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Article

Econophysics and Landauer Principle. Redefining of the Economic Temperature *via* the Landauer Principle

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Abstract

Redefining of the notions of econophysics based on the Landauer principle is suggested. Economic temperature is defined via the economic Landauer principle. The economic temperature is proportional to the minimal monetary cost associated with erasing or transmitting one bit of information in a given economic system. The introduced definition is useful for high-frequency trading. Clausius formulation of the Second Law of Thermodynamics for economic systems is formulated as follows: energy/money cannot spontaneously flow from a colder economic system to a hotter economic system. Carnot and Szilard’s economical engines are addressed. The Carathéodory formulation of the Second Law of Thermodynamics is re-shaped as follows: in every neighborhood of any equilibrium economic state, there exist states that cannot be reached by the process, which does not spend money or information. Optimal-power Curzon–Ahlborn economic engine is discussed.

Keywords: Landauer principle; econophysics; economic temperature; high-frequency trading; Carathéodory principle; Szilard’s economical engine; Curzon–Ahlborn economic engine

1. Introduction

Thermodynamics, i.e. the science devoted to the study of thermal processes is a relatively “young”, but very important, field of physics. Our paper is devoted to the extension of main ideas and notions of thermodynamics to econophysics, which is an interdisciplinary field that applies statistical-physics/thermodynamics methods to economic systems in order to identify universal, emergent, and scaling properties of collective economic dynamics [1–4]. Albert Einstein stated that thermodynamics “is the only physical theory of universal content, which I am convinced, that within the framework of applicability of its basic concepts will never be overthrown” [5]. Rigorously speaking, Einstein is saying: as long as concepts like energy, entropy, temperature, and equilibrium make sense, thermodynamics will not be overthrown. This is crucial. Thermodynamics is not claiming absolute truth, but scientific framework-stability. At the same time, the temperature, which is the basic notion of the thermodynamics, is not defined with the same degree of rigor, as the main notions of the classical mechanics. Let us survey the definitions of the temperature: i) the microscopic understanding of temperature is that the temperature of a substance is related to the average kinetic energy of the particles of that substance [7–11]; ii) the macroscopic definition of the temperature emerges from the concept of entropy, and the temperature is defined with the equation:

$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_{N'} \tag{1}$$

where E and S are the energy and entropy of the system correspondingly and N is the number of particles constituting the given thermodynamic system [11]. It is recognized from Eq. 1, that the macroscopic definition of temperature is not related to the averaging of the kinetic motion of particles constituting the system, and may be introduced for systems containing an arbitrary number

of particles [12]. The stitching of these definitions is not smooth, Obviously the microscopic definition of temperature forbids negative absolute temperatures, whereas the macroscopic definition, supplied by Eq.1, permits them [12]. The problem of the relativistic transformation for the temperature remains open and highly debatable [12–15]. For the review of the problems related to the rigorous definition of temperature see ref. 12. There exists one more possibility to define the temperature. This is the possibility based on the Landauer principle [16–28]. Aphoristically shaped the Landauer principle states, that “information is physical”. In other words, storage/erasure of information is a physical process requiring energy [16–28]. In its tight meaning the Landauer principle in its simplest meaning states that the erasure of one bit of information in a given system requires a minimum energy cost equal to $k_B T \ln 2$, where T is the temperature at which erasure occurs and k_B is the Boltzmann constant [16–28]. It should be emphasized that the Landauer principle establishes the energetic cost of information erasure, and does not predict the minimal cost of its storage. This information storage/erasure asymmetry is very important [16–28]. Rolf Landauer also applied the suggested principle to the transmission of information and reshaped it as follows: an amount of energy equal to $k_B T \ln 2$ (where $k_B T$ is the thermal noise per unit bandwidth) is needed to transmit a bit of information, and more if quantized channels are used with photon energies $h\nu > k_B T$ [18]. We demonstrate that the Landauer principle enables redefinition of “economic temperature” and reshaping the laws of econophysics.

The paper is built as follows: i) we define the notion of the economic temperature via the economic Landauer principle; ii) Clausius interpretation of the Second Law of Economic Thermodynamic is discussed; iii) Carathéodory interpretation of the Second Law of Economic Thermodynamics is suggested; iv) Carnot, Szilárd and Curzon–Ahlborn economic engines are introduced and analyzed; v) limitations of the introduced economic temperature are discussed; vi) trends of future investigations are envisaged.

2. Results

2.1. Re-Definition of the Economic Temperature

There is no unified approach to the definition of temperature in economic systems. Temperature is introduced in economics as: i) measure of inverse rationality/the degree of randomness (bounded rationality) in agents’ decisions [29], ii) price volatility / market agitation [30], iii) measure of the scale of wealth fluctuations [31], iv) inverse market efficiency [32], v) definition exploiting the energy/entropy of economic systems. In this case, the economic temperature as defined as:

$$T = - \left(\frac{\partial U}{\partial S} \right)_X, \quad (2)$$

where U is the utility/energy, S is the entropy and X defines state variables [33]. This definition resembles, but does not coincide with that supplied by Eq. 1.

