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The Material Entropy and the Fourth Law of Thermodynamics in the Evaluation of Energy Technologies of the Future

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Abstract: The primary purpose of this article is to use the laws of thermodynamics, mainly the second and fourth laws, to evaluate three energy technologies of the future: fusion, solar, and fission. Among the criteria used to evaluate them, the most important are the amount of matter needed to sustain the technology itself and the environmental impact. Much emphasis is placed here on the fourth law of thermodynamics, which introduces the concept of material entropy. Zemansky–Georgescu-Roegen's Law of Inevitable Dissipation of Useful Concentrated Matter states that, in the economic process, some matter is inevitably degraded and becomes unavailable matter. This has tremendous implications for humanity as a whole since the Earth is thermodynamically a closed system, meaning that it cannot exchange matter with space but is open to the flow of solar energy. This results in the need to conserve matter and natural resources. This law can be used as an important criterion for the selection of energy technology. Moreover, the flow–fund model, which was proposed by Georgescu-Roegen, was used to assess the viability of energy technologies. The final conclusion is that there is no Promethean technology of the third kind yet, but the closest to meeting this condition is solar technology. Technology based on nuclear fission has been rejected due to its adverse ecological effects, while fusion technology has proven to be less useful due to the matter criterion, the negative environmental impact, since radioactive waste only becomes safe for humans after 500 years, and the risks associated with nuclear proliferation. Solar technology can become Prometheus III only after all of humanity is involved with this project, which requires profound social changes, widespread demilitarization, and the development of organic agriculture. This implies the necessity of the emergence of a global solar society based on an economic system called solar communism.

Keywords: entropy of matter; fourth law of thermodynamics; flow–fund model; energetic dogma; viability of energy technology; solar energy; nuclear fission energy; controlled fusion energy; Promethean recipe; entropic debt

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1. Introduction

Nicolas Georgescu-Roegen is a well-known but underappreciated pioneer of applications of the laws of thermodynamics to economics. Over time, his concepts have become an important trend in research known as ecological economics or bioeconomics. He is known for his many controversial views, which to this day have not been satisfactorily explained, although they are critical to the survival of humanity. The main purpose of this article is to demonstrate that Georgescu-Roegen's key thermodynamic views were correct and can be applied to the evaluation of three energy technologies of the future: fusion, solar, and fission. The choice between these technologies is particularly important now, at a time of global warming, which is causing catastrophic climate change. The consequences of this choice could help the survival of the human species, enable economic growth and development, or lead to a true climate catastrophe known from various dystopias [1].

Having clarified the uncertainties surrounding the fourth law of thermodynamics, I was able to proceed with the main goal of this work, which is to use this law to evaluate three of humanity's energy technologies: fusion, solar, and fission. The choice of these technologies as the most important for humanity's survival was made by Georgescu-Roegen himself. He also formulated the concept of a Promethean energy technology that meets the conditions for viability, meaning that it is capable of sustaining all the processes of the economic system. Accordingly, selected energy technologies must be evaluated within the flow–fund matrix. In addition to the material entropy criterion, I also use an ecological criterion based on the other laws of thermodynamics. Moreover, I take into account the entropic debt, the average LCOE, the fulfillment of the Promethean condition regarding the viability of the technology, and the type of energy conversion. There have only been two Promethean technologies in human history so far, the mastery of fire and the steam engine, while a third such technology is still a matter of the future. The in-depth analysis in this article indicates that Prometheus III will soon be solar technology.

2. Zemansky–Georgescu-Roegen's Law of Inevitable Dissipation of Useful Concentrated Matter

In Nicholas Georgescu-Roegen's view, the fourth law of thermodynamics applies to closed systems that can exchange energy with the external environment but are closed due to the flow of matter. In such systems, material entropy gradually increases until it reaches the maximum level associated with a homogeneous mixture of matter and, thus, its greatest disorder. This state is characterized by the absence of qualitative differences between materials so that all matter eventually becomes unavailable. In this state, we address the material death of the system. This complements Kelvin's hypothesis of the heat death of the universe resulting from the operation of the second law of thermodynamics, which is valid for isolated systems [2].

The source of the fourth law of thermodynamics is phenomena such as friction, viscosity, inelasticity, electric resistance, and magnetic hysteresis [3] (p. 193). This results in the dissipation of matter in the environment, best exemplified by the abraded tires of vehicles moving on the road. This dissipated dust cannot be recycled due to the finitude of human existence. This type of matter is irrevocably lost to humans. Only secondary raw materials such as waste paper, scrap metal, or broken glass can be recycled. Georgescu-Roegen refers to this matter as garbojunk. It is still accessible to man, but it no longer has a usable form. No single general mathematical formula can be given to describe the entropy of matter, as is the case with energy degradation, because matter in bulk is heterogeneous, and the dissipation factors vary from one type of matter to another.

The fourth law of thermodynamics can be formulated in several equivalent ways:

1. A closed system (i.e., a system that cannot exchange matter with the environment) cannot perform work indefinitely at a constant rate [4] (p. 304);
2. In a closed system, matter continuously and irrevocably degrades from an available to unavailable state [5] (p. 121, footnote 24);
3. Unavailable matter cannot be recycled [4] (p. 304);
4. Complete recycling is impossible [6] (p. 60);
5. A closed system that can perform mechanical work steadily constitutes the perpetual motion of the third kind [5] (p. 121, footnote 24).

The equivalent of the fourth law of thermodynamics is even found in the Bible. During the Sermon on the Mount, the Lord Jesus Christ delivers the following words:

> *Do not store up for yourselves treasures on earth, where moths and vermin destroy, and where thieves break in and steal. But store up for yourselves treasures in heaven, where moths and vermin do not destroy, and where thieves do not break in and steal. For where your treasure is, there your heart will be also.* (Matthew, 6: 19–21, NIV)

After in-depth research, it was found that the forerunner of the fourth law of thermodynamics was the well-known physicist Mark W. Zemansky, who, decades before Georgescu-Roegen, had formulated the concept of a perpetual motion machine of the third kind in an identical way [3] (p. 193). He was engaged in the study of dissipative effects occurring in machines as a result of friction and similar phenomena. This led him to discover the phenomenon of external mechanical irreversibility, which involves the dissipation of work into internal energy. If there were no friction in nature, machines could operate indefinitely without violating the laws of thermodynamics, the first and second. In that case, they would run, but they would not perform work. The lack of dissipation of work in machines precisely means the existence of a perpetual motion machine of the third kind. This means that the thermodynamic effects of friction cannot be identified with the first two laws of thermodynamics, and a qualitatively new law is needed.

An unintended consequence of Zemansky and Georgescu-Roegen's work is the confusion over the existence of different kinds of perpetual motion machines in physics. By convention, each such machine is associated with a specific law of thermodynamics: zeroth, first, and second. There is also the concept of a perpetual motion machine of the third kind associated with the third law of thermodynamics [7] (pp. 283–284). Therefore, what Zemansky and Georgescu-Roegen discovered should be classified as a perpetual motion machine of the fourth kind. Their discovery proves not only the existence of the fourth law of thermodynamics based on dissipative effects but also its independence from the other laws of thermodynamics.

Paul A. Samuelson, who received the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel in 1970, referred to the law discovered by Georgescu-Roegen as Georgescu-Roegen's Law of Inevitable Dissipation of Useful Concentrated Matter [8] (p. XVII). In light of the above, one should refer to Zemansky–Georgescu-Roegen's Law.

