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THE IMPACT OF SELECTED COOLING SYSTEMS ON THE URBAN NATURAL ENVIRONMENT

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Purpose: The aim of the paper is to indicate the possibility of using refrigerants which do not have a harmful effect on the destruction of the Earth's ozone layer and the urban environment.
Design/methodology/approach: The environmental impact of refrigerants was characterized. Selected refrigerants and their place of application are described. The impact of selected refrigerants on the urban environment is presented.
Findings: An attempt has been made to identify the absolute environmental impact of selected stationary refrigeration systems in operation in cities, i.e. home refrigerators, individual air conditioners, heat pumps, air conditioning systems of large-format stores – shopping centers, or cold stores. Both the direct impact related to the refrigerant used in the system and the indirect one related to the energy consumption to drive the device have been considered.
Practical implications: Use of new refrigerants that do not damage the Earth's ozone layer.
Originality/value: The environmental impact of different refrigerants is presented. The paper is addressed to technical services and personnel responsible for the design and operation of refrigeration and air-conditioning equipment.

Keywords: cooling systems, refrigeration, urban environment.

Category of the paper: Viewpoint.

1. Introduction

Refrigeration, closely related to many industries, plays an important role in the modern world. It allows for creating not only a comfortable and healthy living environment, but most of all it is an indispensable means for the production, processing and storage of food. In practice, the most common are steam compressor refrigeration systems, the operation of which is based on the process of evaporation and condensation of the working medium. The operation of these systems, however, is associated with some negative impact on the natural environment, which results from the properties of working factors and CO2 emissions accompanying the process of generating energy necessary to supply the cooling system.

The depletion of the ozone layer and the impact on global warming are two major environmental problems faced by the refrigeration industry. Today it is known that CFC and HCFC refrigerants, which have been widely used in cooling systems for years, are responsible for the leakage of the ozone layer. The process of destroying the ozone layer is as follows: the CFC or HCFC factor emitted to the atmosphere in the stratospheric layer under the influence of strong UV radiation decomposes and releases a chlorine atom, which, reacting with ozone, reduces it to an oxygen molecule. The ozone depleting capacity of a substance is determined using a comparative unit known as the Ozone Depleting Potential (ODP). The discovery of the ozone hole and the identification of the substances responsible for this state were the basis for adopting the 1987 Montreal Protocol. The protocol adopted a plan for the gradual decommissioning of halogenated refrigerants (United Nations, 1987). As research and observations show, this allowed for a gradual restoration of the ozone layer (Newchurch et al., 2003). However, this is a very slow process and it is expected that only between 2040 and 2070 will it be possible to obtain the level of ozone from before the 70s of the last century. The refrigerants in use today have a zero ozone depletion potential. So it can be concluded that this problem has been solved.

Another major environmental problem is the global warming effect of refrigeration systems. It is measured by the amount of greenhouse gas emissions to the atmosphere accompanying the operation of the cooling system. It is the sum of the direct emission of the refrigerant from the installation and the emission of carbon dioxide generated during the production of energy to supply the cooling system, which is included in the TEWI index. The individual global warming potential of a refrigerant is determined by the GWP (Global Warming Potential) index. It represents the amount of infrared radiation that a substance can absorb compared to carbon dioxide (for which GWP is 1). According to reports published by IIR (Coulomb, Dupont, 2017), in 2016 refrigeration systems were responsible for 7.8% of global greenhouse gas emissions, while in 2004 this value was 1.4% (Coulomb, Dupont, 2017). This increase is mainly due to the constantly growing number of refrigerating appliances in operation. Under the 1997 Kyoto Protocol, substances with high GWPs are gradually phased out of use (Coulomb, Dupont, 2017). Thus, the direct environmental impact of the refrigerants is gradually reduced. It has been assumed that by 2030 the maximum allowable GWP of the refrigerant is to be around 450. The reduction of indirect greenhouse gas emissions by cooling systems is achieved by improving the efficiency of cooling systems and the use of low-emission or zero-emission energy sources to power them.

Currently, there are approximately 5 billion refrigeration systems in operation, including domestic, commercial and transport refrigeration systems, air conditioning systems, heat pumps as well as cryogenic systems (Dupont et al., 2019). Fig. 1 shows the share of individual sectors in this balance. According to the report published by IIR, over 40% of all refrigerating appliances in operation are domestic refrigerators (fridge-freezers). Air conditioning systems also have a large share in this balance, respectively 22% are home appliances, 10% commercial and 20% car air conditioning systems.

