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ENERGY AND ENVIRONMENT IN TERMS OF EVOLUTIONARY ECONOMICS*

by

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I. Evolution and Energy[1]

The regularities prevailing in physical systems, in particular those concerning the flow of energy between and within the systems, constitute a central theme of evolutionary theory. This applies both to the theory of biological evolution and to theoretical ecology (a discipline concerned with the macrophenomena of biological evolution). As early as 1908, the chemist, natural philosopher and Nobel laureate Wilhelm Ostwald realized that life as such can be understood as a permanent competition for the limited availability of free energy [Ostwald 1923]. Like all complex structures, the existence of living organisms is dependent on the supply of energy as a prerequisite for metabolism to take place. For living organisms, the necessity of energy supply follows from a thermodynamical disequilibrium: man, for example, has a body temperature of 36.6°C, whereas the average ambient temperature in Central Europe is as low as 10°C.

Another reason for the energy demand of a system results from the requirements of the reproduction process: it is based not only on the transmission of information, but also on the accumulation of energy bound in organic substances (growth of biomass). The resulting changes in organic matter constitute the impetus for the rapid succession of mutations and fluctuations of biological structures; without these alterations, higher forms of life could not have developed within the relatively limited period of time available in the history of evolution. Finally, active and passive resistance to threats and dangers, *i.e.*, the response to the challenges of continuously changing conditions, also requires a certain input of energy.

The development of ordered states and structures is the essential feature of biological life and biological evolution. Ludwig Eduard Boltzmann was the first to prove in 1886 that living structures essentially rely on using free energy in order to resist the regularities of the Second Law of Thermodynamics. 85 years later, Georgescu-Roegen [1971] provided the following formulation of the question under discussion, along with an economically relevant answer:

> Given that even a simple cell is a highly ordered structure, how is it possible for such a structure to avoid being thrown into disorder instantly by the inexorable Entropy Law? The answer of modern science has a definite economic flavor: a living organism is a *steady-going concern* which maintains its highly ordered structure by sucking low entropy from the environment so as to compensate for the entropic degradation to which it is continuously subject. [Georgescu-Roegen 1971:191-192.]

From the point of view of the system as a whole, this results in a complex pattern of energy flows whose essential structural features can only be described and modelled with a high degree of abstraction and simplification. This is one of the topics studied within the domain of ecology. In general, ecologists presume externally predetermined changes such as climatic changes or anthropogenic influences, thus enabling the process of change taking place within the system to be simulated numerically on the basis of a number of assumed or well-known behavioral reactions. Thus, data can be obtained on questions as to where harmful substances will concentrate and how the ecological structure will change through selection and mobility. In some cases, the mathematical results can be verified by experiment. It is not possible, however, to anticipate the effects of mutation – or, for example in economics, to predict the impacts of innovation or the timing and direction of "bifurcations". Thus, the structural evolution of an ecosystem is only partially predictable.

From the viewpoint of an individual organism, however, the energy problem appears to be different. For the individual, access to free energy supplied by the environment always entails certain expenses, or *costs*; thus, in spite of a theoretically abounding energy potential, energy is a scarce commodity. Therefore, it is an essential prerequisite for maintaining its vital functions that each individual organism should accomplish the exchange of energy and matter with the environment efficiently, *i.e.*, at an expense as low as possible. In economics, efficiency can be measured on the basis of the costs involved, *i.e.*, the input evaluated at market prices. This, however, requires the free development of competitive market prices, unaffected by any misallocations of proprietary rights and the resulting external costs – an essential prerequisite for ensuring the system's supply requirements which would otherwise be jeopardized by the depletion or destruction of its available energy resources. Such a supply guarantee depends on the following condition: an individual or the whole species must be capable of adapting itself with sufficient flexibility to alternative sources of supply in case certain food and energy supplies should be lost. Thus, adaptability – adjustment combined with flexibility and mobility in ecological niches – is the vital strategic skill in surviving supply problems and shocks. It is only to a modest extent that nature resorts to the strategy of making provisions (*e.g.*, stockpiling food supplies) for critical times, thus supplementing and extending the scope of action and reaction.

Characteristically enough, the methods applied by a biological system for producing, storing, and using energy rank among the most essential and distinctive features of the various species in that they determine their respective stages of development in the evolutionary hierarchy. This shows quite clearly that the development of a biological system is essentially linked to the changes and developments taking place in the energetic subsystem concerned. In this context, it makes no difference whether migration or substitution are called forth by a sudden shortage or depletion of the source of energy used so far or whether other factors are involved as well: the changing environmental and overall conditions, including endogenous developments such as the growth of its own population, inevitably initiate a process of search and experimentation aimed at seeking out newly formed ecological niches which provide a relative optimum of energy supply. After passing through one or more phase transitions, the overall system may eventually rely upon these niches for balancing its energy requirements (*i.e.*, as soon as the original energy supplies run short).

As a rule, the individual search processes lead to different results since there are various approaches providing solutions to supply problems. What kind of long-term chances and risks these balancing processes entail, cannot be anticipated during the phase transition as such. In retrospect, some developments turn out to be an ecological deadlock. This already proves the necessity of heterogeneous behavioral response on the part of the individual: the chance of survival presupposes the experiment, along with the risk of its failure. The species as a whole is sustained by its successfully innovating individuals.

The evolutionary point of view is particularly suited for describing the relationships between an open system and its energetic subsystem. The same applies to the economic system. According to this interpretation, the development and the balancing processes of the economic system show analogies with corresponding biological and ecological processes: the economic system, too, is a highly complex system which finds itself in a state of disequilibrium with its environment and which can therefore only be maintained on the basis of a certain energy input. Thus, the methods of energy production and use constitute an important criterion for assessing the viability of an economic system. Once again it is worth noting that it is not the scarcity of energy resources which is the decisive factor, but rather the efficient use of energy – from its supply to its final consumption. Table 1 shows the energy potential available to mankind.

