Nicola Armaroli and Vincenzo Balzani

Energy for a Sustainable World

From the Oil Age to a Sun-Powered Future

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To Claudia and Carla

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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

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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.

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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 (μ)	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

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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 Heath Organization
WNA	World Nuclear Association
WWII	World War II

Part One
Living on Spaceship Earth

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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 $29\,\mathrm{km\,s^{-1}}$, 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

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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.

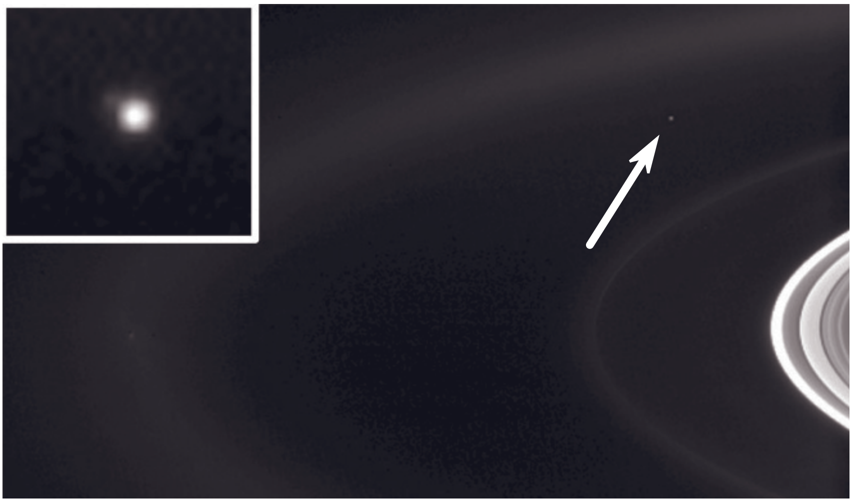

Figure 1.2 Photograph taken by the Cassini Orbiter spacecraft on September 15, 2006, at a distance of 1.5 billion kilometers from Earth. The dot to the upper left of Saturn's rings, indicated by the arrow, is the Earth. Saturn was used to block the direct light from the Sun, otherwise the Earth could 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_2. 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