technical transactions

No. 2022/005

mechanics

sciendo

Energy audit of refrigerated shelving

Tomasz Mołczan

tomasz.molczan@doktorant.pk.edu.pl | https://orcid.org/0000-0003-2149-1905

Damian Cebulski

damian.cebulski@doktorant.pk.edu.pl | https://orcid.org/0000-0001-6227-9025

Marcin Piasecki

marcin.piasecki@doktorant.pk.edu.pl | https://orcid.org/0000-0002-2718-9339

Piotr Cyklis

pcyklis@mech.pk.edu.pl | https://orcid.org/0000-0002-0188-1108

Faculty of Mechanical Engineering, Cracow University of Technology

Scientific Editor: Stanisław Młynarski, Cracow University of Technology
Technical Editor: Małgorzata Mazur, Cracow University of Technology Press
Language Verification: Timothy Churcher, Merlin Language Services
Typesetting: Małgorzata Murat-Drożyńska, Cracow University of Technology Press

Received: September 3, 2021
Accepted: March 24, 2022

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing interests: The authors have declared that no competing interests exist.

Citation: Mołczan, T., Cebulski, D., Piasecki, M., Cyklis, P. (2022). Energy audit of refrigerated shelving. *Technical Transactions, e2022005*. https://doi.org/10.37705/TechTrans/e2022005

Abstract

This article describes how an energy audit of equipment and the resulting design changes can have a major impact on reducing the electricity consumption of refrigeration equipment. The legal basis introduced by legislation forcing work on the improvement of refrigeration unit is provided. Eight points detail and describe the changes applied to the construction of cooling units. Additionally, a list of the refrigerants which are used is presented, along with the essential parameters of their work. The following analysis includes a description of the research performed along with the measured and calculated results for individual optimisations. The basic parameters that were used for comparison are: daily electricity consumption [kWh/24 h] and the temperature of the packages placed in the device [°C]. Finally, the percentage differences in energy consumption for each modernisation are summarised in a tabular form. The device used for the tests was the VARNA refrigerated rack, model 900, manufactured by P.P.H.U. JUKA Sp. z o.o. sp. k.

Keywords: energy audit, refrigeration, refrigerated shelving

Index of symbols

E_C – daily energy consumption for the examined device, kWh/24 h
E_{Lig} – lighting energy consumption for the examined device, kWh/24 h
E_{Com} – energy consumption of the chiller for the examined device, kWh/24 h
E_{Wen} – energy consumption of evaporator fans for the test subject, kWh/24 h
E_{Hea} – energy consumption of the condensate evaporation box heaters for the device under test, kWh/24 h
E_L – rated power of lighting, kWh
E_{CC} – compressor rated power, kWh
E_{WC} – rated power of condenser fans, kWh
t_w – working time of the aggregate, h
E_{WE} – rated power of evaporator fans, kWh
E_H – rated power of heaters, kWh
t_h – theoretical working time of the heaters, h
ε – COP coefficient for the device, –
q_0 – cooling unit capacity of the device, kJ/kg
l_t – theoretical unit work of compressing the device, kJ/kg
h_1 – enthalpy at the compressor suction point, kJ/kg
h_2 – enthalpy at the compressor discharge point, kJ/kg
h_3 – enthalpy at the outlet from the condenser, kJ/kg
h_4 – enthalpy at the point after the expansion element, kJ/kg

Indexes:

I – for test 1
II – for test 2
III – for test 3
IV – for test 4
V – for test 5
VI – for test 6
VII – for test 7
VIII – for test 8

1. Introduction and analysis of the literature

Refrigeration devices belong to the group of energy-consuming devices, hence the desire to improve their energy efficiency. Generally, the method used on a macro scale to improve this parameter is an energy audit. This applies not only to industrial enterprises and residential buildings but also to specific devices on a micro scale. Efficiency relates to the ratio of net energy used (or product) to the energy input. For cooling devices, the COP (coefficient of performance) is close to this definition, but unlike the pure COP of the cooling cycle, the energy cost is all the energy used, including lighting, control, fans, etc. Therefore, the methodology of the procedure should cover a broader spectrum of tests than the tests of the COP itself, i.e. the cooling cycle (Skrzypulec, Konopka-Cupiał, 2008).

Large-scale commercial networks use approx. 40–60% of their total energy demand to maintain appropriate temperatures inside refrigeration devices. This is why the development of production technology and the construction of refrigerating unit is so important (Skrzypulec, Konopka-Cupiał, 2008).

As noted by the authors of the publication on refrigerants with a low GWP coefficient (Heredia-Aricapa, Belman-Flores, Mota-Babiloni, 2019) they can be successfully utilised in devices that use a medium that pose a greater level of harm to the environment. The most popular thermodynamic factors used in refrigeration devices are R134a, R410a, R404a, but due to their negative impact on the environment, there is a current search for new refrigerants that are preferably neutral to the Earth's atmosphere. These alternatives should be factors characterised by a zero value of the ODP number (ozone depletion potential) and a low GWP factor (global warming potential).

In order to protect the environment, the Parliament of the European Union has introduced legal regulations regarding the use of factors that have a negative impact on the environment. The regulation of the European Parliament and of the Council No. 517/2014 of 16th April 2014 is the binding directive on fluorinated greenhouse gases. As a result of the regulation, developed countries have to reduce greenhouse gas emissions by 80–95% by 2050 compared to 1990 levels. According to the stipulations of the Regulation (EU) nr 517/2014, regarding the avoidance of the use of greenhouse gases, their emission should be by 2030 decrease by 1/3 in relation to the level in 2010, if alternative technologies are available (safe, energy-saving or with a low impact on the climate).

Another aspect that manufacturers must pay attention to is the energy efficiency of their solutions. In view of the above, while making an audit, a closer analysis of each and every energy-consuming device ought to be made in order to either improve its working or to exchange it for an alternative based on different technology which is significantly less energy consuming.

Valve Shaban et al. (2020) and Almogbel et al. (2020) note that the use of an inverter compressor as compared to an on/off compressor can reduce the demand for electricity by 32–44%, with a well-optimised cooling system.

Another element is lighting, the use of light points based on LED technology reduces electricity consumption by this element. Research conducted on the change of lighting throughout a house has shown that the potential benefits of introducing this change strongly depends on the number and duration of operation of individual lighting elements. Due to better efficiency of the proposed solution, less heat energy is released into the environment, which does not need to be removed from the refrigerated rack – this also affects the total daily electricity consumption (Onuma et al., 2020).

An alternative solution is to shut down devices. Chaomuang et al. (2019) and Nattawut, Flick, Onrawee (2017) point out the great benefits of this solution. When the rack is closed, the temperatures drop and the temperatures are evened out across the individual load levels. The main advantage of this solution is a significant reduction in electricity consumption.