3. Energetic Dogma versus the Actual Relationship between the Economic Process and the Environment

There is a notion in the main science current on the relationship between energy and matter, which can be called the energetic dogma. It states that the dissipation of matter, predicted by the fourth law of thermodynamics, can be completely eliminated, provided a sufficient amount of energy is available. Therefore, matter is not important; only energy counts. In other words, according to the energetic dogma, a perpetual motion machine of the third kind is possible [6] (pp. 53–56). Such views have been expressed by many researchers. Here, one will be shown, presented by a well-known economist, Kenneth E. Boulding:

> *In the case of material systems, we can distinguish between entropic processes, which take concentrated materials and diffuse them through the oceans or over the earth's surface or into the atmosphere, and anti-entropic processes, which take diffuse materials and concentrate them. Material entropy can be taken as a measure of the uniformity of the distribution of elements and, more uncertainly, compounds and other structures on the earth's surface. There is, fortunately, no law of increasing material entropy, as there is in the corresponding case of energy, as it is quite possible to concentrate diffused materials if energy inputs are allowed. Thus the processes for the fixation of nitrogen from the air, processes for the extraction of magnesium or other elements from the sea, and processes for the desalinization of sea water are anti-entropic in the material sense, though the reduction of material entropy has to be paid for by inputs of energy and also inputs of information, or at least a stock of information in the system. In regard to matter, therefore, a closed system is conceivable, that is, a system in which there is neither an increase nor a decrease in material entropy. In such a system, all outputs from consumption would constantly be recycled to become inputs for production, as, for instance, nitrogen in the nitrogen cycle of the natural ecosystem.* [9] (Boulding, 2011, p. 7)

It is astonishing that the energetic dogma is applied to the Earth, which—thermodynamically—is a closed system, i.e., it is open to the flux of solar energy but closed to the flux of matter. If the Earth was an open system, which could exchange not only matter but also energy with the environment, the energetic dogma would be justified.

In order to justify the truth of the fourth law of thermodynamics, Georgescu-Roegen prepared the flow–fund model, which he used both for studies of the standard economic process as part of the energetic dogma but also to examine the process under conditions that take into consideration its actual relations with the environment [6] (pp. 56–58, 63–64). The fund factors (agents) include the capital, people, and Ricardian land. They are used during the process, but their size remains constant. On the other hand, the flow factors undergo transformation.

3.1. The Flow–Fund Model under the Conditions of the Energetic Dogma

Table 1 shows the flow–fund matrix, which analytically describes the economic process in line with the energetic dogma [6] (pp. 56–58). Complete matter recycling is possible in this situation as long as people have a sufficient amount of energy. In other words, energy, not matter, is important in the struggle for humanity's economic survival. The positive coordinates of the matrix are outflows of any kind, whereas negative coordinates represent the inflows. Subsequently, the economic activity is divided into consolidated processes and aggregated commodities in the following manner:

- P_1: produces controlled energy, CE, from energy in situ, ES;
- P_2: produces capital goods, K;
- P_3: produces consumer goods, C;
- P_4: completely recycles the material wastes, W, of all processes into recycled matter, RM;
- P_5: maintains the population, H.

Table 1. The economic process in relation to the environment according to the energetic dogma.

Product/Process	**P_1 (ES → CE)**	**P_2 (Produces K)**	**P_3 (Produces C)**	**P_4 (W → RM)**	**P_5 (Maintains H)**
			Flow Coordinates		
Controlled energy (CE)	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
Capital equipment (K)	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
Consumer goods (C)	*	*	x_{33}	*	$-x_{35}$
Recycled matter (RM)	*	$-x_{42}$	$-x_{43}$	x_{44}	*
Energy in situ (ES)	$-e_1$	*	*	*	*
Wastes (W)	w_1	w_2	w_3	$-w_4$	w_5
Dissipated energy (DE)	d_1	d_2	d_3	d_4	d_5
			Fund Coordinates		
Capital	K_1	K_2	K_3	K_4	K_5
People	H_1	H_2	H_3	H_4	H_5
Ricardian land	L_1	L_2	L_3	L_4	L_4

During each of these processes, part of the energy transforms into dissipated heat, and thereby it becomes unavailable. This dissipated energy, DE, is channeled back into the environment. The energy flows between the economy and the environment consist of the input flow, e_1, and the output flow:

$$d = \sum_{i=1}^{5} d_i \tag{1}$$

According to energetic dogma, matter cannot be transferred to an economic process from the environment, nor can it leave the process. The whole matter in the economy is totally recycled. Neither a growing nor a declining economy can be a test for the energetic dogma but a stationary process whose characteristic features include reproducibility. In other words, material growth cannot be based on an environmental flow of energy alone, whereas a declining economy may not need a flow of environmental matter. One should not forget that each energy flow requires a material transmitter. This means that an economic process cannot be conducted without a material scaffold, which is represented by its agents, i.e., the fund coordinates. One should mention here the capital equipment, K, people, H, and Ricardian land, L. At the same time, in order to meet the reproducibility condition, the output flow of capital, x_{22}, is intended to maintain the capital funds, K_i; therefore, its wear and tear must be compensated for with the maintenance flows x_{2i}. This means that the consumed capital, K, is fully restored during the economic process. In the same manner, the flows x_{i5} maintain the population, H, on a constant level. After expressing all flows in the physical units, the conservation laws on the macro level have the following form:

$$d_1 = e_1 - x_{11}\ , \tag{2}$$

$$d_i = x_{1i}\ ,\ \ (i = 2,\ 3,\ 4,\ 5)\ , \tag{3}$$

$$w_1 = x_{21}\ , \tag{4}$$

$$w_2 = x_{42} - x_{22}\ , \tag{5}$$

$$w_3 = x_{23} + x_{43} - x_{33}\ , \tag{6}$$

$$w_4 = x_{44} - x_{24}\ , \tag{7}$$

$$w_5 = x_{25} + x_{35}\ , \tag{8}$$

According to Georgescu-Roegen, this model assumes that every recipe is feasible, i.e., it creates its own product when it is supported by specific funds and when specific inputs are directed to it. The feasibility of every recipe does not have to entail the viability of the technology, which depends on all the processes taken together [6] (p. 58). The necessary and sufficient conditions for the viability of the technology of a reproducible economic system shown in Table 1 are as follows:

$$x_{i5} \geq x^0_{i5}\ ,\ (i = 1,\ 2,\ 3), \tag{9}$$

$$\sum_{i=2}^{5} x_{1i} = x_{11}\ , \tag{10}$$

$$x_{35} = x_{33}\ , \tag{11}$$

$$\sum_{i=1,2,3,5} w_i = w_4\ , \tag{12}$$

$$\sum_{i=1,\ 3,\ 4,\ 5} x_{2i} = x_{22}\ , \tag{13}$$

$$\sum_{i=2,3} x_{4i} = x_{44}\ . \tag{14}$$

where x^0_{i5} denotes the minimums determined on the basis of the normal standard of living, and it is evident that the variable subscript differed significantly from the fixed one.

Georgescu-Roegen points out that the theoretical foundation for complete recycling is provided by the quasi-static process, which uses the van't Hoff box (or van't Hoff equilibrium box) [10] (pp. 139–141). It is a vessel of unchangeable volume, which contains various substances taking part in the reaction. These substances are in the equilibrium state [11]. The vessel walls are permeable to some substances and impermeable to others. The application of this vessel is limited to reactions in a homogeneous system, e.g., to gases or dilute solutions [12,13] (pp. 118–119).

Usually, a reaction has the following form:

$$A + B = C + D. \tag{15}$$

The box contains four substances $A,\ B,\ C,\ D$ in a state of equilibrium. Subsequently, 1 mol of substance A and 1 mol of substance B are introduced into the box isothermally and reversibly through walls permeable only to one of them at the equilibrium concentration or pressure. Later, assuming that a chemical reaction occurred, 1 mol of substance C and one mol of substance D are removed through walls permeable only to them while the equilibrium concentration or pressure is maintained. It is found that the transformation of A and B into C and D under conditions of the equilibrium concentration and pressure goes on, and it occurs without mechanical work, as the box volume is constant. At the end, the box and its contents are in exactly the same state as at the beginning. Under these conditions, no actual external work was performed during the chemical transformation. If substances A and B are under an arbitrary pressure or concentration at the beginning, then work will be performed to bring them isothermally and reversibly to the concentration corresponding to the equilibrium. After this stage is reached, they can be introduced into the equilibrium box, where they will come into reaction and turn into substances C and D, which in turn can be removed at the equilibrium concentration value, with the in and out operation not requiring any work [14] (p. 103).

