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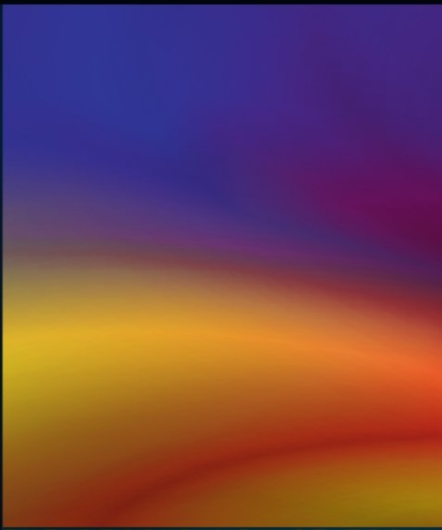

Reiner Kümmel

THE SECOND LAW OF ECONOMICS

Energy, Entropy, and the Origins of Wealth

Springer

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Energy, Entropy, and the Origins of Wealth

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And it was the amount of energy a single
human could produce that dictated
military potential, standard of living,
happiness, and all besides.
Isaac Asimov*, The Naked Sun, 1956*

To
Christa and Stephan,
Lukas, Florian, Franziska, and Jakob

Foreword

Physicists contribute in various fields of sciences for a better understanding of our world. This is linked to the type of education they have to undergo. During their studies they are trained to solve problems, rather difficult and tricky problems in many cases. They like to do that, otherwise they would have chosen the wrong field for themselves. With this attitude in mind, they have made numerous significant contributions to such different fields as chemistry, biology, medicine, and what is of particular interest here, economics. Since physicists are used to working with equations, which represent their ideas in a transparent, logical, and consistent frame; they will naturally carry over that attitude to other fields in which they are working. This distinguishes them from those scientists who express their ideas solely in words and descriptions.

The author of this volume, Reiner Kümmel, is a physicist in the best sense. He received excellent training at world-renowned universities and despite considerable scientific success in a special field of physics, namely, superconductivity, he remained a generalist. What started as a hobby, namely, the study of the laws and driving forces of economics, rather soon became a serious occupation and a new branch of interdisciplinary work. His personal experiences, which he gained in different parts of the world, made him realize what former President Bill Clinton used as the 1992 campaign catch phrase: "It's the economy, stupid!"

After his studies in Germany Reiner Kümmel spent his postdoctoral years in Urbana (Illinois) as an assistant of John Bardeen, one of the true giants of science. In the USA he experienced the prosperity and wealth of the world's leading economic power. A few years later, he became acquainted with the life and struggle, of the people in Colombia, where he served for three years building up a master's program at the Universidad del Valle in Cali in the spirit of Kennedy's Peace Corps. The huge difference in living conditions between the USA and Germany, on the one hand, and Colombia, on the other, together with his determination to do something to improve the lives of people, provided the background for his increasing engagement in economics. He realized rather soon that as a well-trained physicist he could make an important contribution to that field.

This monograph is the result of more than three decades of research in economics. His main contribution and message is a serious study of the consequences of incorporating energy and entropy into the models of economic development. I am sure that entropy is a subject that still deserves more attention than it has hitherto received in economics, simply because it is a concept one needs to get used to. By the way, the well-known Max Planck thought lifelong about it. So it is natural that concepts of that type take a long time before they penetrate into such a different field like economics.

I am sure that this book will fill a blank space and I hope that it will stimulate students and researchers alike. In any case, it will widen our views on economics and contribute to the development of this important science for the benefit of mankind.

Dresden, October 2010 Peter Fulde

Preface

Thermodynamics was a subject I thoroughly disliked when I was a student. I just could not understand the physics behind the rattling of exact, inexact, and partial differentials. And my interest in economics matched Thomas Carlyle's characterization of the field as the "dismal science," although at that time I did not appreciate the Malthusian basis of Carlyle's description.