Table 1: Energy potential (energy storage) in evolution

	potential (TWyr)
short–term storage	
hydro power	5
wind, waves and tides	350
biomass	1 000
long–term storage	
fossil energy	15 000
fission of uranium (conventional technology)	> 250
fission of uranium (breeder technology)	14 000
By comparison: The present rate of energy consumed throughout the word amount to 14 tera-watt–years (TWyr) per year (world energy consumption).	

Source: Based on data from Taube (1988: 260f.)

2. The Problem of Energy and Environment in terms of Evolutionary History

The development of human society from the age of gatherers and hunters to our modern industrial society is characterized by increasing settlement densities, by a growing per–capita energy consumption, and by the use of higher energy densities.

The dimensions of the first two factors are shown in Table 2.

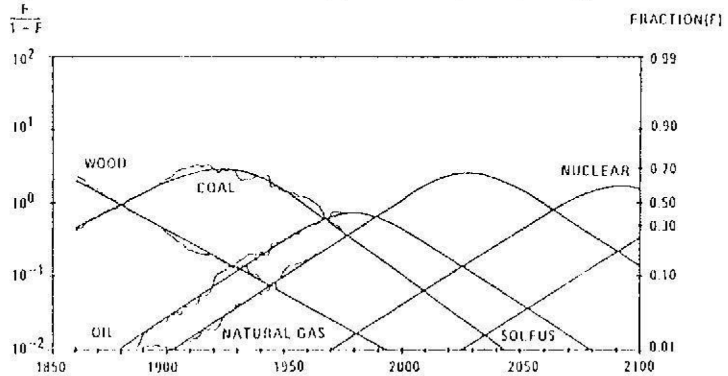
Table 2: Development of energy consumption and population density

	population / *km²*	*kW* / *capita*
gatherers and hunters	2.5	ca. 0.1
agrarian societies	25	ca. 1.0
industrial societies	250	ca. 10

Source: By the author's own calculations.

According to the substitution process studied by Marchetti/Nakicenovic [1979], McDonald [1981], and Marchetti [1985], the market penetration of a new energy carrier will invariably take place *before* the energy carrier dominating so far becomes completely exhausted (see Figure 1). As mentioned above, this process of replacing diminishing primary energy sources by new supply options is characterized by a transition from energy sources with low energy density to those with high energy density. Measured in eV, the dimensions are approximately as follows: 10^{-6} (wind and water power), 10^{0} (molecular power), 10^{6} (nuclear power). In terms of the technical options available today, the range of energy densities accessible to man covers twelve (!) decimal exponents.[2]

Figure 1: Fractional market shares (F) of various primary energy sources



Source: Adapted from *McDonald* [1981:16].

3. Energy Use and the Increase of Entropy

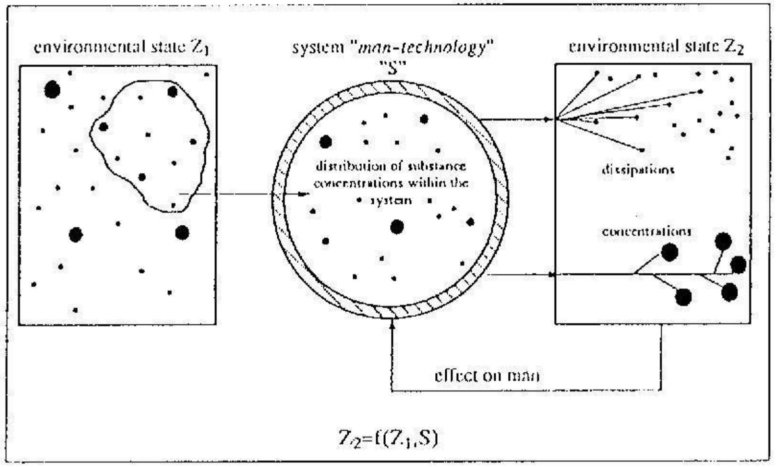
Due to the validity of the Second Law of Thermodynamics, the creation of ordered states within a subsystem is necessarily associated with increasing "disorder" in the surrounding systems. Accordingly, the creation of ordered, controllable states – *e.g.*, in the economy – will invariably result in "disorder" in terms of increased entropy in the surrounding subsystems – *e.g.*, in the environment. In other words, economic growth as a structuring process will impose a strain on the surrounding systems (environment) in that it creates "disorder" (increase of entropy).

In this context, it should be pointed out that such a process does not necessarily result in the destruction of those segments of the environment which are important to *human* life. Even if it should be possible to handle the material flows in such a way that dissipation into surrounding environmental subsystems does not occur (*e.g.*, by avoiding such dissipations or by establishing non–dissipating sinks), such a process would still result in "disorder" in the surrounding systems; however, again according to the Second Law of Thermodynamics, that "disorder" would only manifest itself in *waste heat* released at the end of the chain of energy utilization, *i.e.*, proceeding from high–density energy to lower–density energy. We are still far away from an economic process organized in such a way. But it is feasible. What we need is: more *energy*, more *knowledge*, and more *capital*.

With regard to their emission densities, the material and energy flows released by a system suggest three basic relationships. First, the emission of substances may effect dilution or rarefaction as compared to the source. For example, carbon dioxide released when burning fossil energy carriers diffuses into the atmosphere, thus being rarefied as against the source. Second, substances taken from an outside system may concentrate in the emitting system. Various biological systems accumulate the substances existing in surrounding systems in diluted or rarefied form in order to return them to the same system in concentrated form. This often implies sophisticated chemical and physical processes, as, for example, in the case of a system emitting laser light, or with plants and fungi containing substances that are poisonous for man in the given concentration. Third, it is also conceivable that the system returns concentration–neutral, *i.e.*, constant, material flows to the environment: if the concentration pattern of the substances taken in by the system is equal to the concentration vector of the emitted substances, the concentration structure of the overall material flows between the environment and the system remain unchanged; in other words, the material flows between the systems involved are balanced.

