ENERGY, CREATIVITY, AND SUSTAINABLE GROWTH

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Keywords: Energy-Entropy Law, Wealth, Agriculture, Industry, Communications, Consumption, Resources, Energy Conservation, Non-fossil Energies, Gross domestic product (GDP).

Contents

Summary

Energy and matter from the stars, food and fuels from photosynthesis, and entropy export into space form the basic package of natural resources in the global life support system. Transitions between the three main epochs of human history, that is, the eras of the hunters and gatherers, farmers and artisans, and, nowadays, heat-engines and transistors, occurred when human creativity developed new means of energy conversion and opened up new energy sources. Since nothing happens in the world without energy conversion and entropy production, energy is the prime mover that, in autocatalytic cooperation with creativity, drives industrial growth along the road of technical progress—and entropy production in the form of pollution and resource degradation constrains that growth. Contemporary mainstream economics pays only marginal attention to these facts. Econometric analysis of industrial growth in Germany, Japan, and the United States exhibits energy as the powerful factor of production that activates capital and substitutes labor in the course of increasing automation. This creates wealth and problems of employment. The action of creativity manifests itself in structural changes and improvements of energy efficiency. Further such improvements and the tapping of nonfossil energy sources—presently more expensive than the combustion of fossil fuels—can support sustainable growth in agriculture, industry, and communications in the developing and industrial countries. The markets need boundary conditions that stimulate such growth and a just sharing of the wealth generated by energy and creativity. The ethics of solidarity and responsibility developed by the

higher religions can guide the necessary reforms, and the institutions to implement these reforms may grow out of the body of the United Nations.

1. Energy–Entropy Law

“Nothing happens in the world without energy conversion and entropy production.” This statement of the first and second law of thermodynamics summarizes humankind’s experiences with natural and technical processes since the taming of the fire. It is the most powerful law of nature and governs our lives in growth and decline. Life is founded on energy flows through ordered structures of matter and inevitably produces emissions of heat and substances, dissipating energy and matter and thus increasing entropy—the physical measure of disorder.

The challenge of sustainable development for a growing number of human beings, born equal with inalienable rights to life, freedom, and the pursuit of happiness, consists in the creative management of sufficient life-supporting energy flows at tolerable rates of entropy production.

The energy–entropy law indicates the growth constraints “natural resources and pollution” and calls upon a consideration of the basic *gifts of nature* in the global life support system. They are *energy and matter* from the stars, *food and fuels* from photosynthesis, and environmental quasi-stability by waste disposal via *entropy export into space*.

2. Gifts of Nature

The stars produce energy and all elements heavier than hydrogen by thermonuclear fusion. The Sun is rather typical of the 200 billion stars of our galaxy. It shines because every second it fuses 600 million tons of hydrogen into helium, converting the mass difference of 4.3 million tons into energy, which travels through space as electromagnetic radiation and delivers the power of 1.74×10^{17} W to Earth. About 30% of this is reflected back into space. Thus, the average power flow into Earth’s atmosphere is 239 W m^{-2}. When stars die they give birth to the elements heavier than helium. Contracting at increasing temperatures they fuse the nuclei of carbon, oxygen, calcium, and others up to iron, the most stable one. The fusion of still heavier elements, like copper, silver, iodine, gold, and uranium, does not produce but consumes energy, which may be provided by stellar explosions in novas and supernovas. Thus, the components of our bodies, like everything else on earth, have been processed through the inside of at least one star.

Photosynthesis in the chlorophyll of plants and algae converts the light of the sun into chemical energy, stored as sugar. Food and fuels have been provided this way since the beginning of biomass growth. Their chemical energy can be transformed into useful work by oxidization. Respiration, the inverse of photosynthesis, does this job in plants, animals, and humans, forming adenosine triphosphate (ATP), which serves as the universal energy currency in living systems. ATP is carried to those parts of the body where work has to be done, be it mechanical work of muscle contraction, electrical work when charges are transported, osmotic work when material is transported across semi-permeable barriers, or chemical work when new material is synthesized. According to Sybesma one can depict the controlled process of the biological energy cycle by the running of a series of water mills driving generators that charge batteries. When photosynthesis is compared to a solar-driven pump used to bring "water" to an elevated level using electromagnetic energy, respiration can be represented as the stepwise downfall of the "water" that drives the "water mills" charging the ATP "batteries." The "batteries" then can be transported to sites where action is needed; when properly connected, they are discharged and perform useful work.