These attitudes changed a lot as I grew older. Fascinated by many-body quantum mechanics, I got a first inkling of the practical usefulness of thermodynamics when John Bardeen of the University of Illinois at Champaign-Urbana gave me a problem for which I had to derive the time-dependent equations of motion for quasiparticles in inhomogeneous superconductors at finite temperatures. Minimization of free energy provided the important quasiparticle distribution function, and more. Later, my colleagues in the Physics Department of Universidad del Valle in Cali, Colombia, asked me to teach thermodynamics in their newly established master program. When I objected that this was the field I was least familiar with, they recommended Frederick Reif's *Fundamentals of Statistical and Thermal Physics* as the best book to improve my state of knowledge. They were right. Reif's combined statistical and phenomenological descriptions of interacting many-body systems pulled the veil from my eyes that had prevented me from seeing the beauty and power of thermodynamics. Finally, I understood entropy.

Then came the shock of the 1972 publication *The Limits to Growth*. I realized how naive I had been when I went to Colombia to join the efforts to industrialize this beautiful, tortured country by teaching physics to its gifted students. If industrialization, done the European and American way, were to spread to the developing countries, entropy production would create problems mankind had never faced in history. The next – oil price – shock, and the concomitant economic recession in 1973–1975, showed the vulnerability of industrial economies to reductions of energy conversion. These two shocks introduced thermodynamics and economics as the third theme, besides superconductor and semiconductor physics, of my teaching and research at the University of Würzburg since 1974.

I owe a lot to people who taught me more about economics and thermodynamics. First, there is the late Wilhelm Dreier, economist and theologian at the University of Würzburg. In joint interdisciplinary seminars on economic growth and its problems, I learned that in economic theory there is practically no room for energy as a factor of production beside capital, labor, and land. I found this hard to believe and asked Wilhelm for a good introduction to economics. He recommended Paul A. Samuelson's textbook *Economics*. This book educated me as much in economics as Reif's book did in thermodynamics. After the publication of my first article in an economics journal, the dean of theoretical physics in Würzburg, the late Helmut Steinwedel, established contact with Wolfgang Eichhorn from the Institute of Economic Theory and Operations Research at the Technical University of Karlsruhe. Working together with Wolfgang during the last 30 years has, hopefully, prevented me from falling into the interdisciplinary traps that await people who venture from their field into other disciplines. At one of the international conferences on economic theory of natural resources organized by Wolfgang, I met the late Willem (Pim) van Gool from the Energy Science Project in the Department of Inorganic Chemistry of the State University of Utrecht. Pim introduced me to energy, cost, and emission optimization in industrial systems, and to all that matters in exergy and enthalpy. Interaction with colleagues from the Working Group on Energy (AKE) and the econophysics community of the German Physical Society (DPG) has also fostered research in energy science and econophysics. During the first of a series of workshops entitled "Advances in Energy Studies," organized in 1998 by Sergio Ulgiati, then at the University of Siena, Charles A. Hall of SUNY at Syracuse, New York, Robert U. Ayres of INSEAD at Fontaienbleau, France, and I discovered our common interest in heterodox economics. Since then I have benefitted greatly from our cooperation and exchange of ideas. Personal encounters with the late Gerard K. O'Neill of Princeton University's Physics Department, and participation in three "Princeton Conferences on Space Manufacturing Facilities," inspired my hope that the collision with the limits to growth on Earth might be mitigated by a timely rediscovery of O'Neill's bold vision of *The High Frontier*.

Students are the heart of research. They work out the difficult details of an idea their advisor suggests and often carry on far beyond that. I was lucky that good students took the risk of doing interdisciplinary research, despite my advising them to be rather on the safe side with theses in semiconductor or superconductor physics. This book has benefitted in one way or another from my former students (in chronological order) Klaus Walter, Bruno Handwerker, Helmuth-M. Groscurth, Uwe Schüssler, Thomas Bruckner, Volker Napp, Alexander Kunkel, Hubert Schwab, Dietmar Lindenberger, Julian Henn, Jörg Schmid, and Robert Stresing. Dietmar Lindenberger, presently at the Institute of Energy Economics of the University of Cologne, is still an active partner in ongoing research. Arne Jacobs from my superconductivity group and Andreas Vetter helped with all sorts of IT problems.

