

Article

Circular Economy: Illusion or First Step towards a Sustainable Economy: A Physico-Economic Perspective

Gunter Stephan

Steering Committee of the National Research Program, Sustainable Economy (NRP73),
Swiss National Science Foundation, CH-3012 Bern, Switzerland; gunter.stephan@vwi.unibe.ch

Abstract: “A circular economy is one that is regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption”, states the widely used definition of the Ellen MacArthur Foundation. This definition conveys two messages. First, it acknowledges that economic activities need natural inputs (energy and material) and generate outputs in the form of waste as well as emissions. Second, it embodies the promise that, through technological innovations, human ingenuity and the market, a full decoupling of the economy from nature can be reached. Obviously both messages are not consistent with each other. Analyzing these issues through the lens of a transdisciplinary approach, which combines insight from thermodynamics with conventional economic theory, is the purpose of this paper. By using such physico-economic perspective, it is argued that not any kind of a circular economy is sustainable. Therefore, indicators are required through which it can be assured that a particular fashion of a circular economy reduces both environmental and social harm.

Keywords: circular economy; entropy and economic activities; sustainable development; environmental taxes



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1. Introduction

The transformation of the traditional linear economy into a circular one is the subject of current environmental policy discussions both in Switzerland and the EU. While the conventional economy can be characterized as “buy-use-throw away”, a circular economy is understood as a loop that minimizes material use, energy flows and environmental impacts without compromising economic wealth as well as social and technical progress [1].

The concept is not a new one. Economists such as Kenneth Boulding, David Pearce and Walter Stahel developed similar ideas in the early 1960s. Most importantly, it goes beyond that of recycling. A circular economy is more than waste management policy. According to the widely used definition provided by the Ellen MacArthur Foundation [2] “a circular economy is one that is regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption”. This definition conveys two messages. First, it acknowledges that economies need inputs (energy and material) from nature for its operation and, therefore, generate outputs in the form of waste as well as emissions. Second, it embodies the promise that, through technological innovation, human ingenuity and the invisible hand of the market, a full decoupling of the economy from the supply of natural resources can be guaranteed. This immediately motivates the question whether the idea of a circular economy is simply the consequence of ignoring the knowledge generated in (inter)disciplinary scientific fields other than the dominant economic theory and, hence, is pure illusion or elite folk science, as Giampietro and Funtowicz [3] discuss in detail.

Geissdoerfer et al. [4] conducted an extensive literature review to investigate the state of the art in the field and to identify the similarities and differences between circular economy and sustainability. They show that the relationship between both concepts is by no means obvious or clear.

This paper discusses the opportunities and risks, and also the limitations of a circular economy. Evaluating pros and cons of the concept of a circular economy, however, is complex and requires the inclusion of different disciplines. Therefore, any discussion of economic aspects of a circular economy can only be successful if a minimum knowledge of ecological and physical principles is granted. Providing such a background is the major purpose of the present paper. It is argued finally if basic principles of thermodynamics are taken seriously, aiming at organizing all economic activities according to the idea of a circular economy, remains an illusion. There will be always elements of a linear economy.

The rest of the paper is organized as follows. Section 2 discusses the so-called material balance approach, which in its simplest version says that every ton of raw material that is withdrawn from nature over the long run turns into waste, which has to be discharged to nature. In other words: resource extraction and disposal of emissions and waste are two sides of the same coin. Such a quantitative view on the interactions between nature and the economy seemingly gives hope that recycling will allow to completely decouple economic activities from nature. However, the pathbreaking work of Georgescu-Roegen [5] has made us aware of the fact that production and consumption are more than the controlled transformation of materials and energy, but might irreversibly change the quality of energy and other raw material. Therefore, Section 3 analyzes how entropy, which is a concept from thermodynamics, can be used in economic theory and which lesson can be learned from such a physico-economic perspective.

To our knowledge, Faber [6] are the first ones who have used entropy as an indicator for capturing the complex economy–ecology interaction through a single measure. Later, Beard and Lozada [7], Ruth [8] as well as Faber et al. [9] followed that tradition, before economists such as Janes [10] and Raine et al. [11] became aware of the fact that the entropy flow generated through economic activities very much depends upon technology choice as well as the organization of production and consumption. In other words: self-organization matters. Ayres [12] writes in his remarkable book that the principles of thermodynamics and the concept of information entropy together characterize self-organization and the direction of evolution. Consequently, the monetary flows, kinetic energy (efficiency) and potential capacity (resilience) are crucial information for economic development. In a recent paper, Yan et al. [13] analyze growth opportunities of the Chinese economy by using information entropy. Their main result is that, over the past four decades of reform and opening-up, China has made remarkable progress in its economic development. However, after the financial crisis in 2008, China's economic development settled on a medium-low level of development. While the traditional perspective is to rank regional development only based on GDP growth, the authors advocate another evaluation method based on efficiency and potential growth. The results of their research indicate firstly that China's regional development in 2007 and 2012 had been unequal between the provinces. Secondly, the authors found that Shandong province had significantly higher indicators for efficiency and potential growth than others under same circumstances. The authors observe that provinces tend to carry out industrial policies and adjust the structure of industry on a local level. This analysis demonstrates the spatial imbalance of efficiency and potential of economic development from the perspective of provincial-level regions. From the perspective of industry, it indicates that the supply chain is too short, mainly focusing on the mining and processing of resources and minerals in the original upstream industry chain, while the downstream is not fully utilized. We will return to that issue in Section 4.

