Study on the Energy and Economic Efficiency of a Hot Air Heating System in an Industrial Hall

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Abstract – **When heating an industrial hall-type building, the following types of heat demand must be considered: for heating, for domestic hot water preparation, for ventilation, for technological purposes, and for losses related to transport and distribution. This paper analyzes aspects related to the heat demand for heating an industrial hall, starting from the existing situation (heating with static radiators, with hot water as the heat transfer medium taken from the urban heating network at a price of approximately 718 lei/Gcal) and rethinking the decentralized hot air heating system with wall-mounted air heaters. Generally, heat requirements are based on a simplified estimate, the accuracy of which depends on the designer's experience in the field. In this paper, the energy performance of the industrial hall analyzed was assessed taking into account the methodologies specified in the regulations. The particularities related to the building's purpose (industrial building), the climatic zone in which the building is located, and the specific features of the type of heating system used (static bodies or wall-mounted air heaters) were taken into account. All these particularities are explicitly specified in the chapter dedicated to the case study, which makes the issues discussed easier to understand.**

Cuvinte cheie: *hală industrială, energie termică, încălzire, aer cald, sistem*

Keywords: *industrial hall, thermal energy, heating, hot air, system*

I. INTRODUCTION

As a rule, the concept of energy is linked to the type of buildings and the installations inside them, so there are increasingly frequent concerns aimed at solving some problems related to the energy efficiency of buildings.

Among these concerns, the most common are:

- reducing energy consumption in old buildings through technical and economic measures (this is also the case for the industrial building that is the subject of the case study in this paper);
- adopting measures, for new buildings, that will result in both quantifiable energy savings and increased comfort inside them.

In order to quantitatively assess heat transfer phenomena through building elements, it is necessary to know the thermodynamic properties of homogeneous materials, through:

- choosing energy-efficient and thermodynamically efficient building materials;
- checking the thermal and hygrothermal properties of an existing building or one that's being designed.

The method for selecting the appropriate construction elements is determined during the design phase, taking into account the thermal characteristics of the materials used for the purpose of [1]:

- achieving the minimum resistance necessary for heat transfer, which has the effect of reducing heat flow on the one hand and preventing condensation on the inner surface of the building element on the other;
- achieving the thermal stability necessary to avoid air temperature fluctuations inside the space in question and on the inner surface of the building element;
- resistance to vapor permeability that limits the risk of vapor condensation inside the building element;
- resistance to outside air infiltration that ensures the thermal insulation capacity of the interior space in question.

In order to reduce specific heat consumption and, in general, heat consumption for heating, measures are needed to rehabilitate and modernize the thermal protection of buildings and heating installations in residential, administrative, production, and social and cultural buildings [2].

II. HOT AIR HEATING OF BUILDING

In Romania, after the introduction of central heating in residential buildings, systems based on static elements, such as radiators, convectors, and convector radiators, have been used over time [1].

As installation technology has evolved and thermal comfort requirements in buildings have increased, in addition to traditional central heating systems, other types of heating systems have begun to be analyzed, adaptable to both residential and industrial buildings, such as: hot air heating systems and low, medium, and high temperature radiation heating systems [3].

Hot air generators are used to heat industrial spaces, warehouses, and workshops, often being a more cost-effective solution compared to traditional systems that use hot water as a heat transfer medium. In addition to the direct benefits, the fact that they do not require a centralized heating system makes these generators particularly recommended for rooms that are heated occasionally or for limited periods.

The strengths of hot air generators are: compactness, lack of thermal energy, and fast and pleasant heating [3].

The operation of these modern heating systems is based on the following mechanism: a fan ensures air circulation through the heat exchanger, which is heated by the gases burned in the burner. The heat exchanger, made of welded stainless steel, transfers heat to the circulating air. The burners can be of the "atmospheric" or "air-blown" type. The gas is ignited by a high-voltage electric arc, and the flame is controlled by ionization [4].