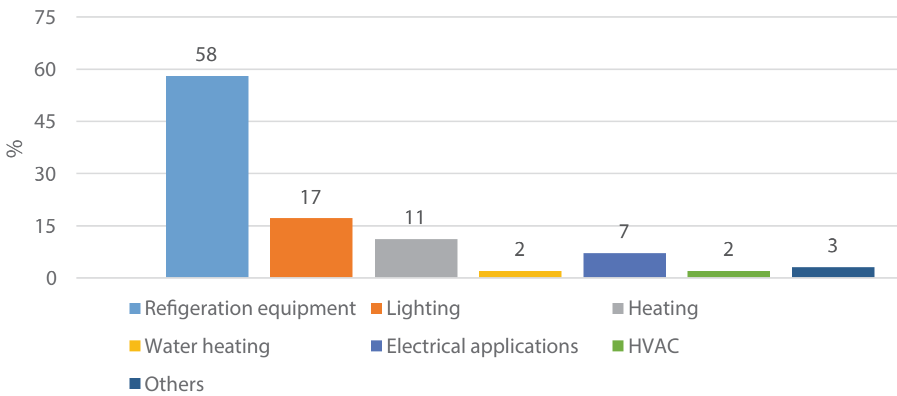

Fig. 1. Energy consumption in a typical American supermarket of approximately 4,650 m^2 (Rhiemeir et al., 2009)

2. Test conditions and device description

The cooling devices were tested in a climatic chamber at the JUKA Sp. z o.o. sp. k. production plant. The chamber allows the maintaining of the set parameters (temperature, humidity) suitable for given climatic conditions. It enables tests for all climatic classes.

The measurements were carried out in relation to the applicable European standards, the scope of which is described in table 1.

Table 1. Lists of standards (own study)

Standard	Range
PN-EN ISO 23953-1:2016-04 (EN ISO 23953-1:2015) Meble chłodnicze – Część 1: Terminologia [Refrigerated display cabinets – Part 1]	The standard contains vocabulary stipulations of' the terminology of refrigerated unit intended for the sale and display of food products. It does not apply to refrigerating machines intended for the sale of food or furniture used in food supply or for similar purposes not related to retail sales.
PN-EN ISO 23953-2:2016-04 (EN ISO 23953-2:2015) Meble chłodnicze – Część 2: Klasyfikacja, wymagania i warunki badań [Refrigerated display cabinets – Part 2: Classification, requirements and test conditions]	The standard specifies the requirements for the construction, properties and performance of refrigerated furniture intended for the sale and display of food products. It specifies the test conditions and methods of control, needed for the requirements, as well as the classification of furniture, its labelling and the list and characteristics declared by the manufacturer.

The appropriate temperature and air humidity in the room is maintained by electric heaters, a cooler and a duct humidifier. These elements are responsible for the processing of the air circulating in the test chamber. Temperature and humidity are determined as the average of the two values of the temperature and humidity sensors. The probes used are the EE210 humidity and temperature transducer from E + E Elektronik. The sensor parameters are shown in table 3. Additionally, the required air flow in the chamber (no more than 0.2 m/s) is ensured. This is performed with the use of a fan forcing air circulation and flow through a perforated wall. The flow velocity measurement is performed by a low-air velocity sensor.

The tests were carried out in conditions corresponding to the third climatic class, in accordance with the PN-EN ISO 23953-2 standard, which specifies the requirements and test conditions for a given class:

Table 2. Conditions in the third climatic class (own study)

Air parameters in the third climatic class	Range
Air temperature in the test chamber	25°C ±1°C
Air humidity	60% ±3%

The quoted standard specifies the requirements for the construction, properties and performance of refrigerated furniture intended for the sale and display of food products. It defines the test conditions and methods of control, meeting the requirements and classification of furniture (PN-EN ISO 23953-2). The chamber is equipped with electrical sockets, which are connected to the Lumel N27P power network parameter meters calibrated by the manufacturer. Technical data of the measuring instruments used are presented in table 3 (below):

Table 3. Technical data of the measuring instruments (own study)

Name	Measured parameter	Range	Accuracy of measurement	Comments	Number of measurement points
EE210	Temperature	−40 to +60°C	±2%	Parameters in the test chamber	2
	Humidity	0 to 100%	±1.3%		2
Pt 100	Temperature	−100 to +250°C	±2%	A sensor that measures the temperature inside the device	23
N27P	Active energy	0 to 999 999 kWh	±0.5%	Electrical parameters of the tested device	1
EE660	Air speed	0.15 to 1 m/s	±0.04 m/s	Parameters in the test chamber	2

https://doi.org/10.37705/TechTrans/e2022005

As previously mentioned, all the temperature meters placed in the device check the correct operation of the device. The results are automatically read and logged at fifteen-second intervals. The duration of the test is at least twenty-four hours. The test packages are placed on the shelves to fill the free space. These are arranged at intervals between each other (according to the relevant standard, the arrangement inside the device is based on the guidelines for multi-level refrigerated cabinets – five shelves with a forced cooling system) to ensure air circulation inside the device. The filling of the packages depends on whether the device in question is intended for cooling or freezing. A temperature sensor measuring the temperature inside the device is attached to the test M-package. During the measurement, it is checked whether the device reaches the set temperature (the test is performed at the minimum setting) on the controller and the minimum and maximum temperatures in the packages are determined.

Another very important parameter is electricity consumption, which is also measured during the test. The test chamber is equipped with electrical sockets that are connected to the electronic meters of the electricity network parameters.

The recording of individual parameters begins after obtaining stable conditions in the test chamber and in the device. The lighting stays on for twenty-four hours.

The test package mentioned earlier is standardised. The device uses two types of packages with the dimensions and weight shown below and in table 4. These are filled with a material with thermal characteristics similar to that of lean beef. It consists of:

- 23 g oxy ethyl methyl cellulose ±1 g
- 764.2 g water ±1 g
- 5 g sodium chloride ±0.1 g
- 0.8 g 4-chloro-3-methylphenol ±0.1 g

Table 4. Dimensions and weight of test packages (own study)

Dimensions [mm]	Weight [g]
50 x 100 x 100	500
50 x 100 x 200	1000

Some packages (M-packages) have an opening for a temperature sensor which is routed so that the probe is in contact with the package and reads its temperature, not the surrounding air. The freezing point of the filling is –1°C. Figure 2 shows the location of the measurement packages in which the temperature is measured.

2.1. Device description

The device tested is the VARNA 90 refrigerated shelf. It is a vertical, five-shelf, open device, manufactured by the JUKA Sp. z o. o. sp. k. company. The basic components of the device are: a cooling unit with an evaporator, fans ensuring the circulation of cold air, electric heaters for the automatic natural defrosting and evaporation of condensate. The main purpose of the device is to store and display food products. It is a piece of furniture intended for commercial facilities such as shops, supermarkets, petrol stations, catering establishments, etc. The usable area is 2.3 m^2. As standard, it has lighting provided by PENTURA fluorescent lamps above each shelf and on each vertical side. The climate class of the furniture specified by the manufacturer is III (maximum ambient temperature +25°C, maximum relative humidity 60%). The operating temperature range of the rack is 4–10°C, which corresponds to the product temperature class H1. The baseline tests for the model described above were carried out on the R452a refrigerant. In figure 2 (below) the dimensions are presented and the location of the temperature sensors is marked. Their distribution relates to the standard described in this chapter on testing refrigeration devices. The temperature measured in the measurement packages enables the estimation of whether subsequent changes significantly affect the temperature distribution in different parts of the device.