The aim of the van't Hoff box is to obtain useful work, which arises from the following diagram:

$$\text{reaction} \rightarrow \text{energy} \rightarrow \text{heat} \rightarrow \text{useful work}\,, \tag{16}$$

without violating the second law of thermodynamics, which is possible even at a constant temperature, using the heat generated during the reaction [15]. After dividing the van't Hoff equilibrium box into two parts, it can generate heat and useful work at the same time, without violating the first law of thermodynamics [16]. However, Kozo Mayumi points out that an ideal box uses a process which actually needs an infinite time for an infinitesimal movement. This shows that complete recycling, i.e., separation of the mixed materials completely, would also have to take place in an infinite time. Therefore, in reality, there has to be a stage at which the recycling process would have to stop. This proves that the energetic dogma cannot be implemented in the real world [17], [18] (pp. 56–61).

The economic process shown in Table 1 presents only one elementary aspect of reality, i.e., that one cannot address energy without a material lever. Therefore, despite the flow complex existing in the Western intellect, it is not assumed that the energetic dogma is so unreal to suggest that the actual processes do not require any material structures accompanying energy at the macro level.

3.2. Flow of Matter and Energy in the Real Economic Process

The Law of Inevitable Dissipation of Useful Concentrated Matter leads one to slightly different conclusion regarding the finitude of natural resources than those reached by Robert M. Solow, another winner of the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, this time in 1987. He claims that the productivity of natural resources will grow exponentially over time due to the substitutability relation with human-made capital [19]. However, the fourth law proves absolute in this regard. A total of 2 billion tons of iron were produced during the period of 1870–1950 in the United States. If all of it had been used at the end of this period, its inventory would have amounted to 13.5 tons per person. However, the total amount of iron in circulation at the time amounted to 60% of the original production, which corresponded to approximately 8 tons per person. The remaining iron was lost irretrievably as a result of oxidation by the air, corrosion by liquids, general wear, and production loss [20] (p. 192). It should also be stressed that approximately 10% of the iron used as the charge in a steel furnace is lost irrecoverably, and the iron which is not converted to steel is lost irrecoverably within about 100 years due to corrosion and other loss factors [21] (p. 156). Therefore, the fourth law of thermodynamics is largely responsible for an increase in the productivity of iron and can be similar with other natural resources.

The flow–fund model can be used to show real relations between the economic process and the natural environment [6] (pp. 63–64). Table 2, which is expanded from Table 1, shows an additional process, P_0, which transforms matter in situ, MS, into controlled matter, CM. It can be seen that even a stationary economy cannot function without a constant inflow of matter from the environment. There are new flows here, s_i, denoting dissipated matter, and DM, which is produced by every process and released to the environment. Moreover, the recycling process, P_4, due to the fourth law, no longer transforms all material waste, as some matter is irreversibly dissipated in the environment and becomes unavailable. Only trash and waste, earlier referred to as garbojunk, GJ, can be recycled. Moreover, there is also a flow of refuse, R, which can largely consist of available matter and available energy, but whose form is not potentially useful.

Table 2. The actual relationship between the economic process and the environment.

Product/Process	P_0 **(MS → CM)**	P_1 **(ES → CE)**	P_2 **(Produces K)**	P_3 **(Produces C)**	P_4 **(W → RM)**	P_5 **(Maintains H)**
			Flow Coordinates			
Controlled matter (CM)	x_{00}	*	$-x_{02}$	$-x_{03}$	$-x_{04}$	*
Controlled energy (CE)	$-x_{10}$	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
Capital equipment (K)	$-x_{20}$	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
Consumer goods (C)	*	*	*	x_{33}	*	$-x_{35}$
Recycled matter (RM)	*	*	$-x_{42}$	$-x_{43}$	x_{44}	*
Energy in situ (ES)	*	$-e_1$	*	*	*	*
Matter in situ (MS)	$-M_0$	*	*	*	*	*
Garbojunk (GJ)	w_0	w_1	w_2	w_3	$-w_4$	w_5
Dissipated energy (DE)	d_0	d_1	d_2	d_3	d_4	d_5
Dissipated matter (DM)	s_0	s_1	s_2	s_3	s_4	s_5
Refuse (R)	r_0	r_1	r_2	r_3	r_4	r_5
			Fund Coordinates			
Capital	K_0	K_1	K_2	K_3	K_4	K_5
People	H_0	H_1	H_2	H_3	H_4	H_5
Ricardian land	L_0	L_1	L_2	L_3	L_4	L_4

The viability of the steady state is represented by the following relations:

$$\sum_{i=2,3,4} x_{0i} = x_{00}\,, \tag{17}$$

$$\sum_{i=0,2,3,4,5} x_{1i} = x_{11}\,, \tag{18}$$

$$\sum_{i=0,1,3,4,5} x_{2i} = x_{22}\,, \tag{19}$$

$$x_{35} = x_{33}\,, \tag{20}$$

$$\sum_{i=2,3} x_{4i} = x_{44}\,, \tag{21}$$

$$\sum_{i=0,1,2,3,5} w_i = w_4\,, \tag{22}$$

Since R can include both energy and matter, one cannot note the relations for the conservation of these items separately, like in the previous case.

4. Evaluation of Energy Technologies under the Flow-Fund Model

Georgescu-Roegen defines technology as a set of feasible recipes, with one recipe existing for producing each commodity. Heating a house with photovoltaic panels is an example of a feasible recipe, whereas producing electricity with thermonuclear fusion is not.

Moreover, it has been suggested that technologies can be viable or not viable, depending on whether Equations (17)–(22) are satisfied [6] (p. 70).

With two viable technologies, $T^1\left(e_1^1, M_0^1\right)$ and $T^2\left(e_1^2, M_0^2\right)$, which provide the same net real income, one will have to be chosen which will prove more beneficial from the environmental perspective. The choice between them is reasonable only when inequalities $e_1^1 < e_1^2$ and $M_0^1 > M_0^2$ exist. If both technologies use a certain terrestrial energy, then an analysis of energy and matter will not provide an answer, but if they use solar radiation, then matter prevails, which shows that T^2 must be chosen. When T^2 is solar technology, and T^1 is terrestrial technology, the answer is clear—T^2 is the preferable one. In the opposite case, the terrestrial source will be used as long as the whole energy in situ is exhausted [6] (p. 70).

This analysis shows the considerable importance of solar energy for the global economy. However, Georgescu-Roegen suggests that there are only feasible recipes in this area, whereas viable technologies are still beyond humanity's reach. The implementation of a viable technology requires developing a recipe for the production of converters of solar radiation, which would allow for producing a sufficient number of new converters only with the use of solar energy converted by other devices of this type. Currently, this is not possible, which leads one to the conclusion that the existing solar technologies are parasites of fossil fuel-based technologies, and they will disappear once these fuels are exhausted. However, Georgescu-Roegen admits in his analysis of the matter and technology that solar energy may be the best option for humanity [6] (pp. 70–71).

When reviewing humanity's entropic problem, Georgescu-Roegen points out that harnessing fire was the first viable technology. Referring to the Greek myth of Prometheus, who stole fire from gods and gave it to people, he calls controlling fire the first Promethean recipe. This resulted in a classification of energy technologies, which—counting from the beginnings of civilization until now—includes only two items, whereas the third is—for now—hypothetical, and it has been demonstrated earlier that it applies to the technology of acquiring solar energy. They will be discussed here individually [6] (pp. 71–74).

