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Sadi Carnot and Paradigm Changes in Physics and Economics

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Abstract

Sadi Carnot entered the Paris Polytechnic School at a very young age. Having been born in 1796, in 1812, he entered that renowned educational institution. He studied mainly physics and economics, spending much of his time visiting industries and studying industrial organization and economics, having become an expert on trade and industry issues in several European countries. The Romanian mathematician and economist Georgescu-Roegen studied mathematics at the University of Bucharest and consolidated his training in statistics in France. He then went on to study economics under the guidance of Joseph Schumpeter, in USA, from whom he was strongly influenced. He obtained his degree in economics under Schumpeter and also became familiar with the ideas of the economist and sociologist Vilfredo Pareto. This training gave him great skill in applying mathematics to economics. He then adopted a markedly interdisciplinary approach in his studies and gradually moved away from orthodox economics. As his studies progressed, he began to apply the concept of entropy to economics, borrowing it from thermodynamics. For him, economics was now viewed from the perspective of natural sciences such as physics and biology.

Keywords

Entropy Concept, Ecological Economics, Sustainability, Energy and Environment

1. Introduction

In the first decades of the 19th century, with the development of new theories to explain electrical and magnetic phenomena, the propagation of light and heat, the Newtonian paradigm began to lose importance as a basis of explanation for these new scientific fields (Vatin, 1993). Despite this, the so-called Laplacian project would be the last "acte de résistance" of a group of scientists faithful to the explanatory framework of Newtonian mechanics and the possibility of its extension to those phenomena in which mechanics showed signs of exhaustion (Oliveira, 2013).

In this paper we do not intend to analyze all the paradigm shifts caused by the emergence of thermodynamics, but to emphasize especially its second law, the law of entropy, which establishes a separation between reversible and non-reversible physical processes. Our main objective is to examine in more depth the application of the concept of entropy to economics, and the creation of a new discipline called ecological economics (Burkett, 2009). These developments, more modernly, have taken over the debates and launched many issues related to energy, the environment and sustainability into the field of economic discussions, all of them having as their origin the work of Carnot when creating thermodynamics (Carnot, 1824).

To go to the origin and rescue of these ideas, we will study the work of the Romanian economist Georgescu Roengen (1906-1994) and his difficulties in breaking with the paradigm established in classical economics or even in neoclassical economics, of considering economic processes disconnected from the environment, as if they were self-sustaining itself, for an indefinite period of time (Mayumi, 2001). New economic visions that break this paradigm introduce the environment in this context, through the concept of entropy (Georgescu-Roegen, 1976).

One of the main consequences of the Romanian economist's studies was the *degrowth thesis* (d'Alisa, 2016). But condemning economic growth—seen as a solution to all social and even environmental ills—sounded like a real delusion. It was a thesis considered very radical not only by conservative economists, but even by some environmentalists. Georgescu said that one day humanity will have to think about stabilizing economic activities, as there will be no way to avoid the dissipation of materials used in industrial processes.

These studies and the new perspectives presented have their origins in Sadi Carnot, even as a reflection and an echo that continues to reverberate more than a century later.

2. The Mutual Influences between Mechanics and Economics

The interactions and multiple exchanges between mechanics and economics are well known. They largely derive from the success that Newtonian theory enjoyed in every sense, but mainly due to its method and way of solving the problems posed by scientific development and, later, also by industrial development, which reached the European continent and the USA.

Some Mechanical Concepts Used in Economics

Both mechanics and economics bear a very strong similarity to each other, as they are two deductive sciences and susceptible to independent formalization of their relations with the observation of facts. Furthermore, in the genesis of both we can find a tension between a philosophical point of view and a pragmatic one. In an attempt to develop a properly substantiated science, economists have often favored a deductive path.