In general, any system – be it an organism or an economic system – selects a suitable subset from the "mix" of concentrated *and* dissipated substances in the environment (environmental state Z_1) and transforms it into that "mix" which is essential for maintaining its own living conditions. Subsequent to the material throughput, the system releases a certain "mix" (vector) of partially dissipated substances into the environment. It is possible – but by no means certain – that this new ratio between concentrated and dissipated substances in state Z_2 of the environmental system has harmful repercussions on the causative system "*man – technology*". Figure 2 illustrates this relationship.

Figure 2: Repercussion of the system "man – technology" on the environment



Source: Translated from *Fritsch* [1991:204]

One of the reasons why dissipations, in environmental terms, are considered to be more important than concentrations, lies in the fact that concentrated substances can be handled and controlled more easily. It is far more difficult to ascertain and to monitor if and how dissipated substances accumulate as a result of physical processes occurring in the various spheres (lithosphere, hydrosphere, and atmosphere) – without man's energy activities – and if and how they might react on vital processes of the causative system from as yet unknown "depositories"; for concentrated, storable substances, for example in the case of the final storage of radioactive waste material, this turns out to be much easier.[3]

However, the waste heat mentioned above must not be confused with the greenhouse effect. The greenhouse effect is known to be caused by changes in the content of the atmosphere, in particular as a result of increased levels of CO_2; it involves different physical properties. In contrast, the use of energy in terms of final energy consumption proceeds from the utilization of higher–density energy towards the utilization of lower–density energy which is ultimately degraded to nonusable waste heat. Under equilibrium conditions, the relation between the final energy consumption (measured in watts) and the waste–heat–related temperature increase is around 3,000 terawatts to 1°C (see calculation in Appendix).[4] At present, we consume less than 14 terawatt–years per year; physically, we are thus in a position to handle the material and energy flows in our economies in such a way that with moderate or even constant rates of energy consumption, along with adequate organizational and technical measures, economic growth remains possible without environmental perturbations. A waste–heat–related temperature increase by 1°C would take place only if the present worldwide energy consumption were increased by a factor of 250 (!) – a development that is hardly to be expected. Thus, the cold outer space turns out to be an ideal sink. In other words: economic growth is not restricted by the undisputed validity of the Second Law of Thermodynamics, but rather by our capability of handling the material flows in such a way that they do not have negative repercussions on our living conditions *on earth*.

4. The Special Role of Electricity in Evolutionary Economics[5]

Already Lenin realized that electricity constitutes a special form of energy apt to call forth structural changes that may have repercussions on social systems. The following quotation is said to be by him: "Soviet Power plus Electricity = Communism". Today, we might reformulate this visionary statement: "Democracy plus Electricity = Human Society". Lenin could not anticipate the crucial importance of electricity in fields of application such as electronics, computer design and modern laser technology. His far–sightedness is all the more remarkable.

There is no exaggeration in saying that for current structural changes in the economy, the availability and use of electrical energy is of similar, if not greater importance than was the availability of fossil fuels, in particular coal, in the early phases of the Industrial Revolution. The qualitative aspects of electricity, which account for its structure–shaping effects, were studied at length by Erdmann [1989b], Erdmann/Fritsch [1989a], Spreng [1988; 1989b] and by various authors in Schurr/Sonnenblum [1986] and other publications. Electricity has the following *advantages*:

- Electricity is not dependent on a material carrier, but constitutes the energy of the electromagnetic field. Thus, no waste material is left where electricity is used. Comparable advantages are offered only by long–distance heat systems and solar collectors: as with electricity, both technologies are based on the principle of closed circuits with go–and–return lines. "Clean" secondary energy carriers are not only relevant in terms of environmental protection and human engineering; they also constitute an inevitable prerequisite for the technological advancement of modern information societies.

- Unlike all other forms of energy, electrical energy virtually has neither mass nor volume so that it can be easily switched on and off. Consequently, electricity allows of precise dosage and control operations for all kinds of application. In particular, the user–oriented *switch on/switch* *off*-advantage is highly important in those fields of application which require instantaneous and exact control operations: microprocessors, transfer systems, computer-aided engineering, computer-aided manufacturing and other high-tech applications are inconceivable without these qualitative properties of electrical energy.

- Another qualitative advantage is the fact that electrical energy is effective without any direct or immediate physical contact. This accounts not only for cost advantages in terms of reduced wear phenomena in electromechanical appliances (engines and relay control systems), but also for well-known applications based on electromagnetic waves (broadcasting), supersonics, microwave heating, induction heating etc. Technologies of the future, with a development potential that can hardly be assessed today, rely on the electromechanical deformation of materials – a process allowing for the formation of entirely novel structures.

- Compared to thermal interactions, electric interactions with matter show only minor undesirable side effects (*e.g.*, heat, magnetic field). In general, the less serious the undesirable interactions, the less cost-effective are the devices for eliminating or controlling these interactions.

- While the release of energy caused by fossil combustion processes produces random, unordered movements of molecules, electricity is based on the ordered concurrence of electrons. This is often referred to as entropic quality, or *exergy*. Its advantages are of particular importance in the field of electrolysis and in laser technology.

- At present, laser technology is undergoing a remarkably rapid development. With about 2 percent, optical laser appliances show a very low rate of efficiency, but this does not detract from their growing application: scanner/terminals are increasingly used in connection with cash registers in department stores; laser printers are popular computer output devices. Equally, new medical applications (laser beams) and innumerable applications in the fields of industrial precision manufacturing (higher quality), laser chemistry (new products), distance measurement, marking, miniaturization (saving of material) and data transmission (glass fibre cable) as well as materials processing with laser beams are technological advances worth mentioning.