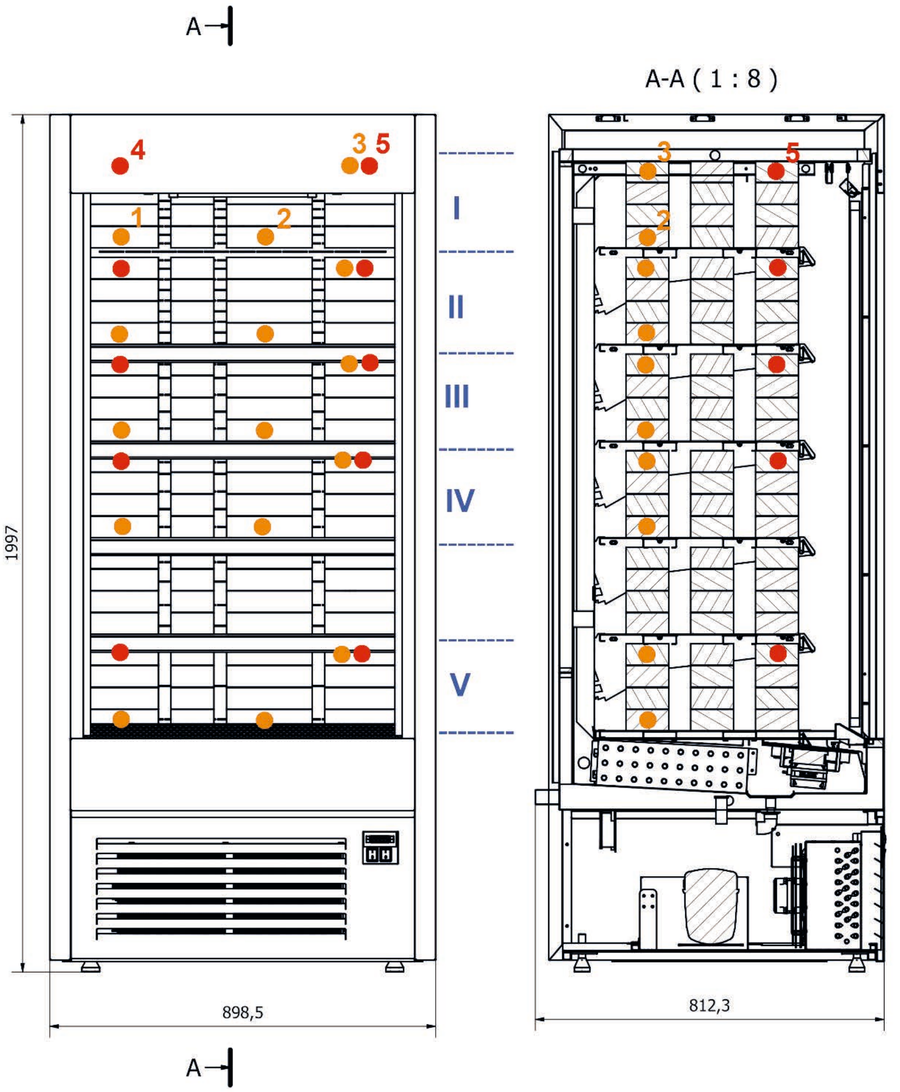

Fig. 2. VARNA refrigerated display rack with glazed sides, marked with measurement packages (I – first level, II – second level, III – third level, IV – fourth level, V – fifth level) (own study)

As shown in figure 2, the temperature inside the measurement packages is measured by a total of twenty sensors – five per shelf (viewed from the front of the device – three in the last row closest to the perforated back and two from the customer's side), each measured shelf is marked with a Roman numeral.

In addition, figure 3 (below) shows a cooling diagram of the device, which shows the individual measurement points in the system for recording both temperature and pressure during the test. On the basis of these values, the individual operating points of the system are plotted on the pressure-enthalpy diagram and this makes it possible to determine the energy efficiency coefficient. In figure 3 items are marked: 1 – steel base, 2 – condenser fan, 3 – compressor, 4 – compressor automation, 5 – dryer, 6 – condenser, 7 – condensate container, 8 – condensate heater, 9 – Schrader valve, 10 – condensate swimmer.

https://doi.org/10.37705/TechTrans/e2022005

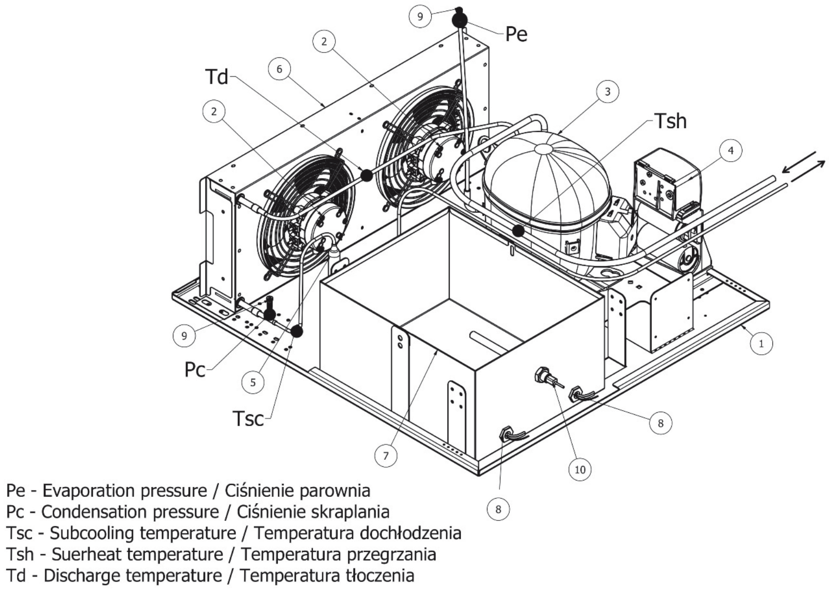

Fig. 3. A cooling diagram of the device with marked measuring points (own study)

3. Research and optimisation possibilities

The purpose of the research is an energy audit of the device in order to minimise electricity consumption. Therefore, it is necessary to estimate the energy consumption and then analyse the effect of subsequent changes on the device. The analyses omitted the power consumed by the main switch, the lighting switch and controller. This was possible because no matter what variant is considered, these elements are always present in the device. Based on the catalogue data recorded in table 5 and the measured parameters, it is possible to calculate the theoretical electricity consumption of the device, which can be described by the formula:

$$E_C = E_{Lig} + E_{Com} + E_{Wen} + E_{Hea}$$

The individual components of the daily electricity consumption can be calculated using the formulas:

$$E_{Lig} = E_L \cdot 24\ \mathrm{h}$$

$$\mathrm{E}_{Com} = \left(E_{CC} + E_{WC}\right) \cdot t_w$$

$$E_{Wen} = E_{WE} \cdot 24\ \mathrm{h}$$

$$\mathrm{E}_{Hea} = E_H \cdot t_h$$

The individual data has been calculated on the basis of the data contained in table 5. The lighting in this cabin is on all the time during the work. The theoretical operating time of the heaters was determined on the assumption that the heaters at full power operate for half the duration of the test. Each time the compressor stops, the accumulated frost on the evaporator melts; this causes water to collect in the tank, just like with defrosting, during which, more water flows into the condensate container: t_h = 12 h.

