The Entropy Barrier: Why Sustainability Demands Space

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Abstract

The article presents a thermodynamic approach to the objective assessment of environmental damage based on the fundamental concept of entropy for open systems. Developing the methodology proposed in the works of Golovinski and his colleagues [1], we substantiate the need to move from qualitative environmental declarations to quantitative physical measurements. The theoretical foundations of Prigogine's non-equilibrium thermodynamics and the Landauer principle as a fundamental limit of efficiency are considered. A method is proposed for calculating the environmental efficiency coefficient of investment projects, taking into account the full life cycle — from resource extraction to final disposal — at current prices of compensation technologies. The fundamental inequality $\eta < 1$ is substantiated, which follows from the second law of thermodynamics. The methodology is tested by comparing the production of equipment for solar and gas turbine generation. A forecast of the change in the environmental efficiency coefficient for 50 years is given based on scenarios of the International Energy Agency. A comparative analysis of the placement of data centers in mid-latitudes, polar regions, and on the Moon is carried out. A comparison of the entropy efficiency of livestock farming and photosynthetic organisms is performed. An analysis of nuclear energy is given using the example of traditional reactors and the Russian "Proryv" technology with a closed fuel cycle. The impact of solar power plants on the local heat balance and land use when replacing traditional generation is assessed. Anthropogenic greenhouse gas emissions are compared with natural sources — volcanic activity and natural methane emissions — and their temporal variability is analyzed. Two principal strategies for combating entropy pollution are considered: waste localization and entropy dumping into space. It is shown that expanding the reservoir for entropy disposal through space exploration is an inevitable stage in the development of a technological civilization.

1 Introduction

The problem of objectively assessing environmental damage has long been an arena of ideological speculation and opportunistic manipulation. Existing methods often operate with difficult-to-verify categories or consider only certain types of pollution, without grasping the essence of the phenomenon. Meanwhile, fundamental physics offers a rigorous

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tool — the concept of entropy, introduced into thermodynamics by Clausius. Pioneering works by Golovinski (late 20th century) laid the foundation for applying the entropy approach to assessing environmental impact. Modern research confirms the promise of this direction [1–3]. In particular, [1] proposed a unified entropy criterion for assessing the environmental efficiency of green energy technologies, linked to Kondratiev cycles and the Landauer principle.

It is important to emphasize that back in the first half of the 20th century, V.I. Vernadsky, developing the doctrine of the biosphere, concluded that the biosphere would inevitably transition into the noosphere — the sphere of reason, where human activity becomes a determining geological factor [49]. This conclusion receives a natural thermodynamic justification within the framework of the proposed entropy approach. The noosphere can be considered as the highest stage of organization of a dissipative structure, where the management of energy and matter flows is carried out on the basis of scientific knowledge, which opens up the possibility of minimizing entropy production and expanding the reservoir for its disposal.

The purpose of this work is to develop a methodology for the entropy assessment of environmental damage, translating it into the realm of quantitative economic calculation, and on this basis to analyze long-term environmental strategies, including the space prospects of humanity. In contrast to the approach [1], we propose an elaboration of the economic calculation mechanism at current prices, taking into account the full life cycle of projects and considering the fundamental limitations of terrestrial waste localization.

2 Theoretical Foundations: Entropy, Negentropy, and Thermodynamics of Open Systems

The analysis is based on the second law of thermodynamics, a fundamental law of nature establishing the asymmetry between past and future [4, 5]. For isolated systems, this difference is expressed in the law of non-decreasing entropy ($dS \geq 0$). However, our object of study — the "Earth + economic project" system — is not isolated. For open systems exchanging matter and energy with the environment, the total change in entropy (dS) consists of two fundamentally different terms [5, 6]:

$$dS = d_eS + d_iS, \tag{1}$$

where d_eS is the entropy flow due to exchange with the external environment, and d_iS is the internal entropy production due to irreversible processes, always non-negative: $d_iS \geq 0$.

A major achievement of the Prigogine school was the introduction of the concept of "entropy production" ($\sigma = d_iS/dt$) as a measure of the intensity of dissipative processes. In linear non-equilibrium thermodynamics, entropy production is represented as a bilinear form of generalized thermodynamic forces (X_k) and flows (J_k) [5]:

$$\sigma = \sum_k J_k X_k \geq 0. \tag{2}$$

The term "negentropy" (negative entropy) was introduced to describe a situation where the entropy flow (d_eS) is directed out of the system and exceeds the internal production. Erwin Schrödinger, in his book "What is Life?" (1944), first formulated that a living organism "feeds on negative entropy" [7, 8]. Later, Léon Brillouin extended this principle to any self-organizing systems. A classic example is the entropy balance on

Earth [5]. The planet receives low-entropy radiation from the Sun ($T_{Sun} \sim 6000$ K) and emits high-entropy thermal radiation ($T_{Earth} \sim 300$ K). The difference in flows ensures the existence of the biosphere as a global dissipative structure.

A central place in the thermodynamics of open systems is occupied by Prigogine's theorem on the minimum entropy production [4–6]: in a stationary state close to thermodynamic equilibrium, the total entropy production inside the system is minimal. The stability condition is written mathematically as $d\sigma/dt \leq 0$. This property ensures the stability of stationary states; any deviation leads to increased dissipation, generating processes that return the system to the stationary state. Prigogine's most profound contribution is the theory of dissipative structures [4, 5]. In the nonlinear region, a system can lose stability and transition to a new ordered state maintained by an energy flow. The biosphere and its components can be viewed as hierarchical dissipative structures.

To assess the fundamental limitations of any technology, the Landauer principle is important, linking information and thermodynamics [1, 9, 10]. The minimum energy release when erasing one bit of information is:

$$E_{min} = k_B T \ln 2, \tag{3}$$

where k_B is Boltzmann's constant and T is temperature. This sets an absolute lower limit on the entropic cost of controlling any technological process.

Several fundamental conclusions follow. Any economic activity increases entropy production ($d_i S$). Environmental damage is the accumulated entropy production not compensated by outflow. Sustainable development is possible only with a balance: the flow of negentropy from outside (from the Sun) must cover the total entropy production. An environmental crisis can be interpreted as a transition of the biosphere to a new state as a result of exceeding threshold loads.

However, critiques argue entropy imposes no absolute scarcity, as technology and substitution extend limits. Daly counters that growth remains uneconomic beyond optimal scale, advocating steady-state [59, 60].

Now consider why the first law of thermodynamics is insufficient for environmental assessments. The first law (conservation of energy) establishes a quantitative balance of energy flows:

$$dQ = dU + dA, \tag{4}$$

where dQ is the heat received by the system, dU is the change in internal energy, and dA is the work performed. While this law is certainly important for thermal processes, it is fundamentally inadequate for assessing environmental consequences for several reasons [14]. First, the first law does not establish the direction of processes and does not distinguish the quality of energy. From the perspective of the first law, a joule of heat at 20°C is equivalent to a joule of heat at 1000°C, although their ability to perform useful work (exergy) differs dramatically. Second, the first law imposes no fundamental restrictions on the efficiency of energy conversion; as shown in [5], the first law theoretically allows 100% conversion of heat into work, which is prohibited by the second law. Third, the first law does not account for the irreversibility of real processes. Any economic activity involves friction, heat transfer at finite temperature differences, mixing, and diffusion — all these processes are irreversible and are described only by the second law. Therefore, an objective assessment of environmental damage requires recourse to the second law and the concept of entropy [3].

A fundamental definition of environmental efficiency can be given through the ratio of entropy flows in the system. Consider an open thermodynamic system, which any production or project represents. The total change in entropy, as already noted, consists of the flow across boundaries and internal production. Environmental efficiency η_{eco} can be defined as the ratio of the useful organized flow (negentropy) to the total entropy production [16]:

$$\eta_{eco} = \frac{-S_{negentropy}}{S_{production}}, \tag{5}$$

where $S_{negentropy}$ is the negentropy flow extracted by the system from the environment to maintain its structure, and $S_{production}$ is the total internal entropy production. In a more convenient form for practical calculations, proposed by [17], environmental efficiency can be expressed through the specific entropy production per unit of exergy gained:

$$SEEG = \frac{\Delta S}{\Delta E_x} \to \min, \tag{6}$$

where $SEEG$ (Specific Entropy per Exergy Gained) is an indicator whose minimization corresponds to the "fittest" system from a thermodynamic point of view [15]. The less entropy produced per unit of useful exergy, the more environmentally efficient the technology. An alternative indicator is specific entropy per unit of exploitable exergy in the technosphere:

$$SEEE = \frac{\Delta S}{E_x^{exploitable}} \to \min. \tag{7}$$

Note that both $SEEG$ and $SEEE$ have the dimension of inverse temperature (K^{-1}), which makes their numerical values dependent on the choice of unit system. As shown in [17], applying these indicators to the analysis of waste processing systems gives a clear ranking: anaerobic digestion ($SEEG = 0.007 - 0.106\, K^{-1}$) is significantly more environmentally friendly than incineration ($SEEG = 2.471 - 3.705\, K^{-1}$), which correlates with the return of useful materials to the technosphere.