Another idea that has its origins in mechanics and is very important to economics is the idea of equilibrium. It has been used since the classical economics of Adam Smith (1723-1790) and David Ricardo (1772-1823), although with different nuances and purposes. The use of ideas and metaphors of mechanical equilibrium by the economy began to have greater scope with the so-called "Marginalist Revolution", consolidating the idea that there is a point in the social world at which all the forces acting on the system cancel each other out. Within this analogy with mechanics, the self-interest of individuals would be comparable to the force of gravity, and which leads them to maximize their utilities, but resources are scarce, and therefore, there are also restrictions on human actions. The problem to be solved becomes finding a combination of goods and services that maximizes people's utility in the context of resource constraints (Mirowski, 1984). Thus, in the view of Jevons (1835-1882), one of the most eminent figures in marginalist economics, differences in individual utilities function as a type of potential energy for exchange. For him, the notion of value was to economics what the notion of energy was to mechanics. Based on these premises, it was possible to develop a mathematical formalism similar to that of Lagrangian mechanics applied to the marginalist model of the economic process (Kirtchik & Boldyrev, 2023).

There is a fundamental difference between applying energy concepts from physics to neoclassical economics. The principles of conservation do not translate directly to the field of neoclassical theory; the sum of income and utility is not conserved and becomes largely meaningless in the economic context. This issue has never been seriously discussed by either the founders of neoclassical economics or their followers.

3. The Physical Concept of Work and the General Theory of Machines

The concept of work derived from physics has been fundamental to scientific development. In this paper we will try to show that it was also very fruitful for the construction of a general theory of machines, anchored in Newtonian theory.

The Change of Newtonian Paradigm

Since the beginning of the 18th century, it was common to calculate the capacity of a machine or engine to perform work depending on the height to which they could lift a certain weight. In this sense, the quantities mgh and $\frac{1}{2} mv^2$ were practically equivalent from the point of view of the operation of most machines. In this way, all those who studied machines began to consider these quantities as being part of the same reality, that is, of the living force (Carnot, 1803). No difference is made between work and kinetic energy, terms still unknown at that time. As we know, it will be Coriolis who will consecrate the use of the term "work", in addition to adding the constant ½ to the term of living force in his most famous book *Du Calcul de l'Effet des Machines*, published in 1829 (Coriolis, 1829). In reality, the use of the term work replacing the terms that were current in the literature at the time is a little more complex, since from approximately 1825 onwards, not only Coriolis started to use it, but also other polytechnic engineers such as Poncelet (1788-1867) and others.

Still without calling the product of force by the displacement of its point of application work, but rather the moment of activity or moment of action, it is in Lazare Carnot's general theory of machines that we can find this difference between living force and work. The beginning of the development of this theory appears in his first "Essay on machines", dated 1783 and is consolidated, as we mentioned in his "Principles". The differentiation between the two concepts appears in paragraph 59 of the "Principles" when he states: "We have just seen that the living force can present itself either in the form Mu^2 of a mass by the square of a velocity, or in the form PH of a driving force for a line. In the first case it is the living force itself; in the second, we can give it the particular name of latent living force". And the latent living force is, evidently, the potential energy of the system.

By differentiating them in this way, Carnot makes it clear that work can be transformed into living force and in a certain way anticipate by 44 years, at least in the strict field of mechanics, the conversion between work and energy. The principle of energy conservation dates back to the late 1850s (Kuhn, 1982).

This was the scientific context and the attempt to use the physical concept of work to study machines, within the Newtonian conceptual framework. As we have already stated on other occasions, it was the polytechnic engineers who brought the Newtonian paradigm to its ultimate consequences. This situation only changed due to the fact that it manifested itself in many ways, that is, that many processes involved the degradation of energy and, consequently, that certain mechanical processes were not reversible. Evidently, a new paradigm should replace the Newtonian paradigm. This change was made by Sadi Carnot.

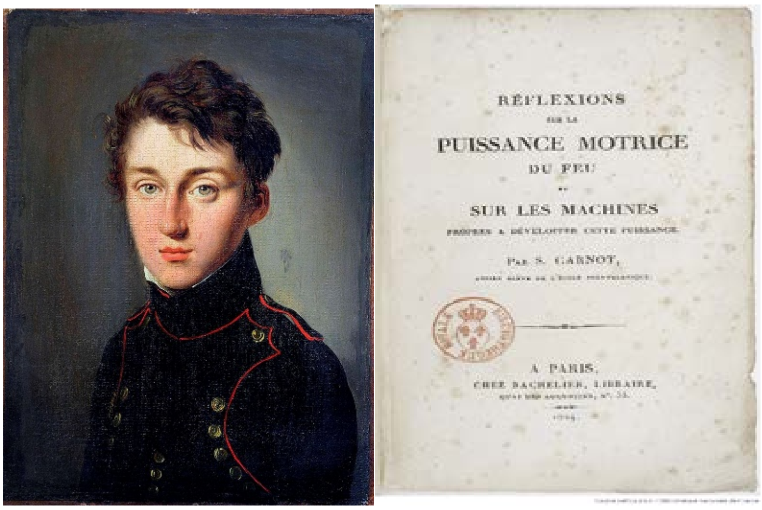
4. Sadi Carnot and the Emergence of Thermodynamics