Evolution has developed the energy economy within the bodies of the living species. Humanity has built its civilizations by mastering and controlling the extracorporeal oxidation process we call fire. Fire liberates the solar energy stored in wood and, all-important for modern industry, in ancient plants and organisms buried in the earth's crust where they became the fossil fuels.

About 300-200 million years ago, during the Carboniferous and Permian periods, photosynthesis and respiration made huge forests grow in warm, swampy freshwater regions. When the trees in these forests died they fell onto the swampy ground, piling up over many generations, each layer being buried by next year's debris. The whole mass of dead vegetation was overlaid by sediments of nonorganic material washed down into the low-lying swamps from the surrounding higher ground. Thus, sealed off from the oxygen of the air, it could not rot away, and a good part of the energy stored in it was conserved when it was squeezed and transformed into peat. When more layers of sediment piled up upon the organic deposits and these sank further down, coming under increased heat and pressure, they were further transformed, first into lignite (brown coal), then (hard) coal, and finally anthracite. The second peak of coal formation occurred in the Tertiary period, which lasted between 64 and 1 million years BP. Then the large deposits of lignite were formed. Oil and natural gas originated from the remains of plants and animals, especially plankton, laid down mainly in coastal regions near or under saltwater and eventually sealed off by sediments that built up to form new layers of rock. Over millions of years they underwent chemical changes similar to those which produced coal, and became the liquid and gaseous stores of solar energy that can be handled so conveniently.

When wood or fossil fuels are burned, entropy is produced. This entropy production consists of the emission heat and of substances like carbon dioxide, sulfur oxides, nitrogen oxides, dust, and others. These emissions change energy flows and the chemical composition of the biosphere to which the living species have adapted in the course of evolution. If these changes are so rapid that biological and social adaptation deficits develop, the emissions may cause severe damage and are perceived as environmental pollution.

Both Sun and Earth get rid of the entropic waste produced on them by the radiation of heat into space. This way they can remain in a quasi-stable state for a long time, which is the prerequisite for the evolution of life as we know it. Thus, entropy export into space is the other life-supporting gift of nature. Together with energy and matter it forms the basic package of natural resources. The influx of solar radiation energy supports entropy disposal on Earth, too. It drives the natural cycles and currents that, to a certain degree, restore to their initial concentrations the substances emitted by the processes of life and industrial production. Unfortunately, it is uncertain whether the natural mechanisms of entropy disposal will be sufficient in the future. The many billion tons of carbon that were incorporated into the fossil energy carriers during more than 200 million years will be delivered back to the atmosphere in the form of carbon dioxide within a few hundred years, if the intensity of the industrial combustion processes is not reduced from its present level of somewhat more than 10^{13} W of heat production. Such big and rapid inputs into the atmosphere cannot be readjusted by the natural cycles. Consequently, the warming radiation field wrapped around the earth by water vapor, carbon dioxide, and other infrared-active trace gases will increase in intensity, and because of this anthropogenic greenhouse effect ,drastic climate changes are to be expected in such a short time that the adaptation processes for human and nonhuman life may become painful. Even without the anthropogenic greenhouse effect climate changes have to be expected once the anthropogenic heat input into the biosphere exceeds a few per mille of the power radiated from the Sun to Earth. The Greek myth of Prometheus bringing the fire without being able to prevent Pandora from opening her box of evils gains new actuality. However, as in Pandora’s box, there is also hope. Human creativity may further unfold and make far-sighted, responsible use of the gifts of nature. The history of energy, technical progress, and the production of wealth has lessons for the future.

3. Energy and Technical Progress

Human history can be subdivided into three main epochs, each of which corresponds to a certain energy system with characteristic driving forces and constraints on economic, social, and cultural developments. Thus, energy is not just one factor among others, but the structure of its utilization impresses on the structure of society. The three epochs are the eras of *hunters and gatherers*, *farmers and artisans*, and *heat-engines and transistors*. Transitions from one epoch to the next occurred when creativity developed new means of energy conversion and opened up new energy sources. Ideas, inventions, and value-judgments are the manifestations of human creativity that determine the course of technical progress.

One million years ago primitive humans lived as gatherers of plants and fruit. This food provided them with energy of about 2 kWh (kilowatt hours) per person per day. Since the days of *Sinanthropus pekinensis* 400 000 BP, humans have mastered the use of fire. By 100 000 BP they had developed weapons, taken up hunting, and consumed 6 kWh per person per day; half of this energy was obtained by burning wood for cooking food and heating homes. The paleolithic societies of hunters and gatherers lived on the natural energy flows without changing them noticeably. Their use of biomass was essentially synchronized to its rate of new formation, save for the extermination of a number of big mammals during the last ice age. The decisive technical achievement was taming of fire. It was accompanied by efficiency improvements in hunting. Spears from fresh wood with tips hardened by fire killed very large animals, such as wood-elephants, which were twice as big as today’s elephants. The gain of food energy per working hour varied between <1 kWh from gathering plants and 11–16 kWh from hunting abundant big game. Correspondingly, the population density of hunter/gatherer societies varied between 1 and 50 persons per square kilometer.