A significant number of cooling systems are located in cities, affecting the environment of urban spaces, directly or indirectly. The article attempts to present the impact of selected systems on this state. The total greenhouse gas emissions related to the use of selected refrigeration devices were used as a measure. For this purpose, working agents and cooling systems were characterized. In the literature on the subject, you can find a whole range of articles dealing with the impact of refrigeration systems on the natural environment. Nevertheless, none of them focus directly on the urban environment.

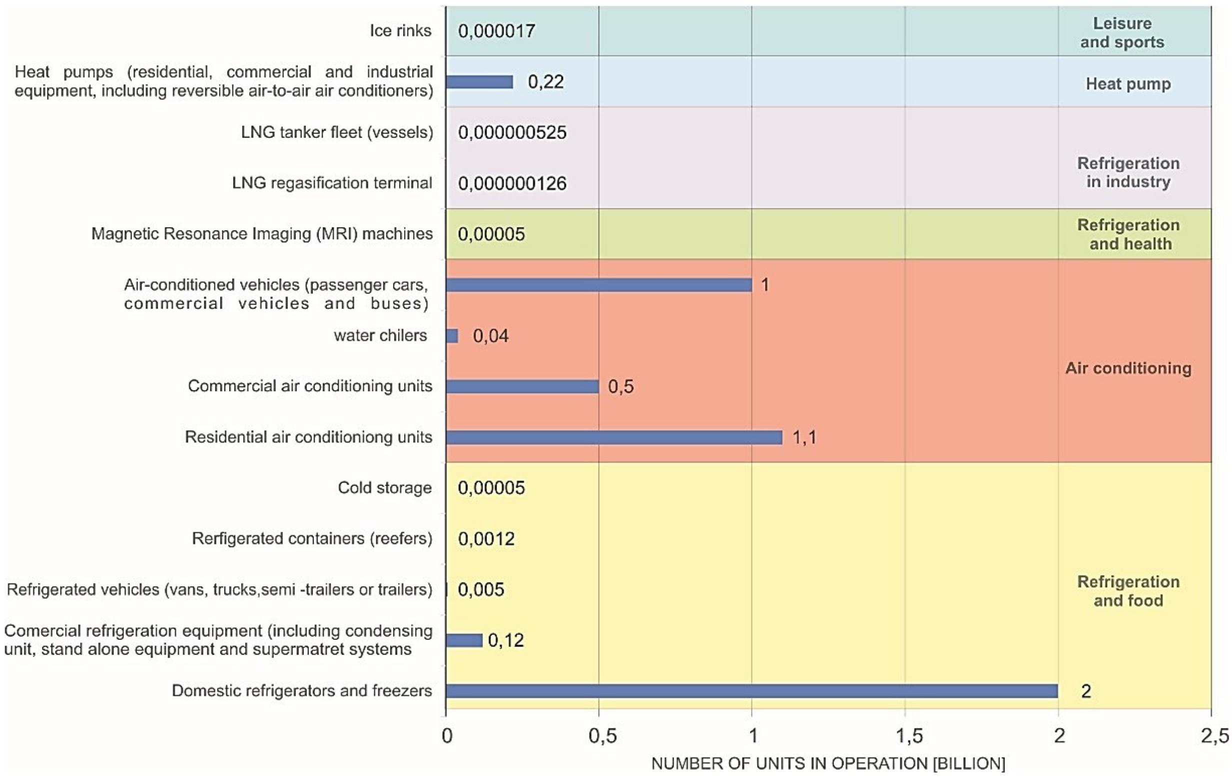

Figure 1. Number of refrigeration system in operation per application (Dupont et al., 2019)

2. Characteristics of selected cooling systems and agents

When analyzing refrigeration systems, the working factors cannot be ignored. When selecting a refrigerant for a given system, both its thermodynamic properties and safety considerations as well as the aforementioned ecological indicators are taken into account. In general, the refrigerants should have: a favorable course of the saturation curve, high volumetric cooling capacity, maintain chemical stability in the entire range of operating parameters, be chemically inert to the materials from which the system is made, and be a non-flammable, non-explosive and non-toxic substance. Table 1 shows the basic parameters of selected refrigerants commonly used in domestic and commercial systems. The table also includes examples of new refrigerants with a low GWP index, ie R1234yf, R1234ze, R32 or R450A, which are substitutes for the currently used substances.