We define the “economic temperature” with the Landauer principle, based on the thermodynamics of information. Consider a given economic system. Erasure of a single bit of information of this system according to the Landauer principle requires the minimal energy given by $E = \ln 2 k_B T$. We re-write this equation as follows:

$$\hat{E} = \ln 2 T^*, \quad (3)$$

where $\hat{E}$ is the cost of electrical power necessary for erasure of one bit of information, $[\hat{E}] = \frac{\$}{\text{bit}}$ and T^* is the economic temperature, $[T^*] = \frac{\$}{\text{bit}}$. It is convenient to keep the multiplier $\ln 2$ in Eq. 3, resembling the Landauer-like definition of temperature. Obviously, the economic temperature is given by: $T^* = \frac{\hat{E}}{\ln 2}$. Let us establish interrelation between the economic temperature and standard Kelvin temperature T . The cost of electrical power necessary for erasure of one bit of information may be expressed with the use of the Landauer principle as follows:

$$\hat{E} = k k_B P_J T \ln 2, \quad (4)$$

where P_J is the marginal electricity cost per Joule, k is the dimensionless coefficient, which depends on a given economic system, $k = 1$ for the economic system operating at the physical Landauer limit

and $k_B P_J T \ln 2$ is the cost of erasing of 1 bit for the ideal information processing systems working at the Landauer limit. For any real computing system $k > 1$. According to US Energy Information Administration (EIA) data the industrial price $P_J^{ind} = 0.084 \frac{\$}{kWh} = 2.34 \times 10^{-8} \frac{\$}{J}$; the commercial price is $P_J^{com} = 0.1319 \frac{\$}{kWh} = 3.67 \times 10^{-8} \frac{\$}{J}$. Comparing Eq. 3 and Eq. 4 yields eventually:

$$T^* = P_J k k_B T \quad (5)$$

It follows from Eq. 5 that at the fixed temperature T the economic temperature T^* of the given system ($k = \text{const}$) is completely defined by the electricity price. Let us calculate T^* for the industrial and commercial electricity prices for $T = 300K, k = 1$, corresponding to the Landauer limit. We calculate with Eq. 5: $T_{ind}^* = 9.69 \times 10^{-29} \frac{\$}{bit}$ for the industrial price and $T_{com}^* = 2.52 \times 10^{-28} \frac{\$}{bit}$ for the commercial price. Actually, for real computing systems $k \gg 1$, as demonstrated in **Appendix A**. Thus, real economic systems operate far from the Landauer limit.

The reasonable questions are: when and why the definition will work. The definition of economic temperature $T^* = \frac{\bar{E}}{\ln 2}$ works for economic systems that satisfy following conditions:

- i) Information is explicitly stored, processed, erased, or transmitted,
- ii) Information-processing events have a measurable economic cost,
- iii) The system operates close to an efficiency boundary, so minimal costs matter

The Landauer-based definition of economic temperature will apply to economic systems that operate as information-processing structures, in which decisions, signals, or records are logically irreversible and incur a minimal, system-dependent economic cost. For example, it is well-expected to work for high-frequency trading (HFT), which is an automated trading strategy characterized by ultra-low latency, high order submission and cancellation rates, very short holding periods, and profits derived from small price differentials rather than long-term asset valuation [34]. HFT is often defined as a strategy that responds to market events in the millisecond environment. It is important that is no human intervention per trade within HFT. In HFT, a single completed trade - or equivalently, a single finalized decision - can be modeled as one logical operation, corresponding to the erasure of at least one bit of information:

$$\text{trade} \leftrightarrow \text{logical decision} \leftrightarrow \text{bit erasure}. \quad (6)$$

Typical profit per trade is tiny on HFT: fractions of a cent, and trading decisions are literally bit operations. In 2016, HFT on average initiated 10–40% of trading volume in equities, and 10–15% of volume in foreign exchange and commodities [35]. Economic temperature $T^* = \frac{\bar{E}}{\ln 2}$ is interpreted as follows: high T^* corresponds to noisy, fast, wasteful markets, low T^* corresponds to slow, efficient, information-preserving markets. Thus, bitcoin-like systems correspond to extremely high T^* , as demonstrated in **Appendix B**. $\bar{E}$ is in turn understood is a minimal transaction or validation cost (see **Appendix B**). The introduced economic temperature is relevant for HFT due to the following reasoning: i) information processing has a real monetary and energy cost, ii) in HFT, erasing a bit too slowly or too expensively means losing money. Thus, we conclude that: the definition of economic temperature supplied by Eq. 3 does not rely on agent rationality, equilibrium assumptions, or utility maximization. Instead, it rests on a structural property common to both thermodynamic and economic systems: decisions destroy information, and information destruction has an irreducible cost. Hence, HFT systems may be viewed as economic Landauer engines, converting information erasure into monetary dissipation. This establishes a direct, physically grounded definition of economic temperature and provides a microscopic foundation for extending thermodynamic reasoning to econophysics. Why the introduced “economic temperature” it is expected to work: it works due to the fact that decisions erase alternatives, giving rise to logical irreversibility.

