2000

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ECOLOGICAL-AND-THERMOECONOMIC METHOD OF ANALYSIS OF REFRIGERATING EQUIPMENT EFFICIENCY

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A new conception of ecological-and-thermoeconomic method of analysis for evaluation of efficiency of using energetic resources in refrigerating equipment is reported. New ecological-energetic coefficients are formulated which reflect anthropogeneous influence of greenhouse gases ejection at refrigerating technique exploitation on the process of global warming of the Earth climate.

INTRODUCTION

In the recent years technological progress in refrigeration industry has been to a considerable extent caused by going over to new ozone-safe refrigerants. However, main regulations of the Convention on restricting greenhouse gases ejections [1], and recommendations on the growth of ecologically stable energetics which have been formulated for the European Union [2] force to evaluate in a new fashion the experience of the world community in solving global ecological problems connected with using refrigeratory equipment.

Anthropogeneous influence of refrigerating technics on the environment is now higher than anytime before. The industry produces more than 100 mln compressors annually [3]. Refrigeration engineering consumes near 12.85 GW·h which is 10 to 20% of the electric energy produced by the industrial countries [4]. In 1995 emission of haloid derivative refrigerants was 0.65 Mt, and it was equivalent to 2.674 Gt of CO_2.

Because of high closure of CO_2 rotation processes, its atmosphere concentration has grown twice in recent 100 years. Annual CO_2 ejections in Europe are now seven times higher than the standard value which, according to specialist's opinion [2] is equal to 1.1 t of CO_2 per head. By this reason it is insistently recommended to state members of the European concord to accept new legislative deeds concerning ecology, such as CO_2/energetic tax, toughening standards of permissible emission of haloid derivative refrigerants, taxation of output of equipment with low energetic efficiency [2]. All these state measures must finally favor not only energy saving but also significant shortening of greenhouse gases ejections.

The field of use of nature refrigerants (inflammable, as a rule) is expanded, and it needs more detailed study. It is impossible to make stress only on negligible value of the global warming potential (GWP) of such nature refrigerants as ammonia or hydrocarbons. One must take into account that the use of inflammable refrigerants will demand additional energy expenses for obtaining constructional materials in order to ensure safe exploitation of refrigeratory equipments [5-8]. Nature is indifferent to causes of additional emission of greenhouse gases during artificial cold production: either it was due to low energetic efficiency of the machinery, or because of leakage of a refrigerant with high value of the GWP, or for the expense of the energy expenditures for obtaining constructional materials of the secondary heat carrier heat exchangers, and compressor workshop building, and the work of pumps and ventilators etc.

The situation in refrigeratory engineering arisen due to seeking optimal refrigerants alternative to R12, R502 and R22 is not accidental. Fundamental methodological error done when choosing new refrigerants has been connected with an attempt to solve appeared macroecological problems using the well self-recommended, but wrong in this case, methods. It is already evident that neither calculating methods of analysis of thermodynamic cycles, nor technics-and-economics and thermoeconomical methods of evaluating efficiency, even at extended accounting for physical and chemical properties of working substances and various technological factors can give a right idea about refrigeration engineering influence on the environment.

Comparative testing of refrigerating machines with various refrigerants is also not a way to quantitative estimation of anthropogeneous influence on nature of individual factors characteristic for compared working substances and their thermophysical, and, all the more, ecological properties. The obtained results of testing must be rather referred to the model of refrigerating machine than to the evaluation of perspectives of new working substance using. So, only conclusion on possible adaptation of new refrigerant to specific model of the refrigerating machine can be obtained as a result of the exploitation tests.

Ecological trend of the problem was initially lost in the overwhelming majority of publications on the turning to alternative refrigerants, where above-mentioned methods of analysis have been used. As a rule, attempts to solve some concrete problems were made, for example, evaluation of efficiency of heat exchangers with various refrigerants [9], or thermodynamic perfectness of new working substances in specific models of refrigerating equipment [7]. However, an influence of the obtained results on general goal function was not considered there, because it has initially remained unformulated. So, traditionally used methods of evaluating efficiency have not been adjusted for solving ecological problems. In addition, when solving concrete tasks of practice, it is too doubtful to determine precise analytical correlations between greenhouse gases emission and economic and social consequences of global climate warming process.

