A thermodynamic analysis of market and planned economies

Soriano, Carles

Geociènces Barcelona, CSIC, Spain

11 October 2025

A thermodynamic analysis of market and planned economies

Carles Soriano
Geociènces Barcelona, CSIC
c/ Lluís Solé Sabarís s/n
Barcelona 08028, Spain
email: csoriano@geo3bcn.csic.es

Abstract

Market and planned economies are considered antagonistic types of material production systems in modern society. Since they are thermodynamic systems, the entropy and energy requirements of each system can be estimated based on its specific characteristics and dynamics. The results show that the entropy and energy requirements of a market economy are much higher than those of a planned economy. This is due to competition for profit, the driving mechanism of market dynamics and self-organization, which is absent in a planned economy. Thus, the entropy and energy needs of a planned economy approach the minimum magnitudes required of a modern economic system that is irreversibly driven to equilibrium with an external reservoir supplying low-entropy energy. Dissipative systems on Earth absorb low-entropy energy from an external source, using it to gain internal order and stability while emitting high-entropy energy. Conversely, a market economy increases its internal entropy during energy exchange with an external reservoir. Large internal entropy in a market economy does not result from summing the entropy of individual capitals. Rather, it results from self-similar dynamics driven by competition for profit, which manifests as larger system property magnitudes.

Keywords capital, competition, entropy, probabilistics, profit, self-similarity

1. Introduction

Thermodynamics emerged in the 19th century with the aim of understanding the physics of industrial processes that were increasingly being introduced into society's material production. The innovation of the steam engine played a major role, as it was a power source for many industrial processes and provided the practical basis upon which thermodynamic theory was developed. In the 20th century, thermodynamic studies expanded into other fields, including biology, information theory, and economics. Initially, thermodynamics focused on understanding reversible processes in physical systems evolving from initial to final conditions of thermodynamic equilibrium. Later, thermodynamics generalized to include irreversible processes and non-equilibrium conditions. Thus, this branch of physics was able to account for most observed processes in nature.

Thermodynamic laws are universal. They are macroscopic laws that describe the processes of matter and energy transformations, from the atomic and subatomic levels, to living organisms and their hierarchical organization, including humans and human societies (Lineweaver and Egan, 2008). However, thermodynamic laws and the mathematical formalism of thermodynamics strictly deal with physical processes and cannot be directly transposed into living organisms and social systems, despite the fact that they are also physical. Living organisms and their social organizations, modify the phenomenal forms of thermodynamic laws, so that they appear as particular manifestations mediated by the internal characteristics of living beings and human societies (Schneider and Kay, 1994; Kleidon, 2023). Therefore, thermodynamic equations cannot be directly applied to human social production processes and economic systems. Doing so without considering the particularities of human and social organizations may lead to incorrect conclusions. In other words, although economic systems are thermodynamic systems, they are more than just physical, and their complexity can only be roughly approximated by the mathematical formalism of thermodynamics.

Economics deals specifically with the material production every society must undertake to reproduce itself according to its particular characteristics. Because producing goods and services involves exchanging energy and matter with the environment, all societies, regardless of their level of complexity, ultimately operate under the laws of thermodynamics. However, how these laws are expressed in economic systems depends on the intrinsic characteristics of each system, which mediate in the phenomenal manifestation of these laws. Since material production has varied throughout human history, the manifestation of thermodynamic laws has also varied in different historical economic systems. Economic laws are particular to each system and superimpose on universal thermodynamic laws, modifying their manifestation. This explains why the manifestation of thermodynamic laws differs between hunter-gatherer, agricultural, and industrial societies.

This study compares the entropy and energy of market and planned economies. These economies are defined as antagonistic end-member cases of material reproduction in modern society. The goal is to characterize the thermodynamics of these economic systems based on their intrinsic features and specific dynamics. To this end, the next section provides an overview of relevant thermodynamic concepts and the relationship between economics and thermodynamics. The third section analyzes the specific characteristics and system dynamics of market and planned economies. The fourth section provides entropy estimates for both economic systems. The fifth section relates the estimated entropies to the energy requirements and economic dynamics of market and planned systems. The discussion section highlights the environmental implications of the thermodynamic analysis of market and planned economies, as well as possible similarities between a market system with a few monopolistic capitals and a planned economy.

2. Thermodynamics and economic systems. Generalities

The material production of society can be defined as a thermodynamic system fed by two external sources of energy: the Sun and the Earth’s interior. Dissipation structures on Earth, such as atmospheric, oceanic and mantle convection cells, and living organisms with hierarchical architectures based on trophic relationships, transform energy from these sources into mechanical work and chemical energy necessary for their own functioning (Schneider and Kay, 1994; Kleidon, 2023). In a sense, dissipation structures are mechanisms of energy storage that is used by an economic system. Stored and direct energy inputs from external sources are converted into the mechanical work necessary for the material production of society throughout a combination of techniques. Thus, the economy is a supra-system of energy dissipation that uses the energy of all other dissipation structures and sources on Earth. From a thermodynamic perspective, the material production of society can be understood as an open economic subsystem that exchanges matter and energy with a larger reservoir acting as an a priori unlimited energy supplier, where the economic subsystem and the reservoir constitute an isolated system (Fig. 1).

2.1. Entropy

Entropy is a property or attribute of energy through which the quality of energy can be quantified (Wark and Richards, 1998; Dincer and Cengel, 2001; Cengel and Boles, 2008). The concept of entropy has evolved from classical thermodynamics, where entropy is a macroscopic variable relating heat flow as a function of temperature, to statistical mechanics, which introduces the concept of probability to thermodynamic systems, to information theory, where entropy is associated with uncertainty. In statistical mechanics, entropy is a physical state variable that measures the randomness, disorder, or freedom of a system. Randomness or freedom is an objective physical state of the system, which reflects as a subjective uncertainty when we try to determine the state of the system in order to interact with it. In the well-known case of an ideal gas composed of freely moving molecules, the position and momenta of the molecules that characterize the state of the system cannot be determined as in classical mechanics. They can only be determined probabilistically, introducing uncertainty in our characterization of the system.

