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THE INFLUENCE OF NATURAL AND ANTHROPOGENIC PROCESSES ON EARTH'S CLIMATE FROM THE PERSPECTIVE OF NONEQUILIBRIUM THERMODYNAMICS

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Keywords: processes far from equilibrium, Earth evolution, entropy production, hysteresis, climate, non-equilibrium thermodynamics.
Abstract. The nature of glacial and interglacial periods interchanges is explained based on general laws of evolution of thermodynamic systems that are far from equilibrium. The duration of these periods depends on quantity of atmosphere entropy production. It is noticed that transitions between periods are realized through hysteresis while atmosphere structure and climate rapidly change. The influence of humanity consumption fossil energy resources, nuclear explosions and powerful volcanic eruption on entropy production in atmosphere is shown. Impacts of carbon, hydrogen, solar and wind power on the Earth's climate are compared. It is noticed that if it was properly organized carbon power sector provide less of an increase entropy generation in atmosphere and its temperature than other types of energy production.

ВЛИЯНИЕ ПРИРОДНЫХ И АНТРОПОГЕННЫХ ПРОЦЕССОВ НА КЛИМАТ ЗЕМЛИ С ПОЗИЦИЙ НЕРАВНОВЕСНОЙ ТЕРМОДИНАМИКИ

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Ключевые слова: процессы далекие от равновесия, эволюция Земли, производство энтропии, гистерезис, климат, неравновесная термодинамика.
Аннотация. На основании общих закономерностей эволюции далеких от равновесия термодинамических систем объясняется природа чередования ледниковых и межледниковых периодов на Земле, длительность которых зависит от количества производства энтропии в атмосфере. Отмечается, что переходы между периодами реализуются через гистерезис и при этом резко изменяются как структура атмосферы, так и климат. Рассмотрен характер зависимости производства энтропии от изменения температуры для циклов потепления и похолодания атмосферы. Показано влияние на производство энтропии в атмосфере потребления человечеством ископаемых энергоресурсов, взрыва ядерных зарядов и извержения мощных вулканов. Сопоставлены воздействия на климат Земли углеродной, водородной, солнечной и ветряной энергетики. Отмечается, что углеродная энергетика при правильной ее организации обеспечивает меньший прирост производства энтропии в атмосфере и ее температуры по сравнению с остальными рассмотренными видами энергетики.

In order to determine the effect of natural and anthropogenic processes on the Earth's climate, we must first understand the nature of ice ages. At the beginning of the 19th century, scientists first learned about the existence of ice ages, discovered the greenhouse effect and began researching the climate change. It was found that the alternation of glacial and interglacial periods in the history of the Earth is accompanied by a change in the atmosphere reflected by the climate on Earth.

Numerous hypotheses were put forward to explain the onset of the climate changing ice age. Among the most common are the hypotheses which attribute the global changes in the atmosphere to volcanic activity, changes in the intensity of solar radiation, large meteorites, and oceanic processes, as well as anthropogenic changes in the natural world, especially during the recent decades. One of the hypotheses was published in 1896 by S. Arrhenius [1], the future Nobel Prize winner. This hypothesis assumed that the change of glacial and warm epochs results from the changes in the concentration of carbon dioxide in the atmosphere. Using a stationary and equilibrium model of the Earth-atmosphere system, he performed calculations demonstrating that if the CO_2 concentration is halved, the average temperature of Europe would decrease by 4-5°C and, conversely, if the concentration doubled, the temperature would increase by approximately the same amount. Temperature changes of this order are already sufficient to cause gigantic changes in the Earth's ice cover. This hypothesis is presented in more detail as it is currently accepted at the international level as the driving force in the fight against fossil fuels, although it is criticized by many scientists around the world [2, 3].

The above hypotheses explaining the onset of the ice age are quite possible, but none of them can scientifically justify the alternation of glacial and interglacial periods. It was established that, once started, glaciation processes, develop according to their own laws independent from many natural forces, which is not accounted for by any of the hypotheses. It should be noted that all the above mentioned hypotheses concerning the onset of the ice age are united by the fact that glaciation begins with a significant change in the balance of energy flows in the atmosphere.

During the glacial and interglacial periods the Earth's atmosphere is characterized by different states. Let us substantiate the transitions between these states from the standpoint of the thermodynamics of irreversible processes. In this case, we will assume that the atmosphere with all its complex cause-and-effect relationships is a highly non-equilibrium thermodynamic system that can find itself in significantly different quasi-stationary states. The theory of thermodynamics of a highly non-equilibrium systems is currently being developed. In [4-7], the general laws of the evolution of such non-equilibrium thermodynamic systems were formulated for the first time, and their applicability to processes both in animate and inanimate nature was verified by means of experiments and calculations. According to these rules:

1. The transition of a non-equilibrium thermodynamic system from a stationary state with a lower entropy production to a stationary state with a higher entropy production occurs only if a physics-based condition is violated in the process of its evolution, which makes the existence of this state impossible. In this case, from all possible states with a higher entropy production, the transition to the state with the lowest possible entropy production occurs provided that such a transition is allowed by physics-based conditions.

2. The transition of a non-equilibrium thermodynamic system from a stationary state with a higher entropy production to a stationary state with a lower entropy production occurs when, in the course of the evolution of the system, the difference between the entropy productions of these two states reaches a certain positive value.

3. Direct and reverse transitions between two stationary states of a non-equilibrium thermodynamic system are characterized by hysteresis. During these transitions, both the system structures and the thermodynamic parameters undergo abrupt changes.

4. The process of transition of a non-equilibrium thermodynamic system from one stationary state to another occurs through non-stationary states, which can smooth out the abruptness of the transition. These laws are based on a general principle formulated as an axiom according to which all the processes in nature strive to reach perfection: of all possible stationary states of a system allowed by the laws of nature, the thermodynamics of irreversible processes, boundary and other physics-based conditions, the most probable state is the one with the minimum possible entropy production. The production of entropy P_S in thermodynamics is defined as the amount of entropy produced (arising) inside a thermodynamic system per unit time $P_S = d_i S / dt$, where the change in entropy $d_i S$ is equal to the value of the elementary reduced heat $\delta Q / T$ absorbed by the system; T is temperature; t is time.