By this reason, development of methods of analysis which should be based on quantitative regulation of any one of main anthropogeneous factors is seemed more pragmatic. Emission of greenhouse gases may be, first of all, one of such factors; its admissible level had been determined rather precisely [11]. Kyoto Protocol regulations [1] will be realized with not only observance of measures for restricting CO_2 ejections at burning organic fuel by electric power stations and emission of halide derivatives of hydrocarbons (including refrigerants). The problem of developing normative ecological-energetic legislative basis is seemed even more important. There is a need in new system of indicators for observance of ecological standards when making energetic audit and management, and it would be worked out in the nearest years. It will help to force machinery not rationally using carriers, raw and construction materials out from the market.

ECOLOGICAL-THERMOECONOMICAL METHOD

The first steps towards development of modern methods of ecological-energetic analysis of efficient use of new ozone-safe refrigerants were made in the paper [10]. There a new criterion named *TEWI* (Total Equivalent of Global Worming Impact) was proposed for more full accounting energetic and ecological factors which influence on the growth of the greenhouse effect. According to the authors' opinion, it takes into account not only direct input of refrigerants' emission in the total radiative forcing, but also indirect input of CO_2 ejections at producing electric power needed for refrigerating equipment exploitation.

The method had some steps of its development, and the *TEWI* expression has the following final form:

$$TEWI = GWP_R L_R N + GWP_R m_R (1-\alpha) + GWP_{LA} M_{LA} + \beta EN, \qquad (1)$$

where GWP_R and GWP_{LR} stand for Global Warming Potentials of the refrigerant and foaming agent correspondingly, kg/year; L_R stands for refrigerant leakage, kg/year; N stands for the time of equipment exploitation, year; m_R stands for the refrigerant mass in the installation, kg; α stands for the refrigerant part which has been utilized after exploitation; M_{LR} stands for foaming agent mass, kg; β stands for CO_2 emission during generation of 1 kW·h of electric power, CO_2 kg/(kW·h); E stands for annual electric power expense for equipment exploitation, (kW·h)/year.

One of the main shortages of proposed method of *TEWI* calculation is incomplete taking into account of all energy expenses connected with making and safe exploitation of refrigerating technics working on flammable refrigerants. In addition, extensive parameter *TEWI* cannot be used as an indicator for ecologic-and-energetic analysis of refrigerating equipment of various output. These obstacles restrained wide use of *TEWI*-analysis to a considerable extent, merely in the cases when equipment with negligible emission of working substance was considered.

The method of *TEWI*-analysis was further developed in the papers [5-7,12] where it was recommended to take into account additional energetic expenses E_i for making equipment, machine-room, ensuring safety measures, and renovation, and repairs when an indirect contribution should be calculated:

$$TEWI_N = TEWI + \sum_{i=1}^{n} \beta E_i \ . \tag{2}$$

Certain merit of such *TEWI*-analysis conception is an ability of its adaptation to detailed methods of efficiency analysis [13-17]. In such approach, system research of refrigerating equipment efficiency and scientific justification of ways of its ecologization can be done on the grounds of equations of energetic and material balances of all kinds of energy carriers used for artificial cold production. Full-scale taking into account of energetic resources used for raw materials production and making equipment, and energy losses caused by irreversibility of processes in refrigerating machine is a necessary demand to correctness of making up the equations of energy balance.

It is quite evident that anthropogeneous influence on nature must be minimized when making optimization of technical devices. There is a need in working-out of new criteria which should determine an upper boundary of this minimum in every specific case. Ecological space for CO_2 may be used for such natural boundary. This term must be understood as maximum velocity of CO_2 adoption by the atmosphere without sufficient global warming even in distant future. As it has been previously mentioned, ecological space per person was estimated equal to 1.1 t of CO_2 per year [2]. Since ejections of CO_2 and other greenhouse gases become the cause of global ecological catastrophe connected with the process of the Earth climate global warming, it seems just logical to integrate the method of TEWI-analysis proposed by Fisher [10] in the detailed methods of thermoeconomical optimization [13-17].

Such method must take into account not only irreversibility of the processes in the plant and direct emission of greenhouse gases, but also all energy expenses for making and exploitation of the equipment including expenses for preventing and compensating a damage caused to the environment.