In statistical mechanics, entropy describes the observed macroscopic state of a system relative to the distribution of its internal microstates, which are defined as the possible configurations of the system's particles. Entropy considers the arrangement of particles as disorder or randomness at the microscale and the relationship between the microstate distribution and the observed macrostate of the system. This randomness leads to an indeterminacy or uncertainty regarding our knowledge of the position and momenta of the particles in the system, which is described by the different expressions of entropy, such as Boltzmann and Gibbs-Shannon entropies.

Most systems in nature are not in thermodynamic equilibrium. Nonetheless, they spontaneously evolve toward a state of thermodynamic equilibrium, where entropy is maximum, thermodynamic gradients are leveled out, and no fluxes of energy and matter are possible. This is essentially the statement of the 2^{nd} law of thermodynamics, which imposes an irreversible directionality for all processes and systems. Thermodynamic systems driven to equilibrium dissipate energy during conversions and exchanges of energy between systems regardless of whether the systems are isolated, closed, or open (Lebon et al., 2008). For instance, a fluid in a closed system absorbing heat inhomogeneously from an external source generates a temperature gradient, based on which matter and energy flow from hotter regions to colder ones within the system. Thermal energy is used to perform the necessary thermodynamic work to move the fluid, while energy is dissipated in fulfillment of the 2^{nd} law. Mantle convection, atmospheric circulation, and oceanic circulation are essentially driven by this thermal dynamics. These processes use temperature gradients formed by the uneven absorption of low-entropy energy inputs from external sources to dissipate high-entropy energy. Dissipation systems on Earth, including the ensemble of living organisms with their hierarchical architecture, self-organize as highly ordered structures by converting external energy inputs into mechanical work while dissipating high-entropy energy (Schneider and Kay, 1994; Kleidon, 2010; Kleidon, 2023). For example, when a system evolves from transferring energy by thermal conduction to thermal convection, it becomes more ordered and stable. In other words, the system becomes more efficient at converting heat into mechanical work, and the temperature gradient stabilizes (Schneider and Kay, 1994; Kleidon, 2010). The opposite holds when the system evolves from convection to conduction.

An economic system is composed of units of production that produce the goods and services necessary for the material reproduction of society. Like other dissipative structures on Earth, an economic system dissipates energy. Concerning economics, entropy describes the internal organization and mutual interaction of the units of production in relation to the observed macroscopic state of the system. Thus, entropy provides an estimate of the disorder or randomness of the economic system by considering the internal configuration and interaction of its constitutive elements. Since the driving forces of such interaction differ qualitatively in planned and market economies, the macroscopic properties of these economic systems, including entropy, also differ quantitatively.

3. Planned versus market. Antagonistic end-member cases of economic systems

In this study, market and planned economies are *ideal* end-member cases of the organization of material production in modern society. They are hypothetical cases, based on, but departing from, the historical cases of market and planned economies in the second half of the past century. These historical examples can be broadly typified as mixed economies and do not exactly mirror the hypothetical cases in this study. For example, commodity production and market were not completely abolished in Soviet-style planned economies, and time was not adopted as the unit of account of labor in most economic sectors. In the so-called welfare economies of the West, there are and have been economic sectors outside the circuit of capital reproduction on a profit and commodity basis. Typically, these sectors include education, health, and domestic labor. Using hypothetical cases based on empirical evidence to develop theoretical frameworks is a common procedure in most natural science disciplines. For example, in thermodynamics, perfect gases and the Carnot engine are idealized cases that differ from physical cases in nature but are nonetheless necessary for understanding natural cases. Therefore, defining hypothetical cases of economic systems is fully justified.

A commodity consists of the dialectical unity of use value and value. The value of a commodity is expressed as exchange value, which, has a monetary expression in the commodity’s price. Profit is a value form, and in market economy every commodity contains a share of the total profit produced in society. Thus, use values are produced as long as they are the unavoidable carriers of the profit contained in commodities, and the more commodities produced, the more value expressed as profit is obtained. In thermodynamic studies, the increase of entropy is often referred to as the tax that must be paid to extract useful work during energy conversions in thermodynamic systems driven by irreversible processes (Dincer and Cengel, 2001; Lineweaver and Egan, 2008). Similarly, it can be argued that producing use values as commodities is the tax that must be paid in a market economy to obtain the profit contained in commodities. The market system shows a natural tendency toward financial hypertrophy because the financial sector of the economy is seemingly free from the burden of producing commodities to obtain profit. In the financial sector, money can be made from money without paying the tax of producing commodities. A planned economy does not produce use values as commodities and is therefore not subject to this tax.

The units of production of an economic system, whether they are the individual capitals or firms in a market economy or simply the units of production in a planned economy, are scientifically organized in order to maximize production outputs relative to inputs. This applies in monetary terms and in terms of the energy and matter that enter a production process to create a final product. It also applies to the optimization of labor, the fundamental activity without which production is impossible. Deviations from this ideal scientific organization of production affect production processes in both market and planned economies. Thus, the structural differences between these economic systems cannot be attributed to such contingencies. Examples of scientific production organization include assembly lines, which were implemented in both market and planned economies last century, as well as the present-day organization of production assisted by robotics and artificial intelligence.