Table 1.
Characteristics of selected refrigerants

	GWP*	ODP	Normal boiling point [ºC]	Molar mass [kg/kmol]	Critical temperature [ºC]	Critical pressure [bar]	Class	Application
R22	1810	0.05	-40.8	86.5	96.1	49.9	A1	Air-conditioning and cooling systems
R32	675	0	-51.6	52.02	78	57.8	A2L	
R134a	1430	0	-26	102.02	101.03	40.6	A1	Car air-con, air-conditioning and cooling systems
R290	3	0	-42.1	44.9	96.74	42.5	A3	medium and low temperature refrigeration
R404A	3922	0	-46.3	97.6	72.12	37.3	A1	Refrigeration, freezing
R410A	2018	0	-51.3	72.6	71.3	49	A1	Air-conditioning and cooling systems
R407C	1770	0	-47	86.2	86.1	46.3	A1	Air-conditioning, heat pumps
R600a	3,3	0	-12	58.1	134.6	36.2	A3	Cooling
R1234yf	4	0	-29.5	114.0	94.7	33.8	A2L	Air-conditioning
R1234ze	7	0	-18.9	114.0	109.4	36.3	A2L	Air-conditioning
R450A	547	0	-23.2	108.6	104.5	38.2	A1	Air-conditioning and cooling
R717	0	0	-33.3	17.0	132.4	113.6	B2L	Cooling
R744	1	0	-	44.01	31	73.8	A1	Cooling, heat pumps

* Counted on a 100-year scale,
A1 – low toxicity, incombustibility, A3 – low toxicity, higher combustibility, B2- higher toxicity, lower combustibility, A2L- low toxicity, lower combustibility,

Source: PN-EN, 2021, Lemmin et al., 2018.

As already mentioned, the analysis of the impact of refrigeration systems on the urban environment was based on selected systems. Taking into account the number of devices in operation, domestic refrigerators and individual air conditioners have been selected.

Fig. 2 shows a schematic diagram of a home fridge-freezer. A typical system consists of a hermetic compressor, a condenser, a regulating element feeding the evaporator (here a capillary tube) and an evaporator. The liquid pipeline supplying the capillary tube is routed in such a way as to heat the contact point of the refrigerator door. This has the dual benefits of preventing the door from freezing and subcooling the refrigerant fluid, increasing the cooling capacity of the unit.

The cooling capacity of modern refrigerators ranges from 60 to 300 W. The average annual energy consumption is approximately 1.8 kWh/year for each liter of refrigerated space, which is the average annual energy consumption for a 362 liter refrigerator 680 kWh. The refrigerants used in the systems are R600a, R290 and, less frequently, R134a. Filling the installation with refrigerant depends on its type and cooling capacity and ranges from 60 to 160 g. Analyzing the solutions of modern refrigerators, the defrosting process cannot be omitted. Many devices are equipped with an automatic system based on electric heaters. Their power varies from 150 to 385, depending on the size of the device. On average, the defrost cycle lasts from 6 to 12 minutes and is carried out once every two days (LG, 2019).