Section 4 discusses consequences of physico-economic view on economic activities and discusses the role of institutional evolutions as well as technological innovations. In particular, it points out the need of indicators through which the environmental as well as

social impacts of different types of a circular economy can be judged. Section 5 concludes the paper.

2. Ecological Cycles and Material Balance

Economists of the 18th and 19th century were already aware of the fact that humans are not outside of nature and that economic activities take place in a close interaction with nature, the environment and its ecosystems. For example, Thomas Robert Malthus [14] concluded from his reflections on population growth and agricultural production that there were limits to growth because of the limited availability of arable land. In 1871, William Stanley Jevons [15] concluded that the production of goods inevitably leads to by-products which are not desirable for further use and have to be disposed in the environment (for a modern view, see [8]).

Mainstream economics still shares the view that economic activities consist in the transformation of matter and energy from one state form to another [16]. This interpretation points to two types of interaction between the economic system and the environment. First, raw materials and energy must be extracted from the environment in order to carry out production and consumption. Second, economic activities produce not only desirable and welfare-enhancing goods and services, but also pollutants and waste that must be removed from the economic system to maintain its long-term functioning.

As stated by the Council of Environmental Experts in its 1987 Environmental Report, every biotic community requires energy, matter and information from the environment in addition to a habitat and releases these substances in modified form back into nature, where they must be absorbed and further processed [17]. Two key insights follow from this statement:

- (1) Humans and the communities they establish are embedded in the global ecological cycles.
- (2) Matter and energy cannot be destroyed, but only changed in their chemical-physical properties.

Simplified, this is the statement of the material balance approach [16]. Methodologically, the material balance approach is derived from the first law of thermodynamics, which states that in a system isolated from the environment, the energy sum always remains constant and energy can only change its state form. In popular scientific terms, this means: Nothing can become nothing only and something cannot become nothing [18]. Since the earth exchanges with the universe no matter, the mass of the used matter remains constant. Raw materials and energy can change their appearance, but the total quantity is constant. Thus, every ton of raw materials that is removed from the environment and is used in economic activities will be returned to the environment. This must not happen immediately. Resources, for example, can remain bound in durable means of production (capital goods) such as buildings or machines for some time. However, even durable means of production wear out, which is why, from a long-term perspective, the material balance is maintained and the former raw materials are returned to the environment in the form of emissions and waste [19].

Like any other living beings, humans do not have a natural predisposition to take care of the unwanted outputs of their activities. Undesirable outputs are waste in the broadest sense including all forms of emissions from productive and consumptive activities. Usually, waste is not considered further, but is regarded as natural phenomena and left to nature. Such behavior does not pose any problem as long as human activities and the resulting materials flow back into the environment and are coordinated with the ecological cycles. Only when the economic system no longer is coordinated with the ecological cycles and more raw materials are extracted from nature per unit of time than nature can provide, or more pollutants and waste are emitted than the ecological cycles can process, is nature then overused. This can eventually lead to the point where man-made emissions begin to disrupt his own activities. Then, at the latest, man registers the environmental harm he causes.

But how does an overuse of ecological cycles by man occur? Essentially, it is because man has detached himself from the natural recycling of the ecological cycles, for three reasons at least: (1) the accumulation of substances, (2) the transformation of substances, and (3) the accelerated turnover of substances.

Substance accumulation is a consequence of man's ability to transport substances in large quantities over long distances. It is the result but also the prerequisite for the sedentariness of man and the formation of agglomerations. Today, people no longer migrate to the materials they need; the materials come to them. One effect of this is the relocation of substances in places where they massively can disrupt local ecosystems. In this context, think of the accumulation of heavy metals in our soils and the resulting stresses on humans, animals and the environment.

Substance transformation is the result of humans' production and consumption. From a material point of view, production and consumption are mixtures of raw materials, energy and auxiliary materials, resulting in two categories of substances that differ in usability and composition:

(1) Desirable goods and products produced to satisfy human needs and usually distributed through markets;

(2) By-products or co-products, which are not the direct target of economic activities, whose creation is essentially shaped by technology and which are often regarded as undesirable.

Three conclusions can be drawn directly from this. First, goods are produced to be used as inputs into other economic activities or for consumption. Such goods have always been considered desirable by society. Accordingly, elaborate structures for production and distribution have been developed. The production and consumption of such goods is largely determined by market conditions and the preferences of economic agents. Reducing emissions directly resulting from the consumption of these products therefore requires changes in behavior and market conditions.