During the last few years drafts of this book have served as a text for my course on thermodynamics and economics, and the feedback from the students who took the course has been very helpful. In that course and this book, I try to summarize the basic facts on energy and entropy, which are taught in Würzburg during the first five semesters of physics studies. This material is supplemented by information on fossil, nuclear, and renewable energy sources, the technological options of using them, and the possibilities of emission mitigation. Of course, it is only possible to discuss a subjective selection from the huge amount of research on these topics. The chapter on economic evolution is quite different from the preceding two chapters. It presents methods and results of research in energy and economic growth since 1980. These things have been published in peer-reviewed journals. The results are not in line with mainstream economic thinking. There are also people in the growing field of heterodox economics who agree with the results but dislike the mathematical methods used in their derivation. For them, the methods are too similar to those of neoclassical economics. The mathematics of orthodox economics, borrowed from classical physics, is attractive to a physicist. The idea has been to incorporate energy, entropy, and technological constraints into the orthodox mathematical machinery and see how the picture of economic evolution changes. The reader may judge for himself or herself whether the new picture, with the dominant role of energy conversion in economic growth and the threat from entropy production to future growth, is convincing or not. The time travel prologue with its qualitative description of natural, technical, and social evolution may facilitate the understanding of energy conversion as the driver of change without any mathematics. Ethical problems concerning economic development, and hope that proper action will be taken, are indicated in the epilogue. Some considerations are repeated in different parts of the book so that the chapters are self-contained and can be read independently of each other.

I am grateful to my colleagues in the Faculty of Physics and Astronomy of the University of Würzburg for not only tolerating my going partly astray from the path of monodisciplinary physics, but also for being helpful in many ways.

Last but not least, I thank my wife Rita for detecting inappropriate wording and lots of typographical errors, bearing with the physicists' priorities, and all encouragement.

Würzburg, October 2010 Reiner Kümmel

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Contents

Chapter 1
Prologue: Time Travel with Abel

Imagine an observer in the state beyond space and time from which one can watch the universe and human history unfold from the beginning to the end. Let us call him Abel. He takes us on a voyage through time and lends us his eyes and insight. This is what we see.

1.1 From the Big Bang to the Sun

A singularity out of nothing blows up in a glaring white. "This is *ENERGY* – the cosmic building stuff," Abel whispers as we watch in awe. "You see the beginning of space–time in the Big Bang 14 billion years ago. Right now the primordial content of the universe has a temperature of 10^{32} degrees."[1]

Space and time expand. The quark soup condenses out of the glittering radiation. Then quarks form protons and neutrons. These fuse into the first light elements: deuterium, helium, and lithium. "Now the universe is 100 seconds old, and its temperature is down to some billion degrees," Abel comments. The cosmos expands further. After 400,000 years matter and radiation decouple; space is filled by a multicolored glow: the cosmic background radiation and its fluctuations. A dark age follows for the next 600,000 years, when the first stars form and fuse the elements heavier than iron, such as copper, silver, and gold. Then stars and galaxies become visible. They proliferate and fill the universe with their shining glory, while it expands to size of over 100 billion light years. The cosmic background radiation has cooled down to a temperature just 2.725 degrees above absolute zero. Abel summarizes what we have seen:

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[1] The Celsius (°C) temperature scale has its zero point at 273.15 degrees above the zero point of the absolute Kelvin (K) temperature scale.

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> "All matter has condensed out of energy, all changes are driven by energy conversion, and all structures originate from energy fluctuations, such as the ones you note in the slightly warmer and colder regions of the background radiation."

Before we rejoice about having the full cosmic vision, Abel cautions us: "You have just seen 5% of what the universe contains. The rest is 20% dark matter and 75% dark energy." He refuses to reveal more about dark matter and dark energy, stating that he is only allowed to show what is already part of human knowledge. When we ask him "What is human knowledge about energy?" he replies, "I'll just give you the grand tour. Details you may look up in the treatise I'll hand over to you at the end of our voyage."