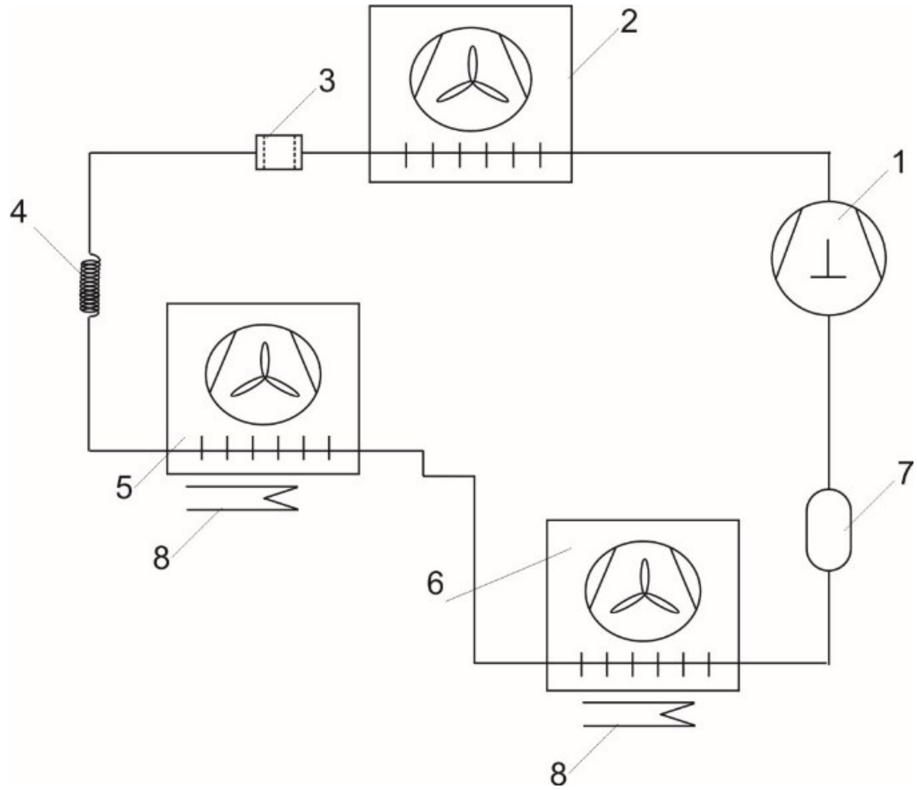

Figure 2. A schematic diagram of a "side by side" home refrigerator system: 1 – compressor, 2 – condenser, 3 – dehumidifier, 4 – capillary tube, 5 – refrigerator evaporator, 6 – freezer evaporator, 7 – liquid separator, 8 – electric defrost heater (own elaboration).

Air-conditioning and heat pump systems can be used in various configurations, in a wide range of capacities. This article focuses on individual split air conditioners (also multisplit), the efficiency of which does not exceed 15 kW. Figure 3 shows an exemplary schematic layout diagram. The use of a four-way valve (2) allows the system to work in the function of both cooling and heating. It is the most common solution that allows to shape the microclimate of rooms all year round. These systems work with the refrigerants R410A, R407C and R134a. Although there has been a trend for several years to introduce alternative substances such as R290 (Weier et al., 2017) or R744 or R1234yf (Juan et al., 2017).

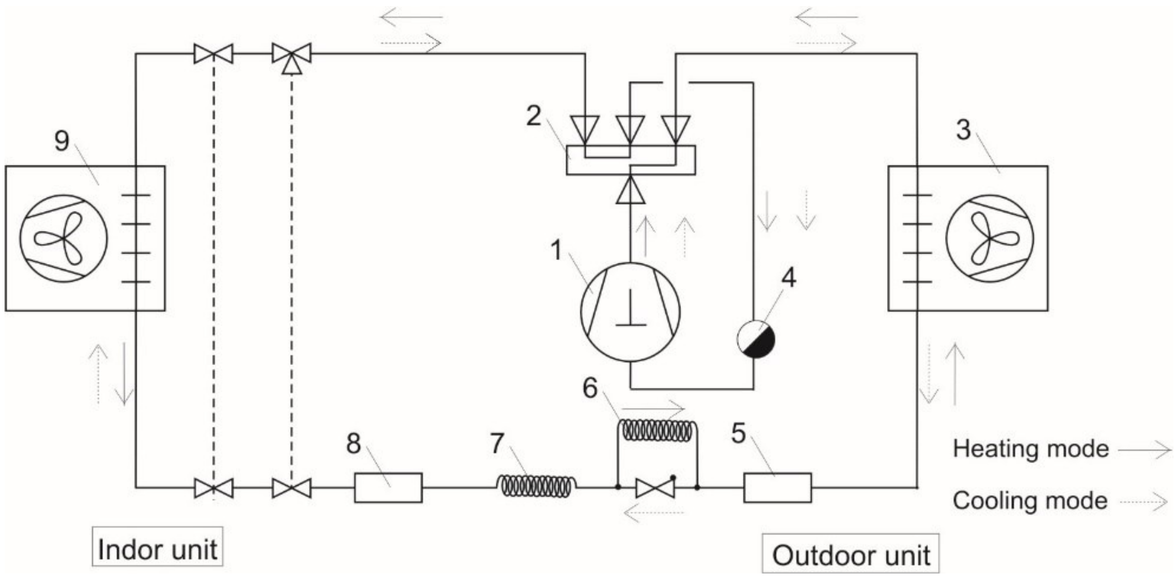

Figure 3. Concept diagram of the air conditioner/heat pump: 1 – compressor, 2 – four-way valve, 3 – condenser/evaporator, 4 – liquid separator, 5 – filter, 6 – caillary tube for heating, 7 – capillary tube for heating and cooling , 8 – filter, 9 – evaporator/condenser (own elaboration).