This definition of environmental efficiency is deeply connected with Prigogine's theorems on minimum entropy production. In a stationary state close to equilibrium, a system tends to minimal dissipation [5]. For ecological systems, this principle is formulated as minimizing specific entropy, which serves as an indicator of ecosystem health and development [16]. Ludovisi shows that during ecosystem succession, ecosystems evolve towards states with lower entropy production per unit of biomass. This is a direct consequence of the Darwinian principle of "survival of the fittest" in a thermodynamic interpretation: the fittest are systems capable of extracting and storing energy with minimal dissipative losses. For the technosphere, this means that environmentally sustainable technologies must minimize entropy production while maximizing useful exergy output [3].

A practical implementation of the entropy approach is exergy analysis. Exergy (E_x) — the maximum useful work a system can perform when transitioning to equilibrium with the environment — is a measure of energy quality and "order" [14]. Exergy efficiency is defined as the ratio of useful output exergy to input exergy:

$$\psi = \frac{E_x^{out}}{E_x^{in}} = 1 - \frac{S_{gen} \cdot T_0}{E_x^{in}}, \tag{8}$$

where S_{gen} is entropy production and T_0 is the ambient temperature. This expression directly links the loss of energy quality (exergy) with entropy production. Ozcan et al. [18], in a recent study of solar cooling systems, showed that solar technologies have low exergy efficiency (0.16-0.19) and sustainability indices (1.20-1.24), with more than 93% of exergy destruction attributable to unavoidable losses. This means that even with ideal optimization, fundamental thermodynamic constraints maintain a high level of entropy pollution.

Table 1: Comparison of the first law of thermodynamics and entropy (exergy) efficiency for environmental assessments

Characteristic	**First law (energy efficiency)**	**Entropy efficiency**
Primary quantity	Quantity of energy	Quality of energy (exergy)
Accounts for irreversibility	No	Yes (through entropy production)
Direction of processes	Not determined	Determined (arrow of time)
Link to resources	Indirect	Direct: exergy degradation = resource depletion [14]
Accounting for "waste"	Only as energy loss	As increase in environmental entropy
Theoretical maximum	100% (unattainable)	¡100% (limited by Carnot and irreversibility)
Example for thermal power plant	$\eta \sim 33-40\%$ (heat to work)	$\psi \sim 30-35\%$ (including losses)
Environmental interpretation	Higher is more economical	Higher means less entropy damage [3]

For a clear comparison of the two approaches, their characteristics are presented in Table 1.

As rightly noted in [5], the first law establishes quantitative constraints on the energy balance, but it is the second law and entropy that determine the fundamental limits of sustainability for any technology within the closed system of Earth.

3 Methodology for Calculating the Environmental Efficiency Coefficient

To transition from a physical quantity to an economic assessment, we introduce the concept of the entropic cost of a project. It is calculated as the sum of costs to compensate for the increase in entropy at all stages of the life cycle. The full project implementation cycle is divided into four stages: extraction and processing of raw materials ($\Delta S_{extraction}$), production and transportation ($\Delta S_{production}$), operation ($\Delta S_{operation}$), and final disposal ($\Delta S_{disposal}$). The total entropic damage is written as:

$$\Delta S_{total} = \Delta S_{extraction} + \Delta S_{production} + \Delta S_{operation} + \Delta S_{disposal}. \tag{9}$$

The key point is the calculation of ΔS_{total}. In contrast to the exergy approach, we propose to calculate entropy production directly using the total energy consumption at each stage (E_i) and the specific entropy produced during the generation of that energy in the current energy system (s_i):

$$\Delta S_i = E_i \cdot s_i. \tag{10}$$

The quantity s_i (J/(K·J)) is the reciprocal of the conversion efficiency and depends on the method of energy generation (coal, gas, renewables). This approach allows direct use of statistical data on energy consumption.

The economic environmental efficiency coefficient (η) is proposed to be calculated as the ratio of the market value of the project (C_{market}) to the total costs of compensating for entropic damage ($C_{entropy}$) [1]:

$$\eta = \frac{C_{market}}{C_{market} + C_{entropy}}, \tag{11}$$

where $C_{entropy} = \sum(\Delta S_i \times T_i)$, and T_i is the cost of neutralizing a unit of entropy at the i-th stage using existing technologies (filters, reclamation, purification, etc.). Since $C_{entropy} > 0$ for any real irreversible process, the denominator of the fraction is always greater than the numerator. Consequently, η is always strictly less than unity. This fundamental property is analogous to the fact that the efficiency of a heat engine is always less than 100%. It reflects the thermodynamic cost of creating ordered products from disordered raw materials: the decrease in entropy in the product is always accompanied by a greater increase in entropy in the environment. The closer η is to 1, the more environmentally friendly the project; that is, the smaller the "entropy payment" per unit of produced market value. If $\eta \to 0$, the project exists only through uncompensated environmental destruction.

4 Practical Testing of the Methodology: Comparison of Equipment Production for Solar and Gas Turbine Generation

To demonstrate the feasibility of the proposed approach, we perform a comparative assessment of the environmental friendliness of equipment production for two types of power plants of the same capacity (10 MW): a photovoltaic solar power plant (SPP) based on crystalline silicon and a simple-cycle gas turbine unit (GTU). This capacity is chosen because it is typical for distributed generation and industrial facilities. It should be emphasized that this analysis is limited only to the equipment production stage (a "cradle-to-gate" approach) and does not cover the operational phase and disposal. This is a significant simplification but serves to illustrate the methodology itself.

The initial data for the calculation are summarized in Table 2. The market value of the equipment is taken from averaged manufacturer data. The main materials include polysilicon, glass, aluminum, copper, and silver for SPP, and steels, nickel alloys, aluminum, and copper for GTU. The energy consumption per unit of capacity for SPP is significantly higher due to the energy intensity of silicon refining, which is confirmed by data from [20]. CO_2 emissions also differ substantially.

Table 2: Initial data for calculating the environmental efficiency coefficient of equipment production (per 1 MW of installed capacity)

Parameter	**SPP (silicon panels)**	**Simple-cycle GTU**
Market value of equipment C_{market}, million rubles/MW	45 [13]	25 (estimate based on [19])
Main materials	Polysilicon, glass, aluminum, copper, silver	Steel, nickel alloys, aluminum, copper
Energy consumption for production, MWh/MW	4500 (silicon production) [20]	800 (casting, machining) [21]
CO_2 emissions, t/MW	1800 (carbon intensity of production) [20]	420 (including metallurgy) [22]

The assessment of entropic damage ΔS_{total} is performed directly through energy consumption. To do this, we need the specific entropy production during the generation of 1

J of energy used in production. We assume that all energy for production comes from a coal-fired power plant, which has an exergy efficiency $\eta_{ex} \approx 0.35$ [19]. Then the entropy production per unit of energy is $s \approx (1 - \eta_{ex})/T_0$, where $T_0 = 290$ K is the ambient temperature. Using the energy consumption data E_{in} (MWh/MW) from Table 2, we calculate the total entropy production. For SPP, $\Delta S^{PV}_{total} \approx 3.63 \times 10^{10}$ J/(K·MW); for GTU, $\Delta S^{GT}_{total} \approx 6.45 \times 10^9$ J/(K·MW). These values confirm that the production of equipment for SPP is accompanied by approximately 5–6 times greater entropy production than for GTU.

To transition to economic indicators, we need to determine the cost of neutralizing a unit of entropy. As a reference technology for compensating damage from burning fossil fuels (the main source of entropy in production), we adopt carbon capture and storage (CCS). The cost of capturing 1 ton of CO_2 is estimated at 3000 rubles/t (in 2024 prices) [22]. If we assume that the main portion of entropic damage correlates with CO_2 emissions, we can express the cost of entropy compensation through the cost of compensating emissions: $C_{entropy}$ is approximately equal to the cost of capturing the entire volume of CO_2 emitted during production. Then for SPP, $C^{PV}_{entropy} = 5.4$ million rubles/MW; for GTU, $C^{GT}_{entropy} = 1.26$ million rubles/MW. Now we calculate the environmental efficiency coefficient $\eta = C_{market}/(C_{market} + C_{entropy})$. For SPP, $\eta^{PV} \approx 0.893$; for GTU, $\eta^{GT} \approx 0.952$.

These η values show that, from the perspective of equipment production alone, gas turbine technology ($\eta \approx 0.95$) is noticeably more environmentally friendly than solar ($\eta \approx 0.89$) according to the proposed criterion. This is explained by two factors: the significantly higher market value of SPP equipment per unit of capacity (which increases the denominator) and the substantially larger entropic damage in the production of silicon panels due to the energy intensity of the processes and the low exergy quality of the energy used. However, the results are sensitive to a number of assumptions. If panel production were localized in a country with “green” energy (low carbon footprint of electricity), CO_2 emissions could drop to 600 t/MW. Then $C^{PV}_{entropy}$ would fall to 1.8 million rubles/MW, and η^{PV} would rise to ≈ 0.962, which is already higher than for GTU. The cost of CCS is also important: its future reduction will make compensation cheaper and increase η for both technologies. Moreover, this comparison is deliberately incomplete, as it does not account for the operational phase. A GTU burns natural gas during operation, producing a huge amount of entropy, while an SPP produces virtually no entropy during operation (excluding maintenance costs). A full life cycle, including 25-30 years of operation, would very likely show an overall advantage for SPP. This demonstrates the limitation of an analysis confined to the production stage and underscores the need for comprehensive accounting of all stages, as required by our methodology.

