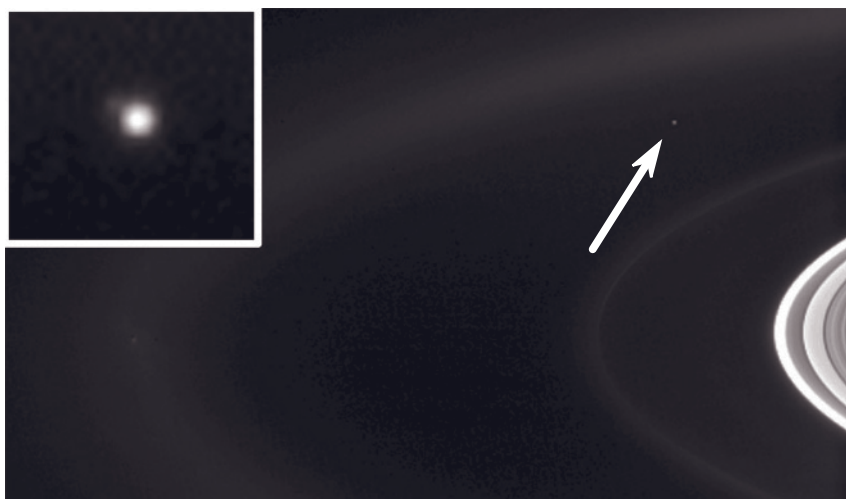
The image taken by the Cassini Orbiter spacecraft on September 15, 2006, at a distance of 1.5 billion kilometers (930 million miles) shows the Earth as a pale blue dot in the cosmic dark (Figure 1.2). There is no evidence of being in a privileged position in the Universe, no sign of our imagined self-importance. There is no hint that we can receive help from somewhere, no suggestion about places to which our species could migrate. Like it or not, Earth is a spaceship. It’s the only home where we can live.

Spaceship Earth moves at the speed of  $29 \text{ km s}^{-1}$ , apparently without any destination. It does not consume its own energy to travel, but it requires a huge amount of energy to make up for the needs of its 6.8 billion passengers who increase at a rate of 227 000 per day (the population of a medium-sized town), almost 83 million per year (the population of a large nation) [2]. Spaceship Earth cannot land and cannot dock anywhere to be refueled or repaired. Any damage has to be fixed and any problem has to be solved by us passengers, without disembarking. We travel alone in the Universe, and we can only rely on the energy coming from the Sun and on the resources available on the surface or stored in the hold of our spaceship.

Earth’s civilization has always depended on the incessant flow of solar energy that sustains the biosphere and powers the photosynthetic production of food. Until a few centuries ago societies obtained their energy from sources that were almost immediate transformations of solar radiation (flowing water and wind) or that took relatively short periods of time to become available (wood) [3]. The feature



**Figure 1.1** Earthrise: a photograph of the Earth taken by astronaut William Anders on December 24, 1968, during the Apollo 8 mission while in orbit around the Moon. This picture is one of the *Life's* 100 Photographs that Changed the World. Credit: NASA.



**Figure 1.2** Photograph taken by the Cassini Orbiter spacecraft on September 15, 2006, at a distance of 1.5 billion kilometers from Earth. The dot to the upper left of Saturn's rings, indicated by the arrow, is the Earth. Saturn was used to block the direct light from the Sun, otherwise the Earth could not have been imaged. Inset: expanded image of the Earth which shows a dim extension (the Moon). Credit: NASA.

that distinguishes modern industrial society from all previous epochs is the exploitation of fossil fuel energy. Currently over 80% of the energy used by mankind comes from fossil fuels [4]. Harnessing coal, oil, and gas, the energy resources contained in the store of our spaceship, has prompted a dramatic expansion in energy use. Powering our spaceship Earth with fossil fuels has been very convenient, but now we know that this entails severe consequences [5, 6].