Future industry growth must be based on the conception of decreasing ejection of radiatively active gases per person, and carrying CO_2/energy tax [2] into effect should considerably favor it. Emission rates must be determined uniformly for all gases having appreciable input the growth of the greenhouse effect at all stages of generation and consumption of energy. This approach can be realized within the frames of ecological-thermoeconomical method of analysis. The essence of this conception is in integrating thermoeconomic methods with the procedure of calculating *TEWI* [10]. In this case, when analyzing refrigeratory equipment, Total Equivalent of Global Warming can be calculated with the following formula:

$$TEWI_N = GWP_R LN + GWP_R m(1-\alpha) + GWP_{LA} M + \beta E_{EX} N + \sum_{i=1}^{n} \beta E_i \ , \tag{3}$$

where E_{EX} stands for exergy at the compressor input, which can be calculated by the following formula:

$$E_E = \left(L_{COMP} + L_{DR}\right)_{INNER} + \left(L_{EVAP} + L_{COND} + L_S + L_{RHE}\right)_{OUTER} + L \ , \tag{4}$$

where L_{COMP} stands for the exergy losts in the compressor, which, in their turn, can be represented as a sum of indicator L_i and mechanical L_{MECH} and electric ones; L_{DR} stands for the exergy losts in the throttle; L_{EVAP}, L_{COND}, L_S, and L_{RHE} stand for exergy losts in evaporator, condenser, sucking line, and regenerative heat exchanger; L stands for minimal theoretic work which must be spent in Carnot reversible cycle for producing given refrigerating capacity Q_o

$$L = Q_o / \varepsilon_C \ , \tag{5}$$

where ε_C stands for the refrigerating coefficient of cooling of inverse reversible Carnot cycle within the interval of environment temperature T_{EN} and mean temperature $T_{S\,mean}$ of cool carrier (or cooling chamber temperature)

$$\varepsilon_c = T_{S\,mean} / \left(T_{EN} - T_{S\,mean}\right). \tag{6}$$

Calculation of total exergetic coefficient is the ultimate aim of various variants of thermoeconomic analysis:

$$\eta_{EX} = \left(E_{EX} - \sum_{i=1}^{n} n_{i-k} \right) \Big/ E_{EX} \ , \tag{7}$$

It does not quantitatively reflect an effect of anthropogeneous influence on nature caused by equipment exploitation. Nevertheless, exergy losts can, in contradiction with cooling capacity Q_0, be transformed to equivalent emission of CO_2. So, calculating energy losts within the frames of thermo-economic method and enclosing them in the $TEWI_N$ balance structure, one can estimate ecological damage and, on the other hand, obtain a whole row of new ecology-and-energy coefficients which reflect an efficiency of energy use. To do that, let us consider balance scheme of $TEWI_N$ contributions which is illustrated by he following diagram:

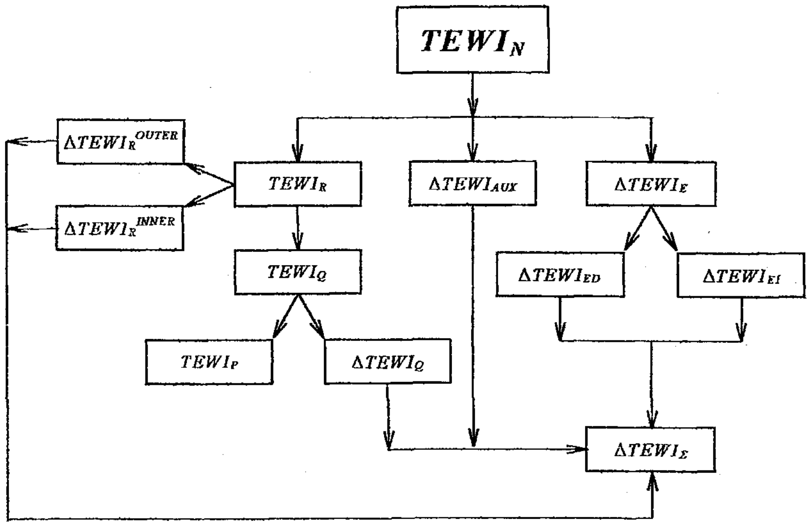

Figure 1. Balance scheme of $TEWI_N$ contributions at cold production.