The global era of hunters and gatherers ended 10 000 to 12 000 BP, when the present warm time with its stable temperatures terminated the last ice age, whose average temperatures were 4–5 °C below the present ones and, in addition, oscillated rapidly. Great progress in the utilization of solar energy drove the dramatic change and rise of civilization called the "neolithic revolution." Humans organized food production themselves by the domestication of plants and animals, replacing hunting and gathering by agriculture and the breeding of livestock, channeling more and more solar energy flows directly and systematically into the human economy as more and more land was dedicated to agricultural use. The early agrarian societies emerged 7000 BP with an energy consumption of about 14 kWh per person per day. They produced food surpluses, which liberated some of their members from food production so that they could specialize in activities like firing pottery, baking bricks, hewing stones, working wood and metals, and fashioning of garments. Artisans joined the farmers, and empowered by both of them the first agrarian higher civilizations blossomed, with urban business centers, trade, art, writing, centralized government, and distinct social strata. Wood was the principal fuel. For most of the time it also served as the universal raw material. Technical progress was also made in metallurgy—the melting and working of metals using fire. The scarcity and high production costs, however, limited the application of metals essentially to the transfer of forces by weapons and tools. When the iron sickle replaced the flintstone sickle the efficiency of harvesting increased substantially. Domesticated large mammals, like cattle, horses, donkeys, water buffaloes, camels, and llamas, which converted the chemical energy of plants into muscular strength, enhanced the power available to humans by nearly an order of magnitude. For instance, the average power delivered by a horse is between 600 and 700 W, whereas that of a man is just 50–100 W, at comparable energetic efficiencies of between 10% and 20%. Animal power could be used for the transportation of people and cargoes, the lifting of weights by winches, and drawing plows. The energetic limits to animal services are indicated by cross-country transportation: a horse consumes one wagon-load of fodder within one week. Thus, it did not make sense to transport fodder by horses and wagons for more than a week. Moreover, the limitations of muscle power resulted in severe social repercussions. The high cultural achievements of agrarian civilizations that we still admire today required huge amounts of work by the human hand, guided by the human brain. But, a single person can deliver at most 100 W. Therefore, agrarian societies needed masses of slaves and serfs, deprived of rights and forced to build the pyramids, temples, palaces and castles, and, most importantly, to cultivate the land to harvest solar energy from plants; it was they who enabled the few members of the feudal ruling elite to live a life of comfort comparable to that enjoyed by most people in the industrial democracies today. In medieval western Europe, in about AD 1400, the average energy consumption per person per day was close to 30 kWh.

People began to use water power for rafting timber and driving mills. The mills ground cereals, operated foundries, and delivered mechanical work for a variety of purposes via shaft-drives, belt-drives, and wheels. The small pressure resistance of wood and its high abrasion limited the distances of power transmission to about 1000 m. Windpower became most important for long-distance transportation by sailing ships. While the higher civilizations of Asia, superior to those of Europe in a number of fields and equal in economic and military power until the beginning of the sixteenth century, constrained themselves to coastal shipping, the Europeans developed the ocean-going sailing ships that with increasing efficiency used the solar power of the wind between the fifteenth and the twentieth centuries and spread European civilization all over the globe by trade and guns. How different the world might be today if the Chinese, who had discovered gunpowder 500 years before the Europeans, had not restricted their use of it to fireworks but had decided to send sailing ships with firearms across the oceans.

The Industrial Revolution burst the chains that tied the economy to the variable solar flows and their collection by the production factor of land. This created the energetic preconditions for the decline of agrarian feudalism and the rise of industrial democracy. The promises of the American constitution and the French revolution could be realized, because energy slaves replaced human slaves and serfs in the production of wealth. Nowadays, heat-engines and transistors, powered by the combustion of fossil fuels and some fission of uranium, provide every person in the industrial democracies with energy services that quantitatively are equivalent to those of 10 to 30 hard-laboring people, and qualitatively go far beyond the luxury that feudal lords could ever afford or imagine—just think of flying and telecommunications.