- Another important property of electricity is the fact that the energy density of a carrier medium is not limited by thermodynamical constraints. In fossil combustion processes, the maximum temperature is dependent on the adiabatic flame temperature of the chemical reaction involved; in general, it does not exceed 1,650°C. In contrast, the temperature levels achieved on the basis of electrical energy are only limited by the temperature resistance of the surrounding containment; in gaseous media, the temperature can reach some 10,000°C (electric arc heating). Already today, this property is made use of for the purpose of special refuse disposal by means of high-temperature combustion; moreover, it is applied in the process of manufacturing extremely pure metal alloys.

- Finally, the qualities of electrical energy include the technical feasibility of extremely high product homogeneity. In Switzerland, network variations amount to less than 5 percent for voltage and less than 0.1 percent for frequency since advanced mathematical and technical processes are used for monitoring complex networks. It is due to this property – which should by no means be taken for granted and which is not attained in numerous countries using antiquated technical processes – that the successful application of modern high-efficiency technologies can be ensured.

These advantages offered by electrical energy should be set off against the following *disadvantages*:

- Insufficient direct storability for long periods of time, in particular in view of the large energy amounts required for electricity supply. For this reason, the capacity of electricity generation must be designed for peak loads demanded only during some few hours of the year. Pump-fed power stations may compensate for daily peaks by pumping water during off-peak periods overnight into elevated storage reservoirs from where it can be discharged during the day in order to meet peak demands; so far, however, economical storage technologies allowing for the compensation of seasonal load variations are not yet available, except, perhaps, for hydrogen technologies which, for the time being, have to be considered theoretical options because of the high costs involved [see *Winter/Nitsch* 1986].

- No reasonable possibility of transporting electrical energy over long distances. True enough, there is no alternative energy form that equals electricity in providing comparable inexpensive transport conditions for short distances, but for longer distances of around 1,000 km, the line and transmission losses of a 380 kV transmission line amount to about 10 percent. Even in the case of modern high-voltage d.c. transmission (HVDC), line losses over this distance are still as high as around 5 percent; in addition, considerable investment costs for HVDC towers have to be taken into account.

- Social and political problems of acceptance. In many industrial countries, the most economical processes for electricity generation encounter social and political resistance. This is true for both fossil-fuelled thermal power plants (air pollution control, disposal of filter dust) and nuclear power plants (radiation risks, problems of final disposal); even hydropower is no exception (landscape conservation and technical risks associated with large water reservoirs). Obviously, however, the political handicap of electricity is limited to some few relatively rich industrial countries. Already in industrial countries with average income, the attitude of the general public towards capacity extension is much more favorable. If the pressure exerted by the public should continue, it will be impossible in the long run to avoid a considerable increase in the price to be paid for this form of energy.

The qualitative superiority of electrical energy refers less to the generation of this form of energy but rather to its use: the energy user may benefit from a number of major advantages. On the other hand, the disadvantages mentioned above constitute an important reason why, in the foreseeable future, electrical energy will not possibly become the *only* form of energy to be used in the service societies to come. At the same time, these drawbacks are a challenge to make stronger research efforts in terms of energy technologies: hydrogen as a medium for electricity storage, high-temperature supraconductors, high-energy laser, safe and economical processes for electricity generation on the basis of nuclear and solar energy sources, and improved efficiency in electricity applications constitute major R&D-tasks of today.

Thus, our intermediate conclusion can be summarized as follows: It is not so much the quantitative aspects of electricity supply that assign a decisive role to electricity in the structural change taking place in our socio-economic system, but rather the *qualitative* aspects mentioned above. This means reorientation for all those who have so far measured energy in tons of coal equivalent or in kilowatt-hours and who are at best interested in its monetary results (physical amounts multiplied by prices).

5. The 'Form Value' of Electricity

The term 'form value' was coined in the American literature to refer to the economic characterization of the qualitative properties of an energy carrier. Schmidt [1986:200], who was one of the first writers to use this term in his research studies, suggests the following definition of 'form value': "the inherent economic value of a commodity resulting from the exploitation of its unique intrinsic properties in the production process". A more precise definition of this term is based on the following consideration (see also *Berg* [1986]): Take, for example, a technology that relies on the use of a certain energy carrier. Even under conditions of optimum technological design, the production process based on the respective technology always involves irreducible costs in terms of the particular energy carrier used. These costs can only be avoided if the first technology is completely replaced by an alternative technology based on another energy carrier or another property of the same energy carrier, *e.g.*, by substituting halogen or laser bulbs for conventional light bulbs. Thus, on the one hand, the form value of an energy carrier depends on the task to be solved, and on the other, on the availability of technical processes that, using properties of other energy carriers, constitute potential, theoretically well–known and economically feasible alternatives. Correspondingly, a breakthrough in research and development tends to have considerable impacts on the form value of energy applications.

The following example may illustrate these considerations. Steam locomotives – historic relics by now – received their power from the combustion of coal. The specific irreducible costs associated with this form of energy application include the fact that the boilers had to be preheated a long time before the departure, that water and coal had to be entrained and continuously supplied in increasing or decreasing quantities, that consequently, in addition to the engine driver, a heater was required, and that thermodynamic laws and technical constraints only allowed a small efficiency ratio (less than 10 percent) and required sophisticated engineering details. Part of these costs were avoided by substituting diesel locomotives for the old steam locomotives, thus assigning a form value to the new technology as compared with the combustion of coal. These costs can be further reduced by using the electromotor, although such a transition necessitates considerable infrastructural adjustment efforts.

In terms of economics, the form value of an energy application constitutes a positive external effect. The price of an energy carrier will always correspond to the opportunity costs of one single form of application: the form value is zero. In this context, the application of the energy carrier is referred to as marginal. In contrast, there are also numerous energy applications with a positive form value, since the needs and benefits to be met by a particular energy carrier are extremely diversified and heterogeneous. This is especially true for electricity.