Beyond the entropy of production, large-scale deployment of SPPs affects the environment through direct changes in surface albedo and heat balance. When replacing a thermal power plant (TPP) with a capacity of 10 MW with an SPP of the same capacity, we must estimate the area required for panel placement and the change in energy flows.

The average installed capacity density for ground-mounted silicon SPPs in mid-latitudes is about 100–120 W/m^2 (accounting for panel efficiency 20% and packing factor). For a power of 10 MW, the required area is approximately 9.1 ha. For comparison, the area occupied by a 10 MW GTU, including infrastructure, is only about 0.1–0.2 ha.

A TPP converts the chemical energy of fuel into electricity. Even in a modern GTU with an efficiency of 35%, the remaining 65% of the fuel energy is converted into heat and dissipated into the atmosphere (via cooling towers or exhaust gases). This heat is added to the atmosphere due to the combustion of fossil fuels, which would not have disrupted the heat balance if left in the ground. Consequently, the operation of a GTU leads to a *net additional heating* of the surrounding area.

In contrast, a solar panel replaces a surface with a certain albedo. Typical soil albedo (α_{soil}) is about 0.2, while the albedo of a solar panel (α_{PV}) is lower — around 0.1. This means the panel absorbs 10% more solar radiation than the soil. The average annual solar radiation flux (R) for mid-latitudes is about 150 W/m^2. The additional energy absorbed by the surface due to replacing soil with a panel is then about 15 W/m^2. Multiplying this by the area of the SPP gives the total heat flow added to the atmosphere due to the albedo change: approximately 1.36 MW.

Compare this with the thermal pollution from a GTU. At a power of 10 MW and efficiency 35%, the thermal power dissipated into the atmosphere is about 18.6 MW.

At first glance, the SPP produces 13 times less direct thermal pollution (1.36 MW vs. 18.6 MW). However, this is not the whole story. The area of the SPP is 50–100 times larger than that of the GTU. Consequently, this additional heat is distributed over a large area and does not create a local "heat island" like a TPP, but it does alter the microclimate over the entire deployment territory. Research [13] shows that in arid ecosystems, large solar farms can create "cool islands" during the day due to shading, but at night they retain heat, altering the diurnal temperature cycle. This change in the temperature regime of the soil and near-surface air affects local ecosystems, evaporation, and precipitation. Thus, when calculating the total entropic damage from an SPP within a full life cycle, these changes in heat balance must also be considered. They can be assessed through changes in the entropy of the surface and the near-surface atmospheric layer [18]. This example clearly demonstrates that the "environmental friendliness" of a technology cannot be assessed solely by CO_2 emissions; a comprehensive physical approach is required.

For clarity, the obtained results of the comparative calculation for the production of equipment for solar and gas turbine power plants are presented in a summary table.

Table 3: Summary results of the environmental efficiency coefficient calculation for SPP and GTU equipment production (per 1 MW of installed capacity)

Parameter	**SPP (silicon panels)**	**Simple-cycle GTU**
Market value of equipment C_{market}, million rubles/MW	45	25
Energy consumption for production, MWh/MW	4500	800
Entropy production ΔS_{total}, 10^9 J/(K·MW)	36.3	6.45
Cost of damage compensation $C_{entropy}$, million rubles/MW	5.4	1.26
Environmental efficiency coefficient η (production)	**0.893**	**0.952**

As can be seen from the table, the production of equipment for SPP is accompanied by almost an order of magnitude greater entropy production. Given current prices of compensation technologies, this yields a lower environmental efficiency coefficient at the production stage. However, this result holds only for the production stage and does not account for the operational phase, where SPP has a decisive advantage.

To assess the change in the environmental efficiency of the considered technologies over the long term, we turn to the forecasts of the International Energy Agency (IEA) presented in the World Energy Outlook 2025 [23]. The IEA develops three main scenarios for the development of global energy up to 2050 and beyond. The first scenario, the Current Policies Scenario (CPS), is based on already adopted laws and measures and assumes conservative technological development. In this scenario, demand for oil and gas continues to grow until 2050, and global CO_2 emissions remain at around 40 Gt per year, leading to a temperature increase of 2.9°C by 2100 [23]. The second scenario, the Stated Policies Scenario (STEPS), considers a broader set of announced policies and targets. Here, oil demand peaks around 2030, the share of electric vehicles in sales exceeds 50% by 2035, and emissions fall to 35 Gt by the mid-2030s [23]. The third scenario, the Net Zero Emissions by 2050 (NZE) Scenario, sets a trajectory for achieving net-zero emissions, requiring unprecedented rates of clean technology deployment and CO_2 capture [23].

The most important factors influencing the dynamics of the environmental efficiency coefficient η for the technologies under consideration include: changes in the carbon intensity of electricity production, reductions in the cost of renewable technologies, evolution of fossil fuel prices, development of carbon capture and storage (CCS) technologies, and changes in the structure of the global energy balance. Based on IEA forecasts, we can estimate the dynamics of the main parameters entering the calculation of η. For solar energy, further reductions in capital costs are expected. According to the Global Energy and Climate Model, by 2035 the cost of photovoltaic panels could decrease by 30-40% relative to the current level [23]. At the same time, a reduction in the carbon intensity of panel production is forecast as global electricity decarbonizes, especially in the STEPS and NZE scenarios. For gas turbine technologies, the determining factor will be the dynamics of natural gas prices and the tightening of emission requirements. In the CPS scenario, gas prices remain moderate, but in STEPS and NZE they rise under the influence of carbon regulation. The cost of CCS technologies, according to forecasts, will decrease with scaling, from the current 3000 rubles/t to 1500-2000 rubles/t by 2050 in the NZE scenario.

For a quantitative assessment of the dynamics of the environmental efficiency coefficient, it is necessary to separately account for the entropic damage from equipment production and from operation. We introduce the full life cycle environmental efficiency coefficient:

$$\eta_{LCA}(t) = \frac{C_{market}(t)}{C_{market}(t) + C_{entropy}^{prod}(t) + C_{entropy}^{oper}(t) \cdot T}, \tag{12}$$

where $C_{entropy}^{prod}(t)$ is the cost of compensating entropic damage during production, $C_{entropy}^{oper}(t)$ is the annual cost of compensation during operation, and T is the service life (assumed to be 25 years for both technologies). For a GTU, the annual entropic damage during operation is determined by the combustion of natural gas. At a power of 1 MW and 35% efficiency, the annual gas consumption is about 2.5 million m^3, resulting in CO_2 emissions of approximately 4500 t/year. At a CCS cost of 3000 rubles/t, the annual compensation cost would be 13.5 million rubles/year. Over 25 years, the accumulated compensation cost would reach 337.5 million rubles/MW, an order of magnitude higher than the cost of the equipment. For SPP, operational emissions are virtually absent, but maintenance costs and periodic replacement of inverters must be considered. We assume annual operating costs at 2% of the equipment cost, which gives 0.9 million rubles/year. Over 25 years, the accumulated costs amount to 22.5 million rubles/MW.

Taking these data into account, we perform a forecast assessment of the dynamics of η_{LCA} for the three scenarios.

The presented forecast demonstrates a fundamentally important pattern. When considering the full life cycle, solar energy has a manifold higher environmental efficiency coefficient than gas, and this gap widens over time as the production of the panels themselves decarbonizes and carbon regulation tightens. In the NZE scenario by 2050, η_{LCA} for SPP reaches 0.85, while for GTU even with active CCS deployment it does not exceed 0.40. The dynamics in the CPS scenario deserve special attention. The absence of stringent regulation leads to a paradoxical situation: as easily accessible gas reserves are depleted and its quality deteriorates (increasing entropic extraction costs), the environmental efficiency coefficient of GTU decreases despite technological progress. This is a direct consequence of the second law of thermodynamics. Extracting each subsequent barrel of oil or cubic meter of gas requires greater energy expenditure and is accompanied by greater entropy production. Thermal pollution as a component of entropic damage also undergoes significant changes. In the CPS and STEPS scenarios, the growth of global energy consumption leads to an increase in anthropogenic heat emissions, which reduces the efficiency of Earth's radiative cooling. In the NZE scenario, by contrast, the reduction in fossil fuel combustion and the transition to renewable sources reduce direct thermal pollution but create new challenges related to the disposal of end-of-life equipment. The IEA forecast indicates the inevitability of exceeding the 1.5°C threshold by 2030 in all scenarios [23]. This means that even under the most optimistic development path, humanity will face the need for active removal of CO_2 from the atmosphere. Technologies such as direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) will become an integral part of the energy system, introducing a new component of entropic costs — the cost of managing the carbon cycle.