Here $TEWI_N$ stands for Total Equivalent of Warming Impact; $TEWI_R$ stands for CO_2 emission at rationally used energy for cold production; $TEWI_Q$ stands for CO_2 emission when generating energy being converted into cold; $TEWI_P$ stands for CO_2 emission when generating energy being spent for cooling products (from usefully spent part of exergy); $\Delta TEWI_R^{OUTER}$ stands for indirect contribution of outer irreversibility of processes in refrigerating equipment in $TEWI_N$; $\Delta TEWI_R^{INNER}$ stands for indirect contribution of inner irreversibility of processes in refrigerating equipment in $TEWI_N$; $\Delta TEWI_Q$ stands for CO_2 emission due to nonrationally used energy spent on cooling interchamber equipment and compensating heat flows into the cooling chamber; $\Delta TEWI_E$ stands for the component of $TEWI_N$ connected with emission of the refrigerant, foaming agents of heat insulation, and energy expenses for obtaining construction materials and manufacturing refrigerating equipment; $\Delta TEWI_{ED}$ stands for direct contribution in $TEWI_N$ of the emission of the refrigerant and foaming agents of heat insulation; $\Delta TEWI_{EI}$ stands for indirect contribution in $TEWI_N$ from energy expenses for obtaining construction materials, manufacturing equipment, renovation, and ensuring fire safety measures; $\Delta TEWI_{AUX}$ stands for the contribution in $TEWI_N$ of auxiliary equipment exploitation (pumps, ventilators); $\Delta TEWI_\Sigma$ stands for contribution in $TEWI_N$ of nonrationally used energy at cold production.

Energetic equivalents as to obtaining unit mass of construction materials must be also used at calculating $TEWI_{EI}$. They can be obtained by the method which have been published in the paper [18].

$$E_i = \sum_{j=1}^{n} m_j P_j + \sum_{k=1}^{m} E_{EE} , \qquad (8)$$

where m_j stands for the mass of separate parts of the compressor or refrigerating plant as a whole, kg; P_j stands for power consumption of j-th constructing material, kWh/kg; E_{EE} stands for energy expenses for manufacturing refrigerating plant assembly under consideration.

Literature data on energy consumption materials [18] are slightly different because of difference in the efficiency of technological processes of their obtaining. But this circumstance does not play, in principle, a role in making an analysis of perspectives of some refrigerant using, because there are several reasons:

- in the first place, keeping to conditions of comparability of compared objects supposes a priori that the values of P_j are not varied;
- in the second place, the first term in Eq.(8) affects slightly the value of $TEWI_N$;
- but small power refrigerating plants are an exception to the rule [5];

In other words, change of material capacity connected with turning to alternative refrigerants will insufficiently affect the values of ecological-thermoeconomic indexes.

Correct formulation of principles of determining the value of $\sum\sum E_{EE}$ is sufficiently complex. The fact is that energy expenses for manufacturing refrigeration machinery affect in this or that way the values of various calculation items: cost of bought articles and half-finished products; energy expenses for technical aims; transport and procurement expenses; expenditure for keeping and exploitation of equipment and so on. In this connection, energy capacity accumulated during previous technological processes of manufacturing bought articles, and energy expenditure of refrigeration machinery plant itself is carried to finished production. Even such calculation items as wages which, as it seems, does not connected with energy expenditure, reflects certainly the level of energy consuming outside the plant. For example, in 1985 near 36% of energy resources of the U.S.A. were spent on domestic needs and trade (27% of them – on cooling and air conditions); annual energy consumption was $9.7\cdot10^4$ kW·h per head [19].

So, a hart of wages and ecological taxes in total cost of produced output is sufficiently large in industrial countries. So, the value of E_{EE} may be evaluated with cost price S, which, in its turn, can be determinated by specific expenditure indices (per mass unit, or power, or refrigerating capacity, per 1 m^2 of heat transferring surface of analyzed refrigerating machine, and so on:

$$E_{EE} = S_D / T, \tag{9}$$

$$S_D = S_A \frac{P_D}{P_A}, \tag{10}$$

where T stands for electric power tariff cost; S_D and S_A stand for prime cost of designed machine and its analog; P_D and P_A stand for mass, refrigerating capacity, power, heat transferring surface etc. of designed machine and its analog.