To simplify matters, let us assume a constant technological know–how in order to obtain a model assessment of the form value associated with a particular form of energy application. In a world without technological progress, the competitive process will eventually lead to the optimum application of the existing know–how and the technology involved until equilibrium conditions are attained. In this situation, the price of an energy carrier is equal to both the marginal profit of its marginal application and the marginal costs of its supply (*optimum optimorum*). If the relative price of this particular energy carrier increases, its application becomes uneconomical, as defined above. In the long run, therefore, it will be replaced in the market. In spite of this increase in price, however, all the other applications of this particular energy carrier are retained until the marginal application is reached. From that moment on, the form value of this energy application has vanished. Should the price continue to rise, this application, too, will be driven out of the market. In other words: in the absence of technological progress, an assumed form value will be fully used by the market participants. Thus, the form value proves to be essentially a phenomenon of disequilibrium.

The form value of electricity is linked to technological progress in that it not only allows for its full usage, but also encourages further technological advances. Thus, the essential economic function of the form value of electricity lies in the fact that its development and use will eventually "break up" the existing production structures. This can be illustrated with historical evidence as provided by Devine [1983] and other writers. According to Devine, the dramatic changes in industrial production processes in the early twenties of this century were linked to the introduction of electrification and the resulting possibility of using electric motors in industrial manufacturing. Previously, the power required in the factories was supplied by central heating stations. It was distributed to the various workplaces via shafts and belts, so that the organization of the premises was restricted by the geometry of this form of energy distribution. Moreover, changes concerning individual workplaces often required plant–wide shutdowns. With the gradual introduction of electromotors around 1920, these constraints and costs could be avoided, *i.e.*, the form value of electric motors was economically used. Although at first only some few innovative companies took advantage of the new situation, competition rapidly resulted in both the propagation of its benefits to the consumers and the development of new marketable products that would have been inconceivable without the innovations triggered off by the electromotor. An outstanding example is the assembly line production of passenger cars.

At this point of the argumentation, it is worth clarifying some misunderstandings and wrong conclusions which are typical of debates on energy policies. The "break–up" of configurative production chains as described above was not primarily linked to more efficient forms of energy application (in quantitative terms). Undoubtedly, electromotors reduce previously unavoidable losses due to friction or start–up and power–down procedures so that part of the energy is saved and substituted for by capital and technical know–how. Similar effects are to be expected for electricity applications such as laser light, supersonics, microwave–heating, arc heating, electrolysis, membrane separation and many other modern technologies. It would be wrong, however, to consider the energetic gains achieved in terms of efficiency as the decisive element in making technical and economic innovations. The crucial point is the fact that progress implies not only productivity improvements in terms of the factor *energy*, but also productivity improvements in terms of *all* production factors (labour, capital, soil, raw materials, *and* energy).

Starr [1989:4] describes the overall economic effect of technologies based on electricity as follows:

> Electricity–based technologies have served to raise the net economic productivity from all factor inputs, including energy. In many cases this productivity improvement is so large as to make the relatively high cost of electricity in energy units a secondary issue. This phenomenon can be attributed to the unique 'form value' of electricity, the critical qualities of which have been described as 'precision in space, in time, and in scale'.

Quite recently, a number of contributions to energy discussions have equated the claim for ensuring economical energy applications throughout the economy with the objective of "energy conservation at any price" (*i.e.*, subordination to the objective of overall economic efficiency). This, however, proves to be a superficial approach. Rather, the economical use of energy means achieving *overall economic* productivity at the highest possible level (minimization of production inputs evaluated at factor costs per unit of output). The historical examples mentioned above as well as new developments indicate that the exploitation of the form value is an important prerequisite.

In this context, Schumpeter's innovative entrepreneur plays a central role. For him, an increase in productivity linked to a particular innovation means the chance of achieving transitory, *i.e.*, temporarily profitable, differential rents by taking advantage of the form value. Although the percentage of energy costs invested into the production process may be small, the profit potential for the initial user will turn out to be a multiple of these energy costs if the form value of innovative electricity applications corresponds to a multiple of the direct energy costs. Thus, the potential of a particular energy application with a positive form value is not limited by the energy costs involved.

Considering the qualitative properties of electricity as described above, it is not surprising that in most countries, the consumption of electricity has increased more rapidly than the gross domestic product (see Table 3). At the same time, the consumption of final energy per national product unit has decreased. It is reasonable to assume that this decrease of energy intensity is mainly due to the substitution of electricity for other forms of energy. The growing importance of electricity and the expected increase in demand have been studied in detail [Fritsch 1991]. Moreover, due to its qualitative properties described above, electricity also exerts an important influence on the technical and economic structure of the social system. Thus, there is an interrelationship between electricity demand and the technico–economic structure of a society: on the one hand, the technico–economic system develops a certain demand for electricity, and on the other hand, this demand – and the structural change involved – is directly affected by its electricity supply system. Therefore, the importance of electricity to communication–intensive and complex industrial societies will not decrease, but rather increase.

Table 3: Electricity Consumption per unit of gross domestic product (in tons of oil equivalent (toe) per 1 million US$, with prices and exchange rates in 1980 US $)

	1960	1970	1980	1985	1988
USA	42	57	65	62	62
Canada	82	93	98	104	105
Japan	33	40	42	40	40
France	19	22	27	30	31
Germany	21	29	34	35	34
Italy	21	27	30	30	31
Great Britain	28	40	38	36	35
Switzerland	24	24	30	33	32
OECD	33	43	49	49	49

Source: By the author's own calculations, on the basis of OECD data [*OECD* 1988; 1990]

Synergetic effects, supply advantages, and demand–led supply situations, along with the resulting additional demand stimulations – these and similar phenomena can be represented in a model on the basis of simplified assumptions, for example in the form of nonlinear differential equations. The following chapter presents a tentative approach, describing the special role of electricity, in particular its 'form value' aspect, within the broader context of evolutionary economics.