5 Comparison of Anthropogenic and Natural Greenhouse Gas Emissions

For a correct interpretation of the scale of anthropogenic impact, it is necessary to compare emissions from human activities with natural sources. Such a comparison allows us to separate the anthropogenic contribution from background natural processes and assess the relative role of the technosphere in the global entropy balance. The two key greenhouse gases — carbon dioxide (CO_2) and methane (CH_4) — are of greatest interest, as they contribute the most to radiative forcing.

Volcanic activity is often discussed in public discourse as a natural analogue of anthropogenic CO_2 emissions. Indeed, volcanoes are a powerful source of carbon. However, a quantitative comparison reveals a fundamental difference in scale. According to estimates from the U.S. Geological Survey, global volcanic CO_2 emissions range from 0.13 to 0.44 billion tons per year [63]. More recent studies under the Deep Carbon Observatory (DECADE) program refine this figure: an analysis of 102 active volcanoes over the period 2005–2017 gives a total emission of about 44 million tons of CO_2 per year from measured sources alone, which, when extrapolated to all the world's volcanoes, yields a value on the order of 0.1–0.3 Gt/yr [53].

For comparison, anthropogenic CO_2 emissions in 2024 exceeded 37 billion tons [62]. Thus, human activity emits 140–250 times more CO_2 into the atmosphere than all the volcanoes on the planet combined [50,51]. The ratio of anthropogenic to volcanic emissions has steadily increased throughout the 20th century, from about 18 in 1900 to 135 by 2010, reflecting a 650% increase in emissions from fossil fuel combustion [52].

It is important to consider the temporal variability of volcanic emissions. Large explosive eruptions, such as Pinatubo (1991, 0.05 Gt CO_2) or Mount St. Helens (1980, 0.01 Gt CO_2), can release in a few hours an amount of CO_2 comparable to humanity's daily emission [50]. However, such events are rare (recurrence of large eruptions is tens to hundreds of years). When averaged over a century timescale, their contribution to the global budget is negligible — on the order of 0.0005 Gt/yr for an eruption the size of Pinatubo [52]. In terms of time intervals, humanity emits an amount of CO_2 equivalent to the Mount St. Helens eruption every 2.5 hours, and the annual volcanic emission every 2.7 days [52].

The hypothetical assumption that volcanoes could emit CO_2 at the level of anthropogenic emissions (more than 35 Gt/yr) contradicts fundamental geochemical constraints. Producing such an amount of CO_2 would require an annual magma output of more than 850 km^3 at a CO_2 concentration of 1.5 wt.%, which is more than 40 times the current estimates of global magma generation at mid-ocean ridges [52]. Furthermore, such a CO_2 flux into the ocean would disrupt its acid-base balance, which is not observed.

Methane is the second most important greenhouse gas, responsible for about 30% of the rise in global temperature since pre-industrial times [54,55]. Its atmospheric concentration has more than doubled over the past 200 years and continues to increase faster than that of CO_2 [54].

The total global methane budget is estimated at about 610 million tons per year, with anthropogenic sources accounting for about 60% (over 360 Mt/yr) and natural sources 40% [54, 55]. The main natural sources include wetlands, which are the largest natural source (about 30–40% of global methane emissions) [57]. Methanogenic microorganisms in anaerobic conditions of waterlogged soils produce CH_4, with major emission regions being tropical and boreal wetlands. Satellite data from Sentinel-5P identify features such as the Sudd (South Sudan) with emissions of about 4.5 Mt/yr and Ibera (Argentina) with 3.3 Mt/yr among the most powerful natural sources [56]. Geological processes release thermogenic methane formed from the decomposition of organic matter in the Earth's crust through natural seeps, mud volcanoes, and hydrothermal systems. Thawing permafrost is a potentially important source sensitive to climate change, although current estimates do not predict a catastrophic increase in emissions from this source in the coming decades; monitoring continues under programs such as NASA's ABoVE [55]. Termites produce methane in their digestive systems during cellulose decomposition [57]. Natural fires generate pyrogenic methane from incomplete combustion of biomass [57].

The temporal variability of natural methane sources is determined by climatic factors (temperature, precipitation affecting the area and productivity of wetlands) and geological processes. Unlike anthropogenic sources, which are largely controlled by economic activity and can be relatively quickly reduced, natural emissions are difficult to manage directly and may increase with climate warming (a positive feedback).

From the perspective of the entropy approach developed in this work, the comparison of anthropogenic and natural emissions has important conceptual significance. Natural sources of CO_2 and CH_4 are part of the global geochemical cycle to which the biosphere has adapted through evolution. Volcanic activity, while a powerful local perturbation, contributes relatively little to the multi-year carbon budget and, importantly, is accompanied by the emission of aerosols (SO_2) that have a short-term cooling effect, partially offsetting the greenhouse effect [50, 58].

In contrast, anthropogenic emissions: are hundreds of times larger than natural ones (for CO_2) and constitute the majority (for CH_4); occur continuously, without the pauses characteristic of volcanic activity; show a steady increase over more than 150 years, whereas natural sources are relatively stable on a historical timescale; and do not contain compensating aerosols — indeed, anthropogenic sulfates are decreasing due to air pollution control, enhancing warming.

Thus, anthropogenic greenhouse gas emissions represent a fundamentally new factor disrupting the established entropy balance of the Earth–atmosphere–space system. Humanity is not simply adding entropy to the biosphere but is altering the planet's radiative regime, reducing its capacity to dump entropy into space. This lends the problem of climate change the character not merely of an environmental issue but of a fundamental thermodynamic challenge requiring for its solution not only technological but also, as will be shown below, spatially scaled solutions.

From the entropy perspective, the key issue is not only emission reduction but also minimizing total entropy production across all stages of the life cycle. Transitioning to renewable energy reduces operational entropic costs but increases the "embedded" entropy in materials and equipment. An optimal strategy requires a balance between these components, which can be found through the proposed environmental efficiency coefficient. In the long term, even the most efficient terrestrial technologies run up against a fundamental limitation — the finite capacity of the Earth's biosphere to absorb entropy. Forecast analysis shows that in the sustainable development scenario (NZE), by the end of the 21st century humanity will approach this limit closely, making the transition to active entropy dumping into space, discussed in subsequent sections, inevitable.

6 Comparative Analysis of the Entropy Efficiency of Data Center Placement: Earth (Mid-Latitudes), Polar Regions, and the Moon

Data centers are a unique object for entropy analysis. Unlike industrial production, where entropy is generated through chemical transformations, a data center converts almost all the electricity it consumes into heat, which must be dissipated into the environment. This makes them "pure" dissipative structures, where cooling efficiency directly determines ecological efficiency. According to the International Energy Agency, global electricity consumption by data centers in 2024 was 415 TWh, equivalent to 1.5% of global electricity consumption [24]. More than 95% of the cooling load comes from heat released by IT equipment [25]. We consider three fundamentally different scenarios for siting a 10 MW data center (a typical modern hyperscale data center): mid-latitudes (ASHRAE climate zone 4A, e.g., Central Europe), polar regions (climate zone 8, e.g., Northern Norway), and the Moon (south pole, peak of eternal light region).

On Earth, heat is removed primarily by convection (air or liquid cooling) and to a lesser extent by radiation. Cooling efficiency is determined by ambient temperature and humidity. The key metric is PUE (Power Usage Effectiveness), which in mid-latitudes ranges from 1.3 to 1.5 for air cooling and can drop to 1.15-1.2 with effective economizers [26]. PUE variability depending on climate zone reaches 62%, confirming the critical role of location [27]. In polar regions, low ambient air temperatures allow the use of "free cooling" almost year-round. Studies show that in zones 7 and 8, PUE can reach values of 1.08-1.12 using direct air economizers [26]. However, extra costs for transport infrastructure and increased equipment wear at extremely low temperatures must be considered.

On the Moon, the situation is fundamentally different. The absence of an atmosphere makes convective cooling impossible — the only mechanism for heat rejection is thermal radiation [28]. The radiative power is described by the Stefan–Boltzmann law:

$$P_{rad} = \varepsilon \sigma A (T^4 - T_{surr}^4), \tag{13}$$

where ε is emissivity, $\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4), A is the radiator area, T is the radiator temperature, and T_{surr} is the surrounding temperature. In a vacuum, the absence of convective cooling creates serious engineering challenges. As noted in technical discussions, “vacuum is actually bad for cooling because radiative heat transfer is not very efficient” [29]. However, radiative cooling has a fundamental advantage: heat is dumped directly into space with an effective temperature of 2.7 K, offering enormous potential if the radiator temperature is sufficiently high. Importantly, the lunar surface experiences colossal temperature swings, from +120°C during the day to -180°C at night [30]. This necessitates either placing the data center in subsurface lava tubes with a stable temperature around -20°C, or at the south pole in “peak of eternal light” regions, where solar panels can receive constant energy and cold traps provide natural heat rejection.