The equipment is equipped with a combined gas valve that includes a pressure reducer, an electromagnetic valve, a differential pressure switch that shuts off the burner in case of exhaust fan failure, as well as thermostats for limiting and regulating the temperature. The heated air is directed into the room through louvered air diffusers that also direct the airflow. In general, hot air generators are an efficient heating system, suitable for halls and rooms where the technological flow, compartmentalization of spaces, low interior height, or the need for a constant supply of fresh air (such as bathrooms, changing rooms, etc.) make the use of radiation heating impractical [4].

The main hot air heating systems currently in use are: infrared dark heater systems in the vacuum version (fig. 1) and in the overpressure version (fig. 2); tube-generator hot air heating systems; Turbo radiant heating systems; industrial convector heating systems; systems with recovery of energy lost by food refrigeration systems [5].

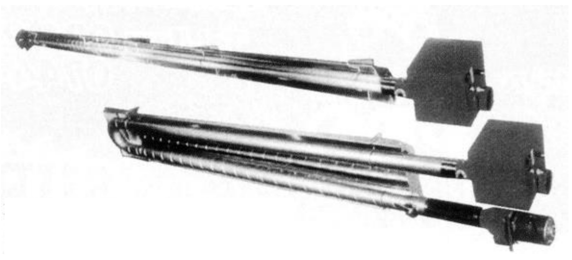
a
b

Fig. 1 Dark wave heating system with overpressure operating mode: a) with straight radiant tube; b) with U-shaped radiant tube [3]

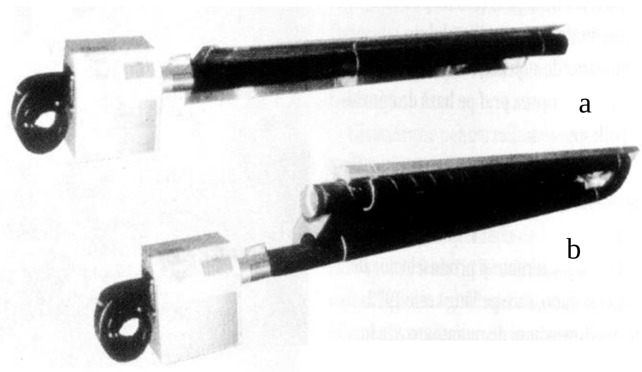

Fig. 2. Dark wave heating system with negative pressure operation and single flue gas exhaust: a) with straight radiant tube; b) with U-shaped radiant tube [6]

For heating halls, it is recommended to combine two types of radiant tubes: dark wave and infrared. To this end, consideration should be given to areas frequently used by staff, the position of machinery (e.g., lathes), electrically operated mobile doors, large glass surfaces, and others. When a comfortable temperature is desired for occupants in a specific area of the room, so-called "warm islands" or zone heating is created, for which infrared radiant tubes are mainly used [7].

Infrared radiant tubes can also be used to reduce the effect of "cold" radiation from large glass surfaces or sliding doors. It is important to note that the intensity of the radiation is not evenly distributed throughout the space, being much stronger in the heated area. The intense circulation of cold air replacing the warm air in the radiated area can cause slight discomfort [8].

If the radiant heat flow comes from a single direction, occupants may experience uneven heat distribution (similar to the "campfire" effect), i.e., "hot in front, cold in back." For this reason, the need to even out the thermal effect must be taken into account when positioning the radiant tubes. The design and implementation of radiant tube heating systems can be flexible in terms of construction and usability, with the possibility of creating both very expensive but inefficient systems and reasonably priced solutions that take into account all relevant technical aspects [8].

III. CONSTRUCTIVE AND ENERGY ANALYSIS OF THE INDUSTRIAL HALL

The studied hall is part of a complex of industrial and administrative buildings located on the northern outskirts of a town in climate zone II. In terms of shelter, it is classified as a moderately sheltered building.

