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NEW INDICATOR FOR THE ASSESSMENT OF THE LIFE CYCLE OF GREENHOUSE GASES EMISSION OF HOUSEHOLD REFRIGERATING APPLIANCES

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Abstract. A method of eco-energy analysis of household refrigerating appliances based on the life cycle of GHG emission assessment is presented. A new eco-energy efficiency indicator is proposed. Calculation of the eco-energy efficiency indicator and traditional energy efficiency index for three household refrigerators has been performed. The qualitative difference in the results of comparison of these indicators for the analyzed refrigerators is shown.

Key words: GHG emission, energy-saving, life cycle analysis, household refrigerating appliance.

1. Introduction

The technological progress in the refrigeration industry, as well as in other industries, is focused on energy saving. In addition, for the last decades the refrigeration industry has been developed within the framework of international legislation such as the Montreal Protocol (limiting the use of ozone-depleting substances) and the Kyoto Protocol (GHG emission reduction).

The problem of replacing the ozone-depleting refrigerants in refrigeration industry can be considered to be practically solved. But as for the compliance with the requirements of the Kyoto Protocol everything is much more complicated. The refrigeration industry is responsible for essential direct and indirect contribution to global warming. Firstly, air conditioning and refrigeration systems are responsible for high consumption of electricity. In accordance with UNEP report [1], refrigeration and air conditioning systems in developed countries consume from 10 to 30 % of the country's total electricity demand. It is well known that the main part of the GHG anthropogenic emission is due to the production of electricity by the organic fuel burning at power plants. Furthermore, ozone-non-depleting hydrofluorocarbon refrigerants that are used in vapor compression refrigeration systems have a high value of global warming potential (GWP). Recently, "natural" refrigerants with a low value of GWP such as isobutane, propane, NH_3, CO_2 have been applied in refrigeration much wider. But the problem of total replacing of the hydrofluorocarbon refrigerants has not been solved yet [2]. It can be concluded that both using "natural" refrigerants and reducing the energy consumption by air conditioners and refrigerators will lead to the decrease in the GHG emission by the refrigeration industry.

The manufacturers of the household refrigerating appliances have made efforts to enhance their energy efficiency class [3]. But at designing new equipment they do not take into account the issues of decreasing the refrigerators life cycle GHG emission. The manufacturers have used different ways to reduce the energy consumption of household refrigerating appliances: choice of optimal refrigerant, enhancement of the quality of thermal insulation, modernization of refrigerator design. But such improvements often lead to an increase in energy and material expenditures on manufacturing household refrigerating appliances. Therefore, the manufacturing indirect contribution to total GHG emission also increases. Taking into account this fact, it can be concluded that low electricity consumption household refrigerating appliances are not always environmentally friendly. Thus, the author considers that the life cycle analysis with the use of energy and environmental indicators is needed for choosing the direction of equipment modernization with the purpose of their energy efficiency enhancement.

The brief review of studies devoted to the environmental analysis of the refrigeration systems

[4–12] allows us to conclude that lately the life cycle climate performance (LCCP) assessment has been the most used method. The conception of this method is in estimation of the equivalent emission of GHG for refrigeration equipment life cycle. In 2016 International Institute of Refrigeration (IIR) developed the guideline of the life cycle climate performance (LCCP) evaluation of heating, ventilation, air conditioning and refrigeration (HVAC&R) systems [13]. But in author's opinion, the main drawback of LCCP assessment is the simplified approach to evaluation of the GHG emission at household refrigerating appliances manufacturing and the lack of consideration of the energy equivalent of human labor in refrigeration equipment manufacturing.

It should be noted that scientists have also used other methods based on GHG emission evaluation for the environmental assessment of air conditioning and refrigeration systems. For example, Carbon Footprint Assessment (CFA) [10, 11], Total Equivalent Warming Impact (TEWI) [9], etc. A number of ecological impacts are considered only in the framework of Life Cycle Assessment LCA [12]. But the author considers that the main drawback of LCA is the uncertainty of the weight coefficients that is used at summarizing different ecological impacts such as ozone depletion potential (ODP), global warming potential (GWP), emission of NO_x, SO_2 etc.

The main purpose of this study is developing a methodology of life cycle analyzing of household refrigerating appliances, which is based on the consideration of GHG emissions and does not require the hard-to-reach information as input data. In addition, a new eco-energy efficiency indicator is proposed for comparison of household refrigerating appliances with both different storage volume of compartments and different life cycle. The proposed method is used for the analysis of three household refrigerating appliances of the same manufacturer.