Second, unwanted emissions were simply left to the environment. They were never the target of economic activities and were usually considered worthless unless they could be used as inputs to human activities. Accordingly, they were not traded on markets but left to the public domain. However, emissions of this kind can be avoided or at least disposed through appropriate technologies, and in some cases, they can even be recycled. Examples of this can be found in the chemical industry. The production of chemical compounds can almost be seen as the art of recycling of actually unwanted by-products as inputs into other production processes (for examples and a detailed discussion, see [20]). Accordingly, markets or comparable institutions must be created to trigger incentives for the introduction of so-called clean technologies.

Third, the after-care treatment of emissions and waste, the so-called end-of-the-pipe disposal, raises additional problems. Such processes do not prevent the pollution of the environment by emissions. They merely transfer pollutants and waste from one environmental medium to another, as can be seen from the example of flue gas cleaning by electrostatic precipitators. There, the pollutants contained in the exhaust air are collected in the filters and bound as filter dust. Ultimately, however, these dusts must be removed from the filters in order to maintain their functionality. Thus, the originally gaseous emissions end up as toxic waste in landfills. Emissions have thus been transferred from the air to the soil.

Let us now turn to the accelerated turnover of substances. The development of modern industrial society and the increasing material prosperity of its population has dramatically increased per capita material turnover. Thus, the material throughput by the economic system has been accelerated and the coordination of economic processes with ecological recycling in the ecosystem has been disturbed. At the same time, the nature of products has also changed. Whereas in the past there were more products in circulation whose structure and composition were recognized by the ecological system and could therefore

be processed immediately, today, synthetic products, such as plastics, are increasingly being produced.

This poses a particular problem. Every ecological system is quantitatively and qualitatively oriented to a certain spectrum of substances. Substances that do not occur in this spectrum are in principle not degradable and usually have a toxic effect on the ecological system. In this context, the pollution of the oceans by plastic waste comes to mind. In addition, there is a close relationship between material turnover acceleration, material transformation and end-of-pipe disposal; because, if such plants are operated, the material turnover increases even further due to the high energy consumption.

What is the economic message of our considerations so far? From an economic point of view, environmental problems primarily represent an unperceived scarcity problem. Economic systems are part of ecological cycles and depend on the use of services provided by nature. However, ecological cycles can only provide their services in the form of resources, energy and disposal to a limited extent. If this scarcity is not perceived in the economic system, this misinformation necessarily leads to misallocation. This disregard of natural scarcity and the resulting overexploitation of ecological cycles can be corrected by appropriate adjustments in the economic system and the creation of incentives with the aim of promoting environmentally compatible economic activity [21]. Therefore, a conclusion from a material balance approach is that establishing a circular economy seemingly avoids these problems. There are two caveats, however: (1) Recycling, which is an important element of a circular economy, is nothing else than an end-of-the-pipe technology, which accelerates energy consumption further, and (2) when humans use the environment as a supplier of raw materials or as a recipient of pollutants, this has not only quantitative but also qualitative aspects.

3. Thermodynamics and Economy

Mainstream economics captures the interplay between nature and the economic system primarily through the lens of the material balance approach, which means that quantitative aspects are addressed primarily. However, changes in quality, the irreversibility and directionality of processes are of central importance. Organisms, and hence humans, transform natural inputs into substances that they themselves can no longer use. This indicates that the quality of substances has changed from “usable for the organism” to “no longer usable”, i.e., worthless. At the same time, these processes are quasi-irreversible, since they can either no longer be reversed at all or at very high expense only. Remember that the efficiency of power machines that convert energy into work is less than one, i.e., only part of the energy input is converted into work, the rest is lost irrecoverably in the form of heat. Energy dissipates. If, on the other hand, the quality of the materials and energy introduced into an economic system would not change during production and consumption, and if the initial materials could always be recovered from the final products, the economic system could be almost completely sealed off from the ecological system. Economic activity could be reduced to recycling, and goods could be produced from waste and emissions by adding some amounts of energy.

This view dominated the conception of economic processes for years, and the recycling euphoria of the late 1970s and 1980s was also based on this perspective. According to that, waste can be eliminated by recycling it. Today, mass-based indicators, such as recycling rates, are used to assess the circularity of individual products, firms and of entire countries. These indicators, however, fail to cover the environmental perspective—one of the most mentioned reasons for moving from a linear to a circular economy. In fact, it is only possible to recover a part of the valuable materials from waste, and even this process cannot be repeated as often as desired according to the laws of physics [22]. Recycling does extend the residence times of materials in the economic system. Ultimately, however, they become waste that must be finally disposed. Therefore, Haupt and Hellweg [23] propose a complementary environmental-impact-based indicator that measures the environmental value retained through reuse, remanufacturing, repairing or recycling. This indicator

extends the focus from end-of-life to the entire life cycle and includes substitution of primary materials. Furthermore, it allows for monitoring the transition towards a circular economy from an environmental as well as an economic and social perspective.