Let us demonstrate with the help of examples the general laws governing the evolution of non-equilibrium thermodynamic systems. For instance, a cylindrical pipe of a certain length and with a given gas flow rate is considered as a thermodynamic system in [5]. In this case, the laws of nature allow two stationary states, that is laminar and turbulent flow regimes. Each regime has its own flow structure, velocity profile over the pipe section, and the law of flow friction against the wall. Figure 1 shows the specific entropy production for laminar ΠS_L and turbulent ΠS_T flow regimes calculated as functions of the Reynolds number $\mathrm{Re} = Vd / \nu$, where V is the average gas flow velocity through a pipe section with a d diameter, ν is the kinematic viscosity of the gas. The specific entropy production ΠS is the amount of entropy that occurs within the system per unit of time over a unit flow.

Figure 1 demonstrates that the production of entropy for the laminar flow regime is less than for the turbulent flow regime. According to the general laws given above, a thermodynamic system can evolve from a state with the lowest possible entropy production to a state with a higher entropy production only if a physics-based condition is not fulfilled. Such a condition for this system is the resistance of the laminar flow to the internal or external disturbances in the flow. In the absence of perturbations, the laminar flow structure formed at the beginning of the flow must exist, according to the axiom, for any values of Re. However, the greater the value of Re, the weaker the perturbations that lead to the loss of stability of the laminar motion, and, once having arisen, they no longer fade with time, but intensify. In Fig. 1, the arrow marks the transition from laminar to turbulent flow at the upper critical value of the Reynolds number $Re_{CR} \approx 9000$. The upper critical value of Re has not been finally determined [8]. In some experiments, it reached the value $Re_{CR}=5\cdot 10^4$.

In another example, the mass of water in a large volume at atmospheric pressure was considered as a non-equilibrium thermodynamic system [6]. This mass of water is boiling under conditions of natural convection on a flat heat-releasing bottom of a vessel bounded by heat-insulated side walls. Two main regimes of water boiling were established experimentally: nucleate boiling and film boiling. The transition from one regime to the other is determined by the heat flux density q, which is the amount of heat passing through the unit area of the heat-releasing surface per unit time. Based on the experimental data presented in [9], the specific entropy production ΠS was calculated as a function of q for nucleate and film boiling regimes. These graphs are shown in Figure 2. In the case under consideration, the specific entropy production is the amount of entropy produced per unit time per unit area of the heat-releasing surface. The developed nucleate boiling regime corresponds to a lower value of the specific entropy production, and the film boiling to a higher value. These boiling regimes differ in the pattern of vaporization, i.e. the hydrodynamic structure in the vicinity of the heat-releasing surface.

In case of developed nucleate boiling, a large number of vaporization centers are formed on the heat-release surface. However, the liquid continues to flow around the heating surface between these centers, and its boundary layer is intensively mixed with the vapor bubbles formed in it. During film boiling, the liquid is separated from the heat-release surface by the resulting layer of water vapor with a lower thermal conductivity, which results in the rate of heat exchange becoming much lower than during nucleate boiling. The nucleate boiling regime evolves into the film boiling regime when the heat flux density reaches the first critical value q_{C1} (Fig. 2). This transition from a state with a lower specific entropy production to a state with a higher production is accompanied by a jump-like change in both the hydrodynamic pattern near the heat-release surface and the thermodynamic and thermophysical parameters. It is similar to the transition from a laminar flow regime to a turbulent flow regime (Fig. 1), accompanied by an abrupt change in the hydrodynamic pattern of the flow and the flow drag force.

The considered transition from a lower to a higher entropy production stationary state, as with other non-equilibrium systems, is characterized by a non-stationarity of the boiling pattern. In different zones of the heat-release surface, various combinations of film and nucleate boiling regimes are formed, alternating randomly. This is similar to the regime of transition from laminar to stable turbulent flow in a pipe, where flow regions with turbulent and laminar moving gas are also undergoing chaotic temporal and spatial change. The transition from nucleate boiling to film boiling is associated with the loss of hydrodynamic stability of the two-phase near-wall layer due to the growth of vaporization centers with increasing q [9]. This is similar to the loss of stability of a laminar flow to disturbances inside and outside the flow. Also a slow increase in the heat flux via a specially selected heat-release surface with fewer vaporization centers made it possible to exceed the normal critical value q_{C1} almost twofold in some experiments [9]. This is similar to an increase in the upper critical Reynolds number, at which the laminar flow becomes turbulent by reducing the disturbances introduced into the flow.

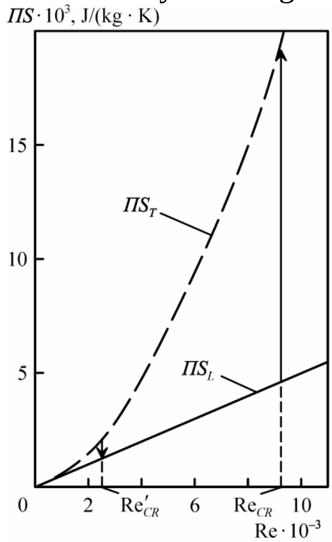

Fig. 1. ΠS as a function of Re number for the laminar ΠS_L and turbulent ΠS_T flow regimes (flow rate 1/7)

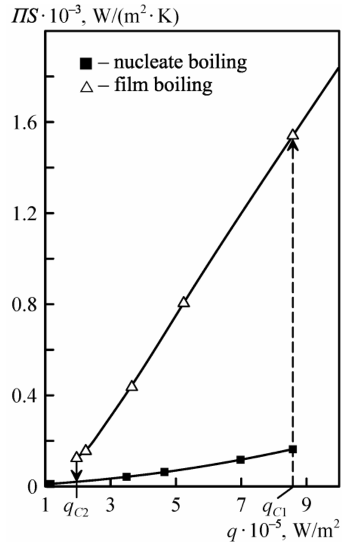

Fig. 2. ΠS as a function of q for two regimes of boiling in a large volume of water

Graphs in Figures 1 and 2 demonstrate that the reverse transition of the thermodynamic system from a higher entropy production state to a lower production state occurs when the difference between the entropy productions of these two states reaches a certain positive value. In the case of boiling liquid (Fig. 2), this corresponds to a decrease in the heat flux density up to the second critical value q_{C2}, which is much lower than q_{C1}. The transition of the turbulent flow regime to the laminar flow regime also occurs at the experimentally established lower critical value $\mathrm{Re}'_{CR} = 1700...2500$, which is much less than the upper value Re_{CR} (Fig. 1). Thus, hysteresis is clearly observed in thermal and hydrodynamic phenomena associated with the transition from one state of the thermodynamic system to the other.

It follows from the above that the considered non-equilibrium systems with the hydrodynamic and heat-exchange processes, from the standpoint of non-equilibrium thermodynamics, conform to the same general laws of evolution given above. The graphs of the change in entropy production for the laminar and turbulent flow regimes (Fig. 1), obtained by calculation, are similar to the graphs for nucleate and film boiling regimes (Fig. 2) plotted by experimental points. Other non-equilibrium thermodynamic systems behave in a similar way.