Our vision zooms in on an average star at the fringe of a galactic spiral arm. Protuberances flicker on its surface, and flares of gleaming hot gases shoot up into the darkness of space. A distant blue planet encircles the radiating sphere.

"The fountain of life," Abel comments, and recites

"Splendid are you in the heavenly mountain of light,
Living Sun, living since the Beginning,
filling all the lands with your beauty.
Great are you, shining in every country,
embracing all the earth with your life-giving rays.

This is how the Egyptian pharaoh Amenophis IV, who calls himself Echnaton, greets the Sun."

We dash toward the Sun. At its surface Abel announces: "The temperature is 5777 K. Let's go to the center. It is just 696,000 km away." Our space–time elevator speeds down past huge, swaying tubes in which gleaming hot gases are driven up by convection. After 200,000 km the tubes disappear, and there is just a glow. Then, farther down, we are surrounded by glorious gold. Abel tells us: "We are in the wedding saloon of the Sun's particles. It is the solar core with a radius of 140,000 km. Here, every second 600 million tons of hydrogen are fused into helium. The mass difference between the hydrogen and the fusion product helium is about four million tons. It is all converted into energy, at 15 million degrees. Watch out for protons and neutrons. They show up as red and black balls. You will also see red dots, the positrons. Photons, the quanta of light, will flash, and neutrinos will appear and vanish chimerically. Here we go."

Space teems with protons. Occasionally, two protons fuse into a black-red compound. "That's deuterium," Abel informs. "And did you see the positron and the neutrino escape?" Deuterium catches another proton. "Now we have helium-3." This happens many times. Each helium-3 compound chases after a partner of the same kind, and in most cases the two merge into a two proton–two neutron nucleus, emitting two protons. At each particle wedding, photons flash up. Like the neutrinos, the photons would like to dash away at the velocity of light. But they are absorbed immediately in the proton–neutron throng, then they are reemitted, reabsorbed, and in this catch-and-let-go game they diffuse away at a crawling pace.

"This has been going on for more than four billion years and should continue at least that long into the future. Four hydrogen nuclei – that's what the protons are – fuse into one helium-4 nucleus. In so doing, they generate two positrons, two neutrinos, and two photons. The photons are almost trapped in the extreme density of matter in the solar core, which is about 150 times the density of water. Therefore, they still need about a million years until they get out of the Sun and provide the Earth with light and warmth."

"People know the Sun's importance for life," Abel adds, "but only few realize that they are also children of long-gone stars."

Sensing our question, he explains: "In the Sun's atmosphere there are traces of heavy elements. These elements, quite common on Earth, can only be generated in fusion processes at temperatures much higher than those in the core of the Sun. Temperatures above 10^8 and 10^9 degrees occur in contracting stars, which have burned up all their hydrogen and fuse higher elements. These fusion processes produce energy, up to iron, ^{56}Fe. The fusion of elements heavier than iron consumes energy. Such elements are cobalt, nickel, copper, tin, silver, gold, lead, and uranium, the heaviest natural element in the periodic table. This energy may have been provided by novae and supernovae. Thus, the Sun, the Earth, and everything on Earth itself have been processed through the inside of at least one star."

We digest the feeling that most components of our bodies have been parts of dying, exploding stars. Then we move back in time by four billion years.