With the observation that in the operation of machines mechanical energy degrades, transforming into heat, which is partly lost and becomes unavailable, it was necessary for a new theory to emerge. It appeared through the hands of Sadi Carnot. Initially as a new theory for machines and later as a general theory for processes occurring in the physical world. Much has been investigated regarding the influence Sadi Carnot received from his father, Lazare Carnot. For the emergence of thermodynamics, it is important to highlight that after a visit of several weeks to his father and younger brother Hippolyte in 1821, in Magdeboug, he became interested in and focused on research into heat engines, and especially steam engines.

A Sadi Carnot's Scientific Endeavor

The resumption of economic relations between France and England in the period called "Restoration" showed the French the predominance of English industry over their own. It was largely due to the progress and use of steam engines constantly improved by English engineers. Sadi Carnot (**Figure 1(a)**, **Figure 1(b)**) was fully aware of this situation when he stated in his greatest work: *The study of these machines is of the highest interest, their importance is immense, their use grows every day. They seem destined to produce a great revolution in the civilized world... They will also probably one day serve as a universal engine and obtain preference over the strength of animals, waterfalls, and air currents.* (Carnot, 1824, p. 2).

Sadi Carnot's first publication was in 1822 and was an essay to find a mathematical expression for the work provided by a kilogram of steam. This document only became public in 1966.



RÉFLEXIONS

PUISSANCE MOTRICE
DU FEU

SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE

PAR S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

(a) (b)

Figure 1. (a) Sadi Carnot; (b) Sadi Carnot's book.

Despite his training at the Paris Polytechnic School and despite the teachings he received from his father Lazare Carnot, it is surprising that he did not follow the 18th century tradition of rational mechanics, so cultivated by d'Alembert and other great French mathematicians. Instead, he decided to use a form that was little explored and that many people would not understand. In general, we can say that he wrote for engineers, but it is necessary to recognize that few engineers read his book, or even used the results found there. The book quickly went out of print and fell into oblivion for many years.

When writing this small book, Carnot had in mind to answer two questions that worried him: a) is there a limit to the power developed by heat? b) is there another technique besides this that is based on steam, to obtain maximum power?

In this way, his method and approaches aim to find a more general theory than the one that rests on the concept of thermal agitation and that goes further than the concept of ether or caloric, in which he does not seem to believe much. He thus introduces the Carnot engine and shows that its operating cycle depends solely on the temperature of the extremes. He also uses the concept of reversibility for the first time and shows its implications by stating its laws (Gillispie & Pisano, 2014).

Carnot outlines his theory of machines in general terms (translation made by the author):

> *The production of movement is always present in steam engines, which is also accompanied by a circumstance in which we must focus... the passage of heat from a body where the temperature is higher or lower, to another where the temperature is lower. Steam is nothing more than a means of transporting heat....the production of motive power is therefore due, in steam engines, not to an actual consumption of heat, but to its transport from a hot body to a cold body. This principle is applicable to every machine set in motion by heat, there may also be production of motive power* (Carnot, 1824: pp. 9-11).

On the question of the maximum power obtained, Carnot expressed himself as follows:

> *The maximum motive power resulting from the use of steam is also the maximum motive power achievable by any other means. But what do we mean by maximum? The necessary condition of the maximum is that there is no change in volume in the body used to carry out the driving power of heat. Any change in temperature that is not due to a change in volume, or a chemical action is necessarily due to the direct passage of caloric, from a less hot body to a colder body. This passage takes place mainly when bodies of different temperatures come into contact... similar contact should also be avoided whenever possible* (Carnot, 1824: pp. 23-24).