2.2. Re-Interpretation of the Second Law of Thermodynamics

One of the possible formulations of the second law of thermodynamics belongs to the Rudolf Clausius and sounds as follows: heat cannot spontaneously flow from a colder body to a hotter body. Let us re-formulate the Second Law of thermodynamics for economic systems for which the economic

temperature may be introduced by Eq. 3. This formulation is shaped as follows: energy/money cannot spontaneously flow from a colder economic system to a hotter economic system [2]. Let us exemplify this interpretation:

i) High-frequency trading vs. long-term investors. Consider two economic subsystems, namely: Hot system: high-frequency trading (HFT) firms operating at high economic temperature T_{HFT}^* , characterized by ultra-low latency, massive order cancellation, and frequent logical erasure events, and cold system: long-term institutional or retail investors operating at a much lower economic temperature T_{LT}^* , characterized by infrequent decisions and low information-processing dissipation. Empirically, money does not spontaneously flow from long-term investors to HFT firms in the absence of informational or structural asymmetry. Instead, HFT extracts value from hot microstructure inefficiencies, i.e. latency gaps, order-book imbalances, and transient arbitrage opportunities, i.e. generated within similarly hot or hotter market segments. A cold investor placing a buy-and-hold order does not continuously transfer money to HFT traders; the value transfer occurs only when the cold system is forced into a hotter regime, e.g., by reacting to short-term price fluctuations, stop-loss triggers, or liquidity shocks. In thermodynamic terms, the cold system must be locally heated before energy (money) can flow. It seems that this conclusion contradicts to the Clausius interpretation of the Second Law of Thermodynamics. The apparent contradiction with the Clausius formulation disappears once one recognizes that, both in physics and in economic thermodynamics, energy (money) flows only along existing coupling channels; in economic systems, such coupling is created when a cold agent is locally driven into a high-frequency information-processing regime.

ii) Latency arbitrage in HFT. Latency arbitrage in HFT is a trading strategy that exploits minimal time differences in market data and trade execution across different trading venues. This practice involves detecting price discrepancies between markets and acting on them before they naturally resolve, typically operating at microsecond or nanosecond timescales. Latency arbitrage in HFT may be interpreted as heat flow from hot to cold. In this case. A hot subsystem rapidly processes and erases information about price changes across exchanges; a colder subsystem, in turn, updates prices more slowly. Profits arise when HFT firms exploit temporary price discrepancies between exchanges operating at different effective temperatures. Crucially, the money flows from the hotter, noisier information-processing layer to the colder, more stable layer only after dissipation occurs in the hot system (computational cost, infrastructure cost, fees). No spontaneous reverse flow is observed: a slower, colder exchange cannot systematically extract value from a faster, hotter one without increasing its own information-processing rate and cost—i.e., without increasing its economic temperature.

iii) Cryptocurrency markets vs. traditional financial systems. Cryptocurrency markets provide an example of extremely high economic temperature T^* (see **Appendix B**). Transaction validation, mining, and consensus mechanisms involve enormous information erasure costs and energy dissipation. Traditional banking systems, in contrast, operate at much lower economic temperatures. Money does not spontaneously flow from cold banking systems into hot cryptocurrency markets. Capital flows into cryptocurrencies are always accompanied by increased transaction costs, volatility exposure, and informational dissipation. In effect, funds must be “heated” (subjected to higher T^* , before they can circulate in the hotter system.

iv) Trading fees and market frictions as entropy production. Transaction fees, bid–ask spreads, and slippage play the role of entropy production in economic systems [36,37]. They ensure that a closed economic cycle cannot yield net profit without dissipation. A trader attempting to extract money from a high-frequency, hot market without incurring informational and transactional costs inevitably fails, just as a perpetual motion machine of the second kind is forbidden in thermodynamics.

Finally, the economic Clausius principle (or Clausius interpretation of the Second Economic Law of Thermodynamics) may be summarized as follows: economic value flows from hot to cold only via dissipation, and never spontaneously from cold to hot.

This principle does not depend on agent rationality or equilibrium assumptions. Instead, it emerges from the logical irreversibility of economic decisions and the Landauer cost associated with information erasure. In this sense, the Second Law of Thermodynamics survives in economics in an informationally grounded form, with economic temperature replacing physical temperature. Just as heat flows from hot to cold unless work is performed, money flows from high-temperature economic subsystems to lower-temperature ones only through irreversible information processing and dissipation.

Now address Constantin Carathéodory interpretation of the Second Law of Economic Thermodynamics, which is formulated as follows: In every neighborhood of any equilibrium state, there exist states that cannot be reached by adiabatic processes. “Adiabatic” means without heat exchange [38–40]. The crucial idea is inaccessibility, not entropy or heat flow [38–40].

First of all, we have to re-define the adiabatic process in the terms of economic thermodynamics. When economic temperature is defined via the Landauer principle, the natural economic analogue of an adiabatic process is a process that does not spend money or information, i.e. does not incur transaction costs, fees, latency costs, computational effort, or information erasure. We also have to define the “economic state”. A thermodynamic economic state is defined as an equivalence class of microscopic economic configurations characterized by identical values of aggregate resources, information content, economic entropy, number of active degrees of freedom N (number of active agents, instruments, strategies, or contracts participating in the dynamics), and institutional constraints.

$$X = (W, I, S_e, N, \Lambda), \quad (7)$$

where W is — aggregate economic energy (total available economic resources capable of doing economic “work” (capital, liquidity, etc.), I is an information content (total usable information held by agents and infrastructures), S_e is an economic entropy, which is a measure of dispersion, uncertainty, or irreversibility in the economic system (wealth distribution spread, order-book disorder, transaction irreversibility, information loss) and Λ denotes institutional and technological constraints (market rules, transaction costs, latency, regulation, clearing mechanisms, and technological limits (including Landauer-type limits).

The Carathéodory principle is re-shaped as follows: in every neighborhood of any equilibrium economic state, there exist states that cannot be reached by the process, which does not spend money or information. When economic temperature is defined *via* the Landauer principle, the natural economic analogue of an adiabatic process is a process that does not spend money or information, i.e. does not incur transaction costs, fees, latency costs, computational effort, or information erasure.