1. The technology of fire control is a Promethean recipe of the first kind. Nowadays, it is one of the most ordinary phenomena, but making use of it changed the whole earlier world. Fire is associated with qualitative energy conversion, as it allows one to convert the chemical energy of flammable materials into caloric power. Moreover, fire is a source of a chain reaction, as a small flame allows for the burning of not only one forest but even all the forests. Harnessing fire allowed people to heat shelters, cook food, smelt and shape metals, and bake bricks and ceramics. This technology is associated with the Wood Age, as wood was the basic fuel at the time and was used until its shortage started to be felt. This happened in the second half of the seventeenth century and made it necessary to seek other sources of energy.
2. A Promethean recipe of the second kind is a coal-fired heat engine, which enables a new qualitative energy conversion, allowing for the transformation of caloric power into motor power. The first heat engine, called an aeolipile, was developed by a Greek-Egyptian mathematician and engineer, Hero of Alexandria, in the first century AD [22]. It was a kind of bladeless radial steam turbine in the form of a ball fixed on an axis with two nozzles in opposite directions [23] (p. 72). It was powered by steam fed from a boiler with water heated by fire, situated under the turbine [24] (pp. 228–232). However, Heron's engine is not regarded as the forerunner of the steam engine, as it was a machine exhibiting technical ingenuity rather than technological progress [25] (pp. 55–56). With respect to the flow–fund model, it would be a feasible technology rather than a viable technology. The steam engine was invented by Thomas Savery and Thomas Newcomen much later, in the pre-industrial revolution times (1760–1840), and the device was improved by James Watt in 1776, which considerably accelerated global economic growth [26,27]. As with fire control, it is a chain reaction in this case, too. With a specific amount of coal and a heat engine, one can excavate more coal and other minerals, which will enable one to produce more heat engines, and

engaging these new devices to work will yield the number of heat engines needed at the moment.

3. A Promethean recipe of the third kind is for a solar collector, which could meet the condition of a chain reaction, i.e., provide enough energy to produce additional collectors of the same type or even more perfect. Currently, there is no Promethean recipe which would allow the global economy, powered with solar energy, to be energy self-sufficient. Nevertheless, methods of solar energy conversion into electricity are still improving, which may suggest that a technological breakthrough is not far away. One should also note that the implementation of solar communism does not only depend on the technological progress alone, i.e., solarization of the global energy infrastructure, but also on demilitarization and the development of organic farming [28,29]. Therefore, the improvement of solar technologies should be simultaneous with profound economic, social, and cultural transformations for which humanity—it seems—is not yet prepared.

Promethean recipes of the second kind are still dominating energy technologies. Steam turbines in thermal power stations, which generate rotary motion, are coupled with electric generators to make use of the motion to produce electricity. Such turbines can be powered by fossil fuels, nuclear fuels, geothermal energy and, in some cases, concentrated solar power (which is the optimum solution due to the heat budget of the Earth) [30]. Even nuclear submarines are powered by steam turbines. It is estimated that 90% of the electricity in the USA is produced by steam turbines, whose maximum efficiency cannot exceed 38%, which is a consequence of the upper limit imposed by the Carnot cycle. Systems of electricity production which do not utilize steam expanding in a turbine include hydropower plants and photovoltaic cells. Therefore, this limitation does not apply to them [31] (pp. 189–190). Moreover, the development of our civilization is still based on fossil fuels. In 2015, at least 85% of the world's total commercial primary energy supply—except the share of traditional biofuel, whose consumption cannot be measured exactly—came from fossil fuels [32] (p. 195). This shows that, despite the continuous perfection of technology, and the appearance of many impressive inventions, such as computers, smartphones, jet aircraft, spacecraft, and modern information and communication technologies, we are still in the 19th century with respect to energy generation technologies, that is, in the embrace of Prometheus II.

5. Possible Candidates for a Promethean Recipe of the Third Kind

Nowadays, there are many feasible energy technologies which are likely to become at least partial solutions to humanity's energy problems in the future, but they cannot be regarded as viable technologies at present. Usually, breeder reactors and controlled thermonuclear energy are mentioned along with solar energy [6] (pp. 70–74).

1. A breeder reactor is a nuclear reactor which converts fertile materials into fissionable fuels and generates heat, which is used for electricity production and, at the same time, produces more fissile material than it uses [33,34] (pp. 53–62). It mainly uses two fertile isotopes, such as uranium-238, which is transformed into fissile plutonium, and thorium-232, which is transformed into fissile uranium. One of the measures of the efficiency of such a reactor is the breeding ratio, meaning the ratio of fissile material produced per cycle to fissile material destroyed per cycle. For breeder reactors, this number is always greater than one [35] (pp. 8–10, 234–236). Theoretical models of breeders indicate that high breeding ratios, reaching as much as 1.84, can be achieved under commercial conditions [36]. The Soviet BR-1 (Bystry Reactor-1) test reactor, put to use in 1955, with a compact plutonium core and uranium blanket, fueled with metallic plutonium and operating without a coolant, reached, depending on the source, a breeding ratio of 1.8 to 2.5 [37,38]. It turns out that the uranium present in seawater provides an amount of fuel for breeder reactors, which will satisfy humanity's demand for energy for the next 5 billion years [39]. However, due to the

threat to the environment and technical issues associated with the operation of such reactors, the hopes associated with them did not materialize [40].

2. A thermonuclear reaction is a very promising source of energy, but the need to control this naturally unstable source is the main issue. One cannot totally exclude the possibility of thermonuclear energy being used only as a weapon, as is the case with gunpowder and dynamite. Nuclear fusion involves the joining of two or more atomic nuclei, producing one or more atomic nuclei and releasing subatomic particles, such as neutrons or protons. Many various atomic nuclei can be used as nuclear fuel, but the synthesis of deuterium and tritium nuclei (hydrogen isotopes) is the most feasible. The largest body of research focuses on this case as it requires a lower—compared with other reactions of this type—plasma temperature to overcome the Coulomb barrier problem. The following reaction then occurs [41] (p. 150):

$$ {}_{1}^{2}\mathrm{D} + {}_{1}^{3}\mathrm{T} \rightarrow {}_{2}^{4}\mathrm{He}\ (3.54\ \mathrm{MeV}) + {}_{0}^{1}n\ (14.05\ \mathrm{MeV}), \tag{23} $$

where the fusion of deuterium $\left({}_{1}^{2}\mathrm{D}\right)$ with tritium $\left({}_{1}^{3}\mathrm{T}\right)$ produces helium-4 $\left({}_{2}^{4}\mathrm{He}\right)$, while releasing a neutron $\left({}_{0}^{1}n\right)$ and emitting 17.59 MeV of kinetic energy, with a loss of a certain amount of mass. Thermonuclear reactions run at very high temperatures, on the order of $10 - 300 \times 10^{6}$ K. At this temperature, matter exists in the form of plasma, containing ionized atoms and free electrons, which is the fourth state of matter. The potential energy that can be obtained from an earth-bound fusion system is huge. Deuterium accounts for 0.015% of all hydrogen isotopes. There is 1.4×10^{18} m^{3} water on Earth, containing 1.4×10^{43} atoms of deuterium. Considering the D-D thermonuclear reaction

$$ {}_{1}^{2}\mathrm{D} + {}_{1}^{2}\mathrm{D} \rightarrow {}_{2}^{4}\mathrm{He} + 23.84\ \mathrm{MeV}, \tag{24} $$

for which there is 11.9 MeV/D, this number of deuterium atoms can provide energy in the amount of 1.8×10^{31} J. At the world's current rate of use, this amount of energy will satisfy all of humanity's energy needs for the next 50 billion years. This huge potential provides encouragement to obtain useful amounts of energy from thermonuclear reactions [41] (pp. 149, 151–152).