Carnot also analyzes the issue of reversibility:

> *The water used to produce steam at the temperature of body A is at the end of the operation at the temperature of body B, where it has cooled. If we want to recommence an operation similar to the first, if we want to develop a new amount of motive power with the same steam, it is necessary to restore things to their primitive state, and it is necessary to bring the water to the same degree of temperature as it had before. This can be done, without a doubt, immediately reestablishing contact with body A: but now we have contact with bodies with different temperatures and loss of driving power. making it impossible to perform the reverse operation* (Carnot, 1824: pp. 25-26).

Carnot also introduces the notion of cycle, very common in the study of engines:

> *The driving power of heat is independent of the agents put into action to obtain it; its quantity is fixed solely by the temperatures of the bodies between which the ultimate result is achieved, which is the transport of caloric. As long as a gas is quickly compressed, its temperature rises, it drops, as long as it quickly expands. These are facts that we can conclude from experience. A mass of air is compressed in a cylinder of varying capacity. Its state is defined at all times by its volume, pressure, and temperature. We then subject it to a series of transformations mov-*

ing the piston in the cylinder, which when returning to its initial state: we will then have described a cycle.

5. The Concept of Entropy

The concept of entropy is one of the most revolutionary concepts in physics. In the History of Science, few situations and events were as shocking and had as many repercussions as its emergence. From the 19th century until today we live with its echoes and consequences.

Explaining Entropy

The second principle of thermodynamics deals with irreversible physical phenomena, and, to this end, it is necessary to introduce a new thermodynamic function that will characterize the degree of irreversibility. This function will be called entropy (Cardwell, 1971).

A transformation undergone by a given system can be reversible, when we can reverse its direction through an infinitely small modification of external parameters that vary continuously. The system will have a series of infinitely neighboring equilibrium states. The irreversibility of systems may be due to the following factors:

- Friction
- Diffusion phenomena (two gases in contact)
- Heat exchanges, for example two systems in contact at different temperatures, with a heat flow flowing from the hotter system to the colder one
- Chemical reaction

The first principle of thermodynamics says that internal energy is a constant relative to the transformations of an isolated system. It is, therefore, a principle of conservation. It does not refer to the passage, that is, the path between two extreme states. The second principle is a principle of evolution: work and heat are no longer equivalent. In this way, we define for each system a state function S, called entropy. It was Rudolf Clausius who named it after the Greek word "tropos" which suggests an idea of direction (Clausius, 1867). Therefore, Sadi Carnot did not invent the concept of entropy; however, it originates from his studies.

If the cycle is reversible, it means that all transformations compensate each other and then we have:

$$\frac{\int dQ}{T} = 0 \tag{1}$$

On the other hand, if the cycle is completed irreversibly, we will necessarily have:

$$\frac{\int dQ}{T} > 0 \tag{2}$$

and negative and positive transformations do not compensate each other.

If the transformation of the system is not adiabatic, the elementary change in entropy appears as the sum of two terms:

$$dS = \delta S_{ext} + \delta S_{int} \tag{3}$$

The first term depends on heat exchange between the systems and the external environment. The second term refers to internal transformations and is always positive: entropy is always increasing for spontaneous transformations; it characterizes the irreversibility of the transformation. We can say that this term refers to the notion of order or disorder of the system.

For all purposes of our work, it is important to analyze living beings in light of the transformations that occur in the fields of physics, chemistry, biology, and the environment. For plants, energy comes essentially from solar radiation. In fact, leaves provide, depending on the species (and the climate), surfaces to remain away from energy balance. Energy enters through photosynthesis to keep the plant within the configuration and away from minimum potential. Furthermore, matter crosses the boundary of the plant cell in the form of carbon dioxide and water, providing the matter for combustion.

For fauna, energy originates from food: through oxidation they provide the necessary energy, as well as the raw material for the constitution of new cells. If plants are deprived of light and animals of food, their reserves are exhausted, and the definitive balance of death appears. To maintain life, a source of energy is necessary.

Evidently, the molecules that make up living beings obey the laws of chemistry and physics, but an enigma arises in the transition from the disorder of atoms (high entropy) to the order of molecules (low entropy). Later, when we deal with economic studies in which entropy is considered, we will see in depth the consequences for society and the future of humanity.

6. Entropy and Economics

One of the most important paradigm shifts that has only recently been studied is that which relates the economy to the physical world around it, through the processing of low entropy materials carried out by industrial enterprises and the consequent release of waste into the environment.