For data centers, we modify our environmental efficiency coefficient η by introducing the concept of entropic cooling efficiency. The full life cycle environmental efficiency coefficient for a data center is:

$$\eta_{DC} = \frac{E_{IT}}{E_{IT} + E_{cool} + E_{transp} + E_{embodied}}, \tag{14}$$

where E_{IT} is the energy consumed by IT equipment (useful work), E_{cool} is the energy for cooling, E_{transp} is the energy for transportation (for polar and lunar scenarios), and $E_{embodied}$ is the embodied energy in infrastructure. For ease of comparison, we introduce an entropic cooling efficiency coefficient:

$$\xi_{cool} = \frac{T_0}{T_{sink} - T_0} \cdot \frac{1}{COP_{real}}, \tag{15}$$

where T_0 is the ambient temperature, T_{sink} is the heat sink temperature, and COP_{real} is the real coefficient of performance for cooling.

The initial data for the calculation are summarized in Table 4.

For a correct comparison, the full life cycle must be considered, including infrastructure creation. Using an approach similar to the previous section, Table 5 presents the calculation results accounting for embodied entropy.

The results require careful interpretation. The polar region exhibits the highest environmental efficiency coefficient (0.882) due to the combination of low temperatures, minimizing cooling energy, and accessible hydropower with a low carbon footprint. This confirms the practice of locating data centers in Scandinavia. Mid-latitudes have the lowest coefficient (0.791) because of high cooling costs and the carbon intensity of the electricity grid. The lunar scenario gives an intermediate result (0.832), which at first glance seems counterintuitive. The enormous capital costs and entropic damage from producing rockets and equipment “eat up” the environmental advantages of free solar energy and ideal heat rejection into space. However, three points are important. First, the calculation is sensitive to delivery costs; if the cost of launching cargo to the Moon drops to \$200/kg, η_{moon} increases to 0.91. Second, a lunar data center has an unlimited service life in terms of cooling. Third, space-based placement solves the problem of planetary thermal pollution.

We introduce an additional indicator — the global entropy efficiency coefficient — which accounts not only for local but also for planetary entropy balance:

$$\eta_{global} = \eta_{LCA} \cdot \left(1 - \frac{Q_{waste}}{Q_{solar}}\right), \tag{16}$$

where Q_{waste} is the heat dumped into the biosphere, and Q_{solar} is the solar energy incident on Earth. For terrestrial data centers, all heat remains in the biosphere, increasing the planet’s entropic load. For a lunar data center, heat is dumped into space and does not affect Earth’s balance. Taking this factor into account, $\eta^{mid}_{global} \approx 0$, $\eta^{polar}_{global} \approx 0$, and

$\eta_{global}^{moon} = 0.832$. From a global entropy perspective, only space-based placement avoids heating the planet. Initiatives such as ASCEND [31] and ISRO [32] for orbital data centers gain thermodynamic justification: they are not merely technological experiments but a necessary step toward breaking Earth's entropic closure.

7 Comparative Analysis of the Entropy Efficiency of Livestock Farming and Photosynthetic Organisms

The entropy approach proposed in this work is universal and can be applied not only to technological but also to biological systems. Livestock farming and plants represent two fundamentally different strategies for obtaining negentropy: heterotrophic (consumption of ready-made organic matter) and autotrophic (direct conversion of solar energy). The aim of this analysis is to compare the entropy efficiency of protein production by various biological systems: cattle, pigs, chickens, and leading photosynthetic plants. The unit of comparison is chosen as 1 kg of protein, as it is the most significant product from a nutritional perspective.

Livestock systems are hierarchical dissipative structures in which entropy is produced at several levels: feed production (crop cultivation using fertilizers, machinery, irrigation); animal maintenance (energy for lighting, ventilation, heating); enteric fermentation (metabolic processes in the rumen of ruminants); manure management (storage, processing, disposal); and transportation and processing of products. According to the Food and Agriculture Organization (FAO) of the UN, global livestock emissions amount to 4.3 Gt CO_2-eq per year, or 12% of all anthropogenic greenhouse gas emissions [34]. Of this, 45% comes from feed production, 39% from enteric fermentation, and 10% from manure storage [33]. From an entropy perspective, livestock farming is a three-stage negentropy converter: solar energy → plants (primary negentropy) → feed → animal → protein. At each stage, dissipation and entropy production occur.

A study by FAO provides a comprehensive analysis of the carbon footprint of various livestock systems using a cradle-to-farm-gate methodology [33]. The functional unit is 1 kg of crude protein in animal food (CPAF). Table 6 presents the specific greenhouse gas emissions for different livestock systems.

Note: Fossil CO_2 was the most emitted greenhouse gas (10.2–27.6 kg/kg protein), exceeding CH_4 by a factor of 10–255 and N_2O by a factor of 284–646. Methane is more associated with ruminants, while N_2O and CO_2 are linked to resource use intensity. Emission intensity is highest for beef (almost 300 kg CO_2-eq/kg protein), followed by meat and milk from small ruminants (165 and 112 kg CO_2-eq/kg protein, respectively). Dairy cattle milk, poultry products, and pork have lower global averages (¡100 kg CO_2-eq/kg protein). A study by Joly et al. (2022) shows a gradient of impact along the species range: producing 1 kg of meat, energy consumption and CO_2-eq emissions increase from chicken to pork and from pork to beef, partly explained by differences in feed conversion efficiency [35]. In absolute figures, without impact allocation, differences between chicken and beef are 2.5-fold for energy (20 MJ/kg to 50 MJ/kg) and six-fold for CO_2-eq (5 to 30 kg CO_2-eq/kg) [35].

Photosynthetic organisms represent a direct channel for converting solar electromagnetic energy into the chemical energy of organic compounds. From the perspective of non-equilibrium thermodynamics, this is a fundamentally different, more efficient path for obtaining negentropy. Research by Michaelian (2022) shows that the process of photon absorption and their dissipation into infrared radiation is a crucial entropy-producing process on Earth [36]. Plant pigments, including chlorophyll, reach peak absorption precisely where entropy production through photon dissipation is maximal for our solar spectrum (430 ¡ λ ¡ 550 nm), while the efficiency of photosynthesis is maximal between 600 and 700 nm [36]. This leads to an intriguing conclusion: the evolution of pigments, plants, and ecosystems may have been directed toward optimizing entropy production, rather than photosynthesis per se. According to Jennings et al. (2018), photosystem I upon excitation in the chlorophyll Qy absorption band exhibits unique thermodynamic properties: the entropy production in the system and its surroundings is numerically less than the decrease in the entropy of the light field [37]. This indicates that photosystem I "feeds on negative entropy" in the Schrödinger sense. Moreover, the exceptionally high quantum efficiency (close to unity) suggests that the evolution of photosystem I proceeded along the path of maximum energy efficiency, rather than maximum entropy production [37].

This apparent contradiction—maximizing entropy production at the ecosystem level versus minimizing it at the molecular level—is resolved by considering the hierarchical nature of biological systems. At the molecular scale (photosystem I), natural selection optimizes energy conversion efficiency to maximize the useful energy captured from each photon. This high efficiency provides a competitive advantage to the individual organism. However, at the level of the whole plant and the ecosystem, competition for resources (sunlight, nutrients) drives systems to utilize the available energy flow as completely as possible. A mature forest, for instance, dissipates nearly all incoming solar radiation into heat, latent heat (evapotranspiration), and biomass production, thereby maximizing entropy production. Thus, the high efficiency of the photosynthetic machinery is a prerequisite for the ecosystem to achieve a state of maximum dissipation. The two principles operate at different scales and are not mutually exclusive; rather, they are complementary.

For a correct comparison, we need to adopt a common functional unit — 1 kg of protein — and consider the full life cycle, including land use and water consumption. Table 7 presents a comparison of the environmental efficiency of protein production from various sources.

*Estimate based on [38] and [41], **author's estimate based on FAO data

As can be seen from the table, plant-based protein sources have a carbon footprint one to two orders of magnitude smaller and land and water requirements an order of magnitude smaller. According to Ferrari et al. (2022), beef generates 25-26 kg CO_2-eq/kg, while cereals generate only 0.5 kg and nuts 1.2 kg [38]. Water consumption for beef is 8700-15400 m^3/t compared to 1600 m^3/t for cereals [38]. A study by EarthShift Global for the Good Food Institute (2024) shows that plant-based meat has, on average, 89% lower environmental impact across most categories compared to traditional animal meat. Beef shows the highest load — 91% higher than plant-based alternatives. Pork and poultry follow with indicators 88% and 71% higher, respectively [39].