2. Method of eco-energy analysis of household refrigerating appliances

Currently, the basic energy characteristic of household refrigerating appliance is daily electricity consumption. This value is used to calculate the Energy Efficient Index – *EEI* of the household refrigerating appliance [3]. The energy efficient class is estimated by the value of *EEI*.

The *EE*I is calculated as

$$EEI = 100 \cdot \frac{AE_C}{SAE_C}, \quad (1)$$

where SAE_C is annual energy consumption of the household refrigerating appliance, kW·h; SAE_C is standard annual energy consumption of the household refrigerating appliance, it should be evaluated by [3], kW·h.

In recent years, the main line of the household refrigerating appliances design is aimed at increasing their energy efficiency class. But the criteria for eco-energy efficiency assessment of household refrigerators have not been developed and implemented in practice yet.

In author's opinion, the *EEI* cannot be used as an integral characteristic for the estimation of the perspective of a new generation of equipment. The main reason is that *EEI* takes into account the equipment energy consumption at its operation. At the same time, the environmental aspects of designing, operation and disposal of refrigeration appliances are not considered. It should be noted that in UNEP report [1] the necessity of the reduction of the life cycle GHG emission at designing energy-intensive refrigeration systems is emphasized.

In accordance with the mentioned above, it is reasonable to use the method of evaluation of the total equivalent GHG emission in refrigeration industry [14–17] for the development of new eco-energy indicators for household refrigerating appliances. The method of the total equivalent GHG emission (*TEGHGE)* in refrigeration industry has been proposed in [14-17]. The whole production string is considered in this method. Its product is artificial cold. The GHG emission at manufacturing, operation and disposal of the equipment, including emission connected with human activity is taken into consideration.

For household refrigerating appliance analysis the equation for *TEGHGE* [14–17] can be written as

$$TEGHGE_{HR} = \sum em_i \cdot m_i^{comp} + \sum em_{util\,i} \cdot m_i^{comp} + $$
$$+ em^{h.l} \cdot T^{h.l} + b \cdot E_{annual} \cdot t$$
$$+ m_R \cdot GWP_R \cdot L_{annual} \cdot t + m_R \cdot GWP_R \cdot g_{R\,util}, \quad (2)$$

were em_i is manufacturing GHG emission for a unit of the *i*-th material used at manufacturing of the equipment, kg CO_2-eq·(kg of the material)$^{-1}$; m_i^{comp} is the mass of the *i*-th material used at creation of the equipment, kg; $em_{util\,i}$ is GHG emission at utilization and recycling of *i*-th material used at manufacturing of the equipment, kg CO_2-eq·(kg of material)$^{-1}$; τ is the average lifetime of the equipment, years; $em^{h.l}$ is equivalent GHG emission from human labor, kg CO_2-eq·(man-hour)$^{-1}$; is labor expenditures for manufacturing of the equipment, man-h; β is an average indirect emission factor for a certain region (country), kgCO_2-eq·(kW·h); E_{annual} is the annual electricity consumption of household refrigerating appliance, kW·h; m_R is refrigerant charge, kg; GWP_R is the global warming potential of the refrigerant, kg CO_2-eq·(kg of the refrigerant)$^{-1}$; L_{annual} is the part of annual refrigerant leakage; $g_{R\,util}$ is the part of the refrigerant end of the lifetime leakage.

The Eq. (3) is recommended to be used for calculating the value $em_i \cdot m_i^{comp}$ (first term of Eq. (2)) if the element of the equipment requires sufficiently large energy and human labor than material resources on its manufacturing. The Eq. (3) can be used at roughly calculating the indirect GHG emission at controllers and electricals manufacturing. This approach for comparative analysis is admissible for such reasons: the prime cost of controllers and electricals is in direct proportion with both labor expenditures and energy consumption for manufacturing these elements of equipment.

$$em \cdot m = b \cdot e_{GDP} \cdot c = em_{GDP} \cdot c, \qquad (3)$$

were e_{GDP} is energy intensity of gross domestic product (GDP) for a certain country, (kW·h)·(monetary unit)$^{-1}$; c is primary cost of equipment components, monetary unit; em_{GDP} is carbon intensity of GDP for a certain country, CO_2-eq·(monetary unit)$^{-1}$.

The data needed for eco-energy analysis using the Eqs. (2) and (3) are considered below.