The hall building consists of (fig. 3): The actual hall building on two levels; the administrative building with its facade facing east, on three levels; the administrative building with its facade facing west, also on three levels.

Functionally, the main building (the hall) is intended for industrial activities involving light work with average heat emissions. The administrative buildings are spaces where materials and raw materials, as well as finished products, are stored and where design, research, and other activities are carried out.

The characteristic elements regarding the location of buildings in the built environment are as follows [9]:

- climate zone: II according to the climate zoning map of Romania in SR 1907-1;

- average outdoor design temperature: $t_e = -15^oC$;

- orientation relative to the cardinal points: the main body of the hall with the facades facing north and south;

- wind zone: IV (4.5 m/s), according to the map of localities in wind zones, from SR 1907-1;

- building category in terms of air permeability: permeable building with windows with a high degree of permeability;

- soil temperature value, θ_p, at a depth of 7 m from ground level, depending on the area where the building is located: θ_p=10°C.

Heat losses through the envelope elements of industrial buildings are determined taking into account the dimensions of the building, the design wind speed, the average

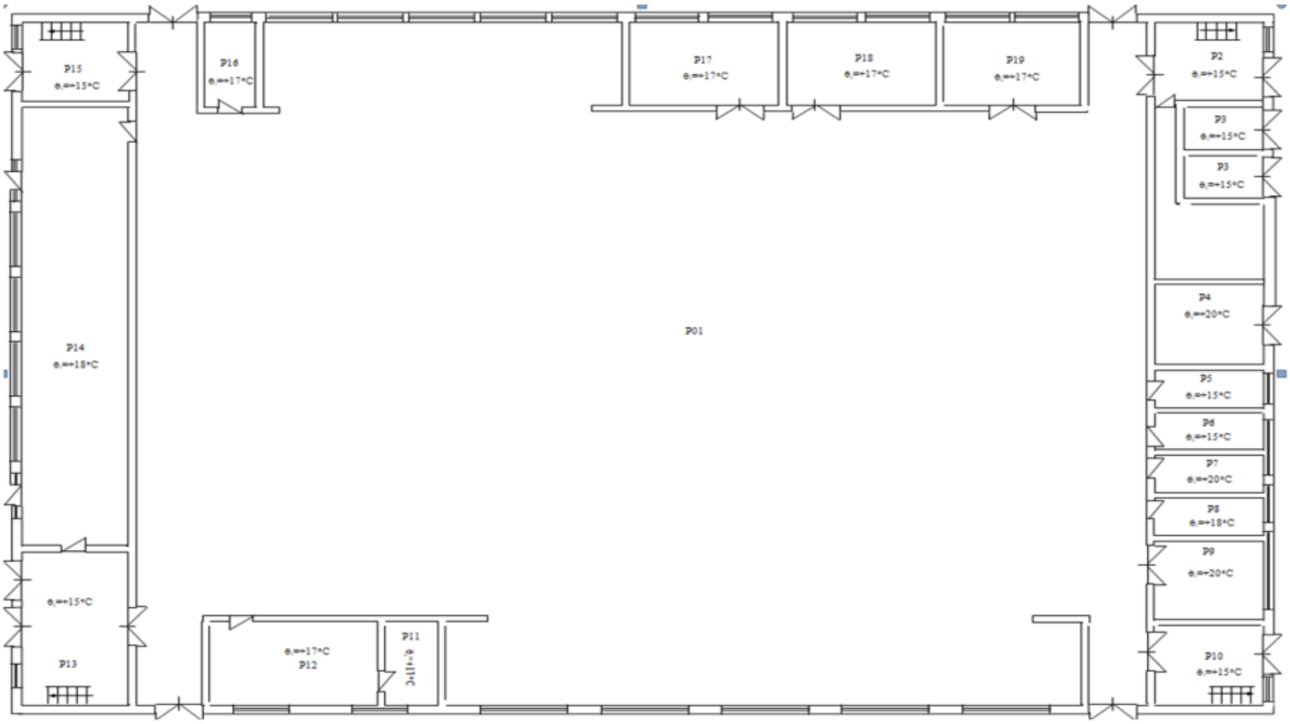

Fig. 3. The section of the industrial hall building

design indoor temperatures specific to each room, depending on its purpose (Table 1), as well as the conventional average outdoor design temperature for a location in climate zone II, $t_e = -15$ºC.