Georgescu Rows against the Current

In a paper published in the Eastern Economic Journal, in 1986 (Roegen, 1986), Georgescu describes in detail and with great clarity, the relationships between entropy and economic processes, although his book which deals with the same subject, and which is considered his best work, is from 1971 (**Figure 2**).

Figure 2. Georgescu-Roengen.

As he mentions at the beginning of the paper, the essence of the laws of thermodynamics is that: in an isolated system, the amount of energy remains constant (first law) while the available energy is constantly degraded, passing into states of unavailability (second law). Thus, entropy is an index that measures the amount of energy available relative to the absolute temperature of the corresponding isolated system:

$$\text{Entropy} = \text{Available energy}/\text{Temperature}$$

Georgescu also highlights that the laws of thermodynamics, unlike other natural laws, express an impossibility. The law of entropy establishes that $\Delta Si < 0$ is impossible.

With regard to economics, Georgescu observes that living beings essentially need low entropy and that this continuous flow of low entropy keeps organisms fully functioning and supports all the organism's activities. Thus, the necessary condition for a thing to have value is to have low entropy. However, the condition is not enough; Thus, the law of entropy is the root of economic scarcity in a stronger sense. This link between entropy and economic scarcity means that it increases constantly. This relationship is neglected by economists, ignoring the scarcity of natural resources and, instead, professing the belief in a superficial scarcity, stating that anything can be obtained as long as we are prepared to invest in the necessary capital, in labor and equipment.

Economists, so-called orthodox, have a vision of the economic system and express it through the so-called circular flow diagram (Daly, 2015). This diagram illustrates the fundamental relationship between production and consumption, and, therefore, shows how products, inputs and money circulate between companies and families. This view of how the economic system works is that of a closed and circular system. Closed, as nothing new enters the system and nothing leaves it either. Its circular characteristic aims to show how money and goods circulate in the economy. The circular flow diagram represents one of the paradigms of the current economy and represents a "pre-analytical view" of the economic system.

Georgescu emphasizes that the economic process is neither self-sustaining nor a circular movement between production and consumption. Furthermore, it cannot be done without a continuous exchange that alters the environment in a cumulative way (Roegen, 1977).

A stronger thesis is postulated stating that technological innovations can always control scarcity. As a natural consequence of these economic conceptions described above, economic growth becomes the main objective. It becomes the general policy as a whole.

7. Entropy and Bioeconomics

The concept of entropy establishes an inseparable link between the economy and the living beings that inhabit our planet. In this way, the fate of species, including humans, mainly, today depends on the role that the biological world plays in the economy.

The Current Economic Model Is at an Impasse

The greatest contribution of the Romanian mathematician and economist Georgescu-Roengen to economic thought was to show that qualitative changes also occur in the economics and that they can play a decisive role for society. One of these changes occurs on a basic physical level, which is the transformation of "useful" energy into "useless" energy. And this is exactly what the production system does, by transforming natural resources or products that society values into waste that is excluded from the production system. If this is the way the economy works, where resources are transformed into waste, then it is not possible to treat the economy as a closed cycle isolated from nature (Gowdy & Mesner, 1998).

These discoveries by Georgescu-Roengen were responsible for his banishment from the community of economists, because, according to them, Georgescu was getting involved with the dark issues of ecology; a discipline that economists of the time found as strange as numerology. With these studies, the economy becomes part of a living and active ecosystem.

Until the end of the 1960s, none of the different schools of economic thought questioned the dominant view of economics that it was an isolated instance of nature. This deeper criticism of the conception of economic thought as being circular and isolated from nature, will only be made by Georgescu-Roengen and represents a break with the predominant paradigm in Economics.

Until the approach taken by Georgescu-Roengen in 1969, 1970 and 1971, the neoclassical economic model had presented a series of weaknesses and inconsistencies, but still without a more adequate characterization. To begin with, what is called production should be called transformation to give a more appropriate dimension to the flows that come into play. What actually happens in the economy is that elements of nature are transformed into economic goods. It should be noted that there is a difference between what enters and exits in relation to what remains unchanged in the production process and what enters, transforms, therefore leaving something else.