1.2 Light on Earth

The Sun is fainter than the one we know. The Earth is wrapped in a uniform gray layer of clouds. While we wonder how cold it may be down there, Abel tunes in: "Earth's surface temperature is about 85°C. It is so hot because of the greenhouse effect in an atmosphere that consists mainly of nitrogen, methane, water vapor, and up to 1,000 times more carbon dioxide than in the atmosphere you know." He explains that during the next 3.5 billion years most of this carbon dioxide will become dissolved in the oceans, where bacteria and algae will produce oxygen from it. The weathering of silicate rocks on the continents, followed by the deposition of carbonate sediments on the sea floor, will also remove carbon dioxide from the atmosphere/ocean reservoir. "This drastic decrease of carbon dioxide has reduced the greenhouse effect to a very convenient level. Between the two revolutions that decisively shape human history – the Neolithic revolution, with its beginning of farming and cattle breeding, and the Industrial Revolution, with its invention of the heat engine – it keeps the average surface temperature of the Earth at a comfortable $+15$°C. Without it you would have a deadly -18°C. And now lets move to the Cambrian, with its explosion of life forms, 530 million years before your time. Since then you can observe the forces that drive evolution."

The Earth has become the blue planet. Oceans surround land masses. Clouds sail through the thin shell of the atmosphere. In a first quick dash we ride the arrow of time through the ages of Earth. They are marked by the trilobites, the first fish and insects, the conquest of the land by plants and reptiles, the forests of giant ferns and shave-grass, the saurians, the conifer and deciduous forests, and the mammals. And during all that time the only inputs into the Earth system are energy, emitted by the Sun, cosmic radiation, and once in a while some rocks from outer space.

Solar energy activates life and fosters its growth. This also becomes dramatically patent by the mass extinctions of species we observe during periods when volcanic eruptions or dust, stirred up by the impact energy of huge meteorites, block much of the sunlight. The catastrophic disappearance of the dinosaurs 60 million years ago makes room for the mammals, which until then had barely survived in ecological niches. We also see how ionizing particles from solar or cosmic radiation, or terrestrial radioactive material, transfer energy to the genes of the living cell. This causes mutations that occasionally result in new species. “Got it?” Abel checks our understanding. “Energy conversion and genetic information processing drive the evolution of species.”

Contemplating the Sun and the Earth, we understand more deeply why the Sun has been revered as sacred throughout the ages. Abel quotes from Shakespeare’s Sonnet VII:

Lo! in the orient when the gracious light
Lifts up his burning head, each under eye
Doth homage to his new-appearing sight,
Serving with looks his sacred majesty;
And having climbed the steep-up heavenly hill,
Resembling strong youth in his middle age,
Yet mortal looks adore his beauty still,
Attending on his golden pilgrimage.

1.2.1 As Life Goes

Our vision zooms in on the nanoworld of the living cell. We enter the interior of an algal cell. “Watch the process of photosynthesis,” Abel recommends.

We see the pulsating green compound of chlorophyll in the center of the cell. Flashes of incident photons dance over its surface. The compound pumps currents of yellow electrons along conducting chains. Red hydrogen and blue oxygen atoms flow out of the watery envelops of the chains. Brown adenosine triphosphate boxes, bearing the letters ATP, are also emitted and move into a dark reaction chamber. A gray gas of carbon dioxide molecules flows into this chamber and mixes with hydrogen. Varying its color several times, the mixture reaches the ATP boxes and reacts with them seethingly. White sugar ribbons emanate and slide toward the border of the cell. There, new cells separate and float away through blue oxygen molecules that bubble out of the wall of the cell.

Our guide comments: “In nature’s sugar plant, chlorophyll converts the energy of the photons into work performed by electric currents that flow along molecular chains and produce adenosine triphosphate. ATP serves all living species as *the* universal energy currency. It is transported to places where work has to be performed. There, ATP gives off the energy from the Sun stored in it and produces sugar and new cells. Summing this up quantitatively, we note that, via the chlorophyll of the living cell, sunlight converts six water and six carbon dioxide molecules into six oxygen molecules and one sugar molecule. This breeds new cells. And now observe the complementary part of the life cycle: the conversion of sugar into work. It’s called respiration.”

We see an Amano shrimp devouring algae. Inside its translucent body, algae fragments merge with blue oxygen balls, which enter from the surrounding water. Brown ATP boxes emanate from the merger zone, accompanied by an undulating glimmer. The ATP boxes dissolve, their energy is transferred to the legs, which begin to move, and the shrimp crawls away, emitting gray carbon dioxide and red-blue water molecules.