Consider the HFT example. Consider an electronic market operating near a local equilibrium state characterized by: i) a stable mid-price, ii) a fixed bid–ask spread, iii) balanced order-book depth, iv) no net arbitrage opportunities. This equilibrium corresponds to a point in the economic state space. Now consider an arbitrarily small neighborhood of this state—for example, a configuration with: a slightly tighter spread, slightly increased liquidity at the best bid, or a slightly improved execution probability. The Carathéodory principle asserts that some of these nearby states are inaccessible without dissipation. Indeed, in HFT one cannot tighten the bid–ask spread even infinitesimally without submitting additional orders. Submitting or canceling orders necessarily consumes computational resources, incurs exchange fees, and erases information (decisions overwrite alternatives). Therefore, reaching certain nearby market configurations is impossible without spending money or information. A “free” trajectory through economic state space does not exist, even locally. The equilibrium is surrounded by inaccessible states unless economic work is performed. This is a direct analogue of the classical Carathéodory’s statement: the neighborhood of equilibrium is not adiabatically connected.

Consider one more example. Consider an equilibrium market state in which all publicly available information is reflected in prices. In an arbitrarily small neighborhood of this equilibrium lie states in which a trader holds a slightly positive arbitrage position. Carathéodory’s economic principle asserts that such nearby profitable states cannot be reached without spending resources.

Any attempt to exploit arbitrage requires placing orders, paying fees, absorbing slippage, and processing information. A “zero-cost” arbitrage path is forbidden. The impossibility of costless arbitrage is thus an accessibility restriction, not merely a profit statement.

And, eventually we address one more example, namely: portfolio rebalancing near equilibrium. Consider an investor holding a diversified portfolio at equilibrium relative to a benchmark. In the neighborhood of this state lie portfolios with marginally higher expected return or lower risk. Reaching these states requires: transactions, information gathering, model updates, reallocation decisions. A hypothetical “adiabatic” rebalancing is one that changes the portfolio without trading, information processing, or decision-making. Such a rebalancing is impossible. Thus, even infinitesimal improvements in portfolio configuration are not freely accessible.

Thus, we conclude that equilibrium points in the economic space are surrounded by inaccessible directions unless money or information is expended. Thus, the Carathéodory formulation of the Second Law translates naturally into economics: every equilibrium economic state is surrounded by nearby states that cannot be reached without spending money or information, reflecting the fundamentally non-adiabatic nature of economic transformations.

2.3. Economic Carnot Engine

One more classical formulation of the Second Law of Thermodynamics is due to Sadi Carnot and is based on the concept of an ideal heat engine operating between two reservoirs at different temperatures. In classical thermodynamics, a Carnot engine extracts work from the heat flow between a hot reservoir at temperature T_H and a cold reservoir at temperature T_C . The Carnot theorem states that no engine operating between two reservoirs can be more efficient than a reversible Carnot engine, whose efficiency is given by:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}. \quad (8)$$

This formulation does not rely on entropy production explicitly; instead, it is rooted in the impossibility of extracting unlimited work from a finite temperature difference. We now construct the economic analogue of a Carnot engine using the Landauer-based definition of economic temperature T^* .

An economic Carnot engine is defined as an idealized information-processing economic system that operates cyclically between two economic reservoirs characterized by different economic temperatures $T_H^* > T_C^*$. The hot economic reservoir corresponds to a high-temperature economic subsystem, such as high-frequency trading (HFT), cryptocurrency mining, or high-volatility speculative markets. These systems are characterized by rapid information erasure, high transaction intensity, and significant monetary dissipation per decision. The corresponds to a low-temperature economic subsystem, such as long-term investment strategies, slow institutional capital, or stable banking systems, characterized by infrequent decision-making and low information-processing dissipation. The working substance of the economic Carnot engine is information: signals, orders, strategies, and decisions. Economic work corresponds to net monetary profit, while economic heat corresponds to irreversible monetary dissipation associated with information erasure, transaction costs, fees, latency, and computational effort.

Let $\hat{E}_H$ be the monetary cost associated with information erasure when interacting with the hot reservoir, and $\hat{E}_C$ be corresponding cost when interacting with the cold reservoir. According to the Landauer-based definition the costs are given by Eq. 3. The net economic work extracted in one cycle is defined with Eq.9:

$$\hat{W}^* = \hat{E}_H - \hat{E}_C, \quad (9)$$

where $\hat{E}_H = T_H^* \ln 2$ and $\hat{E}_C = T_C^* \ln 2$. The economic η_{ec} efficiency of the engine is then defined as (Eq. 5 is involved):

$$\eta_{ec} = \frac{\hat{W}^*}{\hat{E}_H} = \frac{\hat{E}_H - \hat{E}_C}{\hat{E}_H} = 1 - \frac{T_C^*}{T_H^*} = 1 - \frac{k_C P_{JC} T_C}{k_H P_{JH} T_H}, \quad (10)$$

where P_{JC} and P_{JH} are the marginal electricity cost per Joule at the cold and hot economic reservoirs correspondingly, k_C and k_H are the dimensionless constants depending on the cold and hot

economic systems respectively, appearing in Eq. 4. In the particular case (and only in this case), when $k_C P_{JC} = k_H P_{JH}$, we extract the classical Carnot formula:

$$\eta_{ec} = 1 - \frac{T_C}{T_H}. \quad (11)$$

This result supplied by Eq. 10 is very strong: the mathematical structure of the Carnot bound survives unchanged when physical temperature is replaced by Landauer-defined economic temperature. Consider HFT as an economic heat engine. HFT systems act as engines that extract profit from price gradients, latency differences, and microstructure inefficiencies. These gradients exist primarily between market segments operating at different economic temperatures. An HFT firm absorbs high-temperature information noise (rapid price fluctuations, order-book changes), performs logical erasure through decision-making, and converts part of this dissipation into monetary profit. The remaining part is lost as fees, infrastructure costs, and energy consumption. The Carnot bound implies that there exists a strict upper limit on the profitability of such strategies, determined by the ratio $\frac{T_C}{T_H}$.