Material balances only capture material flows. From a long-term perspective, however, it is important to also consider stocks of materials and their changes, as well as ecological service capacities and their development. For example, it is not the flow of carbon dioxide (CO_2) into the atmosphere, i.e., the current emission, that is responsible for the predicted climate effect, but the change in CO_2 concentration, which is ultimately equivalent to the change in the stock of carbon dioxide deposited into the atmosphere.

How can qualitative changes, the directionality and irreversibility of processes logically consistent be incorporated within the framework of economic theory? One possibility is to use concepts from thermodynamics and make them applicable to economic considerations. There are different attempts for integration laws of thermodynamics into mainstream economics. Examples are [6–8] as well as [9–11], to name only a few.

Thermodynamics is a discipline of physics that deals with the behavior of systems with a large number of particles. Compared to classical Newtonian mechanics, where the motions of a few bodies are studied, there are two crucial differences. First, to describe the behavior of aggregates with a large number of particles, one needs physical quantities that do not appear in classical mechanics. Entropy is such a quantity. Second, thermodynamic systems exhibit phenomena that are unknown in classical mechanics. In classical mechanics all processes are in principle reversible. For example, in the laws of motion the direction of motion is not fixed. The planetary system could move in the opposite direction even without changing the laws. This does not apply to thermodynamic systems. There, processes are directed and irreversible. Therefore, besides the concept of entropy, another principle (which can be formulated with it) is needed, which shows the direction and directionality of processes.

3.1. Entropy and Free, Available Energy

To get an impression about how the concept of “entropy” is understood and used in economics, we start with a thought experiment. Consider a simple thermodynamic system isolated from the environment, consisting of two gas containers. In the initial state, both containers are separated from each other by an impermeable membrane, the first one (Behälter 1) is filled with an ideal gas and the second one (Behälter 2) is evacuated. If the separating wall is penetrated, gas flows from the filled container into the empty container until the gas is distributed equally between the two containers in the final state (Endzustand) (see Figure 1).

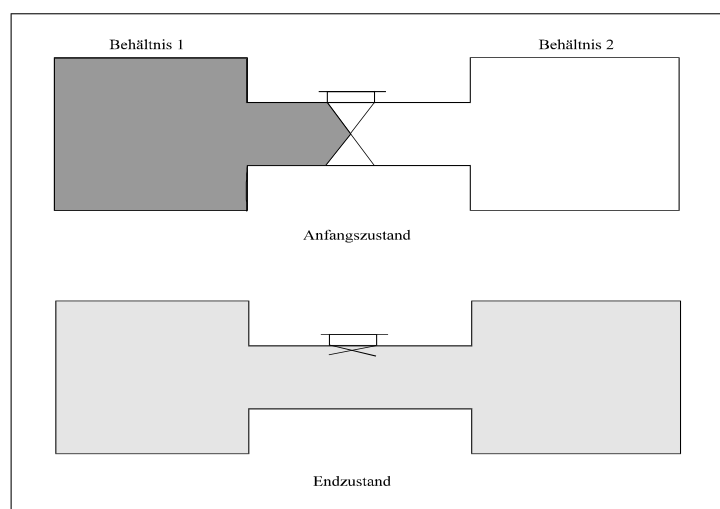


Figure 1. Thought experiment.

With respect to energy and mass of material, the initial (Ausgangszustand) and final states (Endzustand) of the described system are completely identical. Since the system under consideration is completely separated from the outside world, the sum of energy and matter always remains constant according to the first law of thermodynamics. Therefore, neither the amount of energy nor the mass of the gas has changed during the diffusion process. Nevertheless, the initial and the final state of this thermodynamic system differ substantially from an economic perspective. In the initial state (Ausgangszustand), the system carries the potential that a part of the energy contained in the system can be used. This could be done, for example, by means of an integrated turbine driven by the gas flow. In the final state, however, this possibility no longer exists.

This example shows that, especially from an economic point of view, systems cannot be adequately described by the two quantities energy and mass. For economic applications, only systems from which energy can be extracted are of interest. With reference to the example shown in Figure 1, this means that the thermodynamic system from our thought experiment has economic value in its initial state, since it could be used in the economic cycle for supplying energy; the system in its final state, however, no longer has this ability [24].

But how can systems be characterized depending on the degree of economically usable energy they contain? Simplistically speaking, entropy is the measure of unavailable energy in a thermodynamic system. It is also said that free and thus available energy corresponds to low entropy. (For a more precise formulation see the Appendix A). In every physical process, including the diffusion of gases, a portion of the free energy dissipates into the system. It is then still present in the system itself, but no longer available for economic action. This process continues, as in the example above, until the entire free energy of a system has been transformed into bound energy, and is thus no longer usable, or, in other words, until the potential of formerly low entropy has been transformed into a potential of high entropy.