TABLE I.
THE INDOOR DESIGN TEMPERATURES SPECIFIC TO EACH TYPE OF ROOM, DEPENDING ON THEIR INTENDED USE

Nr. crt.	Room destination	Conventional indoor design temperature, [°C]
1.	Plastic injection hall – medium-effort work category	17
2.	Entrance hall, toilets, interior corridors, stairwell	15
3.	Storage rooms, Repair workshop 2, Metrological inspections, Sprinkler room, Assembly lines	18
4.	Bathrooms, Repair workshop 1, Partners' office, Fire safety office, Plastic section manager's office 1, Plastic section manager's office 2, Labels office	20
5.	Changing rooms	22

The heat losses resulting from transmission through the building elements are determined in accordance with the methodology presented in SR 1907/1-1, 2, 3, taking into account at all times the corrected thermal resistance of the opaque and glazed surfaces.

The total area of the studied hall is 2,854.80 m², the total area of the exterior walls is 4,062.60 m², and the total area of glazed elements is 1,344.946 m², representing a glazing percentage of 33.10%, distributed as follows:

-exterior windows on metal frames, double-glazed with two glass panes spaced 2–4 cm apart: 532.190 m², representing a glazing percentage of 13.10%;

-Nevada glass 0.2 × 0.2 m, 7 cm thick: 73.20 m², representing a glazing percentage of 1.80%;

-skylights with frosted glass on metal frames, single-glass pane: 704.14 m², representing a glazing percentage of 17.33% [10].

The construction characteristics of the opaque and glazed elements are as follows [10]:

-Total usable height of the hall: 9.90 m;

-Exterior walls with an interior-measured height of 9.90 m and a total thickness of 30 cm, made of aerated concrete (BCA) type GBN-50, in three layers: two plaster layers, one interior made of lime mortar with $\delta_{,i}$ = 2 cm and a thermal conductivity coefficient λ_i = 0.70 W/(m·K), and one exterior made of cement plaster with $\delta_{,e}$ = 3 cm and a thermal conductivity coefficient λ_e = 0.93 W/(m·K), between which is the BCA layer with δ_{BCA} = 12.5 cm and a thermal conductivity coefficient λ_{BCA} = 0.27 W/(m·K).

- Interior walls with an interior-measured height of 9.90 m and a total thickness of 20 cm, made of aerated concrete (BCA), in three layers: two plaster layers of lime mortar on the interior and exterior with δ_i = 2 cm and a thermal conductivity coefficient λ_i = 0.70W/(m·K), between which is the BCA layer with δ_{BCA} = 16 cm and a thermal conductivity coefficient λ_{BCA} = 0.27 W/(m·K).

Exterior windows type 1 is on metal frames and sashes, with double-glass panes spaced 2–4 cm apart, inward-opening, without special sealing;

- exterior windows type 2, made of frosted Nevada glass, in strips 0.60 m high at the level of the second floor, with a total length of 122.00 m, having a minimum corrected thermal resistance of 0.479 (m²·K)/W;

- exterior doors are metal (aluminum) with a total thickness δ_{UE} =4 cm, constructed from two aluminum sheets 3 mm thick, with a thermal conductivity coefficient λ_{Al} = 220 W/(m·K), between which is a PVC foam layer 3.4 cm thick, with a thermal conductivity coefficient λ_{Pol} = 0.05 W/(m·K).