From the standpoint of the second law of thermodynamics, the superiority of plants is explained by fundamental reasons. First, the length of the trophic chain: plants are at the first trophic level, directly utilizing solar energy, while animals are at the second level and above, meaning multiple energy conversions with dissipative losses at each level (conversion efficiency between trophic levels is only 10-20%). Second, ruminant animals produce methane through enteric fermentation — a high-entropy product with a global warming potential 28-36 times that of CO_2 [33]. Third, livestock farming is associated with nitrous oxide (N_2O) emissions from manure and fertilizers, adding an additional entropic contribution with a global warming potential 265-298 times that of CO_2. A study by Habib and Khan (2018) in Pakistan shows that the emission intensity of buffalo and cattle milk is 184.9 kg CO_2-eq/kg protein compared to a global average of 110.0 kg, while for beef and mutton it is 606.4 kg compared to a global average of 235 kg. Poultry and eggs have the lowest figures, at 49.6 and 20.8 kg CO_2-eq/kg protein, respectively [40].

An intriguing conclusion from photosynthesis research is that plant evolution may have optimized not for maximizing photosynthesis but for maximizing entropy production [36]. Plant leaves and climax forests generate greater entropy production than, for example, deep ocean water. This aligns with the principle of maximum entropy production for mature ecosystems. However, photosystem I, as shown by Jennings et al. (2018), evolved toward maximum energy efficiency rather than maximum entropy production [37]. This apparent contradiction is resolved by considering the hierarchical nature of biological systems: at the molecular level, selection favors efficiency; at the level of the whole organism and ecosystem, it favors maximizing dissipation. It is important to note that the differences between animals and plants are not absolute and depend on specific production methods. A study by Joly et al. (2022) shows that when accounting for ecosystem services of pastures, the impact gradient may change. Mavroeidis et al. (2024), using Greece as an example, show that the carbon footprint of wheat and maize depends significantly on tillage methods, indicating the potential for further reducing the entropic footprint of crop production through agronomic practices [41].

8 Entropy Analysis of Nuclear Energy: Comparison of Traditional Reactors and the Closed-Fuel-Cycle "Proryv" Technology

Nuclear energy occupies a special place in entropy analysis due to its unique combination of high energy density, minimal operational emissions, and the complex problem of managing long-lived radioactive waste. From the perspective of the second law of thermodynamics, a nuclear reactor is a dissipative structure that converts nuclear energy into heat, followed by conversion into electricity. However, the full entropy balance must consider the entire life cycle — from uranium mining to final waste isolation. The aim of this analysis is to compare the entropy efficiency of two fundamentally different nuclear technologies: traditional slow-neutron reactors (VVER, PWR) with an open nuclear fuel cycle, and the innovative Russian "Proryv" technology, implemented in the BREST-OD-300 project with a fast-neutron closed fuel cycle [42, 47].

For a correct assessment of nuclear technologies, a systemic exergy analysis accounting for all stages of the fuel cycle is required. The thermo-ecological cost (TEC) methodology, developed for analyzing energy systems, allows expressing the total consumption of exergy from non-renewable resources per unit of product [43, 44]. TEC accounts not only for direct exergy expenditures during operation but also for indirect costs of mining, transportation, uranium enrichment, construction, decommissioning, and the additional exergy consumption needed to compensate for environmental damage from harmful emissions [44]. The main non-ideality of the nuclear fuel cycle from an exergy analysis perspective appears at the stages of conversion, enrichment, and fuel fabrication, where significant energy quality losses occur [43]. Traditional slow-neutron reactors are characterized by an open (once-through) fuel cycle: uranium is mined, enriched, used once, and spent fuel is sent to storage without reprocessing. The uranium utilization rate in such a cycle does not exceed 0.5–1%, as most of the uranium-238 remains unused [46].

The Russian "Proryv" (Breakthrough) project represents a fundamentally new approach to nuclear energy, based on three key elements: the BREST-OD-300 fast neutron reactor with lead coolant, possessing inherent safety features; mixed nitride uranium-plutonium fuel (MNUP), allowing high burnup; and an on-site closed fuel cycle, including fuel fabrication and refabrication modules and spent fuel reprocessing [42, 47]. In a closed cycle, spent fuel is reprocessed to extract plutonium and other actinides, which are then used to manufacture fresh fuel. This allows, first, the involvement of uranium-238 (constituting more than 99% of natural uranium) in the energy balance through its conversion to plutonium-239, and second, a radical reduction in the volume and toxicity of long-lived waste [42]. According to developers, the closed cycle can increase uranium utilization to 95% and reduce the volume of radioactive waste requiring disposal by tens of times [46]. Furthermore, the technology involves "burning" the most hazardous long-lived transuranic elements in the fast neutron spectrum, transforming them into short-lived or stable isotopes. Fuel for BREST-OD-300 is characterized by a burnup of 6% of heavy atoms initially, with the prospect of increasing to 12% during operation, significantly higher than traditional reactors [46]. This means more complete utilization of the fuel's energy potential and less waste per unit of energy produced.

For a comparative assessment, we apply our environmental efficiency coefficient $\eta = C_{market}/(C_{market} + C_{entropy})$, adapting it to the specifics of the nuclear fuel cycle. The functional unit is 1 MWh of electricity produced over the life cycle (including construction, operation, decommissioning, and waste management). A service life of 60 years is assumed for both technologies. The initial data for the calculation are summarized in Table 8.

The exergy efficiency of fuel production (ψ_{fuel}) shown in Table 8 is an intermediate thermodynamic indicator that measures how much of the exergy (available work) invested in mining, enrichment, and fabrication is preserved in the final fuel. A higher ψ_{fuel} means lower entropy generation during the fuel preparation stage. This value is not to be confused with the overall environmental efficiency coefficient η; rather, it is one of the inputs used, together with other parameters, to compute the total entropic damage $C_{entropy}$ and subsequently η.

The assessment of entropic damage $C_{entropy}$ for nuclear technologies must consider three main components: the cost of compensating greenhouse gas emissions at all life cycle stages, the cost of long-term isolation of radioactive waste, and decommissioning costs. At a CCS cost of 3000 rubles/t CO_2, the C_{CO_2} component is 0.04–0.05 rubles/kWh for a traditional reactor and 0.024–0.03 rubles/kWh for BREST-OD-300. The critical difference lies in the cost of waste isolation. Traditional reactors require deep geological repositories with an isolation period of up to 100,000 years. Using discounting methods and accounting for intergenerational risks gives a significant present value (estimated at 0.15–0.25 rubles/kWh). The closed cycle technology reduces the period of potential waste hazard to 300–500 years [46], lowering the isolation cost by an order of magnitude (0.02–0.04 rubles/kWh). Considering these estimates, for a traditional PWR $C_{entropy} \approx 0.24$ rubles/kWh, $C_{market} \approx 0.50$ rubles/kWh, $\eta_{PWR} \approx 0.68$. For BREST-OD-300, $C_{entropy} \approx 0.057$ rubles/kWh, $C_{market} \approx 0.75$ rubles/kWh, $\eta_{BREST} \approx 0.93$.

The obtained values show that the closed cycle technology has a significantly higher environmental efficiency coefficient due to the radical reduction in the volume and toxicity of waste and more complete utilization of natural uranium. The higher capital costs are offset by the reduction in entropic damage at the waste management stage. From the perspective of the second law of thermodynamics, the advantages of the "Proryv" technology can be explained as follows. First, the closed cycle implements multiple uses of fuel materials, analogous to increasing the overall exergy efficiency of the system. In an open cycle, most of the potential exergy of uranium-238 remains unrealized and passes into waste, increasing the entropic load on the environment. Second, "burning" long-lived actinides in the fast neutron spectrum represents a process of transforming highly organized nuclear material into fission products with significantly shorter half-lives. From an entropy perspective, this accelerates natural decay processes that would otherwise stretch over millennia. Entropy production is concentrated in time, allowing controlled disposal of the remaining fission products in geological formations. A study of entropy evolution in a fuel rod under deep burnup [45] shows a characteristic U-shaped evolution: an initial decrease due to self-organization of the neutron field, followed by stabilization and then an increase due to material degradation. The minimum entropy value is reached approximately 45 years into operation, which can be considered the thermodynamic limit for efficient fuel use. The design parameters of BREST-OD-300 with a burnup of 6–12% of heavy atoms approach this limit. Third, the use of lead coolant and inherent safety features reduces the risk of accidental releases, which represent a catastrophic increase in entropy with uncontrolled dispersal of radioactive products in the biosphere.

For completeness, we compare the obtained environmental efficiency coefficients of nuclear technologies with those previously considered in the article: solar energy (full life cycle, NZE 2050 scenario) — $\eta \approx 0.85$; gas turbine generation with CCS (NZE 2050) — $\eta \approx 0.40$; polar data centers — $\eta \approx 0.882$; lunar data centers (prospective) — $\eta \approx 0.832$–0.91; beef — $\eta \approx 0.10$–0.15; plant proteins — $\eta \approx 0.85$–0.95; traditional nuclear reactor (open cycle) — $\eta \approx 0.68$; BREST-OD-300 — $\eta \approx 0.93$. The closed nuclear cycle demonstrates the highest environmental efficiency coefficient among all technologies considered, comparable to plant protein sources and surpassing even prospective space-based data centers. This is explained by the unique combination of high energy density, minimal operational emissions, and radical waste reduction.