3. Solar technologies unquestionably stand the greatest chance of becoming the Promethean recipe of the third kind. They are constantly improving, which gives one hope for a rapid breakthrough. The effectiveness of solar cells is constantly increasing, which, in fact, does not depend on the technology applied, although the fastest growth has been observed for relatively new technologies, where the following results were achieved: quantum dot cells (various types)—18.1%, organic cells—18.2%, perovskite cells—25.7%, perovskite/Si tandem (monolithic)—32.5%, two-junction (non-concentrator)—32.9%, three-junction (non-concentrator)—39.5%, four-junction or more (non-concentrator)—39.2%, four-junction or more (concentrator)—47.6% [42]. Technological progress in this area is extremely fast. The world's most efficient four-junction solar cell, with an efficiency of 47.6% at a concentration of 665 suns, was developed in 2022 [43]. New solutions are appearing at a nearly exponential rate. Three examples can be mentioned. A solar cell can be integrated with a triboelectric nanogenerator, which converts mechanical energy into electricity. Thus, electricity is produced even when it rains [44,45]. A photovoltaic panel can be fitted out with a thermoelectric generator, which—by making use of the temperature difference between the cell and the surroundings—generates additional electricity, both at night and during the day [46]. Furthermore, a nighttime photovoltaic cell (a thermoradiative cell) generates electricity at night by using infrared radiation (heat) emitted from the Earth's surface (a heat source) toward deep space (a heat sink) [47]. Solar energy has a huge potential for humanity, as one hour of solar flux falling on the Earth's surface provides an amount of energy equal to its annual consumption by the global economy [48] (p. 14). It is noteworthy that the free energy received from the

> sun within four days is comparable with the highest estimates of terrestrial energy resources [49] (pp. 303–304).

Georgescu-Roegen points out that the technologies that make use of low- or high-intensity energy need large amounts of matter, which in the former case is needed to concentrate the weak flow (solar energy), while in the latter it is needed to contain potentially dangerous and unstable sources (thermonuclear energy) [6] (p. 70). This indicates the need to take into account material entropy, i.e., the fourth law, in designing future energy systems, regardless of whether they are based on solar or thermonuclear technologies. In the late 1970s and early 1980s, the role of matter, both in solar and thermonuclear technologies, was rather important (and in the latter case—even huge). Nowadays, however, the development paths for these two recipes have parted significantly. The material entropy associated with obtaining solar energy decreases gradually as photovoltaic panels become increasingly thin and efficient, whereas it increases rapidly with each attempt at harnessing thermonuclear energy.

6. Promethean Recipes of the Third Kind and the Criterion of Matter

With the basic knowledge of candidates for Promethean recipes of the third kind, one can formulate forecasts on the potential winner in this energy race. It seems that breeder reactors have the smallest chance due to still unresolved technology issues and a considerable environmental hazard [40]. Therefore, two options remain: solar and thermonuclear energy. Using the criterion developed by Georgescu-Roegen, one should choose a technology of solar energy acquisition, although the choice could be difficult nowadays because—as has been shown above—thermonuclear energy in situ can be practically inexhaustible. However, the fourth law and the matter criterion can be helpful in this case.

Currently, there are two major areas of research on thermonuclear energy: inertial confinement fusion and magnetic confinement fusion [34] (pp. 75–83) and [50]. In an inertial confinement fusion reactor, a small pellet of thermonuclear fuel, usually with a diameter of several millimeters, is compressed to a huge density and temperature by focusing a very strong laser beam on it. Thermonuclear fuel consists of several milligrams of deuterium ${}^{2}_{1}\mathrm{H}$ and tritium ${}^{3}_{1}\mathrm{H}$. Thermonuclear energy is produced for a very short time, only for several nanoseconds, until the reaction ends. The time needed for burning the pellet must be shorter than the disassembly time, which is a condition for an efficient thermonuclear burn. The experiments conducted at the National Ignition Facility (NIF), which owns a laser with the highest energy in the world, involve directing up to 192 powerful laser beams into a centimeter-sized cylinder, called a hohlraum, which contains a pellet of the thermonuclear fuel. Laser beams enter the hohlraum through laser entrance holes and hit its interior, generating X-rays. This results in an implosion, which compresses and heats partially frozen hydrogen isotopes to extreme pressures and temperatures so that fusion reactions can take place. NIF generates temperatures in excess of 180 million degrees Fahrenheit and pressures in excess of 100 billion Earth atmospheres [51]. Ignition is reached when a self-sustaining fusion reaction produces a greater amount of energy than that provided by the laser. The implosion speed exceeds 400 km/s, which allows for a fusion reaction before the fuel is disassembled. A nuclear fusion in a small capsule of the reactants is so fast that they cannot escape due to their own inertia. Hence, the name of the method—the fuel is entrapped in the reactor by its own inertia. On 5 December 2022, a breakthrough in the history of research took place, as an experiment with the NIF laser far surpassed the ignition threshold. As a result, 3.15 megajoules (MJ) of fusion energy output was produced from 2.05 MJ of laser energy delivered to the target [52,53]. On 13 December 2022, this achievement was confirmed by the United States Department of Energy [54].

Magnetic confinement fusion is an approach which uses the electrical conductivity of plasma to contain its expansion with magnetic fields. This purpose is usually attained with tokamaks, in which a combination of the toroidal and poloidal fields creates a magnetic field with helical paths around the torus. In this manner, plasma is entrapped in the tokamak [55].

The tokamak, called ITER (International Thermonuclear Experimental Reactor), which is being built in France, and whose main goal is to create burning, or self-sustaining, fusion plasma, is the greatest international project in the field. Moreover, it will generate 500 MW of fusion power for 400 to 600 s while using only 50 MW of power supplied to the tokamak by the systems that heat the plasma. In other words, a fusion energy gain factor (Q), i.e., a ratio of the fusion power generated in the reactor to the power required to maintain plasma in the steady state, will be $Q \geq 10$. The condition $Q = 1$ is called a breakeven, or in some sources, scientific breakeven. The current record of energy production with the use of nuclear fusion is held by the NIF reactor, mentioned earlier, which reached $Q = 1.54$ in December 2022. The other goals of the ITER reactor include demonstrating and testing the technologies which will be needed to operate fusion power plants in future, testing tritium breeding, and demonstrating the safety of a fusion plant [56].

Let it be assumed that among all the available possibilities, one must choose an energy technology which is to become the Promethean recipe of the third kind. As the review above shows, one can choose between solar technology, $T^2\left(e_1^2, M_0^2\right)$, and thermonuclear technology $T^1\left(e_1^1, M_0^1\right)$ as the NIF reactor or the ITER reactor (terrestrial in Georgescu-Roegen's nomenclature). It can be easily demonstrated that both thermonuclear technologies require, for now, huge material scaffolds and—being experimental installations—they do not yet provide energy for consumer purposes, i.e., $e_1^1 = 0$. Solar technologies do not require such extreme material scaffolds and, what is more, they already provide considerable amounts of energy, i.e., $e_1^2 \gg 0$. Therefore, there is $e_1^2 \gg e_1^1 = 0$ and $M_0^1 \gg M_0^2$. If $T^1\left(e_1^1, M_0^1\right)$ is, for evident reasons, treated as a pseudo-solar technology, as the thermonuclear reaction is the source of energy in both cases, then the conclusion is evident and $T^2\left(e_1^2, M_0^2\right)$ is the preferred technology. Even if one takes into consideration that nuclear fusion uses unlimited energy in situ, the environmental criterion still makes one prefer solar technologies, seen as safer [6] (p. 70). The waste produced during thermonuclear fusion may also pose a threat to humanity and the environment.

To conclude the issue, it is worth analyzing the problem of the economic profitability of both technology types, if the thermonuclear technology in energy generation can be regarded as real. Let it be assumed that it can. Although there are still no thermonuclear power plants, advanced research programs exploring the issue do exist [57]. However, it should be pointed out that the characteristic features of present fusion technologies include a huge material scaffold and high cost, counted in billions of USD or EUR.

For example, the National Ignition Facility occupies a ten-story building the length of three football fields. In fact, the building consists of three interconnected ones: the Optics Assembly Building, the Laser and Target Area Building, and the Diagnostics Building. It was completed on 31 March 2009, and the total cost amounted to USD 3.5 billion [58,59]. The success of exceeding the ignition threshold is only the first step toward the commercial use of inertial confinement fusion, and there are at least decades of further studies and experiments ahead [60,61].