The another example is delivered by cryptocurrency mining. Cryptocurrency networks represent extremely hot economic reservoirs, with enormous information-erasure costs per validated block (see **Appendix B**). Traditional financial systems act as colder reservoirs. Any attempt to extract profit by arbitraging between these systems is subject to a Carnot-type bound: no strategy can convert the high dissipation of the hot system into monetary gain with efficiency exceeding $\eta_{ec} = 1 - \frac{T_C}{T_H}$. The Carnot formulation immediately forbids economic perpetual motion machines of the second kind: strategies that claim to extract profit from information processing without dissipation, or with efficiency exceeding the Carnot-type bound. Any such strategy will require $\eta_{ec} > 1 - \frac{T_C}{T_H}$, which is impossible. Thus, schemes promising risk-free arbitrage without transaction costs, latency costs, or information-processing effort are economic analogues of thermodynamic perpetual motion machines and are forbidden by the Landauer-based Economic Second Law. Therefore, the economic Carnot principle demonstrates that profit extraction is fundamentally constrained by information thermodynamics. Economic systems may be viewed as information engines, and markets as thermal environments, in which monetary profit plays the role of work and transaction costs play the role of waste heat. Thus, the economic Carnot principle demonstrates that profit extraction is fundamentally constrained by information thermodynamics.

2.4. Alternative Understanding of the Economic Temperature

We do not think that the unique understanding of the economic temperature is possible. The alternative definition of the economic temperature based on the Landauer principle, We still define economic temperature T^* with the Landauer-like limit supplied with Eq. 3, namely: $\hat{E} = T^* \ln 2$. However $\hat{E}$ is now the cost of electrical power necessary for transmission of one bit of information. This is the “information friction” based definition of the economic temperature, exploiting the original idea by Rolf Landauer, demonstrating that there exists an energy limit necessary for the transmission of 1 bit of information. Interrelation between economic and thermodynamic temperature is still given by Eq. 5, in which k is the dimensionless constant depending on the channel of the information transmission.

Consider a high-frequency trading (HFT) firm operating on an electronic financial exchange. The firm’s profit critically depends on the transmission, processing, and erasure of information - order-book updates, price changes, and trading signals—at extremely high rates. Each economically relevant event (e.g., best bid changes by one tick) corresponds to a binary decision at the level of the trading algorithm: i) act / do not act; ii) submit order / cancel order, iii) route order / suppress order. Thus, the trading process naturally decomposes into a stream of bit-level operations. Information friction and minimal energy cost. Transmission of a single bit from the exchange to the trading engine (and further to the execution venue) is not free. It requires: electrical energy for signal generation and

amplification, energy for error correction and noise suppression, irreversible logical operations (bit erasure, overwriting buffers, cache clearing).

Even in the ideal limit, the minimal electrical energy cost per transmitted bit is bounded from below. In the spirit of the Landauer principle, we write this bound as $\hat{E} = T^* \ln 2$. In this example, the economic temperature T^* measures the irreducible monetary cost of fast information flow in the market. A high T^* market is one where even a single bit of actionable information is expensive to transmit (high energy prices, regulatory overhead, latency penalties, infrastructure scarcity). A low T^* market corresponds to cheap, abundant, and efficient information transmission. It should be emphasized that T^* is not a behavioral or psychological quantity. It is a technological and infrastructural parameter, fixed by: electricity prices, communication hardware, exchange protocols and latency arbitrage competition.

Crucially, this cost is irreversible. Once the bit is transmitted and processed, the spent electrical energy is dissipated as heat and cannot be recovered. This makes high-frequency trading a natural economic realization of Landauer's information friction, where profits are extracted from information asymmetries, but information processing necessarily produces entropy in the economic sense (transaction costs, fees, infrastructure depreciation).

Thus, the economic temperature T^* quantifies the minimal irreversible monetary cost per bit of information, providing a physically grounded and operational definition of temperature in economic systems. This interpretation of the economic Landauer principle is directly bridged to the Carathéodory principle (see Section 2.2). Consider two economic states. Although the difference between the two states is arbitrarily small in economic terms, reaching the neighboring state requires the acquisition and processing of at least one bit of information (e.g., detecting a price change and reacting to it). By the Landauer-like bound, transmission of this single bit necessarily costs at least $\hat{E} = T^* \ln 2$. Therefore, the transition cannot be performed by an economic adiabatic process.

2.5. Economic Szilárd Engine

Now we consider minimal Szilard's economical engine. Thermodynamic Szilard's minimal engine is the cleanest possible thought experiment showing why the Landauer limit is unavoidable. The engine consists of a single molecule in a box connected to a heat bath at temperature T .

