

Article

Sustainable Electric Radiant Heating Systems for Industrial High-Bay Spaces: Experimental Performance and Decarbonization Assessment

Nicoleta Tănase ¹, Mirela Sanda Toropoc ^{1,*} and Tiberiu Catalina ^{1,2,*} 

¹ Faculty of Building Services Engineering, Technical University of Civil Engineering of Bucharest, 020396 Bucharest, Romania; nicoleta.tanase@utcb.ro

² National Research and Development Institute URBAN-INCERC, 021652 Bucharest, Romania

* Correspondence: mirela.toropoc@utcb.ro (M.S.T.); tiberiu.catalina@utcb.ro (T.C.)

Abstract

The decarbonization of industrial heating systems is one of the major challenges of the current energy transition. Gas-fired radiant tubes dominate industrial heating in large-span, high-bay buildings due to their high efficiency and low operating costs; however, the absence of equivalent electric solutions capable of replacing them represents a significant technological and scientific gap. This paper presents the design, construction, and experimental characterization of an innovative electric radiant tube prototype developed within the INFRAEL research project. The prototype consists of a 100 mm diameter steel tube housing nickel–chromium resistive elements in various configurations, powered from a 230 V AC supply. Thermal measurements were performed using Type K thermocouples distributed along the tube, a non-contact infrared thermometer, and thermovision imaging, complemented by MATLAB R2025b Trial-based interpolation for mapping the thermal field on a receiving plane placed 2 m below the tube. Experimental results show that at a total power of ~1.2 kW (two resistors in parallel), the tube surface reaches temperatures exceeding 250 °C, corresponding to medium-wave infrared emission (~4 μm). A single 630 W resistor yields surface temperatures of approximately 136–160 °C. The temperature distribution on the receiving plane is relatively uniform. The study identifies key optimization directions—resistor geometry, thermal insulation, and integration with photovoltaic sources—with the goal of developing a competitive, zero-carbon alternative to gas-fired radiant heating systems in industrial environments.

Keywords: electric radiant tube; industrial heating; infrared radiation; photovoltaic integration; energy sustainability; decarbonization; transition



Academic Editor: Cinzia Buratti

Received: 1 July 2026

Revised: 21 July 2026

Accepted: 27 July 2026

Published: 3 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

The need for reliable, abundant, and affordable electricity from renewable sources has occupied a central position in the energy crisis faced by many countries over the past decade. Renewable energy sources—wind, solar, hydroelectric, ocean, geothermal, biomass, and biofuels—constitute alternatives to fossil fuels that help reduce greenhouse gas emissions, diversify energy supply, and lower dependence on volatile fossil fuel markets, particularly oil and natural gas [1,2].

Within the framework of the European Green Deal [1], which sets a binding target of climate neutrality by 2050 and emission cuts of at least 50–55% by 2030, and Romania's Energy Strategy 2025–2035 (with a perspective to 2050) [3], the electrification of industrial

processes using renewable sources is a priority axis for reducing the carbon footprint of the industrial sector. Among the processes with significant decarbonization potential, the heating of industrial spaces—as well as adjacent spaces such as workshops, terraces, and automobile service centers—represents a major consumer of natural gas and has a direct impact on greenhouse gas emissions.

Heating solutions used in industrial buildings rely primarily on two principles: gas-fired radiant heating and electric radiant heating. Gas-fired radiant tubes are the dominant technology in industrial spaces characterized by large ceiling heights, frequent door openings, and low thermal inertia—conditions under which rapid system start-up is essential—owing to their high energy efficiency, uniform temperature distribution, and low operating costs. These systems operate by heating a metallic tube to temperatures between 250 °C and 600 °C, generating infrared radiation that directly heats surfaces and the working area, thereby reducing the thermal stratification losses typical of convective systems.

Electric radiant solutions currently available on the market—electric radiant panels with quartz or halogen elements, and gas-fired ceramic panels—offer strong localized efficiency and are well suited to zone heating or small halls, but remain inefficient for the general heating of large industrial halls due to high electricity consumption. At present, no commercial electric radiant tubes exist that can replace gas-fired radiant tubes in industrial applications (halls, workshops, terraces): such systems would require very high installed power levels, would result in non-competitive operating costs, and, in the case of quartz or halogen electric panels, would face a comparatively short service life.

Recent studies, however, highlight growing interest in electric solutions powered by renewable sources, particularly photovoltaic (PV) panels. Coupling electric radiant systems with PV generation significantly reduces their carbon footprint, transforming electric heating into a genuinely sustainable option. Nevertheless, photovoltaic production is seasonal and covers only part of the winter energy demand, which necessitates hybrid systems or intelligent energy management strategies [4,5].

