Chapter 2
Indicators and Measures of Energy Efficiency the Warehouse

Measures to improve the energy efficiency of a warehouse and reduce its power consumption can bring more or less satisfactory results. The aim is to maximize the reduction of energy consumption with the lowest possible investment cost, and taking into account the environmental aspects (renewable energy). Reducing energy intensity means lower energy costs for the company.

To be able to assess the degree of energy intensity of a warehouse, one can use indicators. The energy consumption of a warehouse is influenced by many factors. The various functional areas of the warehouse have a different impact on the total energy consumption of the storage system. Knowledge about energy efficiency indicators can help spot areas particularly important to reduce energy intensity. It also allows noting what factors have the greatest impact on energy consumption and promotes seeking improvements in these areas.

The basic physical values used in reducing the energy intensity are energy, work, and power:

- Energy—"*physical value used to quantitatively describe various processes and effects*",
- Work—"*a scalar value which is a measure of energy given to a physical system*",
- Power—"*a value characterizing a physical system in terms of energy*".

Apart from work, the second means of transferring energy is heat, defined as "the amount of heat, energy and labor are the same value." Their SI unit is the joule (J). The work of one joule is performed by moving the force point 1 N in accordance with its direction by 1 m.

$$1\ \mathrm{J} = 1\ \mathrm{Nm} = 1\ \mathrm{Ws} = 1\ \mathrm{kg\ m^2/s^2} \tag{2.1}$$

The unit of power is the watt (W). It is the ratio of the amount of energy, heat, or work to time.

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P. Zajac, *The Energy Consumption in Refrigerated Warehouses*,
EcoProduction, DOI 10.1007/978-3-319-40898-9_2

$$1\ \mathrm{W} = 1\ \mathrm{J/s} = 1\ \mathrm{Nm/s} \tag{2.2}$$

In practice, the most commonly used unit of work, energy, and heat is not joule or watt second, but a kilowatt-hour (kWh). 1 kWh is equivalent to the consumption of energy by a device in an hour of work and with the power of 1000 W, or 1 kWh.

The global energy consumption in the warehouse is made up of the following several components:

$$E_{\mathrm{glob}} = E_{\mathrm{ośw}} + E_{\mathrm{śr.tran.}} + E_{\mathrm{klim}} + E_{\mathrm{urz}} + E_{\mathrm{prac}} \tag{2.3}$$

where

$E_{\mathrm{ośw}}$ the energy used for lighting the warehouse
$E_{\mathrm{śr.tran.}}$ the energy consumed by transport in the warehouse (both conveyors and means of transport)
E_{klim} energy consumed to maintain appropriate weather conditions in the warehouse (e.g., consumed for heating, cooling, humidification and dehumidification, air distribution throughout the warehouse)
E_{urz} energy consumed by other equipment, e.g., blinds, automatic identification units, etc.
E_{prac} energy emitted by people working in the warehouse

Energy consumption can be related to time units, e.g.,

$$\left[\frac{\mathrm{kWh}}{\mathrm{day}}\right], \left[\frac{\mathrm{kWh}}{\mathrm{year}}\right], \left[\frac{\mathrm{kWh}}{\mathrm{h}}\right]$$

However, you can also specify the total energy consumption per cargo unit passing through the warehouse:

$$\left[\frac{\mathrm{kWh}}{\mathrm{CU}}\right]$$

This indicator is often used in practice; it also allows determining the cost of energy consumption generated by a cargo unit in the warehouse.

In addition to the references to the cargo unit, one can refer to the unit of area or volume of the warehouse or storage area:

$$\left[\frac{\mathrm{kWh}}{\mathrm{m^2}}\right], \left[\frac{\mathrm{kWh}}{\mathrm{m^3}}\right]$$

Such reference is most often used when determining the energy used for heating or cooling.

Usable energy delivered to the warehouse, usually in the form of electricity, heat, or solar radiation is converted into another form of energy (mechanical kinetic

and potential, thermal, light…). However, not all energy is used for the desired purpose. Examples are incandescent lamps that can only convert 5 % of energy into light; the rest of the energy is converted into heat. Therefore, one must introduce indicators pointing to the share of the types of output energy obtained from the input energy, e.g., the ratio of light energy to heat energy obtained from electricity:

$$E_{\text{en}} = \frac{E_{\text{ligh\'en}}}{E_{\text{heaten}}} \ [\%] \tag{2.4}$$

In the case of energy recovery, one can use the indicators depicting its share in total usable energy used for a process in which the energy is recovered, or the ratio of energy recovered in all processes to total energy:

$$\text{ratio of energy recovered in the process} = \frac{E_{\text{recov. in proc.}}}{E_{\text{total process}}} \tag{2.5}$$

$$\text{ratio of total energy recovered} = \frac{E_{\text{recov}}}{E_{\text{glob}}} \tag{2.6}$$