Firstly, fossil fuels are a nonrenewable resource that is going to exhaust. We have consumed 1 trillion barrels of oil in the last 140 years, and currently the world's growing thirst for energy amounts to almost 1000 barrels of oil, 93 000 cubic meters of natural gas, and 221 tons of coal per second [7]. How long can we keep running this road? Secondly, the use of fossil fuels causes severe damage to human health and the environment. It has been pointed out [8] that the energy challenge we face relates to "the tragedy of the commons" [9]: we treat fossil fuels as a resource that anyone anywhere can extract and use in any fashion, and Earth's atmosphere and oceans as a dump for their waste products, including more than 30 Gt per year of CO<sub>2</sub>. A third critical aspect concerning fossil fuels is that their uneven allocation, coupled with the unfair distribution of wealth, leads to strong disparities in the quality of life among the Earth's passengers.

## 1.2

### An Unsustainable Growth in an Unequal World

#### 1.2.1

##### Population Growth and Carrying Capacity

In the last 100 years there has been a rapid population growth due to medical advances and massive increases in agricultural productivity. In 1950, the world population was 2.6 billion, with an increase of 1.5% per year [10]. In 2010, it was more than 6.8 billion, but with a lower rate of annual increase (1.1%), that is expected to decline further until 2050, when the Earth will be populated by about 9.2 billion people. At that time, the median age of the world population will be 37.3 years, up from 26.6 in 2000 [11].

The population size of a biological species that a given environment can sustain indefinitely is termed carrying capacity. Overpopulation may result from growth in population or reduction in capacity. The resources to be considered when assessing the carrying capacity of a given ecological system include clean water, clean air, food, shelter, warmth and other resources necessary to sustain life. In the case of humans, several additional resources must be considered, including medical care, education, sewage treatment, waste disposal, and, of course, energy.

Clearly, spaceship Earth has a limited carrying capacity, but it is quite difficult to assess the maximum number of humans who can live on it in satisfactory welfare conditions, also because "satisfactory welfare" is a somewhat subjective concept. An alarm bell, however, comes from the estimation of the ecological footprint, defined as the amount of biologically productive land and sea area

needed to regenerate the resources a human population consumes and to absorb and render harmless the corresponding waste [12]. In global hectares per person, in 2006 the Earth's biocapacity was 1.8, while the average footprint was 2.5. In 2009, the Earth Overshoot Day, that is, the day when humanity begins living beyond its ecological means, was September 25 [13]. In other words, mankind uses biological services faster than the Earth can renew them.

### 1.2.2

#### **Economic Growth and Ecologic Degradation**

The expansion of the human enterprise in the twentieth century was phenomenal, particularly because of the availability of low-cost energy. Unfortunately, however, it has caused bad consequences that we have now to face. Ecologists emphasize that dominant patterns of production and consumption are causing environmental devastation and a massive extinction of species [14]. Climatologists warn about anthropogenic climate change [15]. Geologists point out that we will soon reach, or maybe we have already surpassed, the peak of oil production [16]. Seismologists wonder whether natural disasters, like the devastating earthquake which in May 2008 killed 80 000 people in China, are triggered by exaggerated human constructions [17]. International agencies inform us that about 6 million hectares of primary forest are lost each year [18]. People are worried about nuclear waste [19], and in affluent countries even disposal of electronic waste causes domestic and international problems [20, 21]. Last but not least, food security is a growing concern worldwide [22, 23].

Some scientists have pointed out that global effects of human activities, directly or indirectly related to the use of fossil fuels, are producing distinctive global signals. Accordingly it has been proposed that, since the beginning of the Industrial Revolution, we have entered a new epoch that can be called Anthropocene [24], in which the Earth has endured changes sufficient to leave a global stratigraphic signature distinct from that of the Holocene or of previous Pleistocene interglacial phases [25].

In spite of these alarm bells, growth remains the magic word of narrow-minded economists and politicians. They believe that the economic growth must continue indefinitely, and therefore they incessantly press for increasing production and consumption. In affluent countries, we live in societies where the concepts of “enough” and “too much” have been removed [26]. We do not take into account that the larger the rates of resource consumption and waste disposal, the more difficult it will be to reach sustainability and guarantee the survival of human civilization.

### 1.2.3

#### **Inequalities**

The goal of ecological sustainability is even more imperative if we consider the problem of disparity [27]: the passengers of spaceship Earth travel, indeed, in very