3. Evaluation of the impact of selected cooling units on the environment

To assess the impact of refrigeration equipment on the urban environment, the TEWI index (total equivalent of the greenhouse effect) was used (PN-EN, 2921). It is calculated in relation to the refrigerant itself and in relation to a specific refrigerating equipment. Its value changes depending on the type of device and depends on the values of parameters adopted in the assumptions, such as: operating time, service life or circulation efficiency. This indicator is described by the following relationship (United Nations, 1987):

$$TEWI = \left[(GWP \cdot L_{annual} \cdot n) + \left(GWP \cdot m \cdot \left(1 - \alpha_{recovery}\right)\right)\right] + (n \cdot E_{annual} \cdot \beta) \tag{1}$$

where:
L_{annual} – medium leak of refrigerant [kg/year],
n – system life time [years],
m – filling [kg],
$\alpha_{recovery}$ – level of refrigerant recovery,
E_{annual} – mean annual Energy use [kWh/year],
β – CO_2 emission indicator at power production [kg CO_2 /kWh].

The first part of equation (1) determines the direct influence of a refrigeration appliance on the greenhouse effect that results from the emission of refrigerants into the atmosphere L annual. To determine this effect, you need to know the refrigerant charged in the installation, the GWP value and the filling amount of the installation. The second part of the equation (1) concerns the indirect influence of refrigeration devices on the creation of the greenhouse effect. It takes into account the CO2 emission generated in the production of electric energy necessary to power the cooling device (β index), with the assumed level of average energy consumption E annual. All quantities in equation (1) must be related to the same time interval. Table 2 contains the data necessary to determine the TEWI index of domestic refrigerators. The data was compiled on the basis of publicly available information contained in manufacturer's documentation.

Table 2.
Assumptions for TEWI calculation of domestic refrigerators

Cooling efficiency [W]	300
Condensation temperature [ºC]	30
Cooling efficiency coefficient	~2.0
Evaporating temperature [ºC]	-20
Subcooling of the liquid refrigerant [K]	2
Overheating of refrigerant vapors [K]	5
Isentropic efficiency of compression	0.85
Average work time [h/day]	12
Refrigerant leakage (per year)	5%
Filling amount [g]	88 g for R600a and R290 /160g for R134a
Automatic defrost cycle	Once a day
Defrost heater power [W]	200
Average time of a single defrost cycle [min]	6
Device operation period [years]	20
β index	0.719 kgCO_2/kWh (11)

Source: own elaboration and Krajowa, 2019.

Fig. 4 presents achieved calculation results of TEWI index.

CO2 emission for each of the analyzed forfeits is practically the same. This is due to the fact that the major part of this emission is related to the process of generating electricity necessary to be fed. The direct CO2 emission related to the refrigerant for R134a is 514 kg CO2 eq, while for R290 it is 0.594 and for R600a it is 0.653 kg CO2 eq. These results relate to the time period of 20 years. Interestingly, the defrost cycle produces nearly 13.067 t CO2 eq, representing 0.55% of the total emissions. The impact of a single refrigeration system on the environment is not significant, but when the total number of devices in operation is taken into account, these numbers become more important and their share in the overall balance increases significantly.

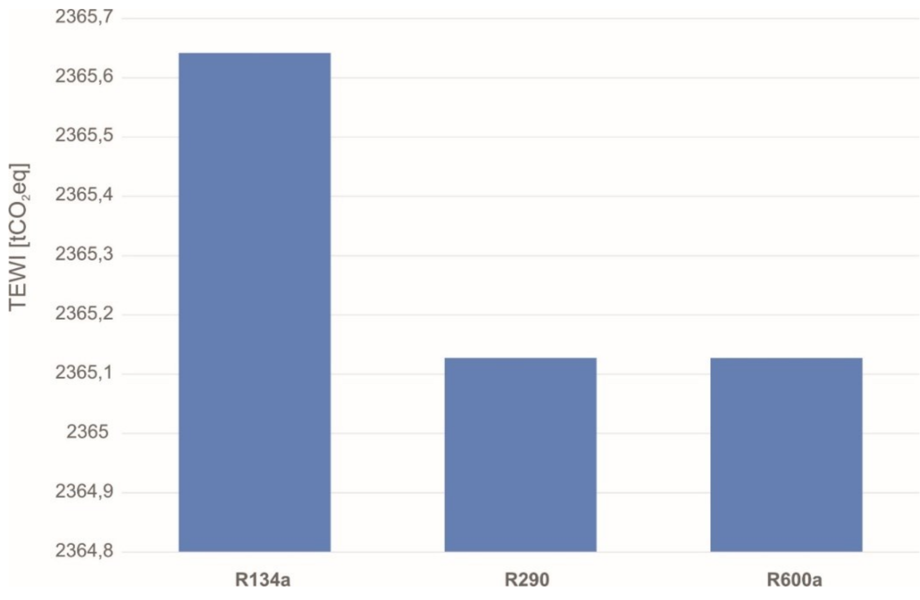

Figure 4. Comparison of the total CO2 emissions of domestic refrigerators for selected working media in the perspective of 20 years of operation.