The construction of the ITER complex started in 2013, and the tokamak assembly has been ongoing since 2020 [62,63]. Plans for 2025 include the completion of the assembly, the beginning of the start-up phase, and the production of the first plasma, although the deuterium–tritium operation will not start until 2035 [64]. The whole complex occupies an area of 180 hectares, with its main part being a human-made level platform with an area of 42 hectares, completed in 2009, 1 km long and 400 m wide, which is equivalent to 60 soccer fields [65]. The ITER Tokamak and its plant systems are located in 39 buildings and technical areas. The central object is the Tokamak Building, constructed from reinforced concrete, which is to have seven stories, stand 73 m tall, and it will be situated 13 m below the platform level and 60 m above it [66]. The ITER machine's weight will be 23,000 tons, i.e., three times as much as the Eiffel Tower. Each of the 18 toroidal field coils has a weight of 310 tons. A total weight of 400,000 tons will be placed in the lower basement of the Tokamak Complex, including the buildings, the main machine, and the equipment [65]. Initially, the project budget amounted to EUR 5 billion, but it soon appeared that the cost of construction and operation could be as high as EUR 18–22 billion [67]. According to other sources, the total cost could reach USD 45–65 billion [68,69]. Nowadays, the ITER reactor is regarded as one of the most complicated engineering projects in the history of humanity and one of the most ambitious enterprises undertaken by multiple cooperating countries, along with the International Space Station and the Large Hadron Collider [70]. This very complicated megaproject involves the cooperation of 35 countries, which represent over half of the world's population [71,72]. To make the picture complete, one should note that the whole device will be experimental, and the net production of electricity will not be its task.

To evaluate the efficiency of future commercial thermonuclear power plants, the engineering gain factor or engineering breakeven is used, defined as the ratio of a plant's electrical power output to the electrical power input of all plants' internal systems [73]. The condition $Q = 100$ must be met to make the thermonuclear technology viable. However, starting a thermonuclear power plant requires another several dozen years of research and experiments. The planned successor of ITER—the DEMO tokamak—will not be limited to sustaining the burning plasma, like its predecessor, but it will be the first real nuclear fusion power station, which will supply electricity to the grid. The linear dimensions of the DEMO reactor will be about 15% greater than ITER, and its vacuum chamber will comprise 2200 m^3 compared with 800 m^3 in the case of ITER [74]. Therefore, Georgescu-Roegen was not very mistaken when he wrote in 1981 that a feasible thermonuclear reactor could be the size of Manhattan [6] (p. 70).

The importance of matter and material entropy increases rapidly under the conditions presented here. Therefore, these elements must be taken into account as criteria for the choice of the right technology. The costs of both energy sources must also be taken into account. When it comes to solar technologies, the average LCOE (levelized cost of electricity) for solar PV crystalline decreased from 359 USD/MWh in 2009 to 37 USD/MWh in 2020. At present, there are no commercial thermonuclear plants, which makes comparisons difficult, but the existing nuclear power plants can be taken into consideration. In this case, an increase in the mean LCOE from 123 USD/MWh in 2009 to 163 USD/MWh in 2020 was observed [75] (p. 8). Moreover, the efficiency of solar technologies is increasing steadily, and it reaches 50% for concentrated solar radiation [43]. What is more, this increase in efficiency is accompanied by a gradual decrease in the material scaffold.

Significant progress (in fact, a true breakthrough) has occurred in the field of scalable techniques for producing ultrathin, lightweight solar cells that are tens of micrometers thick. These innovative solar cells can be easily attached to any surface and used as a power source. The power of these cells per kilogram is 18 times greater, and the weight per m^2 is 100 times smaller compared with silicon PV modules on glass substrates. These achievements are even better if a comparison is made against CdTe thin film PVs on glass substrates because, in this case, the power per kilogram is 28 times greater and the weight per m^2—130 times smaller [76].

Considering the fact that multiple technical issues associated with the startup and operation of thermonuclear technologies are still unresolved, the fourth law indicates that the development of solar power plants is the most prudent choice, which is highly likely to bring us to the production of clean energy by the year 2050. When it comes to thermonuclear technologies, this is a thing of the future, and it is not even certain whether they will be viable. There is no need to spend a significant amount of money for the construction of thermonuclear reactors on Earth when there is already a reactor in operation at a safe distance from us.

7. Is the Present Solar Technology Viable?

In order to prove that the present solar technology is not viable, Georgescu-Roegen proposes that the schematic flow matrix presented in Table 3 should be considered, which represents the structure of solar energy technology [6] (pp. 197–198). There are four processes here:

- The process P_1 converts solar energy, SE, into controlled energy, CSE, with the aid of some collectors, CL, and some other capital equipment, K;
- Process P_2 produces collectors with the aid of the energy controlled by P_1, and also some capital equipment;
- Process P_3 uses CSE to produce capital equipment for all purposes;
- Process P_4 supports all other activities of production and consumption with the necessary CSE and capital equipment as well.

Table 3. The reduced flow matrix of a technology.

Elements	$\boldsymbol{P_1}$ **(SE → CSE)**	$\boldsymbol{P_2}$ **(Produces CL)**	$\boldsymbol{P_3}$ **(CSE → K)**	$\boldsymbol{P_4}$ **(CSE+K) → ALL**
Controlled solar energy (CSE)	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$
Solar collectors (CL)	$-x_{21}$	x_{22}	*	*
Capital equipment (K)	$-x_{31}$	$-x_{32}$	x_{33}	$-x_{34}$

The Promethean conditions for viability, (9)–(14), are as follows:

$$x_{11} = x_{12} + x_{13} + x_{14}\,, \tag{25}$$

$$x_{22} = x_{21}\,, \tag{26}$$

$$x_{33} = x_{31} + x_{32} + x_{34}\,. \tag{27}$$

A technology based on the conversion of energy in the process P_1 is not viable if

$$x_{11} < x_{12} + x_{13} + x_{14}\,, \tag{28}$$

or even

$$x_{11} < x_{12}\,. \tag{29}$$

The last inequality underscores the current situation, reminiscent of Georgescu-Roegen's time: no pilot facilities exclusively manufacture solar collectors using solar energy conversion (SE → CSE). As a result, while practical solar recipes are feasible, there is a dearth of viable solar technology [6] (p. 198).

Georgescu-Roegen points out that a viable technology, like a viable species, must maintain itself after it emerges from the previous technology. The threshold between the old and the new technology can be overcome only at an additional cost from the old prices. The viability of solar technology only requires that its material scaffold should be self-supporting, which is a condition independent of the current profitability of the production of solar collectors [77]. Therefore, developing a pilot of full-fledged solar technology should be the nearest goal in perfecting the solar technology to prove its viability independent of prices [78] (pp. 1052–1053).

The next stage of Georgescu-Roegen's reasoning involves demonstrating that contemporary recipes for using solar energy are parasites of fossil fuel-based technologies [6] (pp. 199–200). Solar collectors were used mainly for heating at his time. In order to determine the technical relations of solar collectors with the associated processes, which existed in the late 1970s and early 1980s, he refers to Table 4, where all the processes make use of only non-solar energy mainly obtained from fossil fuels. A new process appeared, P_0, which represents the production of fossil energy, FE. In a simplified approach, the process P_4 receives only heat from the production complex.

Table 4 shows that

$$x_{00} = x_{01} + x_{02} + x_{03}\,. \tag{30}$$

Table 4. The past and present technical relations of solar collectors with the associated processes.

Elements	P_1 (SE → CSE)	P_0 (Produces FE)	P_2 (Produces CL)	P_3 (CSE → K)	P_4 (CSE+K) → Heat
Controlled solar energy (CSE) [1]	x_{11} $[x_{11}]$	* $[-x_{10}]$	* $[-x_{12}]$	* $[-x_{13}]$	$-x_{11}$ $[-x_{14}]$
Solar collectors (CL)	$-x_{21}$	*	x_{22}	*	*
Capital equipment (K)	$-x_{31}$	$-x_{30}$	$-x_{32}$	x_{33}	*
Fossil energy (FE)	$-x_{01}$	$+x_{00}$	$-x_{02}$	$-x_{03}$	*

[1] Brackets indicate the present state of controlled solar energy.