Huge armies of energy slaves create our wealth. It all started in England with the steam engine, developed by James Watt from Newcomen's steam pump in the middle of the eighteenth century. It was first used to pump water from the coal mines, thus making possible the exploitation of energy reserves not accessible before. As coal became cheaper and cheaper it could be afforded in more and more areas of production. It powered the steam engines driving the spinning and weaving machines of the increasingly mechanized textile industry, and the trains of the rapidly expanding railroad system. It substituted charcoal in the blast furnaces. Iron became so cheap that it displaced wood from many of its applications. The rich world of iron technology unfolded, and the many branches of mechanical engineering emerged. New building materials like Roman and Portland cements were found. Coal and iron were the catalysts of the industrial transformation of first England, then continental Europe and North America. Human creativity had opened up the treasure of the cheap fossil energies, and these, in turn, stimulated new discoveries and inventions.

Since then the autocatalytic cooperation of energy and creativity has been driving the industrial growth engine in the positive feedback loop of declining costs and increasing demand. The steam engine has become obsolete, to be replaced by the much more efficient modern heat-engines: steam-turbines, gas-turbines, petrol engines, and diesel engines. They move ships, aircraft, trains, trucks, cars, bulldozers, cranes, combine harvesters, and many other machines that have liberated humans from tough physical labor. They drive power plants and all the electric devices connected to them, like machine tools, refrigerators, radios, and computers.

During the first half of the twentieth century the electronics industry grew so rapidly that one could figure out when the electronic valves in its products would consume all electricity output. Hence Bell Laboratories started the search for a more energy-efficient electronic control device, and John Bardeen, Walter Brattain, and William Shockley developed the transistor between 1946 and 1948. The transistor has replaced electronic valves, relays, and mechanical switches in information processing and the switching of energy flows. Much smaller both in size and demand for electrical energy, transistors operate the global computer network that interconnects heat-engines and people in the generation of wealth by work performance and information processing. The limit to transistor density in this net, and thus to the intensity of increasing automation, is drawn by entropy production in the form of waste heat, into which the resistors of the transistors convert electricity. If this heat cannot be disposed of sufficiently rapidly by thermal conduction the transistor complex will melt down. The fossil fuels, torn from the earth with the help of the heat-engines, also power the furnaces that heat homes and provide the process heat for the chemical and metallurgical industries. In 1995 primary energy consumption per person per day was 133 kWh in Germany and 270 kWh in the United States (this corresponds to a total of about 40 and 90 energy slaves per capita in Germany and the United States, respectively).

The history of energy use and technical progress indicates a close interrelationship between them. Human creativity and the gifts of nature have made possible developments that, in the 50 or more years of peace among the industrially advanced nations since World War II, has led to a Golden Age for their peoples unprecedented in history. Justly, the other peoples on earth aspire to the same. A quantitative analysis of the production of wealth may be helpful in finding the proper path.

4. Wealth

The wealth of nations is traditionally measured by their gross domestic product (GDP). This is the monetary value of all goods and services produced in a country during one year. Growth of GDP is the aim of economic policy everywhere.

There has been some criticism of considering GDP also as a measure of the quality of life, because in an industrial country the GDP includes, for example, all services and goods required to mitigate the effects of traffic accidents or cure diseases from pollution, whereas in a tropical island republic it does not include the joy of moving leisurely in a warm breeze among lush flowers and colorful fish. Nevertheless, people like to live in countries where a high GDP per capita indicates that the average individual commands a rich consumer basket of material goods and services. The increasing migration from the warm "South" of low GDP per capita to the cold "North" of high GDP per capita demonstrates this. People agree in general that the "North" is better off materially than the "South," because it uses technology and natural resources more intensively. It is important to understand in detail how this happens, and if and how it may continue in the future.

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Biographical Sketch

Professor Reiner Kümmel was born in 1939 in Fulda, Germany. He studied physics from 1959 to 1964 (Diplom-Physiker) at the Technische Hochschule, Darmstadt, and then became assistant to Professor Otto Scherzer at the Institute for Theoretical Physics from 1964 to 1965. From 1965 to 1967 he worked as research assistant to Professor John Bardeen in the Physics Department of the University of Illinois, Urbana, United States. He graduated in 1968 (Dr.Phil.Nat.) and was assistant to Professor Peter Fulde at the Institute for Theoretical Physics at the University of Frankfurt am Main. Between 1970 and 1973 he was Assistant Professor and Associate Professor in the Department of Physics at the Universidad del Valle, Cali, Colombia, under the auspices of the German Academic Exchange Service and the

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