Being though pragmatic, reported method of calculation of E_{EE} and, consequently, $\Delta TEWI_{EI}$ is sufficiently justified, because a number of technics and economics indices which can be used for comparison of variants under consideration, is usually restricted on initial stages of "optimal working substances."

The components of $TEWI_N$ can be calculated with the following formula:

$$TEWI_R = \beta E_{EX} N. \tag{11}$$

$$\Delta TEWI_{ED} = GWP_R LN + GWP_R m(1-\alpha) + GWP_{RL} M. \tag{12}$$

$$\Delta TEWI_{EI} = \sum E_i \beta. \tag{13}$$

$$\Delta TEWI_R^{INNER} = (L_{COMP} + L_{DR})\beta N. \tag{14}$$

$$\Delta TEWI_R^{OUTER} = (L_{EVAP} + L_{COND} + L_S + L_{RHE})\beta N. \tag{15}$$

$$TEWI_Q = TEWI_R - \Delta TEWI_R^{OUTER} - \Delta TEWI_R^{INNER}. \tag{16}$$

$$TEWI_L = TEWI_Q - \Delta TEWI_Q. \tag{17}$$

$$TEWI_P = (\text{energy needed for cooling products})\ \beta N. \tag{18}$$

$$\Delta TEWI_Q = (\text{heat flows to the freezing chamber+interchamber equipment cooling})\ \beta N. \tag{19}$$

$$\Delta TEWI_\Sigma = \Delta TEWI_R^{OUTER} - \Delta TEWI_R^{INNER} + \Delta TEWI_Q + \Delta TEWI_{ED} + \Delta TEWI_{EI} + \Delta TEWI_{AUX}. \tag{20}$$

Several coefficients characteristic for ecology-and-energy efficiency of using energy resources can be obtained within the frames of the proposed balance scheme of contributions to $TEWI_N$. Here they are:

1. Coefficient of reduced emission of greenhouse gases

$$tewi = \frac{TEWI_N}{TEWI_Q}. \tag{21}$$

This coefficient characterizes a degree of ecological safety (as to greenhouse effect) of obtaining a unit of cold (exergy of cold). The value of *tewi* is always greater than unity. Its low value corresponds to low level of ecological damage at generating unit of exergy of obtained cold.

2. Coefficient of direct ecological influence of refrigerating storage

$$\delta = \frac{TEWI_R}{TEWI_N} = 1 - \frac{\Delta TEWI_E}{TEWI_N}. \quad (22)$$

This coefficient is always less than unity. It characterizes ecological influence of greenhouse gases emission when manufacturing refrigerating equipment and ensuring its safe exploitation. Making ecological examination, it must choose the refrigerant having the higher value of this coefficient. It is expedient to evaluate the coefficient of direct ecological influence when making examination of perspectives of a flammable refrigerant use, because it takes into account CO_2 emission due to energy expenses connected with obtaining construction materials of refrigerating storage and auxiliary equipment.

3. Coefficient of indirect ecological influence of refrigerating storage

$$\gamma = \frac{TEWI_P}{TEWI_R} = 1 - \frac{\Delta TEWI_R^{INNER} + \Delta TEWI_R^{OUTER} + \Delta TEWI_Q + \Delta TEWI_{AUX}}{TEWI_R}. \quad (23)$$

It characterizes a level of inner and outer losts of exergy at refrigerating storage exploitation. This coefficient is always less than unity. It rises with lowering heat flows into the freezing chamber, rationalizing refrigerating cycle and optimal choice of auxiliary equipment.

4. Coefficient of ecological-thermoeconomic perfection

$$\varphi = \frac{TEWI_P}{TEWI_N} = 1 - \frac{\Delta TEWI_\Sigma}{TEWI_N}. \quad (24)$$

This complex coefficient gives the means to evaluate ecological-thermoeconomic perfection of obtaining artificial cold, taking into account nonrational expenditure of energy resources when making equipment and its exploitation, and direct emission of the refrigerant and foaming agents. It is obviously that:

$$\varphi = \delta \gamma. \quad (25)$$

5. Coefficient of energy use when exploiting refrigerating equipment

$$\mu = TEWI_P / TEWI_R. \quad (26)$$

It is often happened in practice that the most perspective refrigerant must be selected from a whole row of others. In this case it is expedient to use following coefficients:

6. Coefficient of ecological expediency

$$\eta_{EE} = \frac{TEWI_{NR} - TEWI_{NRalt}\left(TEWI_{QR}/TEWI_{QRalt}\right)}{TEWI_{NR}}, \quad (27)$$

where subscript *"alt"* refers to alternative refrigerant. If the turn to alternative refrigerant is expedient, then $\eta_{EE}>0$.