Let us consider the Rayleigh-Benard convection [5] occurring in a horizontal layer of liquid with a vertical temperature gradient created by heating the layer from below. Depending on the heating temperature or, to be precise, the Rayleigh number Ra, various stationary (stable) states of fluid motion appear in the layer in the following forms: hexagonal Benard cells; two-dimensional cells resembling the rotation of rolls in opposite directions (Fig. 3); three-dimensional cells and other organized structures [10]. Each stationary state has its own value of entropy production. States with a lower entropy production evolve into states with a higher production when certain critical values Ra_1, Ra_2, Ra_3, etc. are reached. Figure 4 shows the nature of the change in the entropy production as a function of Ra for four stationary states.

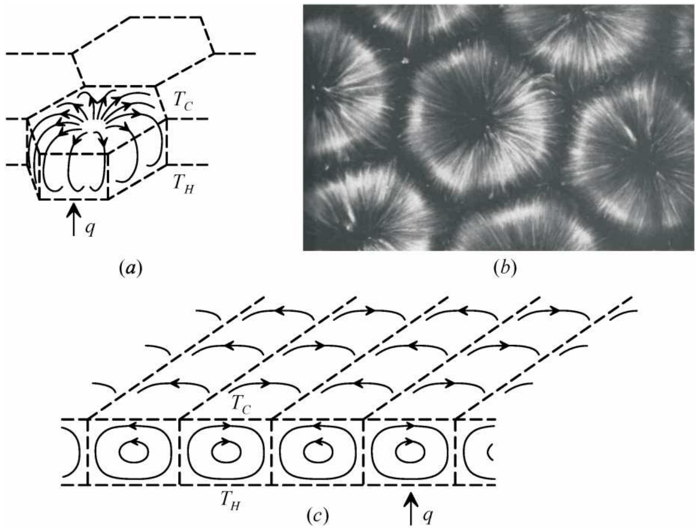

Fig. 3. Convective cell types: *a* – hexagonal Benard cells;
b – photo image of Benard cells; *c* – two-dimensional rolls

When the fixed layer is slowly heated from below, with a small temperature differential across the layer, the heat is completely removed through thermal conductivity, and there are no convective flows. This state corresponds to Curve *0* in Figure 4. With an increase in the heating temperature, convective flows appear, and when the value of Ra_1 is reached, a new stationary state of a non-equilibrium system is formed with the honeycomb-like structures of fluid movement known as Benard cells. This case corresponds to Curve *1* in Figure 4. As the heat flux further increases, the flow structure is preserved at first, and then the Benard cells begin to collapse. The unsteady states are formed through which the thermodynamic system at the Rayleigh number Ra_2 transfers into a new stationary state, for example, with a roll structure of the fluid flow. This flow is presented by Curve *2* in Figure 4. At the Rayleigh number Ra_3, a new stationary flow structure is formed, and so on. Figure 4 shows that as the Rayleigh number increases, the thermodynamic system evolves from a state with a lower entropy production to a state with a higher entropy production.

Experiments demonstrated that with a decrease in the heat flux into the thermodynamic system, and hence the Rayleigh numbers, its reverse transition from the stationary state with a higher entropy production to the stationary state with a lower entropy production occurs at lower Rayleigh numbers than the direct transition [10]. In Figure 4 reverse transitions correspond to the primed Rayleigh numbers Ra'_1, Ra'_2, Ra'_3. Thus, transitions between two stationary states of a non-equilibrium thermodynamic system are characterized by hysteresis, as in other considered systems.

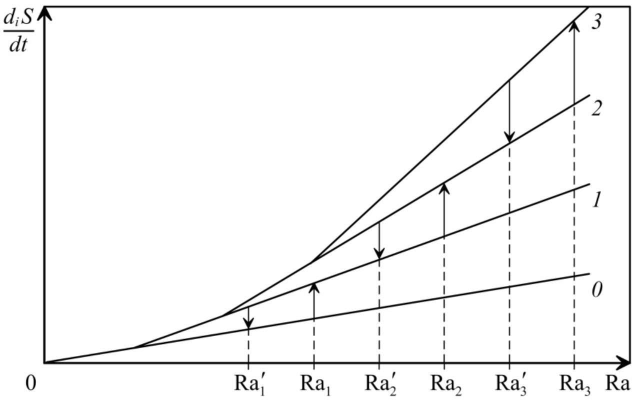

Fig. 4. Change in the entropy production as a function of Rayleigh number

It follows from [4-7, 11-16] that non-equilibrium processes occurring in fluid dynamics, heat transfer, aerodynamics, magnetism, optics, heterogeneous catalytic and homogeneous periodic chemical reactions, in biological systems and a number of others, are subject to the same general laws given above concerning the changes in the state of non-equilibrium thermodynamic systems in the course of their evolution.

Let us apply these regularities to the Earth's atmosphere, which is a mass of air in a gaseous shell surrounding the Earth and rotating with it. The internal energy of the atmosphere is incomparably small compared to the energy of the Earth interior and the World Ocean, but it makes the life on Earth possible.

Let us apply these laws to the Earth's atmosphere, which is a mass of air in a gaseous shell that surrounds the Earth and rotates with it. The internal energy of the atmosphere is incomparably small compared to the energy of the Earth’s interior and the World Ocean, but it makes life on Earth possible.

The energy flow enters the atmosphere through its upper boundary, mostly as radiant solar energy. Occasionally, there may be a flow of energy caused by other cosmic or planetary phenomena leading to the formation of powerful electromagnetic radiation or meteor showers. The radiant energy of the Earth's surface and the reflected solar energy are removed from the atmosphere into space.

Through its lower boundary, the atmosphere exchanges radiant energy and heat and mass flows with the Earth via heat transfer and convection. The currents in the World Ocean, a giant accumulator of thermal energy, have a particularly strong influence on heat and mass flows. Intermittently, the energy of the Earth's interior, released during tectonic shifts and volcanic eruptions and accompanied by large emissions is emitted into the atmosphere. In the last century, such minerals as oil, gas, coal, uranium ore, etc., were increasingly being mined, and their energy, as a result of human activity, transfers into the atmosphere in the form of heat.