Moreover, x_{02} must be of the same order of magnitude as x_{12} in Table 3 ($x_{02} \approx x_{12}$). According to Equation (30) and Inequality (29),

$$x_{00} \gg x_{11} \,, \tag{31}$$

which confirms the parasitic nature of the recipes for harnessing solar radiation. They could not exist without technologies based on other kinds of energy.

8. Discussion

Undoubtedly, solar technologies at the times of Georgescu-Roegen parasitized other energy sources, mainly fossil energy, but now Table 4 can be modified slightly by introducing additional flow factors provided in brackets to it. This means that controlled solar energy (CSE) also powers all economic processes, including P_0, which produces energy from fossil fuels. Evidently, the Promethean condition of viability

$$[x_{11}] = [x_{10}] + [x_{12}] + [x_{13}] + [x_{14}] \,, \tag{32}$$

cannot be met even nowadays, and, evidently, solar collectors cannot be produced without the use of other energy sources in the current state of technology. However, in some areas, such as construction and transport, there are pilot installations in operation which are powered fully or in large part with solar energy, so instead of Inequality (29), there is the following relationship:

$$[x_{11}] \cong [x_{12}] \,. \tag{33}$$

Moreover, the situation nowadays is a little better than in the late 1970s and early 1980s, because certainly

$$[x_{11}] \gg x_{11} \,. \tag{34}$$

Georgescu-Roegen sees the benefits of solar energy, as he regards the Sun as the only steady and completely healthy source of energy, but he doubts whether it will enable people to drive cars at the speed of one hundred kilometers per hours, to live in skyscrapers, or to fly in jets [78] (p. 1055). However, what used to be impossible slowly begins to come true. Electric cars driving at the speed mentioned above are no longer something extraordinary, and they can be powered by electricity produced by photovoltaic panels. Several prototypes of solar cars have been constructed in recent years. They are intended for use on public roads, and they use self-contained solar cells for full or partial powering with solar radiation. One of them, Lightyear 0, entered volume production in December 2022 [79]. Production of another car of this type, the Aptera solar-powered EV, is set to start in 2023 [80,81]. With vehicles of this kind, users can skip the charging grid and drive in a more sustainable manner. The moment is probably approaching when skyscrapers become energy self-sufficient owing to see-through solar cells [82]. There are skyscrapers and office buildings mostly powered by solar energy, and the next ambitious project in the field is planned. Apple's Spaceship Headquarters in Cupertino, California, whose construction cost amounted to USD 5 billion, is equipped with a 17-megawatt onsite rooftop solar installation, which satisfies 75% of its energy demand [83,84]. A skyscraper has been designed in Australia called the Sol Invictus Tower, which is to have 60 floors and acquire more than 50 percent of the building's baseload power from solar panels [85]. Moreover, self-sufficient solar homes have been a real thing for some time [86]. What is more, a prototype airplane called Solar Impulse 2, powered by solar energy, had its first solar flight around the world in 2015–2016 [87]. Therefore, a technological barrier in the form of an operating pilot solar installation has been overcome in some areas, which at least cancels Inequality (29).

In modern times, the digitalization of power systems has facilitated the decentralization of power generation and the integration of solar radiation and other renewable sources into smart grids [88,89]. For the current technologies to be regarded as Promethean recipes of the third kind, they must certainly be perfected, which is why humanity's considerable effort is directed toward pursuing this goal. However, this is not a sufficient condition. The Promethean condition for viability will be met when the solarization of the global power infrastructure takes place. Therefore, not only changes arising from technological progress are required, but—most importantly—socioeconomic changes will make introducing solar communism possible [90]. Only after solar technologies trigger a chain reaction, as was the case with fire and the steam engine, can one talk about the real Promethean recipe of the third kind. For this to happen, all of humanity must participate in obtaining solar energy due to its dispersed nature. This requires common demilitarization as well as developing and implementing strict plans for biosphere conservation and the propagation of organic farming.

Tables of technological processes, such as Tables 3 and 4, cannot be prepared for thermonuclear energy because there has been no active (or even pilot) fusion power plant, and scientific effort has been focused on attempts at controlling energy generated from the fusion of atomic nuclei. It is only known that according to the matter criterion, solar technologies should be chosen, and fusion energy should not be used by humanity. However, one can go a step further in the research and verify the ecological criterion thoroughly. Even now, it is possible to evaluate the ecological effects of fusion energy technologies, in which the second law of thermodynamics (the entropy law) can be used. The point is that relations between fusion energy and the mean entropy budget of the Earth should be established.

The entropy budget describes the entropy flow between the Earth and space [91,92]. Thermodynamically, the Earth is a closed system, i.e., it does not exchange matter with space, except meteorites and spacecraft, but it is open to energy flow. The flux of solar radiation with a high temperature and low entropy reaches its surface, and waste heat is emitted to space, which plays the role of a heat sink. It is mainly infrared radiation, which has low temperature and high entropy. For the climate system equilibrium to be maintained, the long-term entropy balance of the Earth must be equal to zero. In this case, the internal production of entropy in the system is offset by the entropic outflow to the environment (deep space) [93] (pp. 161–172).

When one considers the long-term mean, the incoming flux of solar energy is equal to the outgoing flux of longwave radiation to space. However, the corresponding entropy fluxes are completely different. The entropy in the longwave radiation which leaves the Earth is about 22 times greater than the entropy in the incoming solar radiation. The total amount of entropy exported by the climate system to space is -925 mW $\mathrm{m}^{-2}\mathrm{K}^{-1}$, whereas the amount of entropy imported by the incoming solar radiation is 41.3 mW $\mathrm{m}^{-2}\mathrm{K}^{-1}$. The irreversible processes in the climate system are responsible for the internal production of entropy, which is equal to the net export of entropy to space effected by the system [91]. The difference between the incoming entropy in solar radiation and the entropy associated with the outgoing radiative heat flow is a natural resource in the form of potential for entropy production, which can be used properly or wasted. After creating a solar society, humanity will have a huge potential for increasing its negentropy resources without increasing the global rate of entropy production [94].

Greenhouse gases, which stop longwave (mainly infrared) radiation emitted from the surface, have been present in the atmosphere of the Earth from time immemorial. They contribute to the formation of the natural greenhouse effect, which helps to maintain the optimum temperature on the surface for biosphere development. The situation has become complicated as a result of human economic activities, which is the cause of what is known as the anthropogenic greenhouse effect. It is caused by increasing amounts of greenhouse gases in the Earth's atmosphere, which is caused, in turn, by burning fossil fuels. These extra amounts of gases capture greater amounts of heat and contribute to an increase in the average temperature above the level which is an effect of the natural greenhouse effect. This results in global warming, which contributes to catastrophic climate change, upsets the biosphere balance, and makes maintaining biodiversity difficult.

Let it be assumed that technological progress enabled people to use thermonuclear energy in economic processes. The only difference between fossil energy and thermonuclear energy is that the latter does not cause greenhouse gas emissions. However, it is worth noting that—like energy from fossil fuels—thermonuclear energy causes the emission of additional waste heat to the atmosphere. If the global economy is not totally based on a direct solar flux, but it uses even relatively clean thermonuclear technologies, then the heat budget of the Earth will change irreversibly, as heat emission will exceed the natural flux from the surface. If the atmosphere contains anthropogenic greenhouse gases, thermonuclear energy will still increase the existing global warming, raising the average temperature on the Earth even further. Therefore, perfecting thermonuclear technologies should be followed by progress in developing and implementing methods of capturing anthropogenic greenhouse gases, mainly carbon dioxide and methane, from the atmosphere. Irrespective of this, excess waste heat from fusion power plants above the natural flux from the surface could become a serious problem in the future.

Since the industrial revolution, with the burning of fossil fuels, our thermal debt toward the environment in a broad sense, i.e., space, which is called entropic debt, has been increasing. Restoring the balance of the natural mean entropy budget requires for energy to no longer be acquired from burning fossil fuels, nuclear fission, and similar processes, as they produce surplus waste heat above the natural flux from the surface. This applies to future thermonuclear power plants—if ones are constructed—as their operation will increase our thermal debt toward space. It is not known exactly how the growing entropic debt can affect the global climate system, biosphere organization and what happens in the universe. Only an economy based on direct solar flux will not upset the heat budget of the Earth [30].