6. A Model Approach

In his study of individualistic phenomena underlying evolutionary economics, Witt [1987] points out that it has not yet been clarified which kinds of algorithms are suited to cover evolutionary facts. Many phenomena imply nonlinearities – *e.g.*, the development and use of market niches due to technical innovations, the self–organized formation of new market structures and, last but not least, the mutual influence of the market participants in their properties as both consumers and investors. The phase transitions involved in these nonlinear systems and the corresponding topos of stable and instable points of reference can be simulated by means of the methods available and represented in two–dimensional or three-dimensional diagrams (see, for example, Weidlich [1991]). Based on the formalism of the master equation, the problem under discussion can be modelled as follows:

Our simple model includes four variables.

For the demand side:

D_1: Percentage of the demand for energy carriers with a low form value, *i.e.*, relatively low electricity consumption as compared to total energy consumption.

D_2: Percentage of the demand for energy carriers with a high form value, i.e., relatively high electricity consumption as compared to total energy consumption.

For the supply side:

S_1: Percentage of the supply of energy with a low form value as compared to total energy production. (A relatively low S_1 may be the result of slowing down the supply of electricity, e.g., via political measures.)

S_2: Percentage of the supply of energy with a high form value as compared to total energy production. (A relatively high S_2 may be the result of an expansive nuclear policy – as is the case in France.)

Due to the identities of

$$D_1 + D_2 = 1$$

$$S_1 + S_2 = 1, \tag{1}$$

the system can be reduced to the analysis of the two variables D_2 and S_2.

On both the demand and the supply sides, the dynamics of the model relies on changed patterns of individual behavior. On the demand side, such behavioral changes depend on

- the autonomous preferences a_d in favor of an energy carrier with a high form value,
- the synergetic effect (imitative behavior) b_d, and
- the supply orientation, measured by the parameter c_d.

On the supply side, the changes in the model are determined by

- the autonomous preferences a_s in favor of energy carriers with a high form value,
- economics of scale in the supply of energy b_s, and
- the demand orientation of supply c_s.

In analogy to the approach of W. Weidlich [1991], the differential equations with regard to the time response of the two variables are:

$$\frac{dD_2}{dt} = -W_{21}^{D}\ D_2 + W_{12}^{D}\ (D - D_2)$$

$$\frac{dS_2}{dt} = -W_{21}^{S}\ S_2 + W_{12}^{S}\ (S - S_2) \qquad (2)$$

For the probabilities of demand shifts from state 2 to state 1 ($W_{21}{}^{D}$) or from state 1 to state 2 ($W_{12}{}^{D}$), respectively, we obtain

$$W_{21}^{D} = \exp\left(-a_d + b_d\,\frac{D - D_2}{D} + c_d\,\frac{S - S_2}{S}\right)$$

$$W_{12}^{D} = \exp\left(+a_d + b_d\,\frac{D_2}{D} + c_d\,\frac{S_2}{S}\right) \qquad (3)$$

By analogy, the probabilities of supply shifts are

$$W_{21}^{S} = \exp\left(-a_s + b_s\,\frac{S - S_2}{S} + c_s\,\frac{D - D_2}{D}\right)$$

$$W_{12}^{S} = \exp\left(+a_s + b_s\,\frac{S_2}{S} + c_s\,\frac{D_2}{D}\right) \qquad (4)$$

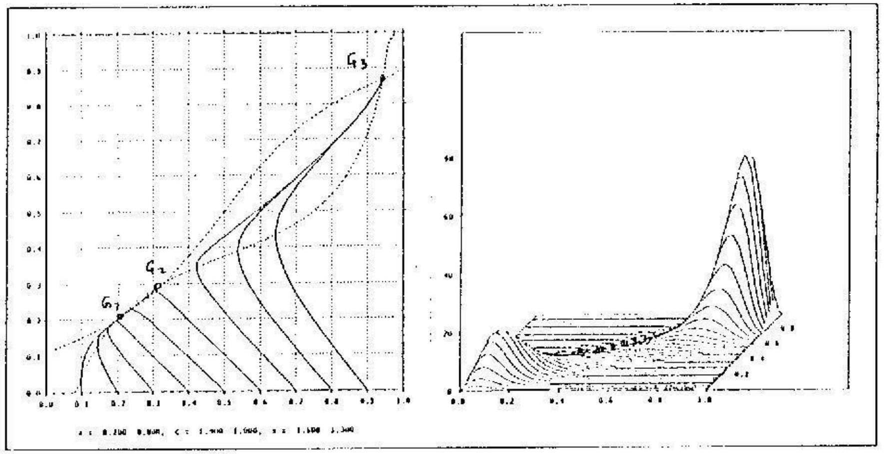
The demand and supply parameters refer to three criteria which may be interpreted in both economic and social terms. The first category includes the autonomous preferences; the second, the synergetic effects, *i.e.*, those components of supply and demand behavior which, for example, are determined by imitating competitors. The third category consists of those parameters describing changes in the supply system on the basis of existing market opportunities or, on the demand side, on the basis of additional stimulations due to supply advantages. In our model, we characterize these processes as *supply/demand effects*.

The following description of a comparison between two cases (Case 1 and Case 2 of our model) is based on an *example* with a given set of parameters:

autonomous preferences:	$a_d = 0.2$ $a_s = 0.0$
synergetic effect:	$b_d = 1.4$ $b_s = 1.0$
supply/demand effect:	$c_d = 1.6$ $c_s = 1.3$

This parameter constellation (Case 1) results in a phase gradient as shown in Figure 3.[6]