The ongoing mass transfer processes with the Earth change the composition of the atmosphere and cause its pollution with aerosol substances (ash, soot, dust, water particles, etc.). This reduces the transparency of the atmosphere and therefore weakens solar radiation and other radiant fluxes. Changes in the composition of the atmosphere, namely the concentrations of water vapor, CO_2, CH_4 and a number of other gases, change the absorption capacity of the atmosphere for infrared radiation, which causes the greenhouse effect. The increasing mass of living organisms and decaying organic matter also affects both the gas composition of the atmosphere and heat fluxes. Photosynthesis has a great influence on the composition of the atmosphere.

All the above processes combined, as well as a number of others, directly or indirectly affect the production of entropy in the non-equilibrium thermodynamic system under consideration, and some of them have a pronounced effect. For example, during active volcanic activity, a large amount of energy, water vapor, carbon dioxide, ash and other emissions can enter the atmosphere in a relatively short period of time, which will lead to a significant increase in entropy production, determined by the amount of entropy that occurs in the atmosphere per unit time. Only the processes occurring during the fall of meteorites or the explosion of bombs in the atmosphere can be shorter in time. Many other processes are slower and, despite the greater energy they contribute to the atmosphere, the production of entropy due to these processes may be less significant.

It should be noted that the gradual change in the energy balance of the atmosphere can be significantly influenced by: 1) the radiant energy of the Sun, which depends on its cyclic activity, the changing distance to the Sun and the angle of the Earth's axis of rotation; 2) the Earth's albedo, which depends on many factors, including the cloudiness of the atmosphere, which increases with an increase in the amount of water vapor; 3) change in the content of greenhouse gases in the atmosphere that absorb infrared radiation; 4) change in the direction of the oceanic currents.

It should also be noted that during the ice age, the World Ocean emitted such an amount of energy through infrared radiation into space that its temperature in the deepest places ranges from +2°C to +4°C. This all despite the eruptions of numerous underwater volcanoes and the flow of water from geothermal vents with temperatures reaching 400°C. The World Ocean absorbs almost the entire imbalance of the thermal energy of the atmosphere, carried by the convection of air masses. If it were not for this giant accumulator of thermal energy, all thermal processes occurring both in living and inanimate nature, as well as in heat and power, transport and other vital systems, would stop as a result of the Earth's surface overheating. Therefore, even slight changes in the water temperature in the World Ocean and the directions of its existing currents will have a significant impact on the state of the atmosphere, and hence on the climate.

Curves in Figures 1-4 show that transitions from one stationary state of a thermodynamic system to another stationary state are realized at certain experimentally determined critical parameters (for example, critical Reynolds and

Rayleigh numbers, critical heat fluxes, etc.), which correspond to well-defined values of just one critical parameter – entropy production. According to the values and directions of the entropy production change for different possible states of a thermodynamic system, one can judge the directions of its evolution and resultant states.

In a quasi-stationary state, a balance is maintained between the amount of entropy produced in the atmosphere, including the anthropogenic entropy, and removed through its boundaries over the same period of time. When an energy flux exceeding the balance value enters the atmosphere through the boundary, there is an increase in the production of entropy inside the atmosphere and its average temperature. If such a flow of energy at which the production of entropy reaches critical values enters the atmosphere (for example, due to volcanic activity only or combined with other energy sources), the non-equilibrium thermodynamic system will evolve from one stationary state (in our case, corresponding to the interglacial period) to another, which significantly differs from the original state both in terms of structure, thermodynamics and other parameters.

When the main causes that led to the transition of the thermodynamic system to a new quasi-stationary state cease, the processes occurring in the atmosphere and on the Earth will tend to reduce the entropy production in order to return the thermodynamic system to its original stationary state. A decrease in the entropy production in the atmosphere is possible due to the outflow of radiant energy into space, and heat and mass transfer with the ocean. At the same time, the average temperature of the atmosphere will begin to decrease. However, in accordance with all of the above, a direct transition of a thermodynamic system from a quasi-stationary state with a lower entropy production to a state with a higher entropy production (corresponding to the upper critical value of the atmospheric temperature) and a reverse transition are possible only through hysteresis. Therefore, the reverse transition must occur at an atmospheric temperature below the upper critical value. The reverse transition corresponds to the Earth’s ice age.

Geological research has proved that the Earth undergoes periodic climate change. Ice ages (eras, epochs) of different duration were replaced by relative climate warming periods when the areas of continental glaciation decreased. The current state of the Earth's climate belongs to one of the interglacial periods of the Cenozoic Ice Age that began about 35 million years ago, which includes several shorter periods of glaciation and deglaciation (epochs). One of these glaciation periods began about 12 thousand years ago and was accompanied by the extinction of the mammoth, musk ox and other animals. About 10 thousand years ago, a period of warming began, accompanied by cold winters and rainy summers. The ensuing interglacial period has continued to the present. Despite the ongoing interglacial period, there have been occasional cases of relative cooling in the recent history of mankind. We mean the Little Ice Age of the 14^{th}-19^{th} centuries, which replaced the warmest period in the recent history of mankind in the 10^{th}-13^{th} centuries. At that time, Greenland was inhabited by the Vikings, since most of it was not covered with ice, and the climate was characterized by relatively warm winters.

Currently, science distinguishes four provisional groups of cycles, composed of the periodicity of glaciation and interglaciation [3].

1) Superlong cycles of 150-300 million years. They are associated with the most significant changes in the atmosphere state and climate on Earth. The rhythms of volcanic and tectonic activity correlate with these cycles. 2) Long cycles spanning tens of millions of years also correlate with volcanic activity. 3) Short cycles of hundreds and thousands of years are associated with changes in the parameters of the earth's orbit. 4) Ultrashort cycles of tens and hundreds of years are associated with the rhythms of solar activity.

Figure 5 shows the expected pattern of changes in the entropy production in the atmosphere depending on changes in the average temperature for all four cycles. In an extra-long cycle, during the ice age (Curve *1* in Figure 5), such an amount of energy, aerosols, greenhouse gases is emitted into the atmosphere from the Earth's interior that its structure, determined by heat and mass convective flows, gas concentration, atmospheric humidity and other parameters, changes significantly, and entropy production increases sharply. The transition of the atmosphere from the interglacial state (curve *0*) to state *1*, as in all non-equilibrium thermodynamic systems, occurs quite abruptly, and unsteady, rapidly changing in time and space structures are formed during the transition. An abrupt change in the atmosphere state leads to the same rapid change in the climate on Earth. It is noted in [3] that the reason for the abrupt climate change is still not clear. It follows from the above that the abrupt change is determined by the general laws of evolution for all highly non- equilibrium thermodynamic systems [4, 7]. When the atmosphere evolves into state *1*, the process of cooling begins, accompanied by icing. In the case under consideration, the beginning of the cooling process can be associated with thick clouds formed during volcanic eruptions containing ash and other aerosol inclusions reflecting solar radiation. Further, when volcanic activity is over, powerful circulation flows (cyclones, vortices) can form in the atmosphere separating aerosol inclusions and heavier greenhouse gases to the periphery of the cyclone by means of centrifugal forces. At the same time, through the inner part of the cyclone the infrared radiation of the Earth will escape into space as if through a pipe, cooling the atmosphere and the ocean. Other processes leading to the cooling of the atmosphere are also possible. When the entropy production in the atmosphere decreases to a certain value (Fig. 5), the atmosphere abruptly passes into the interglacial state (*0*), and the process of warming begins.