The failure of the neoclassical model was to treat all factors in a simplistic way. The category of factors that do not change in a given process are capital, land, and labor force. The constituents within the process that are changed represent the category of flows. Agents transform these flows of energy and materials, coming directly from nature or another production process, into final products, of course, but also into waste.

As we saw above, there are input and output flows throughout the production process. The flows that exist are those provided by nature (solar energy, rain, oil, nutrients from agricultural soils, minerals, etc.) and those originating from other production processes (steel, wooden boards, etc.), maintenance (spare parts and lubricants, for example). Alongside the flow of products, inevitably arise from any production process, a flow of waste that conventional production theory does not consider. Flows are material substances and energy that cross the boundary of the production process and should not be confused with services provided.

The big problem with neoclassical economics is the fact that it considers all flows as if they were of a similar nature, and based on the hypothesis that the substitution, which must necessarily occur between them, has no physical limits. According to this reasoning, natural resources can be easily and indefinitely replaced by capital.

8. Theory of Economic Degrowth

Georgescu-Roegen was one of the first economists to rigorously investigate the relationships between economic activities and the environment, in light of thermodynamics. With these studies, he created a new school of thought: ecological economics. The law of entropy showed him that it was necessary to abandon the dogma of infinite growth and focus on environmental sustainability and the well-being of society. This is where the program of economic degrowth emerged.

A Program for Degrowth

The theme of economic degrowth had its origins in many academic debates and in the actions of some social movements in Europe, at the beginning of the 1970s. It was at the beginning of this decade that international capitalism began to enter a cycle of crisis, after the so-called "30 glorious years" that began in 1945 with the end of the Second World War. The end of this virtuous circle is expressed by the oil crisis and is when the economic system goes into crisis on a global scale. Evidently, this new situation has led to increased criticism of the model of production and unlimited consumption of natural resources.

The current ecological economists, despite some divergences, are nevertheless unanimous in defending the idea that it is impossible to continue increasing production in a sustainable way, given the biophysical limits of the planet. Alongside Georgescu-Roegen's work, some political actions stood out, such as the publication of *the Club of Rome Report* (1972), which had the title: *The Limits of Growth*, pointing out the consequences of rapid population growth, considering the finiteness of resources.

The starting point for the theory of degrowth is the publication in 1971 of Georgescu's book, entitled: *The Entropy Law and the Economic Process*, where the term degrowth appears for the first time, and, according to him, the neoclassical economic model of the economy, does not consider the second law of thermodynamics. In other words, the concept of entropy had to be incorporated into economics, as only then could the degradation of energy and matter be part of economic analysis. For Georgescu, infinite growth is incompatible with a finite world (Missemer, 2017).

- The complete prohibition of weapons production, thereby releasing productive forces for more constructive purposes.
- Immediate aid to underdeveloped nations.
- Gradual decrease in population to a level that could be maintained only by organic agriculture.

- Avoidance and strict regulation if necessary, of wasteful energy use.
- Abandon our attachment to "extravagant gadgetry".
- Get rid of fashion.
- Make goods more durable and repairable.
- Cure ourselves of workaholic habits by rebalancing the time spent on work and leisure, a shift that will become incumbent as the effects of the other changes make themselves felt.

If we analyze, even superficially, the propositions made by Georgescu in order to live in a more balanced and sustainable society, we can prove that some of them are completely unrealizable within the framework of the current system. The first proposition to prohibit all production and trade in weapons, in a society that thrives on war, with a military-industrial complex that commands the largest and most developed nation on the planet, commanding the entire system of scientific production and technology, it seems to us a task far from being achieved.

Another proposition that is difficult to implement is the one that insinuates the abolition of the fashion production and consumption sector. It is one of the most profitable sectors in today's society.

However, in the context and list of propositions postulated by Georgescu, we would like to dwell a little on the one that talks about reducing the population so that everyone uses organic food. This is a return, even if embarrassed, to Malthusianism, in addition to leaving the current model of production and consumption untouched. When we observe that the most developed countries, mainly the USA, with a small percentage of the planet's population, consume an amount of energy completely disproportionate to the size of their population and that, if all other countries imitated them, it would be impossible to adopt and generalize this model, we will come to the conclusion that the planet would be small and not everyone would be covered.