Table 5. R452a base unit – technical data (own study)

No.	Varna 90 R452	Name	Quantity	Power [W]	Sum of power [kW]	Working time within 24 hours
1	Compressor R452a	Embraco	1	769	0.769	14.6 h
2	Evaporator fan	Elco fan motor	2	38	0.076	24 h
3	Condenser fan	Elco fan motor	2	38	0.076	14.6 h
4	Condensate evaporation heater	PTC heater	2	350	0.700	24 h
5	Lighting	Fluorescent lamp L = 1223 mm Fluorescent lamp L = 623 mm	2 6	28 14	0.056 0.084	24 h

Moreover, after changing the factor, the COP calculation is performed. This is a theoretical coefficient of cooling capacity and is defined as the ratio of the cooling power to the power consumed by the unit. On the basis of the read data, it is possible to make calculations written by the following equation (Nattawut, Flick, Onrawee, 2017):

$$\varepsilon = \frac{q_0}{l_t} = \frac{h_1 - h_4}{h_2 - h_1}$$

The standard device is manufactured for the R452a refrigerant, which is a zeotropic mixture. A schematic diagram of the refrigeration system is shown in the previous section in figure 3. It consists of an on-off compressor, a capillary as an expansion element, a condenser and an evaporator. The electrical installation consists of an evaporator and condenser fans, a compressor power supply, a device controller, heaters for evaporating the condensate accumulating in the container and lighting.

3.1. Device optimisation capabilities

Parallel to the changes introduced in the refrigerants used, changes are made to the construction of cooling devices in order to reduce the consumption of electricity. Modern construction and technological solutions rely on the use of improved heat exchangers, adjusting the capacity to temporary demand, the accumulation of cold by closing devices, e.g. with covers and doors, and improving the control of the device.

Devices using environmentally friendly R290 gas have 10–15% lower energy consumption compared to devices filled with high GWP gas – R404a. Devices with the applied SCROL variable speed compressor give another 10–15% of energy savings. In plug-in devices, device aggregates give heat to the commercial space, which in winter is a very beneficial effect because there is a natural heat recovery. However, in summer, units equipped with water condensers, with the use of an appropriate water network, return heat to the said network, which replaces the cooling of the temperature inside the commercial area with the use of air conditioners (Skrzypulec, Konopka-Cupiał, 2008). The energy audit of the device should be conducted individually for the intended use, but most often manufacturers, perform this activity for the main customers who declare longer cooperation.

The energy analysis of the device, which is an energy audit, should include all elements that can reduce energy consumption, especially:

- Thermal barriers – the use of doors, usually transparent, so that customers can see the products inside the devices. The use of doors minimises the infiltration of outside air.

https://doi.org/10.37705/TechTrans/e2022005

- Location of the fan's electric motor outside the device – removal of additional heat gains reduces the need for cooling.
- Improving the design of the evaporator fan and/or the fan motor by increasing air circulation and increasing the efficiency of the evaporator will allow heat exchange by the circulating medium, which is air.
- Control of thermodynamic parameters – condensation and evaporation pressures as well as subcooling and superheating temperatures for automatic control of the correct operation of the circuit.
- Minimising the gains of heat and moisture from the outside air – in addition to the use of doors on the devices, the presence of technological openings for removing condensate from the evaporator is necessary for electrical and cooling installations. Due to the fact that the chiller is usually located under the device, it is necessary to ensure separation of recirculating and outdoor air, which repels heat from the condenser. There must be insulating refrigerants and siphons on the condensate-draining pipe through which warm air can enter.
- Compressor and fan rotational speed control – selection of electrical components with efficiency properly matched to a given device, enabling their highest efficiency.
- Selecting a two-stage compressor with indirect cooling – an indirect cooling system may be appropriate for larger systems. It may be a more environmentally friendly solution, as is the use of modern expansion valves and other elements of cooling apparatus, the constant change of the settings of which may affect the consumption of electricity by other elements of the system, e.g. compressors.
- Changing the technology and settings of lighting – lighting is a key element, thanks to which, the chances of purchasing the displayed product increases. Due to the large number of light points, it may be justified to choose a technology that is characterized by low electricity consumption, e.g. LED technology.
- Heat recovery – for individual customers, waste heat recovery is often an unprofitable topic, but it brings benefits and increases the efficiency of the entire system. One of the solutions may be the use of a water condenser which can heat water, e.g. process water.
- Reducing energy consumption and achieving stability of internal temperatures using a device control – modern controllers allow changing the settings to night mode and react when the temperatures in the device exceed the permissible values, informing the user about the problem, which can sometimes help to avoid a significant failure.

Reducing electricity consumption by cooling devices can also be achieved through the proper use of the device and service. According to Rhiemeir et al. (2009) the most important aspects of the service and use are:

- Correct refrigerant charging
- Adequate air humidity in the room
- Cleaning of the evaporator and condenser

A case study of a cooling device for which the energy audit was applied is presented below. The audit showed that it can bring positive changes:

1. Conversion of the cooling system into an ecological refrigerant.
2. Replacing lighting with energy-saving alternatives.
3. Replacing the condenser and evaporator fans with energy-saving alternatives.
4. The use of a float sensor that switches the heater in the condensate container at certain liquid level to the automatic condensation water-evaporation system.
5. Application of a night curtain at the time of closing the premises.
6. Change from an on-off compressor to an inverter compressor.
7. Energy audit of an example cooling device.

A twenty-four hour test was performed, the results of which are presented below. These values will serve as a benchmark for future tests. Figure 4 shows the average packet temperature in the device before any changes. It can be seen that the temperatures fluctuate around 6°C, which means that the rack meets the requirements for devices within a given temperature class, which is defined as H1 for the device under test. For this class, the standard defines that the highest and lowest temperature of the package measured during the tests cannot be higher than 10 or lower than 1°C – this was obtained.