The values of GHG emissions at manufacturing and recycling of some materials used in household refrigerating appliances are presented in Table 1.

Table 1

GHG emissions at manufacturing and recycling of some materials [13]

Material	Mixed manufacturing GHG emissions*, (kg CO_2-eq)·kg^{-1}	100 % recycled material manufacturing emissions, (kg CO_2-eq)·kg^{-1}
Steel	1.43	0.54
Aluminum	4.50	0.63
Copper	2.78	2.46
Plastics	2.61	0.12

* The materials were obtained from both raw materials and recycled material

Equivalent emission of human labor $em^{h.l}$ can be explained as emission connected with satisfaction of biological, material, and cultural requirements of people. According to Rugani et al. [18], this emission depends on the labor grade. For the developed countries the value of the $em^{h.l}$ is greater than for the developing countries. For the comparative analysis of one-type equipment manufactured in the same country the average value of $em^{h.l}$ =0.46 CO_2-eq·(man-hours)$^{-1}$ can be used [18].

Indirect emission factor or carbon intensity b characterizes the GHG emission at production of 1 kW·h of electrical energy. We can use the information of official site World-statistics [19] to estimate the coefficient b for a certain country. At present, the value of β for Ukraine is 0.697 kgCO_2-eq (kW·h)$^{-1}$ [19].

The values of GWP for different substances including refrigerants are presented, for example, in [20]. For the most used in household refrigerating appliances ozone-non-depleting refrigerants R134a and R600a the GWP is equal to 1300 and 20 kg CO_2-eq·(kg of refrigerant)$^{-1}$, respectively.

The values of energy intensity of GDP e_{GDP} (total primary energy consumption per dollar of GDP for different countries) and values of carbon intensity of GDP for different countries are presented in IEA Atlas of Energy [21]. For Ukraine in 2016 e_{GDP} =0.760 toe·(thousand 2005 US$)$^{-1}$=8.839 kW·h·(US$)$^{-1}$ and em_{GDP} =1,6 kg CO_2-eq·(US$)$^{-1}$.

Annual refrigerant leakage L_{annual} as well as the end of lifetime refrigerant leakage $g_{R\,util}$ for different equipment type can be taken from [22]. For household refrigerating appliances it should be recommended that L_{annual} =5 % from the part of the refrigerant charge and $g_{R\,util}$ =0.

The information on the content of different materials and components of household refrigerating appliances is not often available. Available data on the approximate structure of material and monetary expenses on household refrigerating appliance production according to the Ukrainian manufacturer information can be used as basic information. The mass percentage composition of four main materials that are applied in household refrigerating appliances manufacturing is presented in Table 2. The same information for residential heat pumps (air conditioners) is also listed in Table 2. In accordance with manufacturer information, the structure of the monetary expenses on materials (Table 2) and components (controllers and electricals) of household refrigerating appliance was 70 % and 30 %, respectively. The indirect GHG emission at producing the refrigerator components in the framework of the proposed approach should be calculated by Eq. (2).

Table 2

Household refrigerating appliances and residential heat pumps main materials percentage composition

Material	Household refrigerating appliance, %	Residential heat pumps (air conditioners) [13], %
Steel	65.4	46
Aluminum	0.6	12
Copper	29.0	19
Plastics	5.09	23

For estimation of the eco-energy efficiency of the household refrigerating appliances with a different storage volume of compartments and lifetime a new indicator is proposed

$$EEEI = \frac{TEGHGE}{V_{eq} \cdot t}, \qquad (4)$$

were *TEGHGE* is the total equivalent emission of GHG of household refrigerating appliance life cycle, kg CO_2-eq; V_{eq} is the equivalent volume of household refrigerator [3], l; τ is the lifetime of the household refrigerator, years.

The equivalent volume of household refrigerators

$$V_{eq} = \left(\sum_{C=1}^{C=n} V_C \frac{25 - T_C}{20} \cdot FF_C \right) \cdot CC \cdot BI, \qquad (5)$$

were *n* is a number of compartments; V_C is the storage volume of the compartment, l; T_C is the nominal temperature of the compartment, ºC; FF_C, *CC*, *BI* are the volume correction factors [3].

The proposed indicator can be used for justifying both choice of the alternative refrigerant and advisability of the modernization of the household refrigerators for the purpose of the enhancement their eco-energy characteristics.