During the long cycle *2*, a smaller amount of energy is injected into the atmosphere through volcanic activity compared to cycle *1*. Therefore, the atmosphere will pass into state *2* in Figure 5, which has a lower value of entropy production compared to state *1*. It should be noted that during the transition of the atmosphere to state *1* or *2*, intermediate states *3* and *4* are not realized, which conforms to the general laws of evolution of non-equilibrium thermodynamic systems outlined above. During volcanic activity such an amount of energy is emitted into the atmosphere in a relatively short time that states *3* and *4* do not have time to be realized, being overlapped by the parent state [4, 7]. Short and ultrashort cycles *3* and *4* are realized due to changes in the amount of solar radiation directed at the Earth, as well as a number of other factors. They correspond to atmospheric states *3* and *4* in Figure 5, which have a lower value of entropy production compared to states *1* and *2*. There can be many more atmospheric states corresponding to the Little Ice Ages. It should be noted that the curves in Figs. 5 are similar to the curves in Figure 4 for the Rayleigh-Benard convection with the structures of some states depicted in Figure 3.

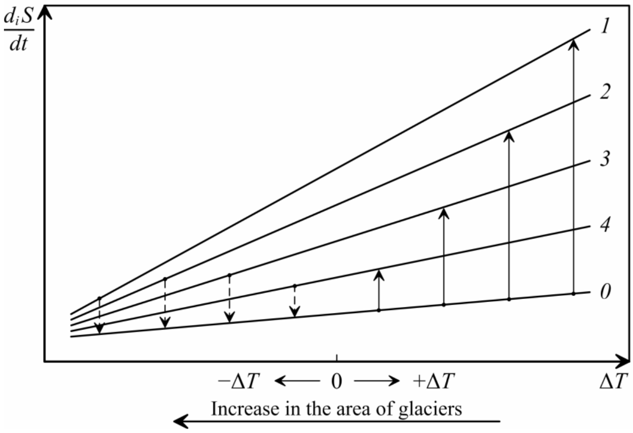

Fig. 5. Probable entropy production as a function of temperature change for four possible warming-cooling atmosphere cycles

Ever since humans lived on Earth, their existence has had an increasingly strong influence on the atmosphere, especially in the last century. It becomes the force that is able to disrupt the regular course of life on Earth and lead to a disaster. The amount of energy consumed by humankind is increasing every year. This leads to an increase in the entropy production in the atmosphere and makes it less resistant to possible natural disasters that can bring the amount of entropy production to the value of the atmosphere transitioning to another quasi-stationary non-equilibrium thermodynamic state until now unknown by the humanity. Moreover, in accordance with the above conclusions, this transition should occur through non-stationary (unpredictable) states, which has recently begun to manifest itself in the atmosphere through a certain change in the Earth's climate. From a new state with a greater production of entropy, the thermodynamic system will be able to return to its original state, as already noted, only through the ice age.

It should be especially noted that by now humanity has accumulated such an amount of energy in nuclear warheads that the simultaneous release of only a part of it will lead to an increase in the entropy production in the atmosphere, exceeding many natural disasters. For example, the entropy production as a result of the consumption of energy resources by mankind is currently of the order of $\approx 10^{10}$ J/(s·K), that is without the increase in the entropy production due to the greenhouse effect. Also, a simultaneous (within 1 s) explosion of only part of all existing nuclear charges in an amount equivalent to 100 Mt will lead to the entropy production increasing by $\sim 10^{15}$ J/(s·K) that is without the change in the balance of radiant energy between space and the Earth as a result of a large number of aerosol particles during the explosion, which will significantly reduce the transparency of the atmosphere. For example, during the eruption of one of the most powerful volcanoes in recent centuries, Tambora (Indonesia), the active phase lasted about 10 days and according to some estimates released $\approx 8.5 \cdot 10^{19}$ J, the entropy production increased by $\approx 10^{11}$ J/(s·K) (without the greenhouse effect and the decrease in the transparency of the atmosphere due to the large number of aerosol particles).

It is possible to assess the impact that fossil fuel energy has on changes in the state of the atmosphere, and hence the climate on Earth, by the amount of primary energy consumed by humanity. There are a number of organizations that keep regular statistics on primary energy, such as the International Energy Agency (IEA), the Energy Research Institute of the Russian Academy of Sciences (ERI RAS). Primary energy is often measured using a ton of oil equivalent (toe) equal to 41.868 GJ. This amount of thermal energy is released during the combustion of one statistically mean ton of oil. For hydro and wind energy, as well as solar energy, the produced electricity itself is considered primary. In practice, the calorific values of different fuels or even the same fuel of different grades differ, and statistics take this into account. According to the statistics of ERI RAS, the world consumption of primary energy in 2020 amounted to 15130 million toe, or $0.63346 \cdot 10^{21}$ J/year. This energy after consumption is converted into heat, which could warm up the entire mass of air in the atmosphere by ~ 0.12 degrees per year. The world ocean accumulates some of this energy, some of it due to the melting of glaciers, and prevents the atmosphere from heating up quickly. For example, if all this thermal energy were used only for the melting of glaciers, then it would be possible to melt about $1.9 \cdot 10^{12}$ tons of ice, which equals 2100 km^3 of ice. To visualize, this volume can be represented in the form of an ice cover 3 m thick occupying a square field with a side of ~ 840 km. To estimate the influence of this thermal energy ("thermal pollution" of the atmosphere) on the state of the atmosphere, we compare it with the annual change in the balance of radiant energy caused by changes in the Earth's albedo.