Further indicators determine the energy consumption by the components of total energy. They allow measuring the share of energy consumed by a group of processes:

$$\text{consumption indicator } E_{\text{light}} = \frac{E_{\text{light}}}{E_{\text{glob}}} \tag{2.7}$$

$$\text{consumption indicator } E_{\text{tran.}} = \frac{E_{\text{tran.}}}{E_{\text{glob}}} \tag{2.8}$$

$$\text{consumption indicator } E_{\text{air-con}} = \frac{E_{\text{air-con}}}{E_{\text{glob}}} \tag{2.9}$$

$$\text{consumption indicator } E_{\text{eq}} = \frac{E_{\text{eq}}}{E_{\text{glob}}} \tag{2.10}$$

The indicators showing the share of the consumption of various types of energy in the warehouse are also important, for example

$$\text{electricity consumption index } E_{\text{el}} = \frac{E_{\text{el}}}{E_{\text{glob}}} \tag{2.11}$$

$$\text{thermal consumption index } E_{\text{therm}} = \frac{E_{\text{therm}}}{E_{\text{glob}}} \tag{2.12}$$

$$\text{renewable energy consumption index } E_{\text{rec}} = \frac{E_{\text{rec}}}{E_{\text{glob}}} \tag{2.13}$$

The indicators indirectly affecting energy consumption are

$$\text{index of heated warehouse space} = \frac{\text{heated volume } V_{\text{heat}}}{\text{unheated volume } V_{\text{nheat}}} \tag{2.14}$$

– effective use of space ratio (see Sect. 1.2)

$$\alpha_m = \frac{A_m}{Z_{\max}} \left[\frac{\text{m}^2}{\text{CU}}\right]$$

– Volume efficiency index (see Sect. 1.2)

$$\beta_m = \frac{V_m}{Z_{\max}} \left[\frac{\text{m}^3}{\text{CU}}\right]$$

– the rate of effective use of equipment

$$\frac{\text{idling time}}{\text{total operation time}} = \frac{t_{\text{idle}}}{t_{\text{total}}} \tag{2.15}$$

– indicators of cargo movements

(a) vertical

$$\frac{\text{total distance traveled by cargo units in the } Y\text{-axis}}{\text{the number of cargo units}} \left[\frac{\text{m}}{\text{CU}}\right] \tag{2.16}$$

(b) horizontal

$$\frac{\text{total distance traveled by cargo units in the X-axis}}{\text{the number of cargo units}} \left[\frac{\text{m}}{\text{CU}}\right] \tag{2.17}$$

– the rate of empty runs of means of transport

$$\frac{\text{the total distance traveled by the means of transport without cargo}}{\text{the total distance traveled by means of transport}} \tag{2.18}$$

– lighting time indicator

$$\frac{\text{warehouse lighting time}}{\text{total time}} = \frac{t_{\text{light}}}{t_{\text{total}}} \tag{2.19}$$

– area ratio of insulated walls

$$\frac{\text{insulated wall area}}{\text{uninsulated wall area}} \tag{2.20}$$

– area ratio of external walls

$$\frac{\text{the outer wall surface area}}{\text{the total wall surface area}} \tag{2.21}$$

– indicator of direct air exchange with the environment (for air exchange in open reloading bays, open doors, and windows)

the sum of the products of air exchange times with the environment and the area of the maximum cross-section of the exchange

$$\sum_i \left(t_{\text{exch}.i} \cdot A_{\text{exch}.i}\right) \quad \left[\text{sm}^2\right] \tag{2.22}$$

The economic analysis related to energy intensity can also take into account the division between energy consumed depending on and regardless of the number of rotating cargo units. The consumption of these energies generates appropriate costs (formula 2.23). Energy consumed regardless of the number of units generates fixed costs (e.g., energy used for heating, cooling, and ventilation). This energy depends primarily on the coefficients of heat transfer through the warehouse walls and ceiling, the surface of the walls and the temperature difference between the environment and the warehouse interior. Variable costs are generated by the use of energy to ensure the rotation of the cargo units. This energy can primarily include the energy consumed by the means of transport, but also for lighting.

$$K_{E_{\text{glob}}} = K_{\text{variable}} + K_{\text{fixed}} \tag{2.23}$$

The indicators that show the share of energy generating variable costs can also be introduced:

$$\frac{E_{\text{var}}}{E_{\text{glob}}} \tag{2.24}$$

The same goes for the energy generating fixed costs:

$$\frac{E_{\text{fix}}}{E_{\text{glob}}} \tag{2.25}$$

The indicators presented in this chapter can be considered key performance indicators (KPIs) and help to assess the degree of achievement of energy goals in the warehouse.

http://www.springer.com/978-3-319-40897-2

The Energy Consumption in Refrigerated Warehouses

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2016, XII, 102 p. 59 illus., 48 illus. in color., Hardcover
ISBN: 978-3-319-40897-2