3. Results of analysis

For examination, the sensibility of the proposed indicator *EEEI* to the variation of the indirect contribution in total GHG emission, the three household refrigerating appliances were analyzed. The analyzed refrigerators have approximately equal characteristics: total storage volume of compartments, temperature of freezing and cooling compartments – minus 18 ºC and 4 ºC, correspondently, the same manufacturer. The main characteristics of the analyzed household refrigerating appliances are presented in Table 3.

Table 3

The main characteristics of the analyzed household refrigerating appliances manufactured by Atlant

Model	XM-4625	XM-6323	XM-6221
Total storage volume of compartments*, l	378	371	373
Storage volume of cooling compartments V_{C1}*, l	206	256	252
Storage volume of freezing compartments V_{C2}*, l	172	115	121
Refrigerator mass*, kg	76	81	84
Daily electricity consumption*, (kW·h)·day^{-1}	0.88	0.81	0.84
Equivalent volume of household refrigerator V_{eq}**, l	586.1	516.1	524.8
Household refrigerator primary cost***, US	307	319	329

* According to the manufacturer catalogue 2019.

** Volume correction factors FF_C, *CC*, *BI* were assumed equil to 1.0 for all analised refrigerators.

*** On 1 January 2019.

The data about the refrigerator mass and primary cost has been used to calculate the *TEGHGE* value. The materials percentage composition of the analyzed household refrigerating appliances was taken according to Table 2. In addition, the expenses at the rate of about 30 % from primary cost on controllers and electricals were taken into account. It should be noted that this assumption will lead to uncertainty in the analysis results. But in the framework of comparative analysis such approach is acceptable because the household refrigerators primary cost is in direct proportion with energy, material and human labor expenses on its production. The human labor expenses on refrigerators production were assumed the same for the analyzed equipment. The average lifetime for a household refrigerating appliance was taken equal to 12 years. Refrigerant R600a is used in all household refrigerators. The mass of refrigerant charge was taken equal to 90 g, part of annual refrigerant leakage and the end of life refrigerant leakage was taken the same for the analyzed refrigerators.

The results of calculation of the energy efficiency index *EEI* and eco-energy efficiency indicator *EEEI* for the analyzed household refrigerating appliances are presented in Fig. 1.

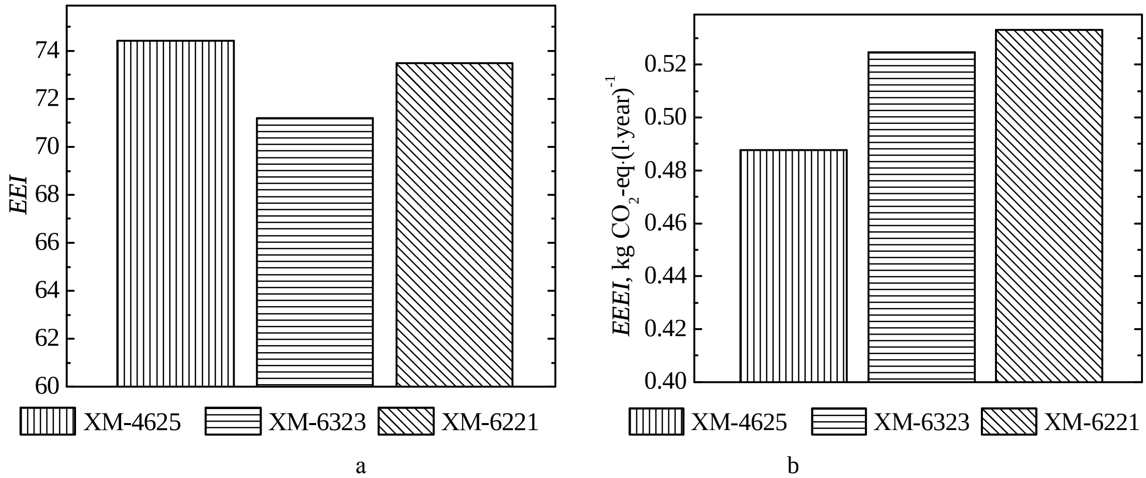

Fig. 1. The comparison of the energy efficiency index EEI (a) and eco-energy efficiency indicator EEEI (b) for the analyzed household refrigerating appliances (Table 3)