The entropy of an economic system, understood as its internal degree of disorder, randomness, or freedom can be estimated. On a merely intuitive basis, it can be stated that a market economy has higher internal entropy than a planned economy. This statement is based on the own concept of market as a *free* market, and on related concepts such as the *invisible hand market* and *laissez faire* economics. These concepts have been central to mainstream economic thought from the time of classical political economists such as Adam Smith and François Quesnay to the present day with economists like Friedrich von Hayek and Milton Friedman. These concepts are firmly entrenched in liberal dogma, which asserts that the profits of individual capitalists ultimately benefit society as a whole. Furthermore, studies on the entropy of the market economy have explicitly acknowledged its inherently non-deterministic, chaotic, and unpredictable character (Farjoun and Machover, 1983; Annila and Salthe, 2009; Scharfenaker and Semienuk, 2017). The *filoentropic* character of the market economy can also be deduced from the dismantling of the so-called welfare state in the Western economies during the neoliberal period of the last century. This dismantling was rooted in the market economy's intrinsic need to evolve spontaneously, free from the restrictions imposed by states and governments during the previous welfare state period.

3.1. Market economy

The economic system of modern society is based on the reproduction of capital through commodity production and labor exploitation. Throughout an historical process that has subsumed any other economic forms not based on capital and commodity production, this has become the dominant mechanism of social reproduction. Historically, market and money are products of human labor that predate capital. However, the market system only achieves full development within the capitalist mode of social reproduction. Advanced capitalist societies in the second half of the 20th century are historical expressions of modern market economies, with the USA and the UK being the best examples, particularly during the neoliberal period of the 80s and 90s. In a modern market economy, society itself cannot reproduce according to its own foundations if capital does not reproduce. This is expressed in the classical relationship of capital

$$M – C – M’, \tag{1}$$

where M is money-capital, C is commodity, and $M’ = M + \Delta M$ (Marx, 1996). According to the equation of capital, the reproduction of society depends on the reproduction of capital, which, in turn, depends on the production of commodities for profit, where profit is the source of ΔM in (1). Therefore, goods and services necessary for social reproduction must be produced as commodities, and a market is needed for the free exchange of these commodities. The commodity is the historical form of the product of human labor that dominates the material production in modern society. However, not all products of human labor are commodities, even though all commodities are products of human labor. For instance, most domestic tasks result in products of labor that are not commodities. The distinctive characteristics of the social reproduction mode based on capital and commodities are summarized in Fig. 2 and explained below.

A) The number of commodities produced in a market economy is potentially unlimited. The commodity realm must expand freely, both extensively and intensively. Intensive expansion concerns all aspects of human life and is limited by the lifespan of each individual. An unlimited intensive expansion of commodities requires an equally unlimited expansion of individuals, which explains the world population's hyperbolic growth in modern times (Soriano, 2025). Extensive expansion concerns all of Earth's geospheres and, potentially, exoplanets. A priori, it is limited only by the size of the universe. The expansion of the commodity realm is evident through the geographic expansion of the market system based on the reproduction of capital for profit from Western Europe to the rest of the world throughout the modern era and the commodification of most aspects of human life.

B) In a market economy, the units of production are capitals, which only produce for profit. Capitals produce to obtain as much profit as possible from the total profit produced in society. However, this can only be achieved at the expense of other capitals' shares of profit. Thus, individual capitals engage in free and disorderly competition with each other for a share of the total profit produced. Competition for profit is governed by the cost-benefit equation

$$C = k + p, \tag{2}$$

where C is the value of commodity C, k is the cost to produce C, and p is the profit obtained in the production process of C. This equation shows that each commodity C contains a share of the total profit contained in a given number of commodities. It also shows that by increasing the number of commodities, an individual capital increases the share of the profit obtained with respect to other competitors producing C. Thus, equation (2) guides the investment of capitals to minimize k and maximize p.

C) A market economy is a monetized system. This means that the price of commodities is the monetary expression of the labor time (MELT) that invariably underlies the production of all kinds of commodities, whether they are sold to the final consumers or to other capitals for their particular production processes. Labor is the only substance of the value expressed as money. In a market economy, the system of prices provides information to individual capitals for their investment strategies aimed at obtaining as much profit as possible. This system has been spontaneously developed around the intrasectorial and intersectorial average rates of profit throughout an historical process. It helps capitals to navigate within the competitive universe of the reproduction of capital on a profit basis (Cockshott and Nieto, 2017).

D) The cost of producing a commodity, C, is expressed as $k = c + v$, where c is the value of constant capital (e.g. raw materials, infrastructure, machinery) and v is the value of the labor force. The main way capitals minimize k and maximize p in equation (2) is by replacing the labor force in the immediate production process by constant capital, which is the human labor of past production processes objectified in machines and other means of production. In other words, by introducing technological innovations in the production processes, living labor is substituted by dead or past labor, and capitals minimize k and maximize p. In this way, capitals are able to produce more commodities than their competitors, which can be sold at lower prices, and thus obtain a larger share of the total profit produced in society. Scientific and technological innovation in modern industry is essentially driven by competition for profit. This is shown in the development of thermodynamics as a branch of physics aimed at understanding and improving industrial processes in the 19^{th} century, and the current development of AI and robotics.

E) The rate at which capitals obtain profit from the productive sector of the economy is expressed as $p' = p / (c + v)$. The main mechanism to maximize profit involves removing human labor from the immediate production process and replacing it with human labor from past production processes. However, only living human labor can create value and, thus, profit at any given time. Past labor, objectified in constant capital, cannot create value or profit independently; rather, its value is transmitted to the new product through the labor activity of living humans. Consequently, the rate of profit, p', decreases in the long term of the capitalist production because living labor is increasingly substituted by past labor in the production processes of society. Empirical time series of the rate of profit in advanced capitalist economies confirm this tendency to decrease despite the mechanisms activated by capitals and governments to counteract it (Carchedi and Roberts, 2018). The main mechanisms undertaken to counteract the decrease in the rate of profit are: trimming salaries, increasing the rotation of capital in equation (1), and further substitution of living labor with past labor to increase labor productivity. In the short term, these mechanisms may give individual capitals a competitive advantage, allowing them to earn larger profits than their competitors. However, in the long term, these mechanisms lead to the overaccumulation of capital in production processes, a further decrease in the rate of profit, and, eventually, crises.