It is important to note that the “Proryv” technology is at the pilot-industrial implementation stage. BREST-OD-300 is expected to be commissioned in 2028-2029 [47]. Full-scale commercial deployment of the closed cycle will require solving a number of economic and regulatory problems. Independent experts emphasize that the “magic purse” — an analogy with self-reproducing fuel — should not obscure the technological complexities associated with spent fuel reprocessing and ensuring nuclear safety in handling plutonium [46]. Furthermore, non-proliferation issues and international control over closed cycles remain subjects of debate. Nevertheless, from a purely entropic point of view, the development path chosen in the “Proryv” project appears thermodynamically optimal: minimizing entropy production at all life cycle stages, maximizing resource utilization, and minimizing uncontrolled dispersal of radioactive products in the biosphere.

9 Comparative Analysis of the Entropy Efficiency of Solid-State Electronics and Photonic Computing

The fundamental importance of the Landauer principle for assessing the entropy efficiency of computing systems is revealed when comparing traditional solid-state electronics with prospective photonic computing. As shown above, the minimum energy release when erasing one bit of information is $E_{min} = k_B T \ln 2$, which at room temperature corresponds to approximately 2.9×10^{-21} J per bit. This limit sets a thermodynamic ideal toward which computing devices can strive, but the actual energy efficiency of current technologies remains far from this value.

Solid-state electronics, based on complementary metal-oxide-semiconductor (CMOS) technology, inevitably dissipates energy during each logical operation, significantly exceeding the Landauer limit. The main sources of entropy include charging and discharging parasitic capacitances, leakage currents in submicron transistors, and Joule heating from current flow. According to Koomey’s law, the energy efficiency of computing doubles every 1.5 years, reflecting progress in miniaturization and architectural optimization [48]. Extrapolating this trend suggests that by 2050, the energy cost per operation will approach the fundamental Landauer limit [48]. Beyond that point, further efficiency improvements will become impossible without a paradigm shift in computing. At that stage, computing will become “heat-limited”: virtually all consumed energy will inevitably dissipate as heat, and the environmental efficiency coefficient of computing systems will be fundamentally bounded from below.

Photonic computing offers a fundamentally different approach to information processing, where photons, rather than electrons, serve as information carriers. In photonic circuits, logical operations can be performed without charge transport, potentially avoiding the Joule losses characteristic of electronic circuits. However, it is important to understand that the Landauer principle remains valid for photonic computing as well: any irreversible transformation of information, including bit erasure, requires energy dissipation. The difference is that in photonic systems, this dissipation can be shifted to other physical processes, such as photon absorption in detectors or nonlinear optical interactions.

Comparing the entropy efficiency of the two approaches requires considering the full life cycle of photons: generation, modulation, transmission, processing, and detection. Sources of entropy in photonic computing include photon generation, where the quantum efficiency of laser sources is far from unity and a significant fraction of energy is converted to heat; propagation losses in waveguides and modulators, where photons are scattered or absorbed; detection, where a photon is inevitably absorbed, converting signal energy into heat; and irreversible logical operations requiring energy dissipation according to the Landauer principle. Current photonic computing systems still lag behind electronic ones in energy efficiency precisely because of high losses in generation and detection. However, theoretically, the photonic approach has the potential to approach the Landauer limit more closely than electronics, as it allows minimization of parasitic capacitances and leakage currents.

For a quantitative comparison, we introduce an entropic computing efficiency coefficient as the ratio of the minimum possible entropy production (by Landauer) to the actual entropy production per logical operation:

$$\eta_{comp} = \frac{k_B T \ln 2}{\Delta S_{op}}, \tag{17}$$

where ΔS_{op} is the actual entropy production per operation, considering all dissipative processes in the system. For modern CMOS processors, η_{comp} is on the order of 10^{-5}–10^{-6}, reflecting the colossal gap between reality and the thermodynamic ideal. For current photonic computers, this indicator is even lower due to the non-optimality of sources and detectors.

The trend for the coming decades is determined by Koomey’s law, according to which the energy efficiency of electronic computing will continue to grow exponentially, approaching the fundamental limit. By 2050–2075, electronic systems will closely approach the Landauer barrier. Further progress will require a transition either to reversible computing, where information is not erased but reordered, or to photonic architectures. Photonic computing, in turn, will improve by reducing losses in generation and detection and by developing fully optical logic elements with minimal dissipation. It is predicted that by 2075, photonic systems could achieve $\eta_{comp} \approx 0.1$–0.01, i.e., only one to two orders of magnitude worse than the thermodynamic ideal, while electronic systems will hit the Landauer limit and be unable to surpass it without a paradigm shift.

From a global entropy perspective, this means that the information and computing sector, currently consuming about 1–1.5% of global electricity and growing rapidly, will face a fundamental constraint: each operation will inevitably produce at least $k_B T \ln 2$ entropy. If the growth rate of computing power continues, heat dissipation will become a limiting factor. Therefore, the transition to photonic and reversible computing is not merely a matter of performance but an environmental necessity, analogous to the shift to renewable energy and closed nuclear cycles.

10 Strategies for Combating Entropic Damage and the Transition to Space

Since completely avoiding entropy increase is impossible, there are fundamentally only two strategies for minimizing damage, which can be combined. The first strategy is the localization of high-entropy waste using long-term engineered barriers to prevent its spread into the biosphere [3]. The second strategy is active entropy dumping into space, primarily in the form of thermal radiation, and in the future, possibly as high-entropy matter [5, 11]. Table 9 compares these two strategies based on key characteristics.

The second path deserves special attention. As rightly noted in [5], Earth already dumps entropy into space through radiation. The technological challenge is to intensify this process. Modern research in the field of thermoradiative elements and materials for radiative cooling demonstrates the fundamental possibility of creating devices that effectively transfer excess heat to cold space [11, 12]. This could become the basis for global or local cooling, compensating for thermal pollution from energy generation.

Analysis shows that most modern “green” technologies suffer from incomplete life cycle accounting. A solar panel generates no emissions during operation, but its production involves a high entropic cost (mining of silicon, rare earth elements, energy-intensive processes). The environmental efficiency coefficient η for solar energy, calculated using the proposed methodology with a full life cycle and current disposal prices, may turn out to be unexpectedly low, comparable to that of gas generation with a CO_2 capture system [13]. A forecast of technological development shows that in the short term (up to 2050), the localization strategy will dominate. Efforts will focus on improving barrier reliability and reducing recycling costs. In the long term (after 2050), a transition to active space utilization is expected. The development of technologies for launching materials into orbit and creating space-based thermal shields could make entropy dumping economically viable. The work [1] considers an example of wind energy, confirming the need for full life cycle accounting for a correct entropy assessment.

Planet Earth is a finite reservoir. The biosphere’s capacity to absorb entropy without irreversible degradation is limited. Localization is merely a delay: space for isolated repositories is exhaustible, and the risks of their failure increase over time. Consequently, the only strategy that removes the growth constraint is expanding the entropy disposal reservoir. That reservoir is the universe. Entropy dumping into space can take two forms: passive or active thermal dumping, where high-entropy radiation escapes into space without heating the atmosphere [11], and physical export of high-entropy matter beyond the biosphere — to the Moon, Lagrange points, or deep space. Furthermore, space is a source of negentropy. Pure asteroid material, not involved in Earth’s cycles, or concentrated solar energy in space allows creating order at lower costs than on Earth. This makes space exploration not just a matter of scientific romance but an existential necessity.

11 Conclusion

The developed entropy assessment methodology allows shifting the discussion on ecology to a rigorous scientific basis. The proposed environmental efficiency coefficient η, for which the fundamental inequality $\eta < 1$ has been theoretically substantiated, provides an objective tool for comparing investment projects, developing approaches from [1, 3]. The methodology was tested on a wide range of objects — from energy installations to biological systems — confirming its universality and revealing key patterns. Comparing the production of equipment for SPP and GTU showed that at the production stage, gas technologies are more environmentally friendly. However, when considering the full life cycle, solar energy has a manifold higher environmental efficiency coefficient, and this gap widens as the global economy decarbonizes and easily accessible hydrocarbon resources are depleted. Land use analysis showed that, despite significantly lower direct thermal pollution compared to GTU, solar power plants require two orders of magnitude larger areas, leading to changes in local albedo and microclimate. This factor, assessed through changes in the territory's heat balance, must be included in the full entropic accounting at the operational stage, which is a subject for further research.

Comparing anthropogenic and natural greenhouse gas emissions demonstrates that human activity emits 140–250 times more CO_2 than all the Earth's volcanoes combined and is the source of 60% of global methane emissions. Natural sources, while significant in absolute terms, are relatively stable over time and are part of the natural geochemical cycle. Anthropogenic emissions, on the other hand, are continuously increasing and disrupting the established entropy balance of the planet. This lends the problem of climate change the character of a fundamental thermodynamic challenge, requiring not only technological but also spatially scaled solutions for its resolution.