9. An Applied Concept of Sustainability: The Smart Cities

Recently, as a result of technological development itself, alongside the urgent problems brought about by urban growth, the concept of smart cities has emerged. They use technology and data to manage resources more efficiently, improve quality of life, and focus on sustainability. Hence the connection of this concept with Georgescu's ideas about an ecological economy.

A Look to the Future

The first studies that emerged and began to debate issues related to sustainability were in the 1970s, although economists were not very concerned with the environment, as for them natural resources were infinite. With climate change and major environmental disasters in different parts of the planet, alternating extreme droughts with floods, and landslides with an increase in the number of deaths, the political situation has changed.

The term "sustainable development" appeared in the UN (United Nations) report whose title was: "New Common Future", published in 1987, by the "World Commission for Environment and Development". A first definition of sustainability appeared: "Sustainability seeks to meet the present needs of society without compromising the ability of future generations to also meet their own needs". In this way, the term sustainability is closely related to the economic and material development of society, with the condition that it does not harm the environment and presupposes the use of natural resources in an intelligent way that guarantees their permanence (Hall & Hansen, 2011).

The world is currently facing a major challenge that involves a significant increase in the urbanization process. It is predicted that by the year 2050, 66% of the entire planet's population will live in cities, compared to 54%, taking 2018 as a reference. This implies that 2.4 billion people will be added to the already urban population existing. Cities currently occupy less than 2% of the earth's surface and consume more than 75% of the natural resources available globally. The creation of new urban spaces, satisfying the conditions of sustainability, will be imperative, given the new living conditions on the planet, in addition to facing the growing scarcity of resources. In 2050, an increase to 90 billion tons is estimated, compared to 40 billion tons of these resources in 2010. These include materials for primary energy flows, raw materials, fossil fuel, water, and others.

The concept of a smart city has been gaining strength and more and more followers among urban planners and they consider that the sustainability of these cities has three dimensions: environmental, economic, and social. In the first case, ecological aspects include the conservation of the natural environment (flora and fauna); the second dimension refers to the production of resources and an efficient and balanced economy; Finally, the last dimension includes equity, the autonomy of communities, the well-being of citizens and the satisfaction of their basic and fundamental needs (Komninos, 2011).

10. Final Comments and Conclusion

The discovery of the second law of thermodynamics by Sadi Carnot in 1824 constitutes one of the most impactful ruptures and paradigm shifts that have occurred in physics throughout its history. It is only comparable to the Copernican Revolution, which radically changed the way of seeing the world and the universe known until then.

As we tried to show, even briefly, Carnot's discovery exhibits a very particular characteristic compared to even more recent ruptures such as those caused by Quantum Mechanics and the Theories of Relativity, restricted and general. It is a prohibitive law, which establishes limits and restrictions not only in the field of physics, but also in biology and economics and, as a consequence, has a scope that affects the animate, inanimate, and social worlds. If we take Newton's Laws for example, they are completely symmetric with respect to time. It does not matter for Newton's Laws whether the flow of time is in the past or in the future. Well, the second law of thermodynamics prohibits irreversible processes in physics, biology, and economics from occurring in the past. The increase in entropy in closed systems is inevitable.

Also, as we have shown throughout this paper, although the second law is two centuries old and the concept of entropy a little less so, its implications for the field of social sciences were only made clear a little more than half a century ago and many problems and new challenges raised by it are yet to come.

Finally, there is the issue of the confrontation between the "green growth" proposal and Georgescu's degrowth theory. Although they are two antagonistic proposals, some comments are necessary. The first proposal starts from the hypothesis that growth is possible, but this requires focusing on efficiency, technological innovation, and the use of renewable energies. With this, it would be possible to continue growing. Georgescu's proposal, postulating degrowth, is based on the fact that many transformations mainly industrial activity, primarily, process low-entropy materials and deliver waste, and therefore high-entropy materials, to the environment. Thus, only degrowth would guarantee long-term sustainability for life on the planet.

Although the two models present themselves from different perspectives, both start from the same premise, with which we disagree: that current economic models cannot be reformed. The dilemma would only lie in whether to grow or not. In our opinion, it is necessary that current models be reformulated and combat the inequalities inherent in them, which are sources of the coexistence of extreme scarcity and extreme waste. Before adopting either model, it is fundamental to combat inequality in the use of natural resources and, especially, the energy produced, always questioning for what purpose and for whom it is produced.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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