Abel continues: “Here you see how the sugar of the devoured algal cell is burned with oxygen so that the moving shrimp’s legs can do work. Again the whole process operates via the conversion of the solar-generated chemical energy of sugar into the chemical energy of adenosine triphosphate. This ATP acts as a sort of battery. As in photosynthesis, this battery delivers energy to those parts of the cell where work must be performed by discharging itself. To be more precise: during the combustion of food, one molecule of sugar combines with six molecules of oxygen to become six molecules of water plus six molecules of carbon dioxide plus adenosine triphosphate. The undulating glimmer you have noticed is caused by waves of waste heat into which, unfortunately, a certain part of valuable energy must always be converted. The same processes occur in the predators that feed on the shrimps, and in all other plants and animals.”

Abel illustrates the cycle of life by a picture [1]: “The controlled process of the biological energy cycle can be depicted by the running of a series of water mills driving generators which charge batteries.... When photosynthesis is compared to a solar-driven pump used to bring ‘water’ to an elevated level, respiration can be represented as the stepwise downfall of the ‘water’ which drives the ‘water mills’ charging the ‘ATP batteries.’ The batteries then can be transported to sites where work has to be done; when properly connected, they can be ‘discharged’ by the hydrolysis reaction when work is performed.”

Then we are shown how the giant stores of fossil fuels are formed from the products of photosynthesis.

In the Carboniferous and the Permian, about 300 million years before the present, huge forests grow in warm, swampy freshwater regions. When the trees in these forests die, they fall onto the swampy ground and are buried by the debris of the following years. Many generations of plants form layers of dead vegetation, which, in turn, are overlaid by sediments of nonorganic material washed down into the low-lying swamps from surrounding higher ground. Thus, the dead biomass, sealed off from the oxygen of the air, cannot rot away, and a good part of the energy stored in it is conserved, when it is squeezed and transformed into peat. As more layers of sediment pile up upon the organic deposits and these sink further down, coming under increased heat and pressure, they are further transformed, first into lignite (brown coal), then (hard) coal, and finally anthracite. Later, in the Tertiary era, which lasts between 64 million years and one million years before the present, we note the second peak of coal formation, when the large deposits of lignite are formed. We also observe the production of oil and natural gas from the remains of plants and animals, especially plankton. These remains are laid down mainly in coastal regions near or under salt water and are eventually sealed off by sediments that build up to form new layers of rock. Over millions of years, in reduction reactions with hydrogen sulfide (H_2S) and with bacterial support, they undergo chemical changes similar to those that produce coal, and become the liquid and gaseous stores of solar energy [2].

1.2.2 Fire and Grain

Abel takes us to the Quaternary, less than a million years before the present. Huge ice masses spread from the north and south poles over the northern and southern parts of the continents, and glaciers creep from high mountains into plains. When it gets warmer, the ice recedes and the land greens, then it gets colder again, and the ice comes back. The average surface temperature of Earth varies rapidly by several degrees Celsius.

In this harsh environment the first humans roam the fields and forests as collectors of plants and their fruit and live on a daily energy budget of about 2 kWh. Then they take up hunting. Although physically much weaker than their prey, such as mammoths, and competing predators, such as bears and tigers, they prevail thanks to the use of tools made from stone and wood.

A huge leap forward in the art of survival is made by the taming of fire, roughly half a million years before the present. We watch the bold leader of a horde grab the fire with a dry branch from the flames that engulf a tree ignited by lightning. The members of his horde begin to guard and nourish the fire. Quickly its domination spreads to other hordes. People learn more and more how to use the energy liberated by the oxidation of carbon and hydrogen in wood for warming their caves, defense against wild animals, cooking plants, roasting meat, and the preparation of weapons such as fire-hardened yew-tree spears. By then, the average energy consumption is 6 kWh per person per day.