7. Coefficient of ecological perfection

$$\eta_P = \frac{TEWI_{NR}\ TEWI_{QRalt}}{TEWI_{NRalt}\ TEWI_{QR}}, \quad (28)$$

It must be greater than 1, i.e. $\eta_P>1$.

Proposed coefficients (21)-(28) are varied within rather wide limits. They are sensitive to variations of factors on which the value of $TEWI_N$ depends. It assists in adopting well-grounded decisions which should lower anthropogeneous influence of used engineering on nature. Besides, these coefficients may form a basis for working-out of new normative-and-legal documentation, the aim which is development of future strategy of development of refrigeratory machine-building.

Ecological-thermoeconomic method of analyses is not alternative to existing methods of estimation of refrigerating equipment efficiency [9, 13-17]. On the contrary, known methods of study of the efficiency do not contradict it, but can be harmoniously adjusted with the conception of ecological-thermoeconomic analysis. At the same time, coefficients proposed here, permit to look in a new fashion at such universally recognized concepts as a class of energetic efficiency of equipment in which ecological aspects were not reflected.

As it is know, countries of European Union , when turning to alternative refrigerants, orientate themselves more and more on wide using of nature working substances, ammonia in the first place. Because of its flammability and toxicity, there is a need in working out a row of measures to ensure safe exploitation of refrigeration machinery. For example, cooling systems with intermediate cool carrier lessen a quantity of ammonia in the mounting, but efficiency of refrigerating equipment is sufficiently lowered in this case. Additional heat exchangers and control units to check ammonia leakages and ventilation systems etc. – all this leads to additional energy expenditure and environment damage when exploiting refrigeratory equipment grows.

As an example of how the said factors are counted it is possible to present the results of the research on the expediency of transferring a refrigerating machine to cool the air MBB3-2-2 to alternative refrigerants (see. Tabl.1)

Tabl.1

Value of ecological - thermeconomic characteristics for refrigerating machine MBB3-2-2 at 5% level refrigerant leakage.

Refrigerant	$TEWI_N$	*tewi*	δ	γ	φ
R404A[1]	256074	2.46	0.69	0.59	0.41
R407C[1]	172311	2.32	0.69	0.63	0.43
R410B[1]	247094	2.08	0.77	0.62	0.48
R134a[1]	135382	2.63	0.63	0.60	0.38
R22[1]	194325	2.20	0.73	0.63	0.45
R717[1]	138692	1.62	0.78	0.79	0.62
R717[2]	147929	1.73	0.73	0.79	0.58
R717[3]	159690	2.34	0.69	0.62	0.43

[1] installation of direct cooling;
[2] the increase of the installation cost by 30 % (fire-preventive measures);
[3] installation with intermediate refrigerant.

Calculation show that the increase energy spending on making refrigerant equipment considerably changes the values of ecological-thermoeconomic coefficients. Thus they confirm the wide possibilities of the methods of analysing alternative refrigerants in refrigeration technology.

CONCLUSION

Method of ecological-thermoeconomic analysis gives the means to take correctly into account such factors as energetic efficiency of use of this or that working substance, material expenses when making the storage, refrigerant flammability, and emission of greenhouse gases, and attested quality of exploitation of refrigerating equipment. The method has multifunctional character, and it may be used at various steps of study of ecological-energetic characteristics, beginning from the analysis of refrigerant use efficiency within the frames of various models of thermodynamic cycles, and ending with studying real systems as their technical realization is complicated (compressor system → refrigerating machine → refrigerating storage → refrigeration technology). Obtained results will reflect anthropogeneous influence of refrigeration engineering on nature. Besides, ecological-thermoeconomic method may be successfully used for ecological-energetic audit and management of plants using refrigeration technologies.

Realization of measures for obtaining optimal values of proposed coefficient will favor the development of ecologically stable energetics, characterized by stabilization of greenhouse gases ejection on the level, which does not cause dangerous anthropogenous changes of the Earth climate.

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