F) The accumulation of capital on a decreasing trend of the profit rate underlies most economic phenomena observed in modern market economies. This includes the overproduction of commodities, the migration of capital from commodity production to the financial sector, financial hypertrophy of the economy, increasing societal debt, economic crises, and world overpopulation. Recurrent economic crises are characteristic of market economies. They are the unconscious and chaotic mechanism by which the economic system resets itself to allow further capital accumulation at a partially restored profit rate. During each crisis, overaccumulated capital that cannot be absorbed by new investments in the productive commodity sector is destroyed, and overproduced commodities that cannot be absorbed by final consumption remain unsold. Crises are necessary moments in which the number, size, and distribution of individual capitals reorganize to allow new cycles of capital accumulation. They are endogenous mechanisms driven by the economic system's self-similar feedback dynamic: the more capital that accumulates at a decreasing rate of profit, the more capital that must accumulate to overcome this decreasing rate, which decreases the rate of profit further. This dynamic is periodically punctuated by crises of capital destruction, which propel self-similarity, and each crisis paves the way for the next. Consequently, the system becomes increasingly weakened in the long term.

Mainstream economics is based on the subjective and arbitrary character of value, as promoted by the marginalist school, as well as on Walrasian market equilibrium theory. This theory assumes that prices are in equilibrium before and after the exchange of commodities (Scharfenaker and Yang, 2020). Mainstream economic thought argues that the pursuit of profit generates spontaneous order and stability in the system on this basis. Competition for profit certainly generates stationary equilibrium of some macroscopic system variables, such as prices, the distribution of profit rates, and the composition of capital in productive processes (Scharfenaker and Semieniuk, 2017). These variables tend to equalize around stationary values in the short-term, and determining their distribution in the market space is an intrinsic probabilistic problem (Farjoun and Machover, 1983; Zachariah, 2009). However, regarding the profit rate, the driving variable of the system's dynamics, equalization occurs at decreasing profit rates in the long-term evolution of the market system (e.g. Linares, 2016). The decreasing rate at which profit is obtained acts as an attractor, driving the system toward a critical point of transition to a different economic regime, which does not necessarily have to be a planned economy. Indeed, the pursuit of profit generates increasing randomness and instability as the system evolves toward criticality, rather than the equilibrium and stability that are praised by mainstream economics. This is evident in how quickly the liberal tenet of a *free* market and *laissez-faire* economics are disregarded when periodic crises in capital reproduction destabilize the market system. In this context, the system is not allowed to evolve spontaneously, and individual capitals are rescued with the labor of society as a whole.

3.2. Planned economy

A planned economy is defined as being antagonistic to a market economy, as well as simpler than a market system (Fig. 2). In a planned economy, the products of human labor are not commodities, but use values that are defined a priori to satisfy the needs of social reproduction. Use values are the goods and services that society needs for its reproduction and can change both qualitatively and quantitatively over time. Use value is the natural or universal form of the product of labor, whereas commodity is a historical form based on value. In a planned economy, time is the unit of account for the labor that individuals and society employ to produce a given use value. This time is the average labor time employed by society to produce a use value, and individuals exchange their labor contribution to produce use values, measured in time (Cockshott and Cotrell, 1993; Cockshott and Nieto, 2017). In other words, they exchange labor time rather than the monetary expression of labor time (MELT), as occurs in a market economy (Fig. 2). Time naturally measures labor by duration, whereas money expresses labor time when labor itself is mediated by value, the historical form of the products of labor, including the labor force. Thus, time is the natural unit of account in an economic system, whereas money is the particular, historical unit of account in a market economy.

In a planned economy, there are not capitals competing for a share of the total profit produced in society, but units of production that produce the use values needed for the social reproduction on a non competitive basis. However, profit and competition for profit, or some other type of reward, can eventually be introduced in a given economic sector if required by society. In a planned economy, this is a predetermined option, not the spontaneous dynamics intrinsic to a market economy. Economic crises are exogenous phenomena in a planned economy, usually driven by external contingencies, such as droughts, floods, and other natural disasters. Along with these external contingencies, human errors can also cause economic crises in both planned and market economies. Thus, exogenous crises are common to any mode of social reproduction, whereas endogenous crises are the particular form of crises that characterize market economies. In a planned economy, production is organized *ex ante*, whereas in a market economy, production is left to the spontaneous activity of individual capitals, and there is an *ex post* regulation of the economic activity, which may include taxing, subsidizing, and others.

In a planned economy, production is subject to planning and agreement regarding what, how, where, and when to produce. In short, the organization of labor, which is the basis of the material production of society, is not left to the spontaneous activity of individual capitals competing for profit. Rather, it is based on decisions that address the needs of social reproduction. This is the main difference between a planned economy and a market economy. A planned economy allows for some degree of self-organization, but this degree is agreed upon and controlled by society rather than by the self-similar dynamics of competition for profit. In a planned economy not all production is centralized. Instead, the degree of centralization depends on the characteristics of the use value being produced. For example, vegetable production, distribution, and consumption can be decentralized, while solar energy can be produced at a local scale but distributed according to a centrally planned network. The Soviet Union in the last century is the best historical example of a planned economy, with its central economic planning agency, Gosplan, which planned the economy every five years. It should be noted that the collapse of the Soviet Union in the 1990s was not a failure of economic planning per se, as the abandonment of economic planning was a political decision made by the Soviet authorities. Among many other decisions, Soviet authorities introduced profit and, consequently, competition for profit in the 1980s. Under commodity production for profit, the planned system rapidly transformed into a market economy.