This observation leads to a hierarchy of systems: Systems with low entropy have a high portion of free, hence usable energy and are economically more valuable than those with high entropy. This is because with increasing entropy, the availability of free energy and thus the quality of the system as an energy source for economic systems decreases.

Before we continue, let us clarify the consequences of these observations [25]: According to the first law of thermodynamics, the law of conservation of energy, all forms of energy are in principle convertible into each other. However, everyday experience teaches us that the direction in which this transformation takes place is not completely reversible. Energy, once transformed into heat, is not reversible. This means that, in an isolated thermodynamic system, the proportion of energy bound in heat constantly increases—and this until there is no more kinetic energy available, and thus any form of mechanical work is impossible because all energy has been transformed into heat.

3.2. Applications of Entropy Theoretical Considerations

How can entropy theoretical considerations be used in an economic analysis of ecological problems? Following the second theorem of thermodynamics, entropy can never decrease in an isolated system: If processes are reversible it remains constant, and if processes are irreversible it always increases [26]. Therefore, in isolated thermodynamic systems only such processes run independently, in which the entropy increases. According to Clausius, this principle determines the direction of all processes [18].

In simplified terms, the second law of thermodynamics states that isolated thermodynamic systems strive in the long run towards a state of maximum entropy and thus minimum structure and order. Structure and order of natural systems are irreversibly destroyed. This phenomenon is often expressed by the statement that the universe is striving towards heat death. This would be a state, in which the entire, formerly free energy was transformed into heat energy, and every order would have dissolved in chaos.

But what is true for the universe as a whole does not have to be true for its parts. In fact, we often observe the opposite in nature and also in the human community. There, in the course of evolution, complex chemical, biological, ecological and social structures have developed, which did not reduce the order in the natural environment, but on the contrary increased it. And these processes of self-organization, which lower entropy at least in their subsystems, are also constantly taking place today (for a more detailed discussion see [11]). For an overview about practical applications, see [27].

Nevertheless, this is not a direct contradiction to the second law of thermodynamics, because the second law only makes statements about isolated thermodynamic systems. From the point of view of the second law, a self-running process is reversible if the systems are open and the entropy increase generated in them can be compensated from the outside by an influx of energy. Our gas experiment confirms this directly. By itself, the gas only spreads out and flows from the filled into the evacuated container. However, for reversing this process and concentrate the entire gas mass in one of the two vessels, energy must be supplied to the system from the outside and gas must be pumped from one vessel into the other.

The evolution of more highly developed systems is therefore not in contradiction to the second law of thermodynamics. However, it must take place in open systems, which can only maintain their low entropy level by releasing entropy to their environment and absorbing energy from it.

3.3. Economic Activities and Entropy

Let us return to the second law of thermodynamics. In other words, it says that without exchange of energy with the environment no system is able to work constantly. However, economic activity is essentially nothing else than permanent work. Therefore, the economic system must constantly exchange energy with its environment.

Energy can only be provided as long as systems of low entropy exist, whose free energy can be used. This observation has direct implications for economic theory and helps to better understand the interactions between economic systems, on the one hand, and their surrounding environment on the other hand. From an entropy theory point of view (for the original work, see [28]), economic systems consist of complex structures that sustain themselves by consuming energy, herewith low entropy potentials, and transforming them into a constant flow of entropy into the environment.

In fact, many economic processes consume resource stocks of high purity and generate emissions in which formerly high-concentrated raw materials are degraded in quality and returned to the environment at lower concentrations. As is shown in Appendix A, any change in concentration is directly related to a change in entropy. Figure 2 (see also [29]) illustrates this relationship. There, the originally high concentrated raw material is mixed with other substances during production and consumption. Finally, its concentration has decreased to such an extent that it no longer can be utilized in the economic system and ends up in the mess of countless landfills and, hence, pollutes the environment.

This illustrates that pure material flow considerations such as the material balance approach are not sufficient to understand the impact of economic activity on the environment. Economic activity cannot solely be seen as the controlled transformation of matter using energy while maintaining the mass of matter. Rather, economic operations create a continuous flow of entropy, transforming low entropy states into high entropy ones. This creates deep interferences in our natural environment and requires that low entropy potentials are permanently available, whose free energy can be used. Here is an important side remark. The digitalization of the economy might lead to a de-materialization of economic activities and hence reduces the material throughput through the economic system. This, however, does not mean that there will be a significant reduction of environmental harm. The process of digitalization will imply increasing energy consumption and hence cause entropy flows.