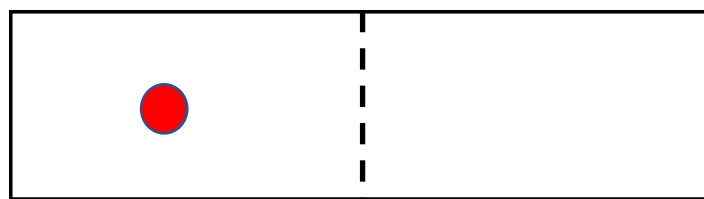


Figure 1. Minimal thermodynamic Szilard's engine is depicted. The engine consists of a single molecule in a box connected to a heat bath at temperature T . Partition divides the box into two equal sub-boxes.

We insert a partition, measure which side the molecule is on (that's 1 bit of information), and then let the molecule expand isothermally, pushing a piston. From this expansion we extract exactly $W = k_B T \ln 2$ of work. So far it looks like a violation of the Second Law, indeed, we extract work from a single heat bath. Landauer's insight closes the loop: to run the engine cyclically, the measurement record (the 1 bit) must be erased. Erasing 1 bit dissipates $E_{min} = k_B T \ln 2$, as heat which is exactly the Landauer limit.

Now we introduce the minimal economic Szilárd engine. We propose to replace physical elements with economic ones, according the Table 1. Now the particle position corresponds to the market state, described by the binary alternative, the partition corresponds to the decision boundary and memory erasure corresponds to the decision finalization / record overwrite.

Table 1. Analogy between physical Szilárd engine and its economic analogue.

Physical Szilárd engine	Economic analogue
Particle position	Market state (binary alternative)
Partition	Decision boundary
Measurement	Information acquisition
Memory erasure	Decision finalization / record overwrite
Heat bath	Economic reservoir at T^*

Now we introduce minimal Szilard’s economical engine. The working substance of the engine is information. An economic Szilárd engine is a minimal economic system that acquires one bit of information about an economic state, conditionally executes an action based on that bit, extracts monetary work from this asymmetry, and must eventually erase the information, incurring a minimal cost $\widehat{E} = T^* \ln 2$.

The economic Szilárd engine represents the minimal microscopic realization of the Landauer-based economic thermodynamics. In this engine, a single bit of economic information is acquired, conditionally exploited to extract monetary profit, and subsequently erased to complete a cycle. The extracted economic work is fundamentally bounded by the Landauer cost associated with information erasure, ensuring compliance with the Second Law. High-frequency trading strategies, arbitrage mechanisms, and cryptocurrency mining may all be interpreted as realizations of economic Szilárd engines operating at different effective economic temperatures. The efficiency of the of economic Szilárd engine is $\eta_{sz} = \frac{\widehat{W}^*}{\widehat{E}} < 1$. Thus the monetary profit of the engine is restricted by the Landauer economic limit: $\widehat{W}^* < \widehat{E} = T^* \ln 2$.

2.6. Optimization of the Power of Economic Engines

Carnot economic engine provides the upper bound on efficiency but delivers zero economic power in the reversible limit [44]. To model maximal profit rate we adopt finite-time (endoreversible) thermodynamics: the internal cycle is reversible while irreversibility is shifted to finite-rate exchange with economic reservoirs. The resulting optimal-power efficiency is the Curzon–Ahlborn form is supplied by Eq. 12 [44]:

$$\eta_{MP} = 1 - \sqrt{\frac{T_c^*}{T_h^*}} .$$

(12)

which is strictly below the economic Carnot limit, established by Eq. 10. As it occurs in classical thermodynamics, maximal profit rate (Carnot rate) requires finite inefficiency, in other words: ultra-efficient markets earn slowly. HFT works near maximum-power regime, not Carnot.

3. Discussion

3.1. Constituting Information-Theoretic Paradigm of Economics with the Landauer Principle

The introduced economic temperature T^* establishes a direct conceptual bridge between the Landauer economic principle and the information-theoretic paradigm of science proposed by John Archibald Wheeler. In 1989, Wheeler formulated the paradigm known as “it from bit,” expressing the idea that physical reality emerges from information. According to this view, every physical event ultimately originates from elementary yes/no questions and their recorded answers; matter, fields, and even space-time arise as secondary constructs from informational acts. In Wheeler’s interpretation, physics is therefore not the study of things, but the study of information acquisition under physical constraints. The Landauer principle provides the quantitative backbone of this paradigm by demonstrating that information processing is inseparable from irreversibility and energy dissipation: the act of erasing or reliably transmitting a bit necessarily incurs a minimal energetic cost.

The present work extends this logic to economic systems. We propose the following reformulation: every economic effect is information-theoretic in origin. Prices, trades, arbitrage

opportunities, market equilibria, and crises do not arise from material exchange alone but from information acquisition, transmission, comparison, and erasure performed by economic agents and institutions. A price change is the outcome of registered information; a trade is a decision conditioned on a finite informational input; a market equilibrium corresponds to a state where no new exploitable information is available. Within this perspective, economic activity is fundamentally an information-processing process implemented in physical hardware: data centers, communication networks, electronic exchanges, and computational devices. Consequently, economic dynamics are subject to the same fundamental limitations as physical information processing. The economic temperature T^* defined via the Landauer-like bound $\hat{E} = T^* \ln 2$ quantifies the irreducible monetary cost of performing one elementary informational act in the economic system. It measures how expensive it is, in economic terms, to ask and answer a single yes–no question about the market. In this sense, T^* plays a role analogous to physical temperature: in physics, temperature quantifies the energetic cost of microscopic disorder, in economics, T^* quantifies the cost of microscopic information acquisition and irreversibility. High economic temperature corresponds to environments where information is expensive, noisy, delayed, or energy-intensive; low economic temperature corresponds to highly efficient informational infrastructures, though never to zero cost.