Abel reminds us of Greek mythology: “Prometheus stole the fire from Olympus, the residence of the gods, and brought it to the humans on Earth. Zeus, the king of the gods, punished him cruelly for this deed, which gave humans so much power and saved them from doom.” To be sure that we really understand the paramount achievement of prehistoric man, he adds Goethe’s reference to Prometheus:

> *Kindle the Fire! Fire's on top.*
> *Greatest the deed of stealing it.*
> *He who lightened it,*
> *he who made friends with it*
> *hammered and rounded crowns for Man's head,*

and quotes from Schiller's "Song of the Bell":

> *Power of fire, how beneficial*
> *if carefully guarded and harnessed by man.*
> *Whatever he forms, and what he creates,*
> *he owes it to you, o gift of the gods.*

We arrive at the dawn of human civilization in the Fertile Crescent between the Euphrates-Tigris and the Nile. Twelve thousand to 10,000 years before the present, the average temperature of Earth rises by more than 4°C and stays nearly constant after that. Still, small fluctuations occur but hardly exceed more than 1°C. After the much stronger fluctuations of the ice ages, advanced humans live for the first time in a nearly stable, warm climate. Photosynthetic biomass production occurs in bountiful, predictable cycles. In this new environment, which feels like paradise compared with the living conditions of the preceding ice age, *Homo sapiens* triggers the "Neolithic revolution": Men and women invent farming and cattle breeding. Instead of just collecting and hunting what grows and lives in grasslands, forests, and waters, humans expand their harvesting of solar energy systematically, and to an extent that grows with the area of the agriculturally utilized land.

"Look at Eve, how she did it," Abel suggests.

We see a woman who collects the seeds of grass. She separates out especially big grains and stores them for times of drought. After a number of fertile years, when the grain store overflows, she throws out the grains from the oldest harvest into the backyard of her house on the bank of the broad river. The next spring, grass plants with bigger-than-average grains of seeds grow in the backyard. The woman gets an inkling of a totally new opportunity of food provision. She sows more of the big-grain seeds and selects again the biggest grains from the blades that grow out of them. After a number of cycles of sowing, harvesting, and selecting, the woman has a field close to her house from which she gets more grain food than from the huge area of the savannah she used to roam when collecting ordinary grass. Meanwhile, her male companion continues hunting, watching her efforts with quite some suspicion. When she finally asks him to help her dig up some more ground in order to expand the area of big-seed cultivation, he first protests full of indignation. After all, he is a hunter and grain care is women's business. But his wife, seductively beautiful in her enthusiasm about her discovery, convinces him to do what he had always considered as something out of question. He joins her in digging and planting and harvesting the new fruit of knowledge. Together they cultivate the special seeds into what finally becomes wheat.

"But Adam is never quite happy with having traded free hunting for tilling the soil. He thinks that he has lost paradise," Abel concludes this vision.

Other people pick up the art of farming. Subsequent generations learn how to domesticate animals. In our privileged view provided by Abel, we see and understand the geographic advantage in food production enjoyed by the inhabitants of the Eurasian land mass and northern Africa over the humans who live in sub-Saharan Africa and the Americas: In Eurasia there are many more domesticable wild plants and animals than on other continents. Domesticated mammals such as sheep, goats, pigs, oxen, cows, donkeys, horses, and camels provide meat, milk, leather, and manure, and they also provide muscle power for plowing the fields, the transportation of goods, and rapid military attack. These animals and domesticated birds such as chicken, geese, ducks, and turkeys convert the chemical energy of plants into high-quality food and physical work for the benefit of man. Furthermore, agricultural innovations diffuse much more easily along Eurasia's east–west axis than along Africa's and America's north–south axes, occupied by geographic and climatic obstacles. "Around those axes turned the fortunes of history" [3].

Our guide adds: "Whereas the food energy harvested per hectare per year by hunters and gatherers is only about 1 kWh, it amounts to more than 3,000 kWh for Indian wheat farmers, and nearly 80,000 kWh in Chinese intensive farming [4]. The energetic yields of agricultural technologies are the foundation of the preindustrial high civilizations around the Mediterranean, in Asia, northern Europe, and southern America. A time-compressed view of the energetics of these civilizations is the next part of the tour I have to offer."