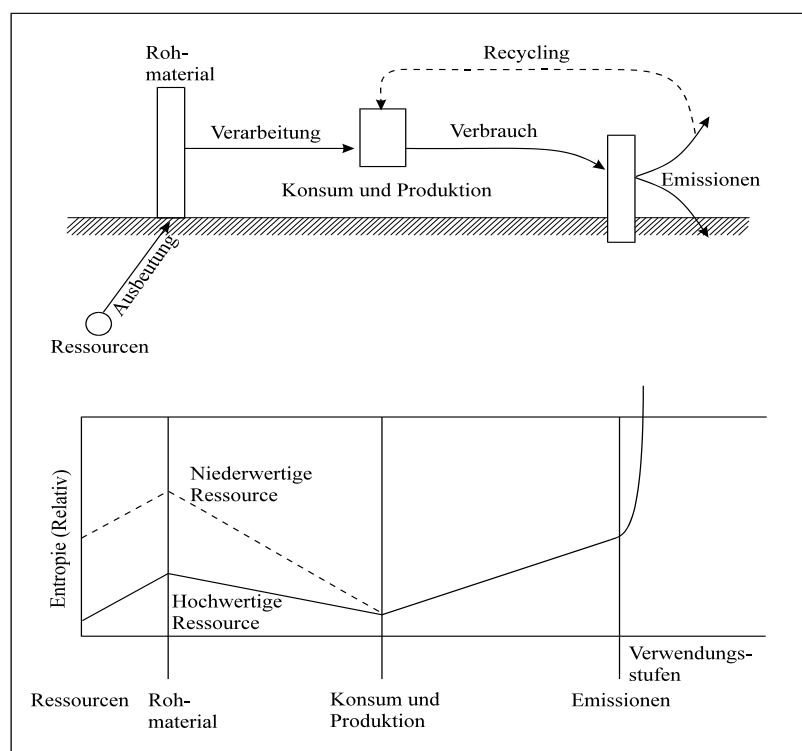


Figure 2. Economies and entropy flow.

The entropy flow triggered by economic activities can be determined. Economic activity means in particular to use and mix resources and energy in order to produce the desired economic goods. Let us accompany a raw material such as copper for example on its way through the economic system and observe the entropy flows occurring in the process. As is shown in Appendix A, a change in copper concentration will lead to entropy flow according to $dS = NR \ln(\chi_1/\chi_2) = NR(\ln\chi_1 - \ln\chi_2)$ (see the Appendix A). Therefore, we can distinguish at least three stages (see Figure 2): First, the raw material (Rohmaterial) is extracted from the environment and processed. This requires energy, which generates an entropy flow. Subsequently, substances are mixed during production and consumption. Thus, the raw material, originally available in great purity, is transformed into a less concentrated form, which again triggers a flow of entropy. Ultimately, the raw material is released into the environment as emissions and waste, thus further mixing, resulting in a further flow of entropy. This observation causes direct consequences for sustainability. Sustainable action must aim at minimizing the entropy flows that economic activity triggers.

3.4. Entropy and Long-Term Perspective: Correcting Prices

Figure 2 illustrates even more. With each extraction, the concentration of resources remaining in the environment decreases. Resource extraction today therefore means that in the future resource extraction will only be possible at higher expenses.

If we intend to answer the question of how to use of a resource optimally over time, then what was just considered must be included in the optimization calculus. In other words, it must be considered that resource extraction today creates disadvantages for future generations in that only resource stocks of lower quality (concentration) are available and these can only be exploited with higher energy inputs. (Again, see Appendix A for clarification.)

If the intertemporal allocation of resources is given to markets, then resource prices should capture these negative effects of resource extraction today on future generations.

Therefore, the market price p of a resource must be composed of at least two components to ensure an optimal allocation [19]

$$p = pE + pZ.$$

Depending on the resource concentration, pE denotes the extraction costs today, and pZ are the additional costs that will arise in the future as a consequence of today's resource extraction. Only if these costs are internalized via the price system, an optimal intertemporal resource allocation is guaranteed.

However, the resource prices observed in reality usually do not tell the ecological truth, as just discussed. Since markets are bad in capturing long-term effects, market prices are essentially determined by the economic costs of extraction and transportation. Thus, market prices in general do not reflect the negative impacts on future generations, the environmental impacts of production and consumption, or the fact that raw materials that are valuable today may become waste tomorrow and contribute to the shortage of landfill volumes. Consequently, the prices of goods and services observed in markets are too low. Price signals distorted in this way thus neither reflect actual scarcity nor enforce the polluter-pays principle, since only part of the actual costs of producing goods is passed on to producers and consumers through prices. Therefore, the operational and economic costs diverge to such an extent that, from an economic point of view, there is a waste of raw materials and an overloading of nature.

4. Discussion

If one takes the entropy theory approach and especially the message of the second law literally, in the sense that the structure and order of natural systems are irreversibly destroyed through economic activities, then it appears pessimistic at first glance. In the long run, it prophesies entropic death, and thus basically the end of the world as we know it. However, two facts should not be overlooked at this point.