- interior doors type 1 are metal doors made of aluminum with a total thickness δ_{UE} = 3 cm, constructed from two aluminum sheets 2 mm thick, with a thermal conductivity coefficient λ_{Al} = 220 W/(m·K), between which is a PVC foam layer 2.6 cm thick, with a thermal conductivity coefficient λ_{Pol} = 0.05 W/(m·K);

- interior doors type 2 are glued plywood doors with a total thickness δ_{UI} = 3.5 cm, with a thermal conductivity coefficient λ_{Pl} = 0.17 W/(m·K).

- interior doors type 3 are metal doors made of aluminum with a total thickness δ_{UE} = 3 cm, with glass covering 40% of the total door area, the glass having a thickness δ_{glass} = 6 mm and a thermal conductivity coefficient λ_{glass} = 0.75 W/(m·K).

The metal part, 60% of the total door area, is constructed from two aluminum sheets 2 mm thick with a thermal conductivity coefficient λ_{Al} = 220 W/(m·K), between which is a PVC foam layer 2.6 cm thick with a thermal conductivity coefficient λ_{Pol} = 0.05 W/(m·K);

- the floor has the following structure: reinforced concrete slab with a density of 2500 kg/m³ and a thickness δ_{RC} = 20 cm, with a thermal conductivity coefficient λ_{RC} = 1.74 W/(m·K), and plain aggregate concrete with a density of 1800 kg/m³ and a thickness δ_{AG} = 4 cm, with a thermal conductivity coefficient λ_{AG} = 0.81 W/(m·K).

- the ceiling at the upper part is a terrace type with glazed surface. The constructed part consists of: an interior plaster layer of lime mortar with δ_i = 2 cm and a thermal conductivity coefficient λ_i = 0.70 W/(m·K), a reinforced concrete slab with a density of 2500 kg/m³ and a thickness δ_{RC} = 20 cm, with a thermal conductivity coefficient λ_{RC} = 1.74 W/(m·K), and a bituminous waterproofing layer with a thickness δ_{hydro} = 0.8 mm and a thermal conductivity coefficient λ_{hydro} = 0.17 W/(m·K).

The glazed part of the terrace consists of fixed transparent glass panes, a single glass sheet, on a metal frame made of OL, with a minimum corrected thermal resistance of 0.17 (m²·K)/W.

The determination of heat losses through the building envelope elements, on the basis of which the thermal energy consumption is also calculated, is carried out taking into account the current standards, with the results presented in Tables II and III.

Considering that activities generating heat take place inside the hall, and knowing that the heat losses through the envelopes (machine casings) are approximately 2.5 kW, that the heat contribution from people working inside the hall (50 persons, at 0.174 kW/person) is approximately 8.7 kW, and that the solar gains are about 70 kW, the total heat gain for the studied hall amounts to 81.2 kW.

This means that the heat demand to be covered by the heating system is: (341.466 + 35.159) – (2.5 + 8.7 + 70) = 295.425 kW.

TABLE II.
HEAT LOSS THROUGH THE ANVELOPE OF THE INDUSTRIAL HALL BUILDING

Nr. crt.	Building element	A, [m²]	R', [(m²·K)/W]	Δt, [°C]	Q_T, [kW]	Q_c, [kW]
1.	Exterior walls made of aerated concrete (BCA)	420,70	0,825	32	16,890	19,372
		65,52		33	2,713	3,013
2.	Exterior window	472,64	0,318	32	61,352	70,369
		59,55		33	7,415	8,233
3.	Nevada glass 0.2 × 0.2 m, 7 cm thick	73,20	0,479	32	5,868	6,731
4.	Exterior metal door	35,89	0,167	32	11,853	13,596
5.	Floor	2545,80	0,668	7	28,492	32,680
		309,00		8	3,700	4,109
6.	Interior wall	626,58	0,938	2	1,350	1,549
6.	Interior wall	228,12	0,938	1	0,255	0,284
		318,24		-1	-0,352	-0,404
		97,23		-3	-0,334	-0,383
7.	Interior metal doors	15,12	0,251	2	0,289	0,332
		11,97		1	0,057	0,064
		21,51		-1	-0,266	-0,305
		4,41		-3	-0,063	-0,073
8.	Interior glued plywood doors	3,36	0,485	2	0,033	0,038
9.	Interior metal doors with glass	3,78	0,255	1	0,018	0,020
				-1	-0,018	-0,020
10.	Terrace above the top floor	2150,66	0,781	32	88,19	101,073
11.	Frosted glass panels on metal frame	704,14	0,382	32	70,783	81,188
	TOTAL Hall	-	-	-	298,177	341,466