1.3 Ancient Empires

The early agricultural societies unfold. Seven thousand years before the present they produce food surpluses that can satisfy an energy demand of 14 kWh per person per day. This liberates some of their members for specialization in crafts such as pottery, and the working of wood, stone, and metal. Craftsmen join the peasants. On these pillars rest the first agrarian high civilizations that rise about 5,000 years before the present. They develop an urban business sector, pronounced social strata, trade, art, and writing. Thus, farmers and craftsmen provide the energetic and technological means that empower the ancient empires of East and Southwest Asia, Egypt, Greece, and Rome.

In the agrarian societies economic and political power is with the land owners, because they are the ones who control the energy derived from the direct and indirect products of photosynthesis. In Latin, the original expression for cattle property, *pecunia*, assumes the meaning of "money" and "wealth." The land-owning nobility accumulates far-reaching political power. Feudalism becomes the dominating political system of the agrarian societies. It gains strength with the increasing energy demand of these societies, as they advance technologically, commercially, and militarily. In medieval western Europe, about AD 1400, the energy demand per person per day is 30 kWh. Despite their impressive cultural achievements, the agrarian civilizations are handicapped in their development by the limitations of the forces that can be derived from muscle power and by the low efficiencies of energy conversion in humans and animals. Inclined planes, pulley blocks, windmills, and water mills give some, but only limited help to surmount the biological barriers.

Abel explains: “The tractive power of a horse is about 14% of its body weight and amounts to about 80 kiloponds.[2] For deep plowing one needs 120–170 kiloponds, and for mowing 80–100 kiloponds. The average performance of a horse is 600–700 W, and a donkey provides 400 W. Thus, a winch, normally powered by four donkeys in order to provide mechanical work, has a performance of less than 2,000 W. A horse can perform work of 3–6 kWh/day, and for this it needs fodder with an energy content of roughly 30 kWh. Thus, its energetic efficiency is between 10% and 20%. The energetic limits of cross-country transportation are fixed by the need of a horse to eat one cartload of fodder per week. Therefore, it does not make sense to use a horse and wagon for the transportation of feed for more than a week. The energetic efficiencies of man and horse are similar. However, the average performance of man is only between 50 and 100 W, at most one seventh of the horse performance” [4].

With this information we understand the sad fate of peasants and slaves we observe during the 5,000 years between the first Sumerian, Babylonian, and Egyptian empires and the nineteenth century. Whenever huge armies invade a country in campaigns that last much longer than a week, they have to confiscate the food for soldiers, horses, and draft animals from the peasants of that country. Thus, in times of war, peasants are often robbed of all they have. The alternative to starvation is for the peasants themselves to join the armies.

Although humans are physically much weaker than oxen and horses, the combination of their muscle power with the skills of the human hand and the creativity of the brain is indispensable for all the sophisticated tasks involved in the construction of the pyramids, palaces, temples, and castles that inspire awe in many generations. Furthermore, the members of the nobility feel entitled to a lifestyle that corresponds to the splendor of the buildings they populate. Since it is energetically impossible for the few members of the nobility to provide the means for their luxurious lives themselves, they need huge armies of slaves, serfs, and bondsmen, deprived of rights, who labor for them in quarries, on construction sites, and most important of all, in the cultivation of land. When the apostle Paul writes his letter to Philemon on behalf of the slave Onesimus, about 25% of the population of the Roman Empire are slaves.

Slavery, and its modification socage, was the prerequisite of the impressive cultural achievements of agrarian societies. The glory of the few rose from the misery of the many.

Our vision zooms in on a narrow strip of land between the Lebanon mountains in the north, the Red Sea in the south, the Mediterranean in the west, and the desert

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[2] The technical force unit “one kilopond” is the force (weight) exerted on a mass of 1 kg by the gravitational field of Earth. It is equal to 9.81 N.