Emerging research directions also include resistive elements with optimized geometries designed to maximize radiant temperature, as well as inductive heating, which can reach high temperatures rapidly and allows precise control of thermal distribution [6,7]. These technologies are being investigated as part of ongoing efforts to develop electric radiant equipment capable of operating efficiently in halls, workshops, and terraces while being powered from renewable sources [4,7].

This paper presents part of the experimental work and characterization of an innovative electric radiant tube prototype developed within the INFRAEL research project. The study aims to address this technological gap by investigating the thermal and electrical performance of the proposed system and by identifying optimization directions toward a viable and sustainable alternative to gas-fired industrial heating. Future research will focus on analyzing the feasibility of inductively heating the tube and increasing its surface temperature, including through the use of conventional Ni-Cr resistive elements, given that these can reach temperatures of up to 650 °C.

2. State of Knowledge and Research Relevance

The scientific literature on industrial radiant heating covers the performance of gas-fired radiant tubes extensively. Sarbu and Tokar [8] provided a detailed numerical model of high-temperature radiant panel heating systems for industrial halls, validating the advantages of radiant systems over convective alternatives in terms of energy efficiency and thermal comfort. It has been demonstrated, through various doctoral research studies, that the fundamental principles of high-temperature radiant heating with radiant tubes

establish analytical and experimental bases applicable to the context of the present study. There are studies that determine the measured or numerically simulated temperature fields in spaces heated with radiant tubes [9,10]

Toropoc and Frunzulică [11] analyzed the economic aspects of radiant heating systems, emphasizing the competitive advantages over other heating forms in large-volume industrial buildings—conclusions directly applicable to the experimental model in this paper.

Regarding the integration of electric heating with renewable sources, the study by Cannava et al. [4] demonstrated the impact of PV self-consumption enhancement strategies in logistics warehouses, showing that photovoltaic coupling can significantly reduce energy costs and the carbon footprint of industrial buildings. Hussein et al. [5] studied the influence of PV panel orientation and tilt angle on energy generation, providing the theoretical basis for the planned future integration of the electric radiant tube with a PV system equipped with solar tracking.

The bibliographic study confirms that gas-fired radiant tubes remain the mature and efficient solution for heating large industrial halls. Existing electric radiant solutions are adequate for zone heating or small halls, but cannot yet replace gas systems in extensive industrial applications. As a result, despite ongoing improvements in electric infrared technology, it cannot yet replace gas-fired radiant tube systems as the heating solution for extensive industrial applications, given the current cost gap between electricity and natural gas. This balance, however, is not fixed: utility-scale solar photovoltaic costs have already fallen by roughly 90% since 2010 and are projected to decline by a further 40% by 2035, positioning solar as one of the cheapest sources of new electricity generation in many regions [12]. Should industrial facilities increasingly pair on-site or grid-supplied photovoltaic generation with electric radiant systems, the current cost disadvantage of electric heating relative to gas could narrow substantially or even reverse, particularly in regions with high solar irradiance and supportive net-metering or self-consumption schemes [13]. In that scenario, the choice between gas and electric radiant heating for large industrial halls would shift from a question of technical maturity to one of electricity generation cost and on-site renewable integration, making continued monitoring of PV price trends directly relevant to the long-term viability of gas-fired systems in this application.

3. Materials and Methods

3.1. Description of the Experimental Model

The experimental model developed within the research consists of a steel radiant tube with an outer diameter of 100 mm and a wall thickness of 2 mm, which constitutes the emitting body for electromagnetic waves in the infrared domain. Inside this tube, electric resistive elements are mounted in various configurations, each having an electrical resistance of 80 Ω and a nominal power of approximately 630 W.

The resistive elements consist of nickel-chromium (Ni-Cr) wire, housed inside a metallic sheath with an outer diameter of 4 mm, the resistive wire itself having a diameter of 0.13 mm. The heated length of the metallic sheath containing the resistive element is 1060 mm, close to the tube length, and is designed specifically for energy transfer by conduction. To ensure the most faithful contact possible with the inner wall of the emitting tube, a system of multiple discs made of 1 mm sheet metal was designed, perforated to allow positioning of the resistors in different positions relative to the lower generator of the radiant tube (Figure 1).

The radiant tube is mounted on supports, covered by a reflective stainless steel screen with a high reflection coefficient, and suspended from the ceiling. The resistors can be pow-

ered individually or in parallel, and each configuration constitutes a separate experiment, with the recorded temperatures analyzed.



Figure 1. Experimental model of the electric radiant tube—cross-sectional view.

The assembly is powered from a sinusoidal alternating voltage source with an effective value of $U = 230\text{ V}$, which allows each resistive element to operate at its nominal parameters. In the parallel configuration, all resistors are subjected to the same voltage, each contributing individually to temperature increase and raising the total power dissipated inside the tube.