Table 3.
Assumptions for TEWI calculation of air conditioning /heat pump unit

Nominal cooling efficiency [W]	1849	2500
Nominal heating efficiency [W]	1799	3015
Cooling efficiency coefficient Cooling / heating	~3.5 /4.0	3.68/4.4
Refrigerant leakage (per year)	5%	
Filling amount [kg]	R410A/1.450	R32/0.58
Device operation period [years]	20	20
Year of production	2001	2020
β index	0,719 $kgCO_2/kWh$	
Mean work time	250 days/8 h/day	

Source: own elaboration and Krajowa, 2019.

The calculations of the TEWI index for selected exemplary air-conditioning units have been shown in Fig. 5. The obtained values of the index were related to the efficiency of each of the analyzed devices.

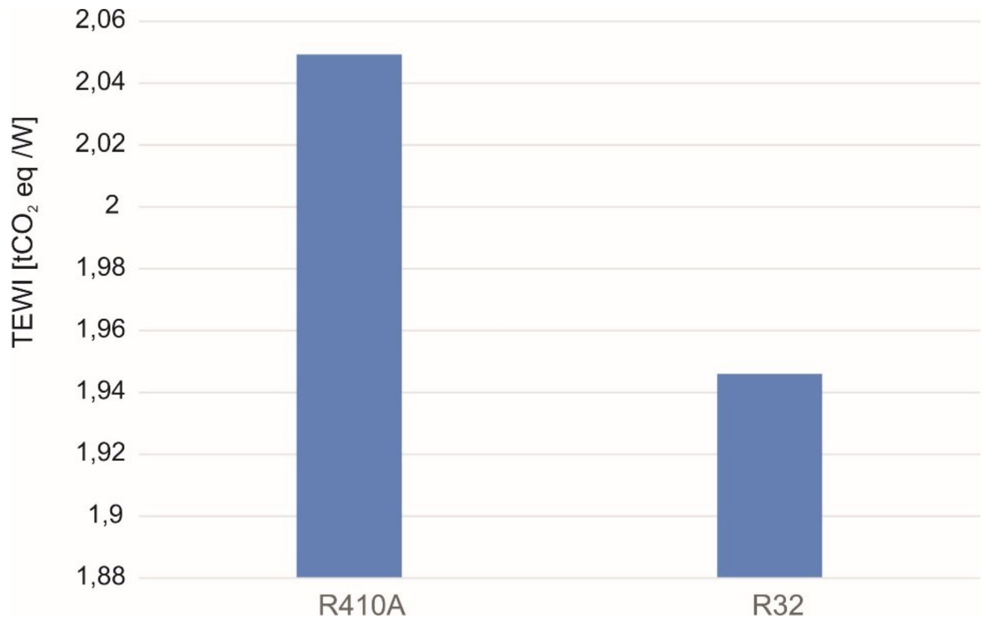

Figure 5. Comparison of CO2 emissions of air conditioners in relation to cooling capacity.

4. Conclusions

Currently, according to EU law, it is forbidden to fill new devices with the frequently used refrigerants for low and medium temperatures, i.e. R404a and R507. Since this year (2022), it is forbidden to use, inter alia, R134a, R407F and R410a. This means looking for substitutes based on pure natural agents as well as agents resulting from their mixtures. Another problem is the high prices of new, ecological substitutes, which result from the monopolization of the production of some of them.

In the coming years and in the long run, small refrigeration systems with a small load of the HFC refrigerant (in the order of a few or a dozen kilograms) will be popular for quite a long time due to relatively low investment costs. All other installations will be implemented with the use of natural factors such as: NH3 (ammonia), CO2 (carbon dioxide) and R290 (propane). These factors have virtually no impact on the greenhouse effect and will therefore be a solution for many years to come, although not all of them are suitable for use in every cooling concept.

Acknowledgements

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