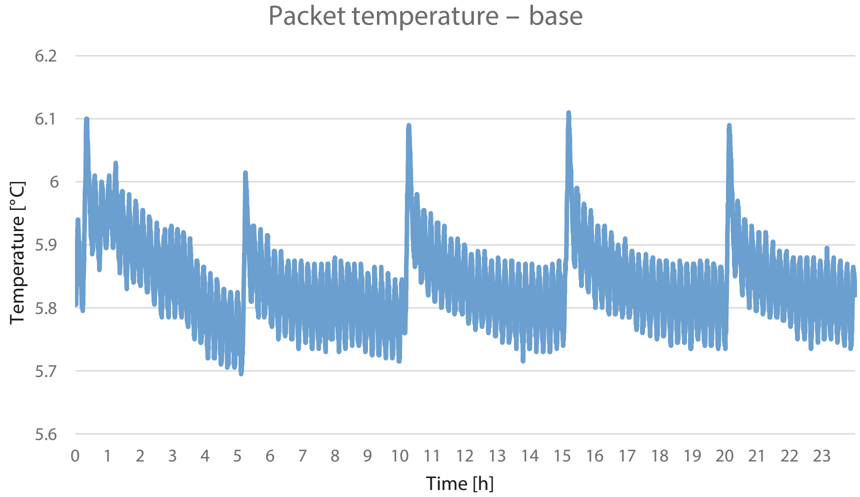

Fig. 4. Average temperature (own study)

The results of the individual calculations are presented in table 14.

I. Conversion of the cooling system into an ecological refrigerant

Due to the applicable law which obliges manufacturers of refrigeration equipment to apply environmentally friendly solutions, they were required to have ended the sale of devices based on thermodynamic factors with a high GWP by the end of 2021. The market trend for commercial refrigeration devices with low capacities is the use of a natural refrigerant (propane), which can be used without any

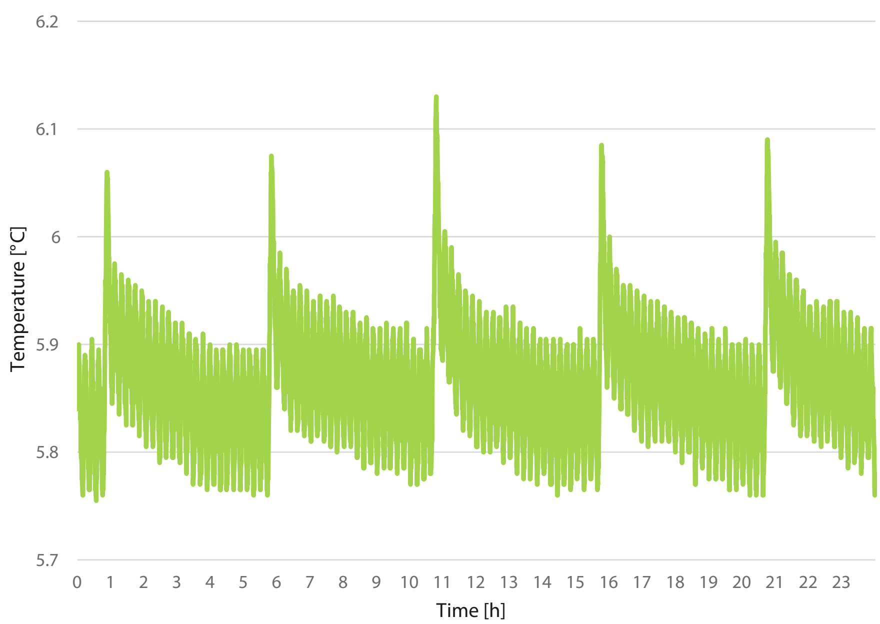

Fig. 5. Average temperature (own study)

https://doi.org/10.37705/TechTrans/e2022005

problems in the coming years. The conversion of the system will consist in the selection of appropriate refrigeration components on the basis of safety data sheets and technical data of components that are used in a standard device.

The most popular refrigerant used in the commercial refrigeration sector today is propane. R290 is a hydrocarbon which is a naturally occurring substance. It does not damage the ozone layer and its impact on global warming (GWP = 3) is negligible. Its disadvantage is its flammability (it has the A3 flammability class). Thanks to the excellent thermodynamic properties and the availability of fittings adapted to this factor, its popularity is increasing, so the initial expenditure can be gradually minimised. The level of working pressure and efficiency are comparable with the properties of the R22 refrigerant, while the discharge temperature is at a similar level as that of R134a (Nattawut et al., 2019).

Figure 5 shows the average packet temperature in the device after changing the compressor to R290.

Compared to the technical data contained in table 5, only the compressor will change for this case, the data of which was read from the manufacturer's cards and is presented in table 6. The rest of the elements remained unchanged.

Table 6. The device after change I – technical data (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]	Working time within 24 hours
1	Compressor R290	Embraco on/off	1	746	0.746	14.57 h

II. Replacing lighting with energy-saving alternatives

In subsequent tests, only electricity consumption was taken into account, as the operating points of the system remain unchanged. In addition to the compressor, the lighting was changed to energy-saving LED technology, which is characterised by its low energy consumption (Onuma et al., 2020). Catalogue data are included in table 7.

Table 7. The device after change II – technical data (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]
1	Compressor R290	Embraco on/off	1	746	0.746
2	Lighting	LED strip L = 1180 mm LED strip L = 670 mm	2 6	13.5 7.5	0.027 0.045

III. Replacing the condenser and evaporator fans with energy-saving alternatives

The selected condenser has two fan motors with constant power consumption which will be replaced by energy-saving motors from the same manufacturer, the current consumption of which depends on the motor load. Additionally, the circulating air in the cooled part is driven by two fan motors that will be swapped.

Table 8. The device after change III – technical data (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]
1	Compressor R290	Embraco on/off	1	746	0.746
2	Evaporator fan	EBM fan motor	2	6.7	0.013
3	Condenser fan	EBM fan motor	2	6.7	0.013

IV. The use of a float sensor that switches the heater in the condensate container at a specific liquid level to the automatic condensation water-evaporation system

Two electric heaters are connected directly to the main switch of the device, which causes their continuous operation and significant power consumption. In order to improve this solution, another condensate container was used – this one had an electric heater and a float sensor. After reaching the appropriate water level (over 80 mm), the float activates the heaters, causing the complete evaporation of the condensate and preventing the container from overflowing. After evaporation and the lowering of the water surface, the float breaks the electric circuit and turns off the heaters. Figure 6 shows a schematic view of the container with the used sensor.

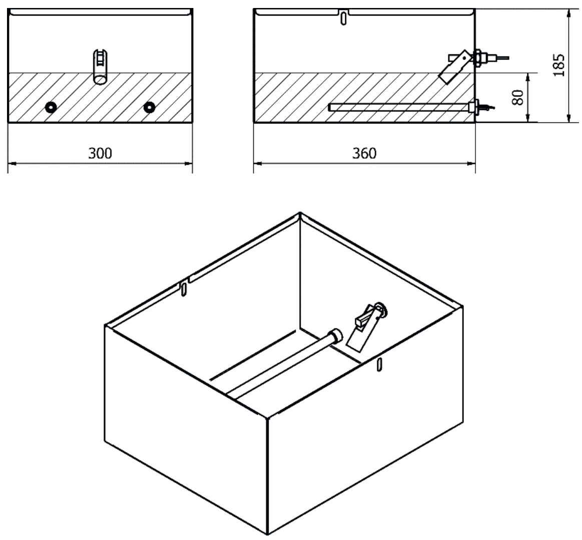

Fig. 6. Condensate container with float sensor (own study)