4. Entropy analysis of market and planned economies

In statistical mechanics, entropy accounts for the distribution of system's particles as internal microstates in relation to the observed macrostate of the system. A given number of N particles can be arranged in an equal or larger number of N microstates, which can arise in an equal or smaller number of N macrostates, that is, $N_{macro} \leq N_{micro} \geq N_{part}$. Consider an *ideal* gas composed of N non-interacting particles or molecules that move freely and are statistically independent. The distribution of each particle is fully described by its momenta and position in the three dimensional space, and describing the microstate of the whole system requires specifying the momenta and position of all particles in a 6N phase space. For a large number of particles, N >> 1, an exact determination of the particles' distribution and the system's microstate becomes impossible, thus a probabilistic approach is necessary. The multiplicity of a microstate is the number of possible combinations of particles for that microstate, and can be expressed as $N! / \Pi_i N_i!$. Using Stirling's approximation for large number of N, $ln\,(N!) \sim N\,ln\,(N) - N$, the multiplicity can be approached to the logarithm of the possible combinations weighted by the number of systems' particles as

$$S = -N \sum_i p_i \, ln \, p_i, \tag{3}$$

where p_i is the probability of the microstates, N is the number of microstates, and S is the entropy or degree of freedom of the system, which defines also our uncertainty in determining the system's state (Brissaud, 2005; Annila and Salthe, 2009; Scharfenaker and Yang, 2020). For a system of N_j particles arranged in N_i microstates, $p_i = N_i / N_j$ is the probability of the i microstate. The entropy of the system can be expressed in bits, nats, digits, and Joules per Kelvin by introducing the Boltzmann constant as a proportionality factor (Gao et al., 2019; Scharfenaker and Yang, 2020; Parrondo, 2023).

A capitalist, market-based economy is an extremely dynamic system, in which capitals are continuously fluctuating over time in search of the highest possible share of profit. In a market economy, competition for profit entails mutual interaction and conditioning between individual capitals. The profit rate is a macrostate variable of the system that is determined by and, in turn, drives competition for profit. It underlies the self-similar dynamics of the system. The distribution of capitals on a profit rate basis describes the system's state at any given time. That is, it shows the position and weight of capitals in the market space with regard to the profit rate, which is the driving force of the economic system. The profit rate is a continuous variable that can be partitioned into discrete bins, and the number of capitals can be aggregated for each bin to construct a histogram whose shape is described by a continuous probability density function (Fig. 3). Since many combinations of capitals lead to the same distribution over bins, a histogram corresponds to many microstates. Thus, the macrostate of a market economy in relation to the possible microstates and to the internal configuration of the system's components is a probabilistic problem.

Although a market economy is more complex than an ideal gas of independent, non-interacting particles, its state can be approximated by equation (3) for comparison with a planned economy. This equation is the Gibbs-Shannon entropy weighted by the number of capitals, N, the main determinant of entropy in a market economy. Equation (3) shows that the larger the number of capitals, the larger the entropy. Empirical distributions of capitals on a profit rate basis have been obtained from national and international institutions, as well as from firms' accounting records, for a given economic sector, an entire national economy, and a given time interval. For example, Wells (2007) estimated the profit rate distribution for a up to 100000 firms in the UK economy in various years, Zachariah (2009) estimated the profit rate distribution for 48 industry sectors in Sweden from 1995 to 2000, Linares (2016) estimated the profit rate distribution for 25000 firms in 15 productive sectors in the US from 1965 to 1966 and from 1990 to 1991.

In a planned economy, there is no profit and no capitals competing for profit. Production units are organized based on agreed-upon decisions to satisfy society's needs on a nonprofit basis. In equation (3), this is equivalent to consider that N approaches to 1 and the summation approaches the minimum intrinsic entropy corresponding to the dissipation of energy in the industrial processes involved in production. Thus, when equation (3) is applied to a planned economy, the entropy approaches the minimum entropy that a non-equilibrium economic system driven to thermodynamic equilibrium with an external reservoir must generate regardless of whether the system is planned or market-based. In the above empirical studies, the number of capitals on profit rate distributions is always a minimum compared to the total number of capitals in a market economy. Therefore, the entropy of a market system is about several orders of magnitude higher than that of a planned system.

5. Balance of energy and entropy in market and planned economies

Entropy is a property of energy that cannot be created from nothing. Since entropy is attached to energy, increases or decreases in entropy imply variations in the energy of the system. The entropy of an open economic system, understood as disorder or freedom, must be fed by energy from an external reservoir. In other words, this is an energy tax that the system must pay for its disorder and any increase in the system's entropy. Therefore, the larger the entropy of an economic system, the larger its energy requirements. In a market economy, competition for profit drives self-similar dynamics whereby the energy requirements due to the system's high entropy fuel further increases in entropy. These increases in entropy then fuel further energy requirements, and so on. The implications of self-similar dynamics in a market economy regarding energy and entropy can be illustrated with the following examples.

Consider an economic sector in which N_i firms compete for the profit contained in a commodity, X. Competition for profit entails increasing the production of X from X^i to X^{i+n}, which, in turn, entails increasing the input of energy. The profit contained in X must be realized, that is, it must be sold on the market. To increase their profit share, individual capitals not only produce more X, but also engage in marketing strategies to sell their overproduction against that of other capitals producing X. The production of marketing strategies requires additional energy and is part of the production process of X. Note that it is irrelevant whether X is consumed in the production processes of other capitals or by individuals. The production of marketing strategies can be assimilated as an internal division of the individual capitals producing commodity X. Alternatively, marketing strategies themselves can become a new commodity, Y, produced in an economic sector independent of the sector producing X, where N_j capitals compete for the profit contained in Y. This new sector has additional energy requirements compared to the state of the system before the expansion of production from X to Y. As a result of self-similarity driven by competition for profit, the commodity realm has expanded, the number of capitals has increased, and the system's energy requirements and entropy have increased.