The weather news from Fobos as of 20th October, 2021 indicates that according to the data of the US observatory and satellite measurements over the past 20 years the terrestrial aurora (light reflected from the planet) has become less bright. The earth is fading, reflecting less light per square meter today than it did 20 years ago. In Figure 6, circles represent the results of studies of the Earth's reflectivity, carried out since 1998 by astrophysicists from the Big Bear Observatory in California [17]. The research results indicate a decrease in the reflectivity of the Earth (albedo), expressed in a decrease in the power of the reflected flux per unit area of the globe (W/m^2). Also in Figure 6, triangles represent similar research results based on the data of the CERES satellite system for 2001-2019. The researchers suggest that the decrease in albedo is associated with a change in cloud cover and a decrease in the area of sea ice (especially in the Arctic) and land ice. As the ice cover diminishes, the Earth absorbs more radiation. The extra absorbed radiation heats the oceans and melts more ice, which could cause greater warming through a vicious feedback loop.

If we fit the data obtained at the Big Bear Observatory over the past 20 years as a linear dependence (dashed lines in Figure 6), it can be seen that the Earth's albedo has decreased by ≈ 0.6 W/m^2 over this period of time. On average, annually it decreased by 0.6 / 20 = 0.03 W/m^2. When using data from the CERES satellite system, the average annual increase in the radiant energy of the sun absorbed by the Earth due to the decrease in albedo was 0.065 W/m^2. The primary energy consumed by mankind in 2020 lead to 0.04 W/m^2 in the amount of heat released into the atmosphere per unit of time (s) and unit area of the globe (m^2). This amount of heat is comparable to the annual increase in the radiant energy of the sun absorbed by the Earth's surface due to a decrease in albedo. The total annual growth of these two types of energy increases the entropy production in the atmosphere and its temperature leading to climate change.

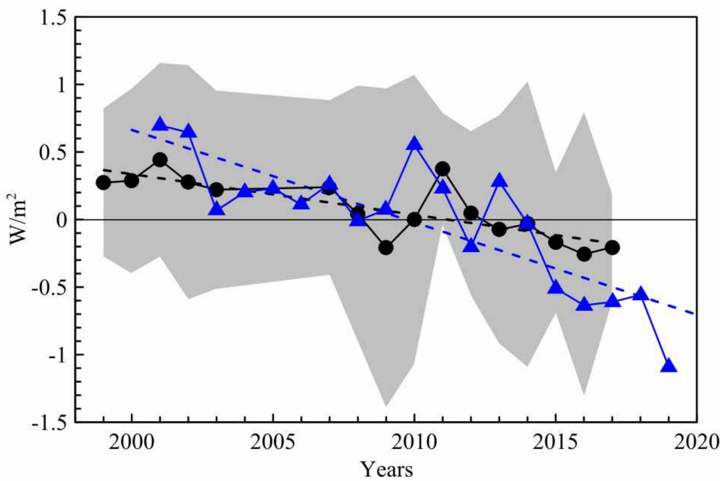

Fig. 6. Annual average anomalies of the Earth albedo in 1998-2017, expressed as a reflected flux in W/m^2 (Error is highlighted in grey)

Climate scientists suggest that the main cause of Earth warming (Fig. 7) is the greenhouse effect, namely the increase in greenhouse gas emissions into the atmosphere associated with industrialization that began in the mid-19th century. Greenhouse gases are gases with high transparency in the visible range of sunlight and high absorption in the mid- and far-infrared ranges.

Water vapor is the main greenhouse gas contributing up to 70% to the greenhouse effect. An increase in atmospheric temperature caused by various factors increases the evaporation of the world's oceans and the total concentration of water vapor in the atmosphere, which, in turn, increases the greenhouse effect. On the other hand, an increase in humidity contributes to an increase in cloudiness, and clouds in the atmosphere not only block the Earth's infrared radiation, which increases the greenhouse effect, but also reflect direct sunlight thereby increasing the Earth's albedo.

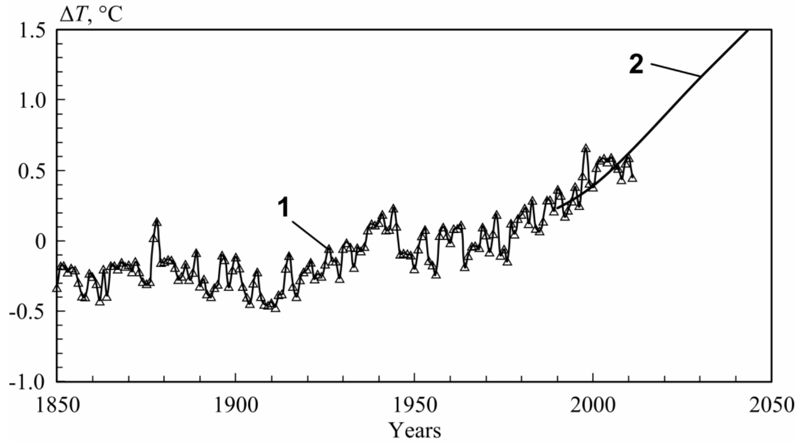

Fig. 7. Changes in the global mean surface air temperature;
1 – instrumental measurement data (CRU2012); 2 – B2 scenario (IPCC 2001)

The second most important greenhouse gas in the atmosphere is carbon dioxide, whose concentration in the atmosphere, according to some data has increased by ≈ 50% since the industrial revolution (Fig. 8). This is the reason why this gas is currently assumed to be the cause of the global warming. But is it? When a 50% increase in the CO_2 content in the atmosphere is mentioned, nothing is said about the multiple increases in the energy consumed by mankind over this period. For example, global primary energy production increased approximately 40 times between 1860 and 2015. According to ERI RAS forecasts, it will increase by ≈ 1.24 from 2015 to 2040. This energy is radiated into the atmosphere in the form of heat. However, these emissions are currently not taken into account, and the entire fight against warming has been focused only on carbon dioxide and, first of all, on fossil energy, as the main source of CO_2 increase in the atmosphere. To determine the effect of hydrocarbon fuel on the concentration of CO_2 in the atmosphere, it is necessary to determine the change in its concentration as a function of the amount of carbon dioxide released during fuel combustion. Since, according to the IEA, in the current energy sector, primary energy production is composed by more than 80% of hydrocarbon fuels, it can be assumed that the curve of CO_2 concentration in the atmosphere as a function of the amount of primary energy consumed by humanity will be similar to the graph of the same parameter as a function of the amount of carbon dioxide released during fuel combustion.