In the calculations, the parameter t_h is 4.8 h. It was assumed that the float would turn on the heaters each time after defrosting for 60 minutes. The automatic defrost interval is 5 h, which for a 24 h test is:

$$t_{hIV} = 1 \cdot \frac{24}{5} = 4.8$$

Table 9. The device after change IV – technical data (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]
1	Compressor R290	Embraco on/off	1	746	0.746
2	Condensate evaporation heater	PTC heater + float activating the heaters	2	350	0.700

V. Application of the night curtain at the time of closing the premises

A night curtain is used only when there is no need to display the products. This is possible after closing the premises and, depending on the opening hours, the operating time of the device with the used night curtain varies. For the purposes of the study, it was assumed that the operating time of the device with and without the curtain would be 12 hours. It should be remembered that depending on the point where the device is located, the interval of work with and without this element will vary. The night curtain is a barrier that minimises the infiltration of warm air inside the device.

https://doi.org/10.37705/TechTrans/e2022005

VI. Change from on-off compressor to inverter compressor

The advantage of a variable capacity compressor is that it can operate in a continuous mode and adapts to the prevailing conditions, maintaining an appropriate amount of cold in the cooling space. This influences its frequency of starts, which limits the high inrush current, extends its service life and stabilises the internal temperature compared to the on-off compressor (Ahmed et al., 2020).

Table 10. The device after change VI – technical data for 3000 rpm (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]
1	R290 compressor	Embraco inverter	1	691	0.691

VII. Final examination

The final test has to show how the device works with the previous changes that were tested individually. Therefore, to provide a comparison with the base unit, the data of which is recorded in table 5, the electrical parameters for the optimised device are recorded in table 11.

Table 11. Final device – technical data (own study)

No.	Varna 90 R290	Name	Quantity	Power [W]	Sum of power [kW]	Working time within 24 hours
1	R290 compressor	Embraco inverter	1	691	0.691	14.6 h
2	Evaporator fan	EBM fan motor	2	6.7	0.013	24 h
3	Condenser fan	EBM fan motor	2	6.7	0.013	14.6 h
4	Condensate evaporation heater	PTC heater + float activating the heaters	2	350	0.700	4.8 h
5	Lighting	LED strip L = 1180 mm LED strip L = 670 mm	2 6	13.5 7.5	0.027 0.045	24 h

4. Research results and analysis

On the basis of the measured average operating points, which are presented in table 12 for the base device, and after conversion to the ecological factor R290, the cycle was drawn in the pressure-enthalpy diagram, which is shown in figure 7. Moreover, the COP coefficient described in the previous chapter was calculated. The individual values of the enthalpy are presented in table 12.

Table 12. Measured operating parameters of the R452a base system and the R290 system (own study)

Parameter	Description	Average R452a	Average R290
Pe	Evaporating pressure	2.88 bar	2.31 bar
Pc	Condensing pressure	17.21 bar	11.82 bar
Tsh	Suction temperature	5.1	7.4
Td	Discharge temperature	70.3	70.6
Tsc	Subcooling temperature	32.1	35.7
Ec`	Daily energy consumption	30.1 kWh/24 h	27.3 kWh/24 h

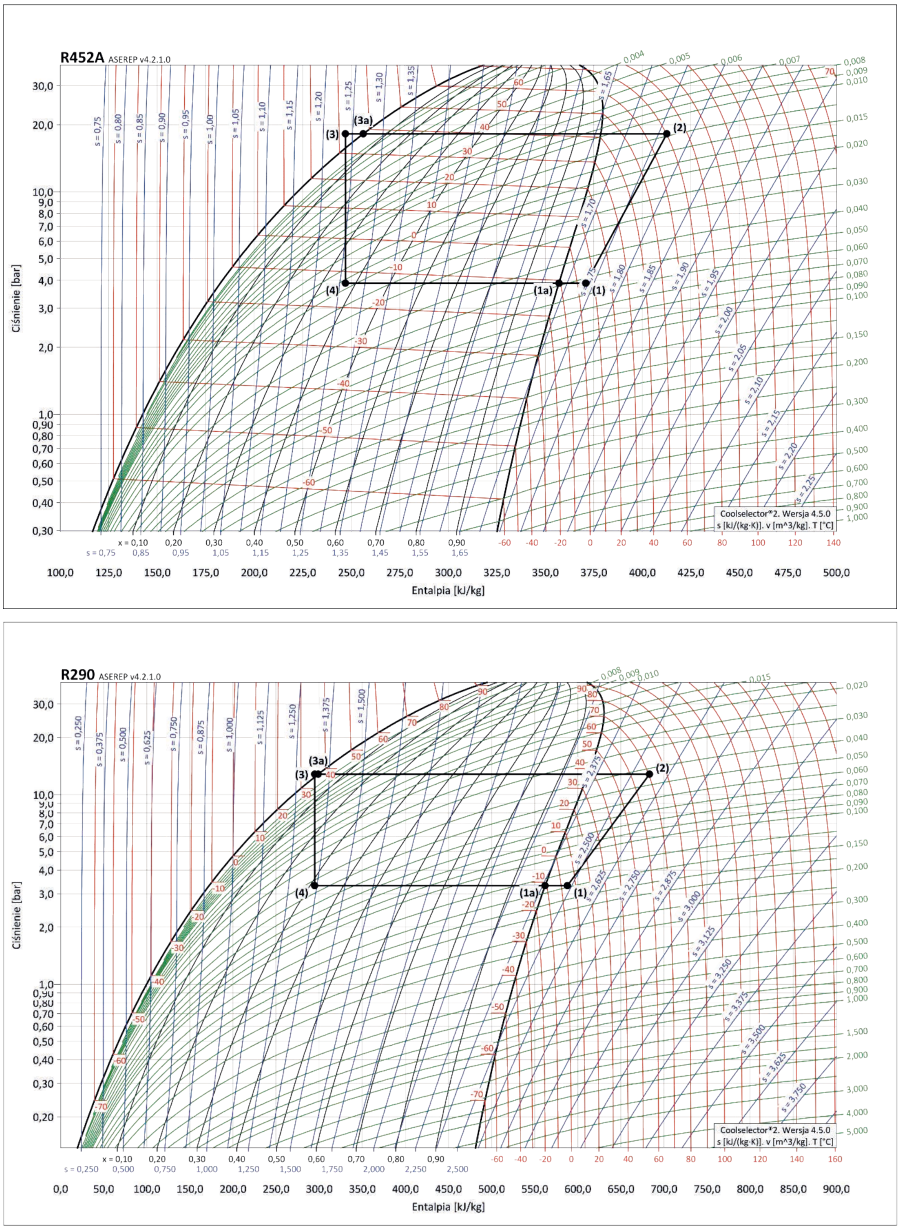

Fig. 7. Pressure-enthalpy diagram for the (from left): R452a base unit, R290 unit (own study)

Table 13. Working points of the R452a base unit (own study)

Point	Description	Enthalpy kJ/kg R452a	Enthalpy kJ/kg R290
1	Compressor suction (h_1)	370.8	588
2	Pumping compressor (h_2)	412.7	683.3
3	Condenser outlet (h_3)	247.0	294.7
4	Behind the expansion element (h_4)	247.0	294.7
5	Calculated COP	2.96	3.08

It can be seen that after changing the thermodynamic medium, the compressor's compression ratio decreased from almost 6 to around 5.3, and the unit compression work of the device increased from 42 to 95 kJ/kg. This proves a reduction in the efficiency of the compression device. Table 14 shows the results of calculations for the individual electricity consumption and the actual value measured.