TABLE III.
HEAT LOSSES DUE TO INFILTRATION THROUGH THE JOINTS OF EXTERIOR DOORS AND WINDOWS

Nr. crt.	Window type	Closure element composition	i, $\left[\frac{W \cdot s^{4/3}}{m^{5/3} \cdot {}^{\circ}C}\right]$	L, [m]	E	Q_u, [kW]	Q_i, [kW]
1.	Exterior window	Double-glazed with two glass panes spaced apart of 2..4 cm	0,0944	1209,60	1,12	6,064	35,159
Total hall			-	1209,60	-	6,064	35,159

IV. RESULTS

The total heat demand to be considered in calculating the annual total heating load will take into account, for glazed elements, both the heat required to heat the infiltrated air and the heat losses through transmission.

Considering that activities in the industrial hall release pollutants in varying amounts, the air change rate results as $n_{ao} = 1\ m^3/(h \cdot m^3)$ [11].

As a result, the heating load required for the hall is 552.56 kW.

During the study, the option of installing air heaters with a nominal power of 60 kW is analyzed, the number of air heaters required being:

$$N_{aerot} = \frac{Q_s}{Q_{n,aerot}} = \frac{552{,}56\ kW}{60\ kW} = 9 \text{ air heaters} \tag{1}$$

The implementation of such a decentralized heating system for an industrial consumer takes into account:

1. Certain technical specifications;
2. A financial analysis regarding investment and operation.

1. Technical installation specifications:

-nine 60 kW air heaters and one additional 15 kW air heater are selected, so that the total installed power of 555 kW provides a safety margin of 2 kW above the calculated demand, being ideal for peak conditions;

-installation height: 6.5–7.5 m (for H = 9.90 m);

-distance between air heaters: ≈ 20 m in both directions;

-inclination angle: 15–20° relative to horizontal;

-coverage area with warm air per heater / hall area: ≈ 330 m²

The distribution of these air heaters along the length of the hall is carried out according to Figure 4, providing a series of practical operational advantages, the most important of which are: uniform heat distribution throughout the hall; redundancy – if one air heater fails, the heating system remains functional; flexible control – the possibility of thermal zoning; energy efficiency – adequate power for the air volume

2. Investment and operating cost analysis:

- initial investment: approx. 660,000 lei (132,000 EUR)

- equipment: 9 electric air heaters of 60 kW: ≈ 540,000 lei, at an estimated price of ≈ 60,000 lei/unit (based on market price extrapolation), and 1 electric air heater of 15 kW ≈ 15,000 lei, resulting in a total equipment cost of 555,000 lei;