Now, consider the same economic sector in a planned economy, where N_i units of production do not compete for the profit contained in the use value X. The number of X does not necessarily increase from i to $i+n$, as required in a market economy where X is a commodity and capitals compete for the profit contained in each X. In a planned economy, an eventual increase in the number of X is agreed upon before production and it can be adjusted iteratively according to societal needs. In this case, a new economic sector with new capitals producing marketing services for capitals in other economic sectors does not spontaneously arise due to the self-similar dynamics of competition for profit. In a planned economy, an increase in the units of a given use value, the number of different use values, and the units of production does not result from the blind dynamics of competition for profit but from the *natural* evolution of society. Consequently, the entropy and energy requirements are much lower in planned system than in a market system. Equally important, any increase in the entropy and energy requirements in a planned economy occurs at non-accelerated rates. In contrast, competition for profit in a market economy drives accelerated rates of energy consumption and entropy increase.

The production of marketing services by an economic sector that consumes society's energy resources and increases the entropy of the economic system is only one example of the intrinsic needs of a market economy regarding entropy and energy. There are many more examples. Consider the increasing judicialization dynamics observed in Western societies. This is a manifestation of the multiple and competing interests in a market-based society. In this context, individual capitals litigate against each other, against public institutions that are supposed to govern for the benefit of society as a whole, and individuals and groups of individuals litigate against institutions and capitals. Many legal disputes in market-based societies have an economic basis and are ultimately rooted in the conflicting interests generated by competition for profit. This increasing judicialization entails additional increases in the energy and entropy requirements of society beyond those strictly involved in producing commodities. The ongoing rapid development of AI techniques is another example of chaotic competition for profit in a new economic sector, entailing growing entropy and enormous energy demand in the global market system.

6. Discussion

A market economy is a self-organized complex system with a self-similar dynamics driven by competition for profit. The entropy of the system does not result from adding the entropies of individual production units, i.e. capitals. Individual capitals try to minimize their own internal entropy as much as possible. However, the interaction of these capitals around profit results in an exponential increase in the magnitude of several system parameters, such as entropy, population, capital accumulation, and profit itself. The emergence of unexpected properties that cannot easily be predicted from the properties of the system's parts is a well-known process in nonlinear complex systems (Martyushev, 2021). For instance, the properties and dynamics of the entire biosphere or a specific ecosystem cannot be predicted by simply adding the properties of individual organisms because their mutual interactions, and those with nonliving matter, result in new quantitative and qualitative properties and dynamics for the whole system. Similarly, the environmental impact of the global market system cannot be reduced to the sum of the impacts of individual capitals. Rather, it emerges as a new type of relationship between the environment and the economic system due to the system's complexity and self-organization around profit. For this reason, the ongoing habitability crisis on Earth cannot be understood from the simple addition of the environmental impact of individual capitals. Rather, the crisis emerges as a new qualitative relationship between the global market system and the Earth, by which this economic system has become a planetary force capable of conducting unprecedented quantitative environmental transformations on Earth (Fischer-Kowalski et al., 2014; Soriano, 2024).

The thermodynamic analysis conducted here explains the Jevons paradox, named after William Stanley Jevons, a founder of the 19th-century marginalist school of economics. In short, the paradox states that improvements in the energy efficiency of industrial processes lower energy costs, thereby increasing demand and potentially leading to the exhaustion of energy resources. However, the eventual depletion of energy resources is better understood as a consequence of the growing energy requirements associated with increasing entropy production in a market system than as a phenomenon related to the supply and demand of energy based on cost. Exhaustion of energy resources is a consequence of the structural characteristics of self-similar, profit-driven dynamics in a market system. In such a system, both individual capital and the system as a whole must increase their consumption of energy from an external reservoir. As with any other commodity, the price of energy depends on the structural features of a market economy and may decrease if energy efficiency improves or increase as the energy resource is depleted. Thus, the Jevons paradox accounts for the structural characteristics of the market system in terms of energy, which depletes and eventually exhausts the reservoir's energy resources. The explanation provided by the marginalist school, which is based on the fluctuation of energy prices according to the law of supply and demand, is merely phenomenological. It does not allow one to grasp the deep foundations of the paradox, of which price fluctuations based on the law of supply and demand are merely an expression.

In a market economy, a uniform distribution of capitals across a large number of bins on a profit rate histogram corresponds to a high system entropy. Conversely a distribution of capitals concentrated in a few bins of the histogram corresponds to a low system entropy (Scharfenaker and Yang, 2020). This agrees with the number of capitals as the determinant factor of the system entropy, as shown in equation (3), since a uniform distribution involves a large number of capitals than a concentrated distribution. The concentration and centralization of capital is a well-known process in a market-based economy (Marx, 1996). Although agreements among a few monopoly capitals regarding the price of commodities and the distribution of market space violate the free market principle and are usually punished by antitrust or anti-monopoly laws, such agreements are not unusual in recent times. The concentration of capitals in a few bins of the profit rate histogram raises the question of what would be the difference between a market economy based on the agreements of a few monopolies and a planned economy in which units of production do not compete for profit. In other words, minimizing the number of capitals in equation (3) would minimize the system's entropy, approaching that of a planned economy. However, in such a scenario, a market system would evolve into an economic regime driven by factors other than capitals competing for profit. This is because, as Marx showed, the profit rate and competition for profit drive the reproduction of capital based on commodity production and labor exploitation. Thus, in the absence of this driving forces the system necessarily evolves into a different regime:

‘The rate of profit, *i.e.*, the relative increment of capital, is above all important to all new offshoots of capital seeking to find an independent place for themselves. And as soon as formation of capital were to fall into the hands of a few established big capitals, for which the mass of profit compensates for the falling rate of profit, the vital flame of production would be altogether extinguished. It would die out. The rate of profit is the motive power of capitalist production. Things are produced only so long as they can be produced with a profit.’ (Marx, 1996, Vol. III, p. 178).

Because an economic system organizes the labor of society, labor exploitation is a central issue of any economic system. This issue requires a thorough analysis, which is beyond the scope of the present study. Nevertheless, with a true democratic planning of economy, the intrinsic features of a planned economy make it better suited to the goal of abolishing labor exploitation than any economic regime resulting from a market system with high capital concentration and centralization.