Analysis of data center placement demonstrated that polar regions are the optimal terrestrial solution ($\eta = 0.882$). However, from a global entropy perspective, only space-based placement avoids heating the planet. A comparative analysis of livestock and plants showed that plant-based protein sources have an order of magnitude higher environmental efficiency coefficient ($\eta = 0.85 - 0.95$ vs. $0.10 - 0.45$), due to the shorter trophic chain and the absence of enteric fermentation. The results of the nuclear energy analysis deserve special attention. Traditional slow-neutron reactors with an open fuel cycle have an environmental efficiency coefficient $\eta \approx 0.68$, which is higher than gas generation but lower than renewable sources. The Russian "Proryv" technology (BREST-OD-300 with a closed cycle) demonstrates $\eta \approx 0.93$ — the highest indicator among all technologies considered. This is achieved through multiple uses of fuel, burning of long-lived actinides, and reducing the period of potential waste hazard to 300–500 years. From a thermodynamic point of view, the closed nuclear cycle approaches the ideal of a dissipative structure, minimizing entropy production while maximizing resource utilization.

Analysis of the entropy efficiency of computing systems shows that the information sector is also approaching fundamental thermodynamic limits. Koomey's law [48] indicates a steady increase in the energy efficiency of electronic computing, which will hit the Landauer barrier by the mid-21st century. Further progress will require a transition to photonic and reversible computing, where dissipation can approach the theoretical minimum. This direction is becoming not just a matter of performance but an environmental necessity, as the heat dissipation of computing power, if current growth rates continue, will become a critical factor in the global entropy balance.

The thermodynamic interpretation of environmental damage developed in this work confirms Vernadsky's prophetic idea of the inevitable transition of the biosphere into the noosphere. Scientifically managed minimization of entropy production and expansion of humanity's operational base into space are the concrete mechanisms for realizing this transition.

At the same time, it is important to emphasize that the proposed methodology, while laying a fundamental foundation for quantitative assessment, represents only the first step towards a comprehensive analysis. Real-world scenarios are infinitely more complex and require significantly broader and deeper interdisciplinary research. For example, the entropy efficiency calculation for nuclear energy presented here is based on ideal operational parameters. A full assessment must incorporate the catastrophic experience of Chernobyl and Fukushima, events that represent extreme, uncontrolled releases of entropic damage with consequences spanning decades and affecting vast territories. Incorporating the probability and consequences of such low-probability, high-impact events into the economic coefficient $C_{entropy}$ remains a profound methodological challenge.

Similarly, the analysis of solar energy's environmental efficiency must extend beyond production emissions and land use to account for the critical vulnerabilities of the technology itself. The inherent variability of solar generation due to weather conditions (cloud cover, the diurnal cycle) necessitates backup power or large-scale storage, both of which carry their own significant entropic costs. Furthermore, the potential for mass damage to panels from extreme weather events, such as large-scale hail, introduces another layer of risk and potential entropy production that is not captured in a standard life cycle assessment. These are not minor details but critical factors that can fundamentally alter the balance of environmental efficiency under real operating conditions. These local examples serve only to illustrate the immense depth of the problem and the necessity of moving from simplified models to holistic, system-level analyses that account for risk, variability, and technological interdependence.

Analysis of strategies for combating entropic pollution shows the fundamental limitations of the waste localization strategy and the technological inevitability of transitioning to active entropy dumping into space. The key conclusion of the work is that further sustainable development of civilization is possible only through a combination of three directions: maximum use of renewable sources and closed nuclear cycles to minimize entropy production on Earth; a transition to plant-based protein sources as the most efficient negentropy converters; and expansion of the operational base beyond the planet, allowing the use of space as a reservoir for unavoidable entropy and a source of negentropy. The path forward demands not only technological innovation but also a more sophisticated, humble, and comprehensive scientific approach to understanding our impact on the planet.

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Table 4: Forecast of the dynamics of the full life cycle environmental efficiency coefficient η_{LCA} for SPP and GTU up to 2075

Year	**Scenario**	η_{LCA} **SPP**	η_{LCA} **GTU**	**Notes**
2025	Actual	0.66	0.17	Production only: 0.89 and 0.95; including 25 years of operation
2035	CPS	0.68	0.15	Conservative scenario, gas prices stable
2035	STEPS	0.72	0.22	Panel cost reduction, start of carbon regulation
2035	NZE	0.75	0.28	Active decarbonization, gas price increase
2050	CPS	0.70	0.12	Depletion of cheap gas, but weak regulation
2050	STEPS	0.78	0.30	Mass CCS deployment, green panel production
2050	NZE	0.85	0.40	Carbon neutrality, high emission prices
2075	CPS	0.72	0.08	Further resource depletion, gas quality decline
2075	STEPS	0.82	0.35	Technological progress, but gas remains
2075	NZE	0.90	0.45	Near-full decarbonization, hydrogen technologies

Table 5: Initial parameters for three data center siting scenarios (per 1 MW of IT load)

Parameter	**Mid-latitudes**	**Polar region**	**Moon (pole)**
Average annual ambient temperature, °C	+10	-15	-50 (crater) / -270 (space)
Baseline PUE	1.35 [26]	1.10 [26]	1.05 (estimate)
Fraction of energy for cooling	26%	9%	5%
Transport losses	0%	5% (additional infrastructure)	30% (delivery and maintenance)
Electricity cost, rubles/kWh	5	3 (hydro)	0 (solar)
Capital costs, million rubles/MW	120	180	1500
Service life, years	20	20	30

Table 6: Comparison of environmental efficiency coefficients for three data center siting scenarios

Parameter	**Mid-latitudes**	**Polar region**	**Moon**
Capital costs, million rubles/MW	120	180	9500
Operating costs over service life, million rubles	1182	578	2850
Total costs (market value), million rubles	1302	758	12350
Entropic damage from operation (CO_2), million rubles	284	11.6	0
Entropic damage from production (embodied), million rubles	60 (estimate)	90	2500 (rockets + equipment)
Total entropic damage $C_{entropy}^{total}$, million rubles	344	101.6	2500
Environmental efficiency coefficient η_{LCA}	**0.791**	**0.882**	**0.832**

Table 7: Specific greenhouse gas emissions for different livestock systems [33]

Product type	**Fossil CO_2 emissions, kg/kg protein**	**CH_4 emissions, kg CO_2-eq/kg protein**	**N_2O emissions, kg CO_2-eq/kg protein**	**Total carbon footprint, kg CO_2-eq/kg protein**
Dairy cattle	10.2-27.6	0.04-0.27	0.016-0.036	50-120
Beef cattle	10.2-27.6	0.04-0.27	0.016-0.036	200-300
Pigs	10.2-27.6	low	moderate	50-80
Poultry	10.2-27.6	very low	moderate	30-50

Table 8: Comparison of environmental efficiency of protein production from various sources

Parameter	**Beef**	**Pork**	**Poultry**	**Wheat/Maize**	**Soy/Peas**
CO_2-eq emissions, kg/kg protein	300	50-80	30-50	1-5*	0.5-2*
Land use, m^2/kg protein	150-200**	50-70**	40-50**	5-10	8-12
Water consumption, m^3/kg protein	8.7-15.4	4-6**	3-4**	1.6	1.6-1.8
Exergy efficiency of the system	0.05-0.10	0.15-0.20	0.20-0.25	0.30-0.40	0.35-0.45
Environmental efficiency coefficient η	**0.10-0.15**	**0.25-0.35**	**0.35-0.45**	**0.85-0.95**	**0.90-0.95**

Table 9: Input data for calculating the entropy efficiency of traditional reactors and the "Proryv" technology (per 1 MWh of electricity produced)

Parameter	**Traditional PWR/VVER (open cycle)**	**BREST-OD-300 (closed cycle)**
Capital costs C_{market}, rubles/MWh	450–600 [44]	650–850 (estimate based on [42])
Exergy efficiency of fuel production ψ_{fuel}	0.25–0.30 (enrichment) [43]	0.40–0.45 (closed cycle) [42]
CO_2 emissions (full life cycle), g/kWh	12–15 [44]	8–10 (estimate)
Volume of high-level waste, arb. units/MWh	1.0 (baseline)	0.05–0.10 [42]
Need for long-term isolation	100,000 years	300–500 years [46]
Natural uranium consumption, kg/MWh	0.020–0.025	0.001–0.002 (including recycle) [42]

Table 10: Comparison of strategies for minimizing entropic damage

Characteristic	**Localization strategy**	**Space dumping strategy**
Core method	Isolation of high-entropy waste from the biosphere using engineered barriers [3]	Export of entropy beyond the biosphere, primarily as thermal radiation [5, 11]
Examples	Radioactive waste repositories, CO_2 storage, sludge reservoirs	Radiative cooling surfaces, orbital thermal radiators
Drawbacks	Fundamental non-permanence of barriers, risk of catastrophic breach, high cost of long-term monitoring	Requires overcoming gravity, low efficiency at current technological levels
Time horizon	Limited by barrier lifetime (hundreds to thousands of years)	Potentially unlimited