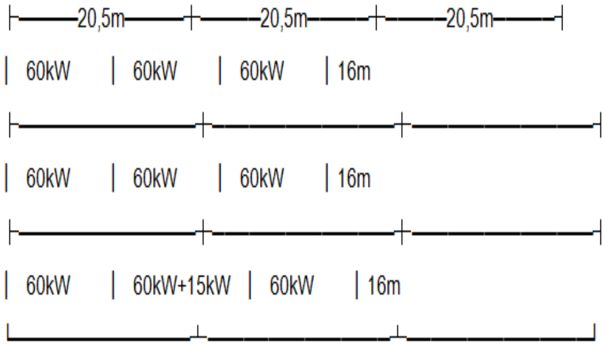

Fig. 4. Layout diagram of the 60 kW air heaters for the analyzed hall

- installation and accessories: installation, three-phase electrical wiring: ≈ 80,000 lei; control systems and thermostats: ≈ 15,000 lei; auxiliary works: ≈ 10,000 lei, resulting in a total installation and assembly cost of 105,000 lei;

- considering a useful service life of 15–20 years, this results in an annual depreciation of approximately 33,000–44,000 lei/year, i.e., a monthly depreciation of about 2,750–3,667 lei/month;

- hourly electricity consumption at maximum installed power is 555 kWh, leading to the following estimates of electricity costs for the equipment: at minimum price (1.03 lei/kWh): 571.65 lei/hour; at average price (1.25 lei/kWh): 693.75 lei/hour; at maximum price (1.55 lei/kWh): 860.25 lei/hour;

- considering a heating season duration of approximately 5 months (November–March), with an average hourly hot air distribution schedule for heating of 10 h/day, and low outside temperatures for 22 working days per month, the following seasonal cost values result for the three scenarios:

- Optimistic scenario: ≈ 628,815 lei/season;
- Realistic scenario: ≈ 763,125 lei/season;
- Pessimistic scenario: ≈ 946,275 lei/season.

V. CONCLUSIONS

In the conclusions section of the case study conducted in this work, certain aspects are analyzed on the one hand regarding the optimization of the investment and operation of the new heating system proposed for the industrial hall, and on the other hand, the technical and economic risks.

The optimization recommendations include:

-Energy contract: In this case, it is recommended to renegotiate the special industrial contract with the electricity supplier with whom the industrial consumer has an agreement, or to negotiate with another supplier, aiming for lower electricity prices;

-Intelligent control: Installation of hot air heating systems with thermostats programmed by hour;

-Additional insulation: Involving extra investment costs in thermal curtains to reduce losses (additional thermal insulation measures for the hall's envelope elements to minimize heat losses);

- Renewable energy: Evaluating the possibility of installing photovoltaic panels to reduce the cost of electricity purchased from the supplier;

-Investment profitability: Depending on energy prices and the procurement strategy.

Regarding risks, technical and economic risks were identified, for which corrective or preventive technical measures are proposed:

a) Technical risks:

-Electrical network overload: Medium probability (~30%), major impact – system shutdown; preventive measures: preliminary energy audit, upgrading the electrical network, if necessary, automatic load management system.

-Uneven heat distribution: High probability in the first month (~60%), minor impact – local discomfort; preventive measures: fine adjustment of deflectors, power adjustment by zones, installation of auxiliary fans.

-Failure of some air heaters: Low probability (5% per year), moderate impact – reduced performance; preventive measures: spare stock (1 air heater), service contract with response time <24h, continuous monitoring system.

b) Economic risks:

These relate to electricity price fluctuations, with two scenarios identified:

-Optimistic scenario: Electricity price decreases to 0.95 lei/kWh, resulting in approximately 17% reduction in electricity costs.

-Pessimistic scenario: Electricity price increases to 1.45 lei/kWh, resulting in approximately 26% increase in electricity costs.

Considering the above economic risks, an impact analysis over a 5-year period was performed, resulting in two possible scenarios:

-Optimistic: Financial savings of 612,000 lei;

-Pessimistic: Additional cost of 936,000 lei.

To mitigate the financial impact on the operational efficiency of the air heater system, the following hedging measures are considered:

1. Signing a fixed electricity supply contract with a supplier for a period of 3 to 5 years;

2. Making an additional investment in photovoltaic panels (350 kWp) to provide some energy independence for the industrial hall under analysis;

3. Implementing a thermal storage system for peak hours

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