Figure 3: Phase diagram and probability distribution: Case 1

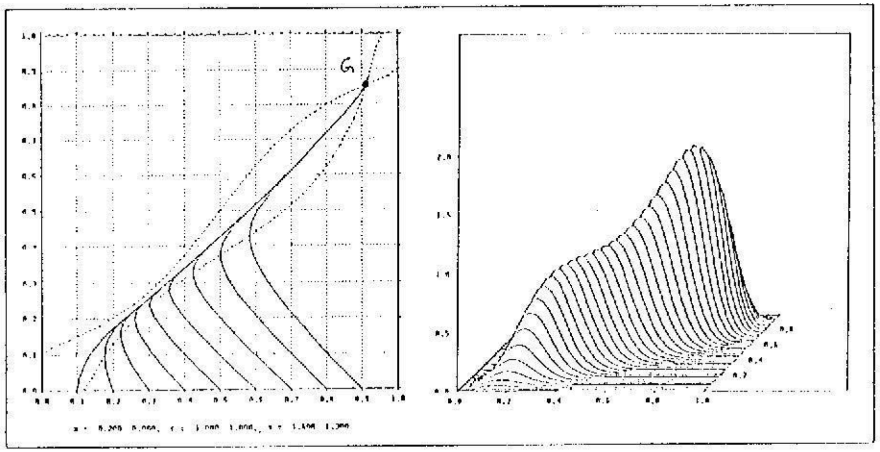


The broken lines in the phase diagram (left chart in Figure 3) represent the solutions for $dD_2/dt=0$ and $dS_2/dt=0$ (see equation (2)). The intersection points correspond to the equilibrium states of the system. For the case under discussion, the diagram shows two stable equilibrium states: G_1 and G_3. Point G_2 represents an instable equilibrium. A comparison with Figure 4 illustrates the sensitivity with which the number of equilibrium states is dependent on the parameters. As against Case 1, only *one* parameter value – the synergetic effect parameter b_d – was reduced from 1.4 to 1.0. All the other parameters remained constant. In Case 2, there is only one point of equilibrium left. This allows a development towards a stable equilibrium interpretable in economic and social terms. The trajectories converge from different original values, moving steadily towards a state with a higher form value.

While Case 2 shows only one point of equilibrium, Case 1 (synergetic effect $b_d = 1.4$) is characterized by two potential points of stable equilibrium, with G_1 (left, bottom) representing a suboptimum market equilibrium. Due to imitation effects, e.g. Johnson effects induced by the media, the market – in spite of autonomous user preferences in favor of energy carriers with a high form value (see parameter $a_d = 0.2$) – may move towards an equilibrium level which does not reflect these preferences.

In addition to the phase diagrams, Figures 3 and 4 also represent the probability densities corresponding to the respective equilibrium states. These probability densities are obtained by formulating the model on the basis of the master equation. (Once again, see *W. Weidlich* [1991] for details with regard to the formulation and interpretation of the stochastic version of the model.) The results shown in the right-hand charts of Figures 3 and 4 indicate the probability with which the

Figure 4: Phase diagram and probability distribution: Case 2



system retains its configuration in the long run (*i.e.*, after convergence of the probability distribution).

Concluding Remarks

A critical analysis of economic theories and dogmas reveals that such important phenomena have at best been treated unsatisfactorily. Whether or not evolutionary economics will succeed in catching up with this theoretical deficit must, for the time being, remain an open question. However, it is reasonable to assume that approaches on the basis of evolutionary theory as developed in other fields of the empirical sciences might be of importance to economic issues at least in heuristic terms since they enable us to ask more relevant questions and to find better answers. This is particularly true for a better understanding of the genesis and the effects of *innovation*, for the diffusion processes with regard to *new technologies* and *new values* (change of values), and for the context of *knowledge*, *mobility*, and *receptivity* on the micro and macro levels. Undoubtedly, it is of decisive importance to a system in which way it proceeds in producing and using energy.

Notes

1. I would like to thank *PD Dr Georg Erdmann* for having checked the manuscript and for his valuable comments. Still, I am responsible for any shortcomings of this article which may remain.

2. See Appendix I for a table indicating the specific energy densities of various storage media.

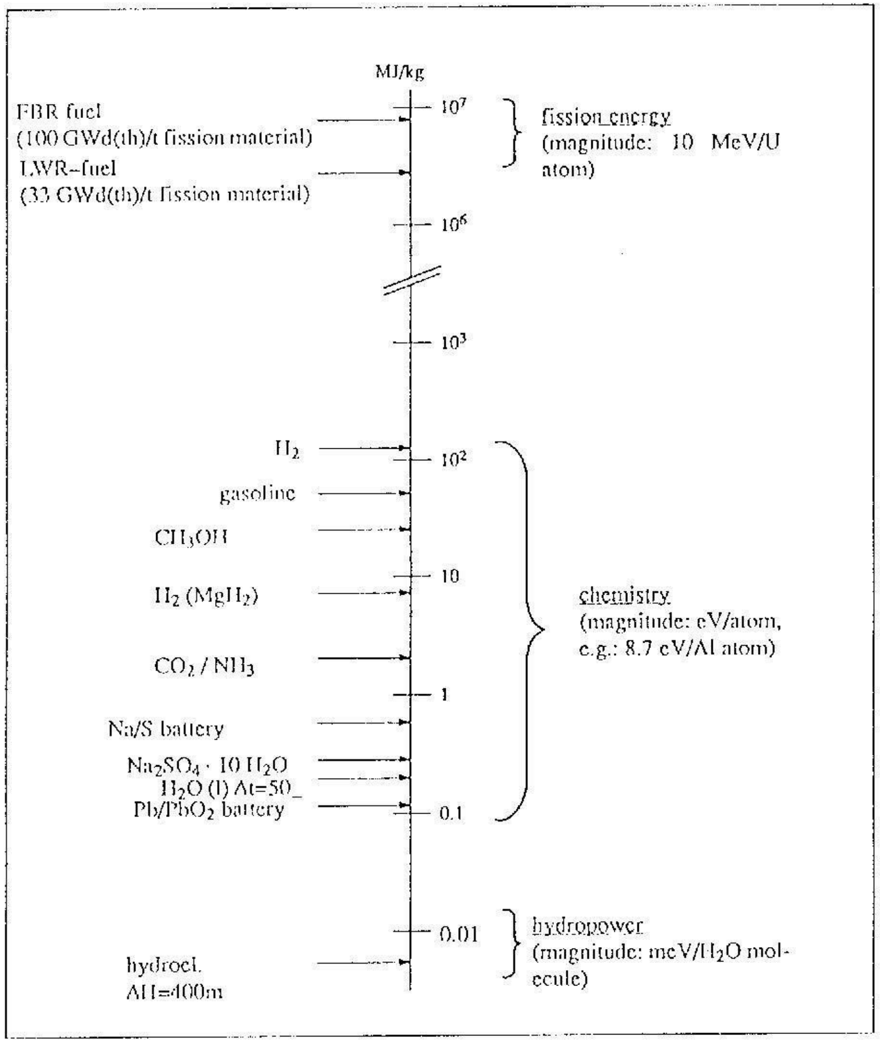
3. For a more detailed discussion of entropy, energy use, environment, and resources, see *Faber/Niemes/Stephan* [1987].