Table 14. Calculation results (own study)

Test	E_{CI}' [kWh/24 h]	E_{CI} [kWh/24 h]	E_{Ligl} [kWh/24 h]	E_{Coml} [kWh/24 h]	E_{Wenl} [kWh/24 h]	E_{Heal} [kWh/24 h]
1	30.1	25.9	3.4	12.3	1.8	8.4
2	27.3	25.6	3.4	12	1.8	8.4
3	23.2	24.0	1.8	12	1.8	8.4
4	24.8	23.2	3.4	11.1	0.3	8.4
5	26.7	20.5	3.4	12	1.8	3.4
6	26.3	–	–	–	–	–
7	26.9	20.5	3.4	12	1.8	3.4
8	19.4	17.4	1.7	12	0.3	3.4

As shown in table 14, the theoretical energy consumption (25.9 kWh/24 h) is lower than the measured values (30.1 kWh/24 h). This may result from the wrong estimation of the energy consumption of individual elements, e.g. heaters, which consume different levels of current depending on the temperature, and the omission of some electrical devices such as a controller or switches. In addition, the rated power of individual components does not take into account the starting currents (the compressor starting current may be even several times higher than the rated value), which also affect the calculated results. Nevertheless, there are opportunities to reduce the electricity consumed.

For test 2, which concerned the change of the refrigerant to R290, it can be seen that the change of the compressor and the thermodynamic medium did not significantly affect the theoretical results. Comparing the measured daily energy consumption, we can see that after changing the factor, there was a decrease in consumption of less than 3 kWh, i.e. by almost 10%. The COP coefficient changed by less than 4% in favour of the solution with a natural factor.

Switching to energy-saving lighting in relation to the base unit reduced energy consumption by approx. 7 kWh/24 h. This is a non-invasive change in the design of the device, which gives a relatively large saving per year. Also, the investment in such a change would pay off for the recipient within a fairly short time.

As in the case of replacing the lighting with energy-saving alternatives, when replacing the condenser fans and forcing the circulation of cold air, we obtained a similar decrease of approx. 7 kWh/24 h in electricity consumption compared to the base device. Replacing the lighting does not affect the construction of the device.

Heaters operating in a continuous mode consume electricity but sometimes only heat up the air that surrounds them. Comparing the energy consumption in the test, during which the condensate container was used with a float which turns on the heaters for the automatic condensation water evaporation system, it can be seen with the standard version that such a change also affects the final result. Undoubtedly, the working time of the heaters is influenced by environmental conditions that cannot be defined in a real building. Under the test conditions, the average relative air humidity is 60%, which does not translate into the conditions throughout the year. For this reason, automation should be used that optimises the work of heaters so that they only function when required.

The use of a night curtain in open shelves is an economically and ecologically sound solution as it reduces electricity consumption when the device is not in use and there is no need to display products. As mentioned earlier, the subject of the night curtain is strongly determined by the client who, depending on the working time of the premises and other variables, may or may not use this improvement. Under test conditions, the operating times with and without the night blind were assumed to be equal. It can be assumed that the sheltering of the shelving works in the same way as installing the door, because air infiltration and heat radiation to the inside of the shelves are both reduced to a very high degree.

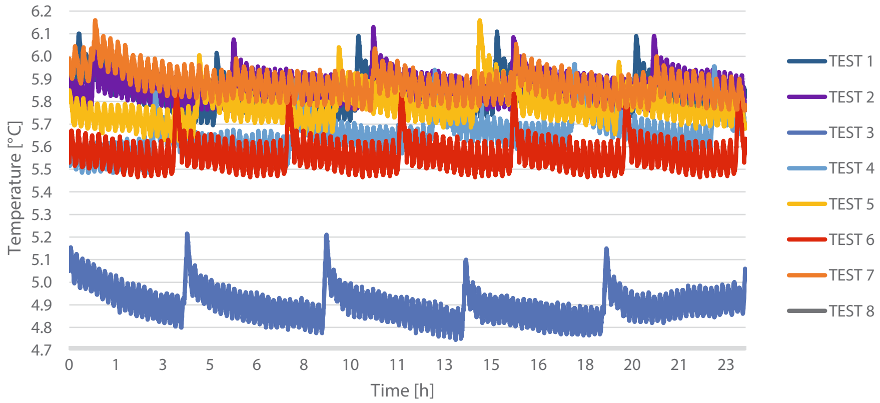

Fig. 8. Average test temperatures (own study)

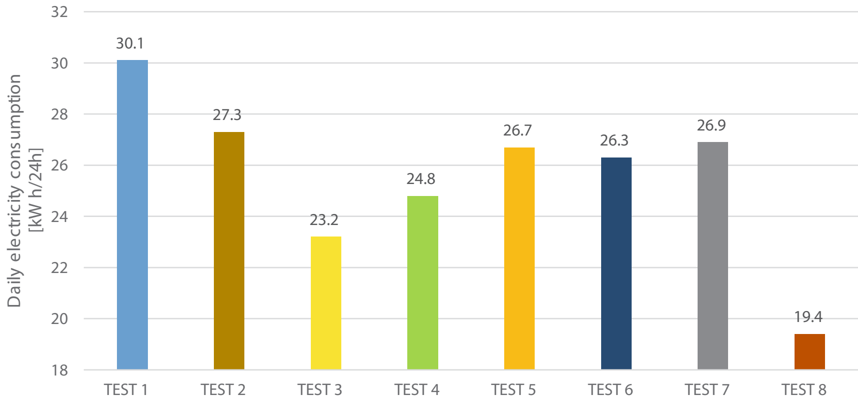

Fig. 9. Electric energy usage (own study)

In test 7, an inverter compressor was used. In order to ensure the best possible control of the generated cold, the controller regulates the rotational speed of the compressor drive motor, which reduces the electrical and cooling power of the device. As can be seen from the results, such solutions also positively influenced the total power consumption.

The final test (8) was to check the correct operation of the device using all previous improvements so that the results can be compared to a standard device.

Figure 8 shows the average temperature graphs for each test, while diagram 9 shows the individual electricity consumption.

Table 15 below shows the data measured in the various variants of the tests performed with the given configuration of the tested refrigerated shelving unit.