Figure 9 shows the annual ratio of CO_2 concentration in the atmosphere to the amount of consumed primary energy. It can be seen that this dependence decreases exponentially and tends to zero. The graph indicates that the concentration of CO_2 in the atmosphere over the years practically ceases to respond to the burning of each successive million toe. It follows that it is not the carbon energy that is causing the sharp increase in the concentration of CO_2 in the atmosphere. This is also indicated by other authors, according to which the current annual anthropogenic share of CO_2 in its growth does not exceed 0.3...2.5% [3]. There is not a single reliable piece of evidence confirming the primitive hypothesis of S. Arrhenius about the climate on

Earth being determined by only one factor: concentration of carbon dioxide in the atmosphere. In accordance with this hypothesis, the temperature of the atmosphere changes due to changes in CO_2 concentration. In fact, the opposite is true. There is direct evidence that the change in the CO_2 content in the atmosphere is a consequence of temperature changes, and not a cause [18, 19]. So, for example, first there occurs a change in the temperature of the ocean, with much larger amount of CO_2 compared to the atmosphere, and then, after a certain period of time, the concentration of carbon dioxide in the atmosphere begins to change [19]. It is important to note the role of CO_2 in photosynthesis. An increase in the concentration of CO_2 in the atmosphere leads to a greener Earth.

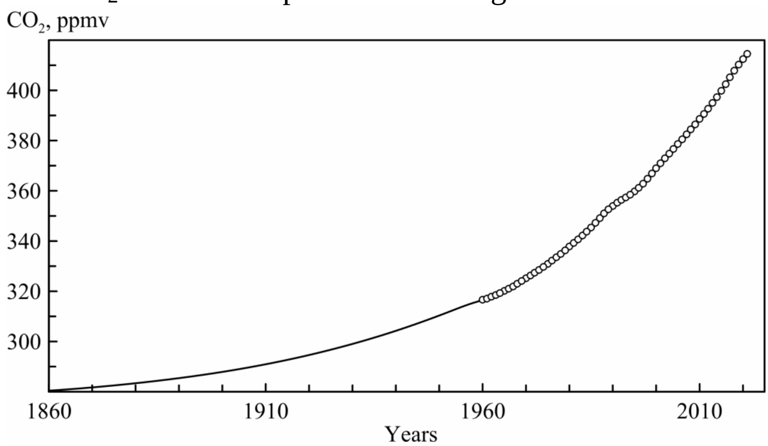

Fig. 8. Changes in the annual average concentration of CO_2 in the atmosphere. Dots represent data from Mauna Loa observatory (Hawaii)

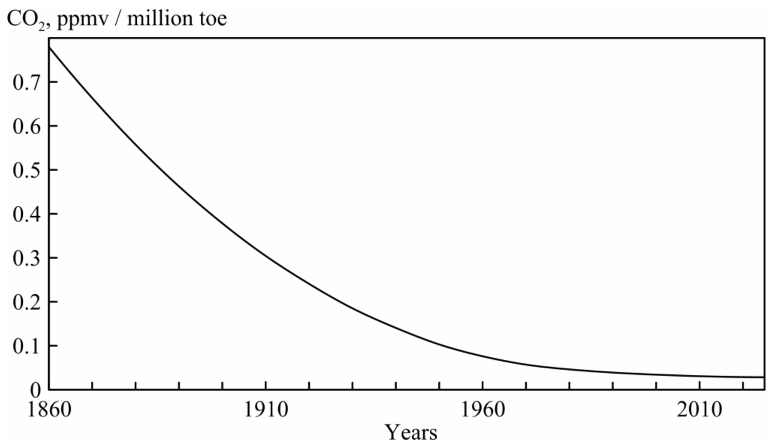

Fig. 9. Ratio of CO_2 concentration in the atmosphere to the amount of consumed primary energy

In recent years, in connection with climate change on Earth, there has appeared discourse on "green" energy and, in particular, hydrogen energy, where hydrogen is used as fuel. The main advantages of such energy are considered to be a large amount of heat released, water vapor and zero carbon dioxide emission when hydrogen is burned in oxygen, as opposed to combustion of hydrocarbon fuels. But some significant shortcomings are hushed up. Hydrogen is the most common element in the universe. However, on Earth, it is present mainly in a bound state. Therefore, energy is required in order to break its chemical bond with another element, for example, an oxygen atom in the process of water electrolysis. The electrical energy is supplied from power plants. Other disadvantages of using hydrogen as a fuel are the complexity of its storage and transportation, high fire and explosion hazard, and the cost of its production.

Let us consider the energy costs required for the production of "pure" hydrogen and its further use to obtain net external work. Naturally, this process will be multi-stage. Let us consider in general terms the conversion of thermal energy into a given net external work (N_{net}) per unit time by means of 3 successive energy converters (Fig. 10). By the efficiency η of the energy converter we mean the ratio of the obtained net effect (as a rule, net external work) to the primary inputs of thermal or other types of energy: $\eta = J_L / J_E$, where J_L is net external work per unit time; J_E is the energy flow entering the converter per unit time. According to the first law of thermodynamics, the net external work of the converter is equal to the difference between the energy supplied to the converter J_E and the heat that the converter emits into the environment J_Q: $J_L = J_E - J_Q$. Each converter has its own efficiency:

$$\eta_1 = \frac{J_{L1}}{J_{E1}} = \frac{J_{E1} - J_{Q1}}{J_{E1}} = 1 - \frac{J_{Q1}}{J_{E1}}; \qquad (1)$$

$$\eta_2 = \frac{J_{L2}}{J_{E2}} = \frac{J_{E2} - J_{Q2}}{J_{E2}} = 1 - \frac{J_{Q2}}{J_{E2}}; \qquad (2)$$

$$\eta_3 = \frac{J_{L3}}{J_{E3}} = \frac{J_{E3} - J_{Q3}}{J_{E3}} = 1 - \frac{J_{Q3}}{J_{E3}}. \qquad (3)$$

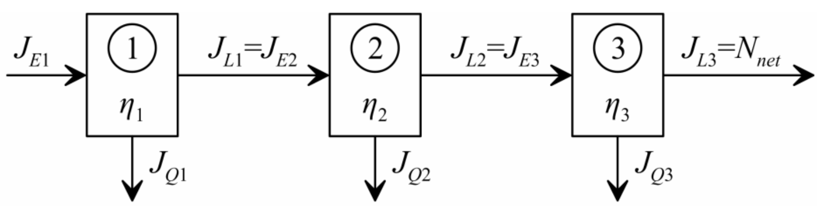

Fig. 10. Block of energy converters

Using (1)-(3) we find the relationship between the energy supplied J_{E1} to the block of converters 1-3 and the net external work per unit time at the output of the block $N_{net} = J_{L3}$

$$J_{E1} = \frac{N_{net}}{\eta_1 \cdot \eta_2 \cdot \eta_3}. \qquad (4)$$

We write the amount of heat discharged into the environment per unit time by three energy converters as:

$$J_{Q\Sigma} = J_{Q3} + J_{Q2} + J_{Q1} = N_{net}\left[\left(\frac{1}{\eta_3} - 1\right) + \frac{1}{\eta_3}\left(\frac{1}{\eta_2} - 1\right) + \frac{1}{\eta_2 \cdot \eta_3}\left(\frac{1}{\eta_1} - 1\right)\right]. \qquad (5)$$