First, the degree of utilization and usability of free energy, and thus of low entropy potentials, depends on the technology used as well as the way we organize economic operations. Today, we are aware that the energy efficiency of the conventional technologies is low. Alternatively, more environmentally friendly technologies with much higher energy efficiency are known and some of them are already available on an industrial scale. However, at the prevailing market prices, they are not used yet due to insufficient economic profitability. This gives rise to the confidence that using market-based instruments for environmental protection such as eco-taxes can correct market prices in such a way that the economic profitability of conventional technologies deteriorates in comparison to alternative technologies, and that the necessary ecological transformation of our society can be achieved [30].

Second, scientists such as Nicolis and Prigogine [31] rightly criticize that the second main theorem is a truncation of reality. Strictly speaking, it is only valid in isolated systems and in the vicinity of a thermodynamic equilibrium. However, the earth is not an isolated system, but is constantly supplied with energy by the sun. Therefore, the system Earth can compensate an entropy increase by external supply of so-called neg-entropy and maintain equilibria far from entropic death in the long term. Furthermore, so-called self-organization can lead to a local decrease of entropy, which is the basis for evolutionary processes. Innovation, by the way, is a form of evolution. In contrast to biological evolution, where nature determines the laws and directs evolution, man and the economy control "economic evolution". This is the perspective taken by [11], who argue that market economies have proven, more than any other known institutional arrangements, their ability to generate new knowledge and structural complexity, and therefore reduce energy degradation. As such market economies are evolutionary stable because of their capacity of growing knowledge and increasing structural complexity.

However, the limits for economic evolution are narrow. This becomes clear if one considers calculations of the Berlin physicist Ebeling [32]: Ecological processes on Earth are

driven by solar energy. This amounts to about 200 watts/m² of earth surface. This energy must be sufficient for all life processes, i.e., for all meteorological, biological, ecological and economic processes together, if no fossil energy sources (or nuclear energy) were available. If we imagine that each of the 6 billion inhabitants who populated this earth in 1994 drove approx. 3 h per day in a middle-class limousine with an hourly consumption of 10 L, then this energy limit would already be exceeded.

What can be learned from entropy-theoretical considerations so far? First, the entropy approach allows to put the manifold interdependencies between the economy and the ecological system on a common basis. The importance of such a view is already evident from the fact that economic systems make use of the environment in at least two ways. On the one hand raw materials are taken from the environment and pollutants and waste are returned to it on the other. Since economic systems are open flow systems, these two functions are inextricably linked, and any intervention or action on one side has immediate consequences for the other.

Second, a thermodynamic view draws attention to the temporal structure of environmental problems and their qualitative effects. In particular, it emphasizes the irreversibility of economic impacts on the ecological system, and highlights the role of free, available energy.

Third, today's choices determine tomorrow's scope for action. How our society develops—which direction technical change takes—always determines how mankind will use nature in the future (see [33]). Unfortunately, such decisions have to be made under uncertainty and ignorance. It is therefore helpful to have rough reference points, quasi guard rails, of which it is certain that developments will only take place within these limits. The first and second law of thermodynamics formulate these guidelines: Every production process that is ever applied, every technology that is developed, must follow these laws, and forecasts that violate this condition define unrealistic scenarios.

Finally, a more scientifically based economic approach to environmental aspects can identify and then analyze problems that were either previously underestimated or for which no theoretical framework existed. This is especially true for issues at the interface between economics and ecology, but also for aspects of the self-organization of dynamic systems.

Then, which lessons can be learned for a circular economy? First, entropy needs to be considered when discussing a circular economy, as the European Academies Science Advisory Council [34] notes: "Recovery and recycling of materials that have been dispersed through pollution, waste and end-of-life product disposal require energy and resources, which increase in a nonlinear manner as the percentage of recycled material rises (owing to the second law of thermodynamics: entropy causing dispersion)".

Second, recovery can never be 100% [6], neither theoretically nor in practice. Material and energy dissipation always happens. There is no guarantee that simple strategies of material cycling, as propagated by the various definitions of this concept, will indeed lead to an economy able to manage the world's resources, pollution and societal demand within environmentally sustainable levels [35]. Therefore, if a circular economy is envied as a completely reversible cycle, there are serious doubts that such an idealized concept is achievable. In real implementations of this concept, either one would have to deviate from the perfect reversibility in order to limit the entropy flow, which would ultimately amount to still having parts of the economy which follow a linear scheme (with waste production), or enormous amounts of energy would be required in order to enable complete circularity. The closer one gets to perfect circularity, the more energy is needed. Of course, with the sun being a (practically) inexhaustible energy source present, we need to be able to harness as nature does it. Therefore, the concept of circular economy is closely related to the energy supply.