The Wheeler paradigm, thus, finds a natural economic analogue: “it from bit” $\rightarrow$ physical reality emerges from information; “economy from bit” $\rightarrow$ economic reality emerges from information. Markets do not merely exchange goods and money; they process information under irreversible constraints. The Landauer-based economic temperature formalizes and quantifies this idea and embeds it into the structure of economic thermodynamics, where irreversibility, inaccessibility, and entropy production arise not metaphorically but as direct consequences of information friction. This viewpoint positions economic thermodynamics not as an analogy borrowed from physics, but as a direct continuation of information-theoretic foundations, placing economics within the same conceptual framework that underlies modern physics.

Thus, we resume our approach in the economic *it from bit* principle, formulated as follows: Every economic phenomenon originates from information-theoretic processes. More precisely, any economic effect—such as a price change, transaction, arbitrage opportunity, or market equilibrium—arises from the acquisition, transmission, processing, and irreversible erasure of information performed by economic agents and institutions.

These informational acts are implemented in physical systems and therefore obey the Landauer-type bound. Consequently, each elementary economic decision requires a nonzero minimal expenditure of resources, quantified by the economic temperature T^* . In this framework, economic systems are understood not as purely abstract exchanges of value, but as physical information-processing systems. The economic temperature T^* measures the minimal irreversible cost of asking and answering a single yes–no economic question. Thus, economic irreversibility, transaction costs, and market frictions emerge as fundamental consequences of information theory rather than contingent institutional imperfections. Examples of the “hot” and “cold” economic markets are supplied in Appendices B and C.

We clearly understand the limitation of the introduced “economic temperature”. The proposed Landauer-based economic temperature T^* has several inherent limitations. It is not a universal descriptor for all economic activity and is most meaningful only for systems in which decisions are explicitly implemented as information storage, transmission, or erasure with measurable costs. The identification of a “bit” is model-dependent and depends on the chosen level of abstraction, while the definition itself targets a minimal irreducible cost and may be far below actual economic costs dominated by institutional, technological, or regulatory overheads. Moreover, separating informational dissipation from other economic frictions (fees, spreads, risk premia) is not always unambiguous. The economic temperature is highly sensitive to infrastructure, energy prices, and market design, and may vary in time, so it should be interpreted as an effective, system- and scale-dependent quantity rather than a universal state variable. It is also possible that the universal definition of the economic temperature, applicable for all kinds of markets does not exist.

3.2. Guidelines for the Future Investigations

The introduced scheme of econophysics is a very preliminary one. If future investigations we plan to introduce the economic temperature T^* for payment rails (card networks, bank transfers).

We also plan to formalize how value/“heat” flow depends not only on T^* gradients but also on coupling strength (information bandwidth, latency sensitivity, access rights). The goal is an analogue of radiative transfer:

$$\dot{Q}^* \sim \int \mathcal{H}(\nu) (T_H^*(\nu) - T_C^*(\nu)) d\nu, \tag{13}$$

where $\dot{Q}^*$ is a value/heat flux (profit-rate analogue), $\mathcal{H}(\nu)$ captures market microstructure coupling and ν is an “information frequency” scale (decision cadence).

It is also desirable to move beyond equilibrium-like statements toward: i) entropy production rates from fees/spreads/slippage, ii) fluctuation relations for profit and loss (P&L) distributions, iii) establishment finite-time bounds linking profit rate and dissipation rate (a “thermodynamic uncertainty relation” style program for markets).

4. Conclusions

In this work, we introduced a Landauer-based definition of economic temperature and demonstrated that it provides a physically grounded and operational foundation for extending thermodynamic reasoning to economic systems. Unlike traditional economic notions of temperature - based on volatility, rationality, entropy, or utility - our definition does not rely on behavioral assumptions, equilibrium hypotheses, or subjective agent models. Instead, it rests on a universal structural feature shared by physical and economic systems: information processing is logically irreversible and incurs an irreducible cost. By reformulating the Landauer principle in economic terms, we defined the economic temperature T^* through the minimal monetary cost associated with erasing or transmitting one bit of information. This definition ties economic temperature directly to measurable physical quantities such as electricity prices, computational infrastructure, and communication efficiency. As a result, T^* emerges as a technological and infrastructural parameter, rather than a psychological or institutional one. Any computation, being conventional or non-conventional, consumes energy [47,48], thus, T^* may be introduced for a broad range of computation based economic systems.

Using this definition, we reinterpreted the major formulations of the Second Law of Thermodynamics in an economic context. The Clausius formulation was shown to correspond to the impossibility of spontaneous value flow from colder to hotter economic subsystems without dissipation. The Carathéodory formulation naturally translated into an accessibility principle: every equilibrium economic state is surrounded by nearby states that cannot be reached without spending money or information. This inaccessibility arises from the Landauer cost of information acquisition and decision-making, even for infinitesimal economic changes.