7. Conclusions

An economic system is a thermodynamic system. It is subjected to the universal laws of thermodynamics, which govern the entropy of the economic system and the input of energy from an external reservoir. Like all dissipative structures on Earth, economic systems dissipate energy by absorbing low-entropy energy from an external reservoir and emitting high-entropy energy out of the system. However, different economic systems have different entropies and energy requirements depending on their particular characteristics.

Market and planned economies are end member cases of the material reproduction of society. Historically, the market system has been dominant over the last centuries and the planned economy has recently emerged to challenge this dominance in modern society. These two systems are antagonistic with regard to the formal organization of social reproduction and the philosophical principles on which they are based. In a planned economy, production units are organized around a previously agreed-upon plan, while in a market economy social reproduction is driven by the spontaneous activity of individual capitals competing for profit. Competition for profit confers the market system with a self-similar dynamics by which the entropy of the system emerges in a much larger magnitude than the sum of the entropies of individual capitals. In the lack of profit and competition for profit, a market system collapses and transforms into a different economic regime.

The entropy and energy requirements of a market economy are several orders of magnitude larger than those of a planned economy. Due to its self-similar dynamics and self-organization around profit, a market economy produces much more entropy than a planned economy, and the energy required to sustain this entropy is also much higher. Conversely, a planned economy produces the minimum entropy required of any economic system, whether planned or market-based, and the energy required for that entropy is also minimal. As a result, a market economy operates on a much larger dimensional scale than a planned economy regarding the entropy production, the energy consumption, and the pace of social reproduction. Furthermore, unlike other dissipative structures on Earth, which use external input of energy to gain internal order and stability, a market economy uses this input to increase its own entropy. Increasing the system's entropy requires additional energy input, which increases the system's entropy, and so on. The thermodynamics of economic systems depend on their specific dynamics. The blind, self-similar dynamics of a market economy's pursuit of profit confer on the system an equally blind dynamic of entropy production and energy requirements.

Acknowledgements

Comments by Maxi Nieto on a earlier version of the manuscript are fully acknowledged.

References

Annila A and Salthe S (2009) Economies Evolve by Energy Dispersal. *Entropy* 11: 606-633.

Brissaud J-B (2005) The meaning of entropy. *Entropy* 7: 68-96.

Carchedi G and Roberts M (Eds.) (2018) A global analysis of Marx's law of profitability. New York: Haymarket.

Cengel YA and Boles MA (2008) Thermodynamics. An Engineering Approach. New York: McGraw-Hill Science.

Cockshott P and Cotrell A (1993) Towards a New Socialism. Notthingam: Bertrand Russell Press.

Cockshott P and Nieto M (2017) Cibercomunismo. Planificación económica, computadoras y democracia. Madrid: Editorial Trotta.

Dincer I and Cengel YA (2001) Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering. *Entropy* 3: 116-149.

Farjoun E and Machover M (1983) Laws of Chaos. A probabilistical approach to political economy. London: Verso.

Fischer-Kowalski M, Krausmann F and Irene Pallua I (2014) A socio-metabolic reading of the Anthropocene: Modes of subsistence, population size, and human impact on Earth. The Anthropocene Review 1:6–31.

Gao X, Gallicchio E and Roitberg AE (2019) The Generalized Boltzmann Distribution is the Only Distribution in which the Gibss-Shannon Entropy Equals the Thermodynamic Entropy. *The Journal of Chemical Physics* 151: 034113.

Kleidon A (2010) Life, hierarchy, and the thermodynamic machinery of planet Earth. *Physics of Life Reviews* 7: 424-460.

Kleidon A (2023) Working at the limit: a review of thermodynamics and optimality of the Earth system. *Earth System Dynamics* 14: 861-896.

Lebon G, Jou D and Casas-Vázquez (2008) Understanding Non-equilibrium Thermodynamics. Berlin: Springer-Verlag.

Linares A (2016) La caída tendencial de la tasa de ganancia y el impacto en los sectores productivos menos rentables: el caso de la aviación comercial estadounidense (1998-2013). Memoria para optar al grado de doctor. Universidad Complutense de Madrid, pp. 328.

Lineweaver CH and Egan CA (2008) Life, gravity and the second law of thermodynamics. *Physics of Life Reviews* 5: 225-242.

Martyushev LM (2021) Maximum entropy production principle: history and current status. *Physics – Uspekhi* 64: 558-583.

Marx K (1996) Capital. New York: International Publishers. Available at marxist.org.

Parrondo JMR (2023) Thermodynamics of Information. *ArXiv:2306.12447v1 [cond-mat.stat-mech]*.

Scharfenaker E and Semieniuk G (2017) A statistical equilibrium approach to the distribution of profit rates. *Metroeconomica* 68: 465-499.

Scharfenaker E and Yang J (2020) Maximum entropy economics. *The European Physical Journal* 229: 1577-1590.

Schneider ED and Kay JJ (1994) Life as a Manifestation of the Second Law of Thermodynamics. *Mathematical and Computer Modelling* 19: 25-48.

Soriano C (2024) Marxism and Earth’s habitability crisis. Cham: Springer Nature.

Soriano C (2025) A critical analysis of current world population studies. *World Review of Political Economy* 16: 199-223.

Wark K and Richards D (1998) Thermodynamics with EES problems disk. New York: McGraw-Hill Science.

Wells J (2007) The rate of profit as a random variable. *MPRA Paper* No. 98235. Available online at https://mpra.ub.uni-muenchen.de/98235/.

Zachariah D (2009) Determinants of the average rate of profit and the trajectories of capitalist economies. *Bulletin of Political Economy* 3: 1–13.