Moreover, thermonuclear power supply entails two other types of hazards. Firstly, one should not underestimate radioactive waste, which will be produced by future fusion plants. Radioactive materials are produced as a result of the inevitable exposure of some equipment elements to a flux of neutrons. The radiotoxicity of fusion waste decreases rapidly compared with the waste from a PWR (pressurized water reactor) fission plant, but it reaches the radiotoxicity of ash in a coal-fired power plant only after 500 years [95]. Secondly, thermonuclear plants could be used for military purposes, as there is a considerable risk that they may contribute to nuclear proliferation [96]. Hence, the construction of extremely costly thermonuclear power plants, which require vast amounts of material and pose a significant safety risk on Earth, should be questioned. Instead, we ought to consider the Sun as a source of clean and healthy energy, which has been operational for an extended period and is situated at a safe distance from Earth.

9. Conclusions

Table 5 compares three selected future energy technologies: fusion $\left(T^1\right)$, solar $\left(T^2\right)$, and fission $\left(T^3\right)$. Criteria such as energy in situ (e_1), controlled energy $\left(x_{11}^1, x_{11}^2, x_{11}^3\right)$, material requirements (M_0), entropic debt, average LCOE, degree of environmental risk, the possibility of being considered Prometheus III, and type of energy conversion were used. It appears that the best energy technology is solar technology, as it is associated with an inexhaustible, natural, and healthy source of renewable energy, no waste heat production over and above the natural flux from the surface, the lowest material entropy $\left(M_0^2 \ll M_0^3 \ll M_0^1\right)$, non-increasing entropic debt, the smallest and steadily declining average LCOE (37 USD/MWh), the greatest environmental safety, the achievement of viability in the near future, as signaled by the existence of pilot installations in transportation and construction, and the easiest conversion of solar energy into electricity through the use of the photovoltaic effect. The inequality $x_{11}^3 > x_{11}^2$ is due to the fact that, in 2021, the share of fission energy in global electricity production was 9.9%, while the share of solar energy was slightly smaller, equal to 3.7% [97]. These relationships are expected to change dramatically in the coming years. There are already concrete plans for Europe to import solar electricity from the Middle East and North Africa [98]. There is also a serious contradiction between solar technology and fission and fusion technologies when it comes to universal demilitarization and ensuring lasting world peace. As is well known, the latter two technologies are linked to the military–industrial complex and can be used for nuclear proliferation. Some of the most important challenges facing humanity in the coming years include stopping the expansion of the entropic debt and then gradually reducing it by developing solar technology and removing anthropogenic greenhouse gases from the atmosphere.

Table 5. Comparison of energy technologies of the future.

Type of Technology	Energy/Matter Criterion	Entropic Debt	Average LCOE 2009–2020 (USD/MWh)	Ecological Criterion	Prometheus III	Type of Energy Conversion
Fusion $T^1\left(e_1^1, M_0^1\right)$	$e_1^1 \gg 0$ $x_{11}^1 = 0$ $M_0^1 \gg 0$	Yes (↑)	0→0	Medium environmental risk; after 500 years, the waste has the radioactivity of coal ash	Not viable	Steam turbine
Solar $T^2\left(e_1^2, M_0^2\right)$	$e_1^2 \to \infty$ $x_{11}^2 \gg 0$ $M_0^2 \ll M_0^1$	No	359→37 (↓)	Environmentally safe provided waste recycling is developed	Approaching viability	Photovoltaic effect, sometimes steam turbine
Fission $T^3\left(e_1^3, M_0^3\right)$	$e_1^2 \gg e_1^1 \gg e_1^3$ $x_{11}^3 > x_{11}^2 \gg 0$ $M_0^2 \ll M_0^3 \ll M_0^1$	Yes (↑)	123→163 (↑)	Very high environmental risk in the extremely long term	Not viable	Steam turbine

Entropic debt is closely related to the energy technologies chosen by humanity. It arises not only from the second, but also from the fourth principle of thermodynamics, as it relates to both energy degradation and matter dissipation. Let us first consider the effects of the second law of thermodynamics. Any economy that uses energy sources other than direct solar flux alters the Earth's heat budget, as it emits thermal radiation in excess of the natural flux from the surface. This is true for fossil fuel-based technologies, as well as for fission and fusion technologies. It is also known that there is a stock of anthropogenic greenhouse gases in the Earth's atmosphere, which has been steadily increasing since the beginning of the industrial revolution. Under such conditions, fission and fusion technologies, even if they do not emit an additional portion of greenhouse gases, still contribute to the intensification of global warming. Greenhouse gases capture some of the long-wave radiation (mainly infrared) emitted from the Earth's surface as waste heat and radiate it back to the surface, resulting in an increase in its global mean temperature. In turn, entropy in the environment increases as a debt for any internal process taking place in the system [30]. In other words, as a result of the second law of thermodynamics, fission and fusion technologies may contribute to the intensification of global warming and, at the same time, increase the entropic debt to the cosmos as an external environment due to the emission of additional waste heat, which may contribute to accelerating the heat death of the universe. This worsens the situation not only on Earth but also in space. Only global solar power can pay off its entropic debt in the form of non-incremental waste heat without leading to catastrophic climate change [99] (p. 21).

On top of all this is the operation of the fourth law of thermodynamics, which talks about the entropy of matter. The entropy debt of matter is the sum of the waste produced by the results of irreversible internal processes and the dissipation of natural resources, or what Georgescu-Roegen calls unavailable matter. It can, over time, lead to the material death of ecosystems on Earth. Sometimes, the sum of the entropy debt of energy and the entropy debt of matter is referred to as the cost of complexity of an economic system, the incurring of which is necessary to maintain its internal complexity in the form of a certain social order, energy technologies, infrastructure, and communication networks. This cost is related to the disruption of the natural circulation of energy and entropy in the biosphere and the violation of the ecological integrity of natural resources, without which humanity has no chance of survival. It includes all that is associated with anthropogenic environmental degradation [100].

The multifaceted battle regarding humanity's choice of the dominant energy technology of the future is being fought today in various contact zones: global, international, national, and even local. It involves energy law and administrative issues, as well as available technical solutions. Therefore, it is taking place simultaneously in the two most important contact zones: human administrative legal contact zones and more-than-human energy contact zones [101].

Jeremy Rifkin believes that the current accumulation of entropic debt far exceeds the capacity of the biosphere to absorb it. The effects of the fourth law are increasingly evident as a result of the depletion of fossil fuels and rare earth minerals, so he proposes that thermodynamic efficiencies and entropic consequences should be taken into account when measuring productivity. In his view, the entropy bill does not take into account the full cost of matter dissipation because if it did, fossil capitalism would have to collapse rapidly [102] (pp. 207–208). Rifkin assumes that the entropic debt can be overcome by humanity's empathic dimension, which could result in a global, biosphere-wide consciousness and distributed capitalism based on renewable energy [103].

In the future, the problem of humanity's entropic debt can be expected to emerge as one of the fundamental issues of international politics. Already in global discussions on climate change, such concepts as greenhouse gas stocks and flows are beginning to be used. The issue of flows is often emphasized by industrialized countries, while the issue of stocks is important for non-industrialized or newly industrialized countries. The stockpile of greenhouse gases began to accumulate in the atmosphere with the advent of the industrial revolution, and the countries where it began incurred the greatest entropic debt and thus contributed the most to the persistence of current levels of carbon dioxide in the air and the resulting global damage. Even a significant reduction in current greenhouse gas emissions into the atmosphere cannot reduce the stock that is already there. Accordingly, James B. Quilligan predicts that the future international system will have to combine the stocks and flows that exist in current accounts between surplus and deficit countries with the stocks and flows of the global commons, which will take into account both renewable and depletable resources [104]. With the goodwill of all stakeholders, this could restore fairness to the world's balance-of-payments adjustment system.

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