We further constructed economic analogues of the Carnot engine, Szilárd engine, and finite-time heat engines. These models demonstrate that profit extraction in markets is fundamentally constrained by information thermodynamics, leading to strict upper bounds on efficiency and power. In particular, strategies such as high-frequency trading and cryptocurrency mining can be viewed as economic information engines, converting information erasure into monetary profit while necessarily producing economic “heat” in the form of transaction costs, fees, latency losses, and energy dissipation. Economic perpetual motion machines of the second kind—strategies promising unlimited profit without dissipation—are therefore forbidden.

Finally, we connected the proposed framework to the information-theoretic paradigm of science, reformulating the “it from bit” principle for economics. In this view, economic reality emerges from information: prices, trades, arbitrage opportunities, and equilibria are outcomes of information acquisition, processing, and erasure implemented in physical systems. The economic temperature T^* quantifies the minimal irreversible cost of these informational acts and thus plays a role analogous to physical temperature in thermodynamics.

In summary, the Landauer-based economic temperature provides a unifying, physically grounded framework for econophysics. It explains economic irreversibility, transaction costs, and market frictions as fundamental consequences of information theory rather than contingent imperfections. This approach opens a path toward a genuinely microscopic foundation of economic thermodynamics and places economic systems within the same conceptual structure that underlies modern physics. Limitations of the introduced economic temperature are addressed.

Appendix A. Calculation of Economic Temperature

We already calculated the economic temperature with Eq. 5 as $T_{ind}^* = 9.69 \times 10^{-29} \frac{\$}{bit}$ for the industrial price and $T_{com}^* = 2.52 \times 10^{-28} \frac{\$}{bit}$ for the commercial price of electricity. Typical system-level energy per bit often quoted around $10^{-14} \frac{J}{bit}$ J/bit, with an aspirational lower bound around $10^{-17} \frac{J}{bit}$ [46]. Table A2 summarizes economic temperatures for the ideal and real economic systems.

Table A2. Economic temperatures calculated for the ideal and real economic systems.

Electricity price	Economic System Regime	Economic Temperature, $T^*, \frac{\$}{bit}$
Industrial	Landauer/ideal	$9.69 \times 10^{-29} \frac{\$}{bit}$
Commercial	Landauer/ideal	$2.52 \times 10^{-28} \frac{\$}{bit}$
Industrial	Typical real system level	$3.38 \times 10^{-22} \frac{\$}{bit}$
Commercial	Typical real system level	$5.29 \times 10^{-22} \frac{\$}{bit}$
Industrial	Aspirational level	$3.38 \times 10^{-25} \frac{\$}{bit}$
Commercial	Aspirational level	$5.29 \times 10^{-25} \frac{\$}{bit}$

Appendix B. Calculation of Economic Temperature for Bitcoin-Like Systems

Consider a Bitcoin-like (on-chain) system is to treat the “information channel” as blockspace, where the marginal cost to write/transmit data is the transaction fee per virtual byte (vB), i.e. sats/vB. Let the fee rate be f sats/vB and BTC price be P_{BTC} , $[P_{BTC}] = \frac{\$}{BTC}$; $1BTC = 10^8$ sats. Then cost per vB: $\frac{\$}{vB} = f \times \frac{P_{BTC}}{10^8}$. Cost per bit (since 1 vB $\cong$ 1 byte = 8bits), $\hat{E}_{BTC} \left[\frac{\$}{bit} \right] = \frac{1}{8} f \times \frac{P_{BTC}}{10^8}$. Hence economic temperature is given by: $T_{BTC}^* = \frac{\hat{E}_{BTC}}{\ln 2} = \frac{1}{8 \ln 2} f \frac{P_{BTC}}{10^8}$. Using a current BTC price $P_{BTC} \cong 65053 \frac{\$}{BTC}$, and averaged transaction fee $\cong 2.5$ sats/vB and median $\cong 0.2$ sats/vB, supplied by BitInfoCharts currently reports, we calculate for the median conditions ($f = 0.2 \frac{sats}{vB}$) $T_{BTCM}^* \cong 2.35 \times 10^{-5} \frac{\$}{bit}$, and for the average conditions ($f = 2.5 \frac{sats}{vB}$) $T_{BTC A}^* \cong 2.93 \times 10^{-4} \frac{\$}{bit}$. These T^* values are enormous compared to the calculated in Appendix A electricity/Landauer-limit example (order $10^{-28} \frac{\$}{bit}$), or actual/real computing systems (order $10^{-22} \frac{\$}{bit}$). This means that Bitcoin-like settlement is an extremely “hot” economic channel (high marginal cost per bit committed to the ledger).

Appendix C. Economic Temperature of the Mobile Internet Data Market in Israel

A commonly cited estimate puts the average price of 1 GB of mobile data in Israel at about \$0.02/GB. So the monetary cost per bit is $\hat{E}_{MI} = \frac{0.02}{8 \times 10^9} \frac{\$}{bit} = 2.5 \times 10^{-12} \frac{\$}{bit}$. Thus, the economic temperature equals: $T_{MI}^* = \frac{\hat{E}_{MI}}{\ln 2} \cong 3.6 \times 10^{-12} \frac{\$}{bit}$. This economic temperature is much smaller that

calculated for bitcoin-like systems, estimated in Appendix B. Thus, we conclude that the mobile internet data market is much more “cold” than the bitcoin market.

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Abbreviations

The following abbreviations are used in this manuscript:

BTC	Bitcoin
HFT	High-frequency trading
vB	Virtual byte

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