Let us consider the process of converting the thermal energy of nuclear (NPP) or thermal (TPP) power plants (converter 1) into electrical energy generated by a fuel cell (converter 3) that consumes hydrogen, which is produced in converter 2. We will assume that to obtain hydrogen in converter 2 the best developed and researched method at present, i.e. electrolytic method of water decomposition, is used. In the electrolytic method, electric current is passed through an electrolyte solution. Depending on the type of electrolyte (alkaline, with solid oxide electrolyte, etc.), the efficiency of this method of hydrogen production can reach $\eta_2 = 50...90\%$. The efficiency of operating thermal power plants and nuclear power plants are in the range $\eta_1 = 35...60\%$, with thermal power plants using a combined cycle (CCP) are characterized by the maximum efficiency The efficiency of hydrogen fuel cells reaches $\eta_3 = 60...70\%$.

Using formula (4), we will determine the values of the energy supplied to the converter 1 by the converter 3 to generate a given net power N_{net} for the cases corresponding to the minimum and maximum efficiency of the converters. For the case of minimum efficiency for all three converters, we write $J_{\frac{E1}{\max}} = \frac{N_{net}}{0{,}35 \cdot 0{,}5 \cdot 0{,}6} = 9{,}52 N_{net}$, i.e. at the minimum efficiency values, the thermal energy to be supplied to the 1st converter must be 9.5 times greater than the net power generated by the 3rd converter. At the maximum efficiency values of all three converters, respectively, we have $J_{\frac{E1}{\min}} = \frac{N_{net}}{0{,}6 \cdot 0{,}9 \cdot 0{,}7} = 2{,}65 N_{net}$.

It follows from the above that the production of hydrogen using electric current and the subsequent conversion of its energy using fuel cells back into electric current (for example, to drive a car) leads to a significant increase in thermal energy emissions into the atmosphere at the same net output power. If, during the transition to hydrogen energy, fossil energy resources are used to produce hydrogen, then they will be needed many times more than currently consumed. This will lead to a more significant increase in the production of entropy in the atmosphere and will accelerate the process of climate warming on Earth.

In recent years, the rapid development of solar and wind powerplants suggested them as potential substitutes to thermal power plants using hydrocarbon fuels. But are they so environmentally friendly enough to be called "green"? Most solar powerplants use silicon to convert sunlight into electricity. Currently, these powerplants convert 13...20% of the radiant solar energy hitting them in the visible and infrared wavelengths into electricity. Most of the remaining energy is converted into heat, which can heat silicon panels up to 40…70°C. Moreover, with each degree over 25°C, the efficiency of the panel drops by about ~ 0.5%, and, accordingly, the efficiency of the solar powerplant. The heat from the panels is removed by convection into the atmosphere warming it up. In this case, the solar battery, like greenhouse gases, absorbs some of the radiant energy and heats up the atmosphere. At the same time, if greenhouse gases absorb radiant energy only in the infrared wavelength range, then solar panels absorb it in the visible range, preventing this radiation from reaching the earth's surface and reflecting from it into space, which leads to a decrease in the Earth's albedo.

Operating thermal powerplants and gas stations have a higher efficiency in comparison with solar powerplants. Therefore, if all thermal powerplants are replaced by solar power plants, the "thermal pollution" of the atmosphere will increase many times, and this is without taking into account the decrease in albedo. If solar powerplants are used to produce clean (green) hydrogen for hydrogen energy industry, thermal emissions into the atmosphere can increase by more than an order of magnitude. All this will contribute to a significantly greater heating of the atmosphere, an increase in the entropy production up to a critical value.

Solar powerplants have many other disadvantages, for instance: on cloudy days and at night, solar energy is not available; their efficiency depends on external factors (precipitation, temperature, direction toward the sun, etc.); the high cost of both manufacturing and disposal of silicon photovoltaic cells; the need for large areas; the need for batteries.

Wind farms use wind energy to generate electricity. Today, the coefficient of wind energy utilization, which equals the ratio of the power received by the wind generator shaft to the flow power acting on the wind surface of the impeller, reaches $\eta_{wind} = 40\%$, the remaining 60% of the flow power is converted into heat while the vortices after the blades dissipate. This efficiency is comparable to the efficiency of nuclear powerplants. However, wind turbines have a number of disadvantages: their efficient operation requires not only the force of wind, but also its constant direction; the turbine blades create low-frequency noise that has a negative impact on humans and scare away animals, as well as endanger the lives of birds; they are placed on huge areas open to winds, changing the landscape of the area; the cost of electricity they generate is higher than the cost of available grid electricity.

It should also be noted that the atmosphere is a physical system and, as such, conforms to the energy, mass, and momentum balance equations. The energy balance describes the radiation, heat and other energy flows passing through the boundary of the atmosphere and generated inside it. The momentum balance determines the atmospheric circulation, which ultimately determines the local temperature and distribution pattern of winds, clouds, and precipitation. All these types of balance are closely linked. Therefore, if wind farms generate most of the world's electricity consumption, the impulse balance can be significantly disturbed, which should lead to a change in both circulation flows in the atmosphere and its heat balance. Currently, this impact of wind farms on the Earth's atmosphere has never been studied and is not being looked into.

It is very difficult to increase the efficiency of a wind farm above 40% in order to reduce the amount of thermal energy discharged into the atmosphere. And as mentioned above, climate change is determined by the amount of heat released into the atmosphere per unit time. A smaller amount of heat emitted into the atmosphere during the production of the same amount of electricity can currently be obtained by using thermal combined-cycle powerplants (CCP) with an efficiency of 60% or more. At the same time, the hydrocarbon neutrality of these thermal power plants can be ensured by installing appropriate filters at the outlet of combustion products to the atmosphere. Even greater efficiency of these stations (80-90%) can be achieved by using the heat flows removed from them to heat houses and supply them with hot water or to cool the air in hot weather using lithium bromine refrigerators. In this case, the lowest "thermal pollution" of the atmosphere will be provided. Diverting heat flows from solar and wind powerplants for heating houses is impossible.

It follows from the above that in the production of the same amount of electricity, thermal power plants with high efficiency discharge significantly less heat into the atmosphere than solar and wind powerplants. The use of combined cycle powerplants (CCP) will reduce the "thermal pollution" of the atmosphere and reduce the growth rate of entropy and temperature production in it.

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