Table 15. Measurement table – climatic class III (25°C /60% Rh) (own study)

Device description	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Air temperature in the test chamber	25°C ±1°C	25°C ±1°C	25°C ±1°C	25°C ±1°C	25°C ±1°C	25°C ±1°C	25°C ±1°C	25°C ±1°C
Air humidity	60% ±3%	60% ±3%	60% ±3%	60% ±3%	60% ±3%	60% ±3%	60% ±3%	60% ±3%
The scope of work of the furniture	4–10°C	4–10°C	4–10°C	4–10°C	4–10°C	4–10°C	4–10°C	4–10°C
Setting on the controller	4	4	4	4	4	4	4	4

https://doi.org/10.37705/TechTrans/e2022005

Device description	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Minimum package temperature	2.1	2.2	1	1.3	2.9	1.9	2.0	1
Maximum package temperature	10	9.9	9.2	10	10	10	10	9.9
Energy consumption value [kW/24 h]	30.1	27.3	23.2	24.8	26.7	26.3	26.9	19.4
Temperature class	H1							
Measuring socket	Measuring socket N27P							

Test 1 – R452 base device
Test 2 – The device after conversion of the cooling system to the ecological refrigerant R290
Test 3 – R290 device after changing lighting to energy-saving
Test 4 – R290 device after changing the fans to energy-saving
Test 5 – R290 device with a connected float sensor that switches at a certain level of liquid to the heaters in the condensate container to automatic evaporation of condensed water
Test 6 – R290 device with a night curtain when the premises is closed
Test 7 – R290 device with inverter compressor
Test 8 – R290 device with all changes

4.1. Economic and environmental issues

In recent years, economic benefits have been closely related to the environment and decreasing energy consumption. The carbon footprint of a product's life is difficult to estimate, but we can calculate potential benefits related to lower electricity consumption which will result in lower operating costs. We asked the manufacturer to provide the price difference for a standard (test 1) and optimised device with applied changes and improvements (test 8). At the time of writing the article, the difference between these devices was 2600 PLN. The price per kilowatt was assumed for the calculation 0.6 PLN/kWh. In the diagram

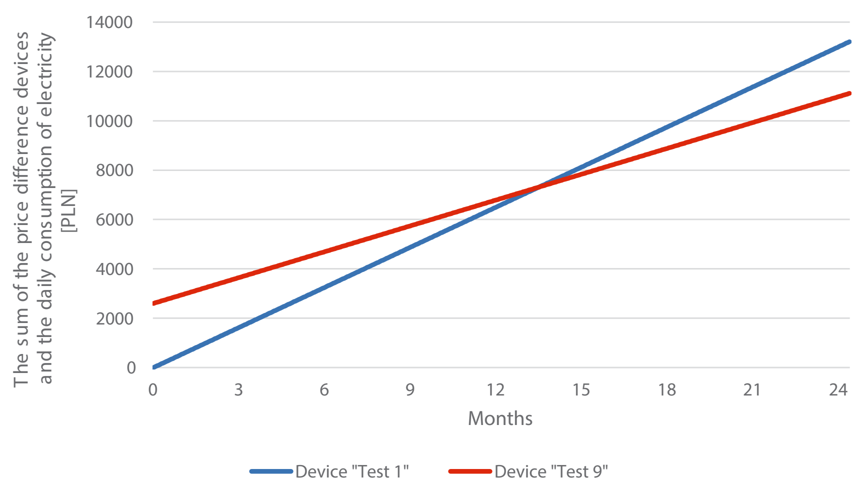

Fig. 10. Rate of return for the optimised device (own study)

below (figure 10), we can see annual energy consumptions and the rate of return for the optimised device. Electricity consumption for specific devices is taken from the previous chapters (table 15). For the same ambient and usage conditions, the rate of return is more than 14 months (on the 406th day). The tendency of the energy market allows the assumption of a further increase in energy costs, allowing the estimation that the rate of return will be even shorter, which is beneficial for the owner.

5. Conclusions

As a result of the research, it was found that each change of a component to an energy-saving alternative had a significant impact on the daily consumption of electricity. After all the changes were made, a 35% decrease in electric power consumption was observed compared to the base unit, for which the installation of the night curtain has the greatest impact.

Additionally, it can be noticed that the change of lighting and the use of a curtain not only reduces electricity consumption, but also has a positive effect on the temperature in the product. This effect is shown in figure 8. This is due to the fact that LED lamps do not heat the products, unlike standard lighting. The curtain isolates the product from the environment, so that heat from outside the refrigeration device does not reach the shelves with the product.

Due to the market trend and legal conditions that strive for the maximum efficiency of devices, economy and environmental friendliness, which translates into the minimisation of electricity consumption, this topic can be developed with further optimisation of electrical and construction elements. The potential of the devices is shown by the problem of producers who have to adapt their devices to appropriate standards in order to be able to sell their products while remaining within certain limits, the exceeding of which results in removing the device from circulation.

References

Almogbel, A., Alkasmoul, F., Aldawsari, Z., Alsulami, J., Alsuwailem, A. (2020). Comparison of energy consumption between non-inverter and inverter-type air conditioner in Saudi Arabia. *Energy Transitions*, *4*, 191–197. https://doi.org/10.1007/s41825-020-00033-y

Chaomuang, N., Flick, D., Denis, A., Laguerre, O. (2017). Experimental and numerical investigation of the performance of retail refrigerated display cabinets. *Trends in Food Science & Technology*, *70*, 95–104. https://doi.org/10.1016/j.tifs.2017.10.007

Chaomuang, N., Flick, D., Denis, A., Laguerre, O. (2019). Influence of operating conditions on the temperature performance of a closed refrigerated display cabinet. *International Journal of Refrigeration*, *103*, 32–41. https://doi.org/10.1016/j.ijrefrig.2019.03.031

Heredia-Aricapaa, Y., Belman-Floresa, J.M., Mota-Babiloni, A., Serrano-Arellano, J., García-Pabón, J.J. (2020). Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A. *International Journal of Refrigeration*, *111*, 113–123. https://doi.org/10.1016/j.ijrefrig.2019.11.012

Onuma, H., Shigeru, M., Toshi, H.A. (2020). How much household electricity consumption is actually saved by replacement with Light-Emitting Diodes (LEDs)? *Economic Analysis & Policy*, *68*, 224–238. https://doi.org/10.1016/j.eap.2020.09.015

PN-EN ISO 23953-2:2016-04. Refrigerated display cabinets – Part 2: Classification, requirements and test conditions.

Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.

Rhiemeir, J.-M., Harnisch, J., Ters, C., Kauffeld, M., Leisewitz, A. (2009). Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment, Environmental Research of the Federal Ministry of the Environment. In *Nature Conservation and Nuclear Safety Research Report 20644300 UBA-FB 001180/e*. Germany.

Skrzypulec, W., Konopka-Cupiał, G. (2008). Efektywne wykorzystanie energii i czyste środowisko – główne kierunki rozwoju w branży chłodniczej i klimatyzacyjno-wentylacyjnej. *Polityka Energetyczna, 11*(2), 97–106.

Valve Shaban, N.A., Nasser, I., Asfar, J.A., Al-Qawabah, S., Olimat, A.N. (2020). Thermodynamic and Economic Analysis of a Refrigerator Display Cabinet Equipped with a DC Compressor and Electronic Expansion. *International Journal of Heat and Technology*, *38*(2), 432–438. http://doi.org/10.18280/ijht.380219