As we can see from Fig. 1 the performed analysis of energy efficiency indexes *EEI* and eco-energy efficiency indicators *EEEI* allows us to make a qualitatively opposite conclusion about the efficiency of the analyzed household refrigerators. The household refrigerator XM-4625 has the greatest value of energy efficiency index *EEI*, consequently it is the worst choice from the energy-saving point of view. But refrigerator XM-4625 is the best choice from the point of view of reducing the life cycle GHG emission. Its value of eco-energy efficiency indicators *EEEI* is the least. Most probably, the reducing of the *EEI* has been received by modernization of the household refrigerating appliance. Consequently, the increase in the indirect contribution in *TEGHGE* occurred at refrigerator manufacturing. As we can see, the increase in indirect emission at manufacturing XM-6323 and XM-6221 was not compensated by reducing the electricity consumption during exploitation. The values of energy efficiency index *EEI* are low but the eco-energy efficiency *EEEI* values are high for these refrigerators in comparison with these values for XM-4625.

Fig. 2 presents the structures of contributions in *TEGHGE* for the analyzed household refrigerating appliances. As can we see, direct contribution in *TEGHGE* for household refrigerators is insignificant. This fact can be explained both by using the "natural" refrigerant isobutane with low GWP and a small charge of refrigerant in the household refrigerating appliance.

As we can see from Fig. 2, the indirect contribution in life cycle GHG emission from electricity consumption of the household refrigerating appliance is sufficiently greater than from its manufacturing. But in the author's opinion, even the insignificant value of indirect emission at manufacturing and utilization of the household refrigerating appliance must be considered at estimation of the refrigerator modernization expediency.

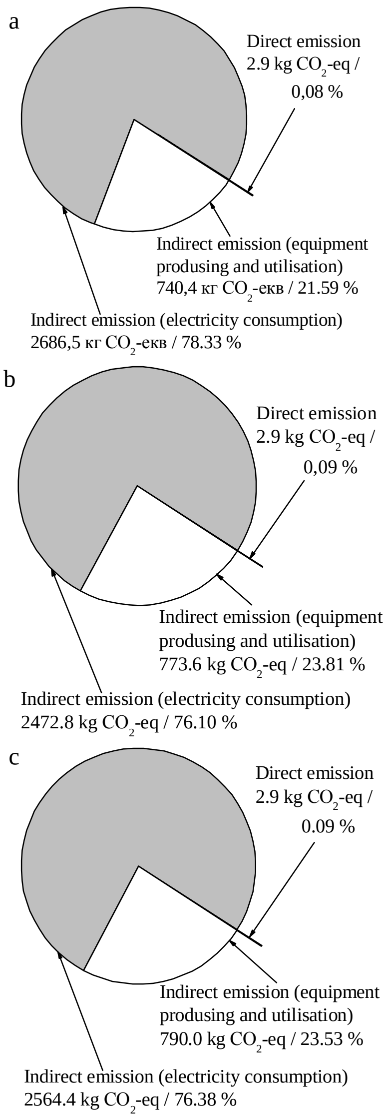

Fig. 2. Structural diagrams of direct and indirect contributions in *TEGHGE* for the analyzed household refrigerating appliances at their lifetime τ=12 years: a – XM-4625; b – XM-6323; c – XM-6221

It should be concluded that indicator ***EEEI*** proposed in this study, together with traditional ***IEE*** can be used to estimate the performance characteristics of the household refrigerating appliances. The author considers that the proposed eco-energy efficiency indicator ***EEEI*** reflects the energy and material usage at artificial cold production more accurate than the energy efficiency index ***EEI***.

Conclusion

The method for eco-energy analysis of the household refrigerating appliance has been proposed. This method is based on considering the life cycle GHG emission. It differs from LCCP that takes into account the emission connected with humane labor and does not require the hard-to-reach information as input data.

The new eco-energy efficiency indicator ***EEEI*** (total GHG emission per equivalent volume of the household refrigerator for its lifetime) has been proposed. In contrast to energy efficiency index EEI, the indicator EEEI takes into account the manufacturing and recycling stages of the refrigerators life cycle.

The performed calculation of the values ***EEI*** and ***EEEI*** for different household refrigerating appliances of the same manufacturer with the same functionality has shown qualitatively different results. Only principal possibilities of using the proposed indicator ***EEEI*** to analyze the household refrigerators are presented in the paper. The accurate information about the material expenses structure of household refrigerating appliances is required. This information is available mainly to manufacturers. The proposed indicator ***EEEI*** together with widely used energy efficiency index ***EEI*** can be used by manufacturers for efficiency analysis of new or restored household refrigerating appliances.

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