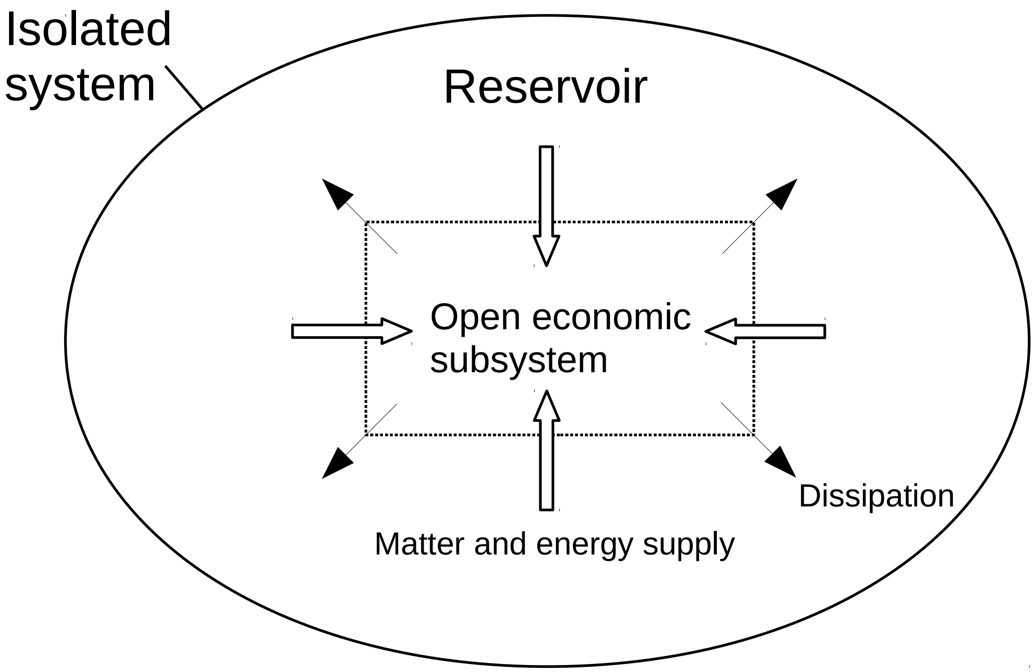

Fig. 1. Thermodynamic hierarchical organization of an economic system that is supplied with energy and matter from an external reservoir.

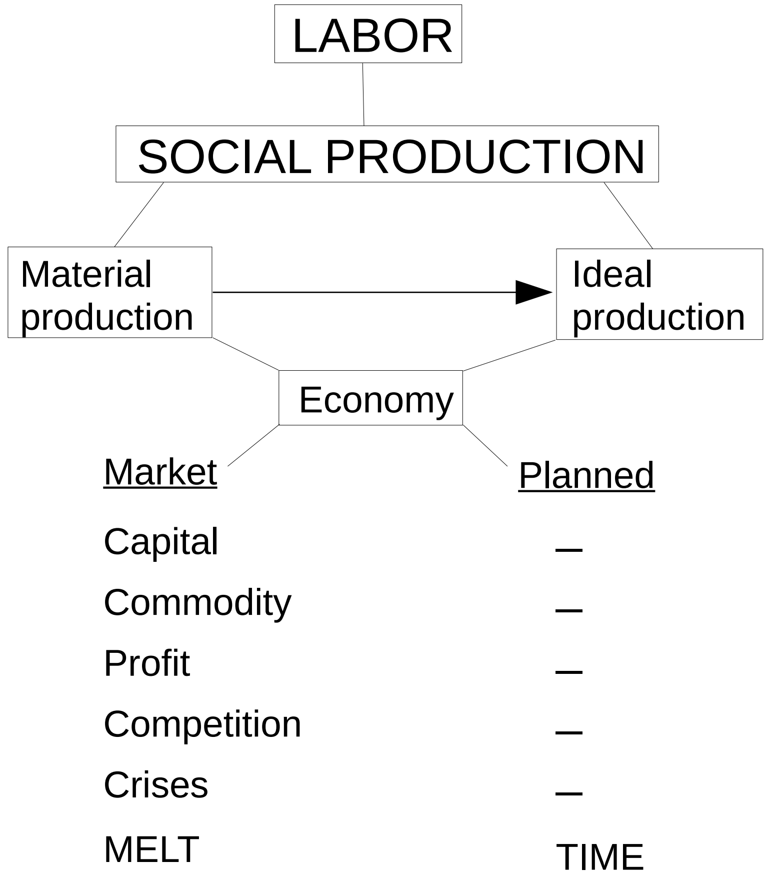

Fig. 2. Organization of the human social production system based on labor. The main characteristics of two hypothetical end-member cases of economic systems in modern society are shown.

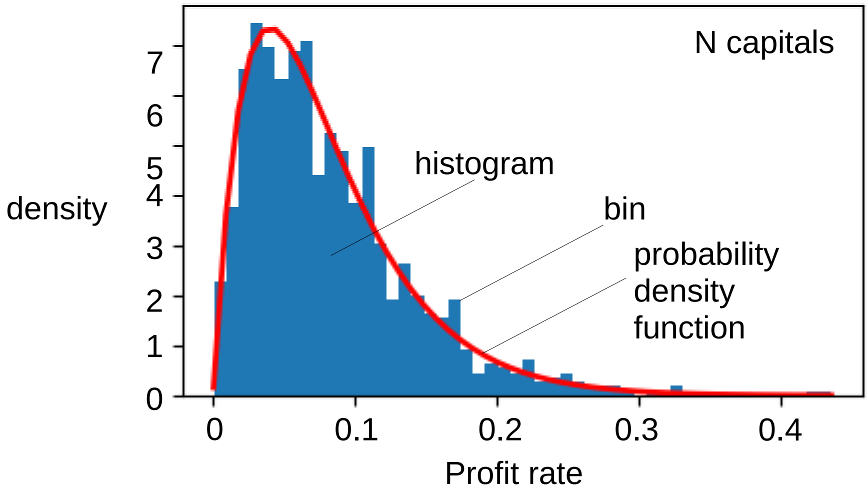

Fig. 3. Gamma-type probability density distribution of the profit rate for N number of capitals in a market economy.