Our considerations so far made clear that a circular economy per se is not sustainable [23]. Nonetheless, this concept has received heavy support in the literature. [36] point to the importance of a circular economy in a globalized world, in which sustainable development is a highly positioned goal. It must be noted, however, that no unique concept of a circular economy exists. There are different concepts of how to establish a version of a circu-

lar economy (see [37]), which significantly differs in how it interferes with the environment and affects economic growth and the distribution of income. Therefore, entropy-based indicators for judging the environmental as well as social impacts of a circular economy must be developed further. An increasing number of companies are applying different versions of the concept of a circular economy as business models in order to close, slow and narrow material loops. For evaluating the progress of a circular economy, practitioners developed a high number of circularity metrics (C- metrics). However, little attention has been given to the interplay between the quantification of circularity and its environmental performance. In particular, existing metrics do not capture all material loops and do not adopt a value chain perspective on material flows. This has motivated Brändström and Eriksson [38]) to develop a material flow-based C- metric, which aims at converting mechanisms of closing, narrowing and slowing material loops into a single-point value. See also [23].

5. Final Remarks

Transforming the existent economy into a more sustainable one requires minimizing the flow of entropy. This, in turn, requires closing the natural resource cycle of modern economies. Consequently, circular economy is increasingly promoted as a solution to decouple economic growth and environmental impacts (see [37]). However, since under today's circumstances resource users fail to pay the cost of their activities and consequently overexploit the resources at their disposal, it is urgent that institutional policy eliminates such subsidies and the politically guaranteed property rights which block resource costs from individual economic decisions. Given that such policy interventions are made, the ecological sustainability of the human economy would follow automatically, as human economic activity (making the most with the least) is only a special case of a principle universal to all organic evolution: that of minimal entropy [11]. Our present situation is a result of the cumulative inertia of thousands of years of technological progress. The difference today is that, unlike previous eras, the power of technology and human numbers has grown so great that it, like nuclear weapons, threatens the entire global ecosystem for the first time in history. But the same technology that damages the biosphere can also measure and heal that damage.

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Appendix A

Let us return to the thermodynamic system represented in Figure 1. If gas expands, it works. Based on such a thought experiment, Robert Mayer (see [39] in the late 19th century already derived the so-called mechanical heat equivalent. This defines a relationship between energy in different states, in particular between mechanical and thermal energy. His considerations led to the conclusion that when a gas expands by the volume dV , the mechanical energy dA , according to the formula

$$dA = pdV, \quad (A1)$$

is required where p is the pressure of the gas.

Now realize that the energy dA required to perform the mechanical work must come from the system by itself. Since the system is completely isolated, total energy U of the system remains constant, but the quality of the energy in the system must have changed. By introducing the variable entropy S , every change in energy dU in a thermodynamic

system can be calculated using the variables temperature T and entropy S according to the equation

$$dU = TdS + dTS \quad (A2)$$

Now suppose that during the process of diffusion temperature stays constant. Equation (A2) therefore reduces to $dU = TdS$. And since the mechanical work $dA = pdV$ that the system has to perform causes a change in thermal energy in the system, we obtain:

$$TdS = pdV. \quad (A3)$$

T denotes the absolute temperature of the gas, dS the change in entropy, p the gas pressure and dV the change in volume.

Incidentally, it is now also clear why one cannot observe entropy directly. It is a derived quantity! But it also becomes clear why the efficiency of thermodynamic systems is less than one. Some of the energy that could potentially be used to do work is always converted into entropy.

In the diffusion process, which we described in Section 3.1 above, the energy remains constant according to the first law of thermodynamics, and the following must apply: $dU = 0$. Furthermore, the universal gas equation also applies

$$pV = NRT, \quad (A4)$$

where N is the number of moles and R is the universal gas constant (see Faber et al., 1995). It follows from the conditions (A1) and (A4) for an isolated thermodynamic system, i.e., a system that exchanges neither energy nor matter with the environment,

$$0 = TdS - (NRT/V)dV,$$

or

$$dS = (NR/V)dV. \quad (A5)$$

From this first-order differential equation, the discrete change in entropy between two states, namely, the initial situation of the thermodynamic system with a gas volume V_1 and the final state with the volume $V_1 + V_2$, can be calculated by integration:

$$S(V_1 + V_2) - S(V_1) = NR \ln([V_1 + V_2]/V_1). \quad (A6)$$

The change in entropy of a thermodynamic system during expansion thus corresponds to the logarithm of the percentage change in volume. Since $(V_1 + V_2)/V_1 > 1$, this process is accompanied by an increase in entropy. The change in entropy is thus a measure of the qualitative change that a system has experienced due to naturally occurring processes.

Finally, by using that the concentration χ of a substance or gas is defined as the number of molecules M in the volume V ; hereby $\chi = M/V$, we directly can be derived from (A6):

$$(dS = NR \ln(\chi_1/\chi_2) = NR(\ln\chi_1 - \ln\chi_2), \quad (A7)$$

This means that a change in entropy is directly related to a change on concentration. The consequences are obvious. If resource extraction implies a reduction of the concentration of raw material, then an entropy flow is generated. If we intend to reverse this loss of quality of materials through recycling, a tremendous amount of energy is required. Formula (A7) indicates, how much energy is required. A detailed discussion can be found in [6]. Ref. [40] has demonstrated that Formula (A7) characterized the energy demand in US copper mining very well.

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