4. The marginal value of 300 TW quoted by *Buttlar* [1975] is an arbitrary value. See *Kümmel* [1982].

5. The following statements summarize the results of a study carried out in cooperation with my colleague *Dr G. Erdmann*. See also *Fritsch* [1989].

6. The following diagrams were programmed and printed out by *Dr G. Erdmann*. I seize upon this opportunity to express my gratitude to him.

Appendix I: Energy Densities



Source: Adapted and translated from *EIR* [1986]

Appendix II: Relationship between Increasing Energy Production and Global Warming by Waste Heat

Any calculations with regard to the relationship between increased energy production and the resulting increase in global temperature are based on the following considerations: The earth, a subsystem of the universe, maintains a constant exchange of energy with the universe. This exchange takes place in the form of radiation (light, infrared radiation, ultraviolet radiation, radioactivity). That part of incident radiation which is absorbed on the earth's surface (including atmosphere) is referred to as the energy input from the universe. On the earth, this input of energy is almost entirely transformed into heat. Heat, however, can also be generated on the earth's surface by converting chemical energy (oil, coal, gas ...) or nuclear energy. Under equilibrium conditions, the overall heat supply to the earth's surface is returned to the universe in the form of heat radiation. For the description of such a state of equilibrium, we select the following parameters:

$E_A{}^0$: annual energy absorption of the earth (heat only)

$E_P{}^0$: annual energy production on the earth (fossil, nuclear)

$E_S{}^0$: annual energy radiation from the earth

T_0: mean absolute temperature of the earth's surface (°K)

Among these parameters, we find the following relations:

$$E_T{}^0 = E_A{}^0 + E_P{}^0 \quad \text{(total energy)} \tag{1}$$

$$E_T{}^0 = E_S{}^0 \quad \text{(energy balance or equilibrium)} \tag{2}$$

$$E_S{}^0 = S_0\, t\, F \quad \text{(energy radiation from the earth)} \tag{3}$$

where S_0 = energy radiation from the earth per time and surface unit
t = 1 year = 3.15×10^7 s
F = earth's surface = $5.1 \times 10^8 = 5.1 \times 10^{18}$ cm^2

The specific radiation from the earth (S_0) is related to the surface temperature via the *Stefan–Boltzmann* Law:

$$S_0 = \sigma\, (T_0)^4 \tag{4}$$

where σ = *Stefan–Boltzmann* constant

$$\sigma = 5.7 \times 10^{-12} \frac{J}{cm^2\ s\ (^\circ K)^4}$$

J = Joule.

The integration of (4) into (3) yields the following equation:

$$E_S{}^0 = \sigma\, t\, F\, (T_0)^4 = 9.157 \times 10^{14}\, (T_0)^4 \frac{J}{(^\circ K)^4} \tag{5}$$

According to equation (1), if the energy produced on the earth ($E_P{}^0$) is increased by ΔE, the total amount of energy is increased by the same percentage. Under equilibrium conditions,

$E_S = E_S{}^0 + \Delta E = E_T{}^0 + \Delta E$ (equation (2)). According to equation (5), this yields a new equilibrium temperature T:

$$E_S = E_S^0 + \Delta E = 9.157 \quad 10^{14} \frac{\mathrm{J}}{(^\circ\mathrm{K})^4} (T)^4 \tag{6}$$

or, solved for ΔE:

$$\Delta E = 9.157 \quad 10^{14} \frac{\mathrm{J}}{(^\circ\mathrm{K})^4} [(T)^4 - (T_0)^4] \tag{7}$$

If $T = T_0 + \Delta T$ (with ΔT = temperature increase), we obtain

$$T^4 = T_0^4 + 4T_0^3 \Delta T + 6T_0^2 (\Delta T)^2 + 4T_0 (\Delta T)^3 + (\Delta T)^4 \tag{8}$$

On the assumption of $\Delta T << T_0$, the terms higher than the first power of ΔT may be neglected in this expression. Thus, equation (8) can be written as

$$T^4 \approx T_0^4 + 4T_0^3 \Delta T \tag{9}$$

Substituting $T^4 - T_0{}^4$ in equation (7) by equation (9) yields

$$\Delta E = 9.157 \quad 10^{14} \frac{\mathrm{J}}{(^\circ\mathrm{K})^4} [4(T_0)^3 \Delta T] \tag{10}$$

Equation (10) can now be solved for ΔT:

$$\Delta T = 2.73 \quad 10^{-16} \frac{(^\circ\mathrm{K})^4}{\mathrm{J}} \frac{\Delta E}{(T_0)^3} \tag{11}$$

In order to obtain an assessment for ΔT, we put $T_0 = 300^\circ\mathrm{K}$ (= 27°C). Thus, equation (11) becomes

$$\Delta T = \Delta E \; 10^{-23} \frac{(^\circ\mathrm{K})}{\mathrm{J}} \tag{12}$$

In other words: The surface temperature of the earth is increased by 1°C, if an additional amount of around 10^{23} J = 10^{11} TJ of energy is produced on the basis of fossil or nuclear energy sources. This corresponds to 3,000 TWyr/yr.

Source: *Fritsch* [1981:321 and ^{2}1991: 331f.]

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