3.2. Measurement Instrumentation

To monitor the thermal behavior of the radiant tube, thermocouples were installed at different points along the tube so that the temperature distribution, heating uniformity, and any thermal loss zones or local heat accumulations could be evaluated. The measurement system included Type K (Ni-Cr/Ni) thermocouples, selected for their extended operating range (-200 – $+1200\text{ }^{\circ}\text{C}$). These were installed in five cross-sections spaced 20 cm apart along the length of the radiant tube (Figure 2).



Figure 2. Thermocouple installation along the radiant tube.

Data were collected with an ALMEMO 2690-8 (Ahlborn) data acquisition station—a universal, portable, high-precision data logger produced by Ahlborn—featuring 5 galvanically isolated measurement inputs, allowing connection of over 65 different types of sensors (temperature, humidity, pressure, flow, voltage, current, etc.). It offers a high measurement speed of up to 50 measurements per second, a backlit graphic display, in-

ternal memory, and the possibility of using an external SD card for long-term recordings. Data connectivity is ensured via USB, RS232, Ethernet, or analog outputs.

For evaluation of radiation distribution in the receiving plane, temperature measurements were performed on the radiation capture surface at a height of $h = 2.2$ m below the radiant tube. A measurement grid (10×14 points) was established in the receiving plane, with a discretization step of 20 cm in both directions, covering a rectangular surface of 2100×3000 mm. The receiving surface was formed from extruded polystyrene panels covered with white paper. Measurement points were marked with 40×40 mm black metallic squares to maximize radiation absorption at measurement locations.

Temperature measurements on the receiving surface were performed using the AMIR 7814 non-contact portable thermometer from Ahlborn, with a distance-to-spot ratio of 60:1, a temperature range of -30 °C... $+900$ °C, accuracy of $\pm 1\%$, and fast response time. The instrument is compatible with the ALMEMO data acquisition system for data transfer to a PC. Thermovision imaging was additionally used for qualitative evaluation of the thermal field of both the tube and the receiving plane.

Temperature data from the measurement grid nodes were processed in MATLAB for numerical calculation and graphical representation of the temperature field on the receiving surface, using interpolation between point values.

For monitoring electrical parameters, a digital multimeter was used to determine the supply voltage, the current absorbed by the assembly, and the active power dissipated by the resistors. These measurements were essential for correlating the applied electrical power with the temperatures obtained in the radiant tube.

4. Results and Discussion

4.1. Analysis of Electrical Parameters

A representative set of electrical measurements recorded on 7 April 2026 is presented in Table 1. The measurements cover six consecutive reading sets during a heating campaign with two resistors connected in parallel.

Table 1. Electrical parameters measured during the heating campaign (7 April 2026, 2 resistors in parallel).

Parameter	Set 1 13:54	Set 2 13:57	Set 3 14:01	Set 4 14:06	Set 5 14:15	Set 6 14:58
U (V)	227.4	226.9	226.5	227.2	227.1	229.5
I (A)	5.45	5.44	5.44	5.45	5.46	5.52
P (W)	1239	1235	1231	1239	1239	1266
Q (VAr)	0	0	0	0	0	0
S (VA)	1239	1238	1235	1238	1240	1270
cos φ	1	1	1	1	1	1

The electrical measurements indicate a supply voltage of 227.4 V and a total current of 5.45 A for two resistors connected in parallel. The total active power absorbed by the assembly is:

$$P_{tot} = U \cdot I = 227.4 \cdot 5.45 \cong 1239 \text{ W}$$

This value confirms the correct operation of the parallel configuration. The equivalent resistance of the circuit is $R_e = \frac{U}{I} = 41.7 \, \Omega$, meaning the value of one resistor is $R \cong 83.4 \, \Omega$. The power dissipated by each resistor is:

$$P = \frac{U^2}{R} \cong 618 \text{ W per resistor}$$

Since $\cos \varphi = 1$, $Q = 0$ and $S \cong P$, the analyzed system presents a purely resistive character, stable, in which electrical energy is entirely converted into thermal energy—a property that is favorable for electrical efficiency, since no reactive power is drawn from the supply. This does not by itself quantify the radiant efficiency of the heater, which depends on the fraction of this thermal energy that is subsequently emitted as infrared radiation rather than lost via convection and end conduction (see Section 5.1).

4.2. Thermal Analysis Along the Radiant Tube

Data acquired by the ALMEMO station through thermocouples positioned at 20 cm intervals along the radiant tube were downloaded to Excel files and represented graphically. Measurements were performed on different days with slightly different outdoor temperatures, which influenced the starting conditions.

4.2.1. Configuration with Two Resistors (~1.26 kW)—3 April 2026

A difference of approximately 12% was recorded between the first and sixth thermocouple readings, as a result of the resistors being recessed relative to the final end of the radiant tube. The ambient start temperature at measurement initiation was 22.9 °C; the average tube temperature after reaching steady state—achieved in approximately 30 min—was 254.4 °C (Figure 3).

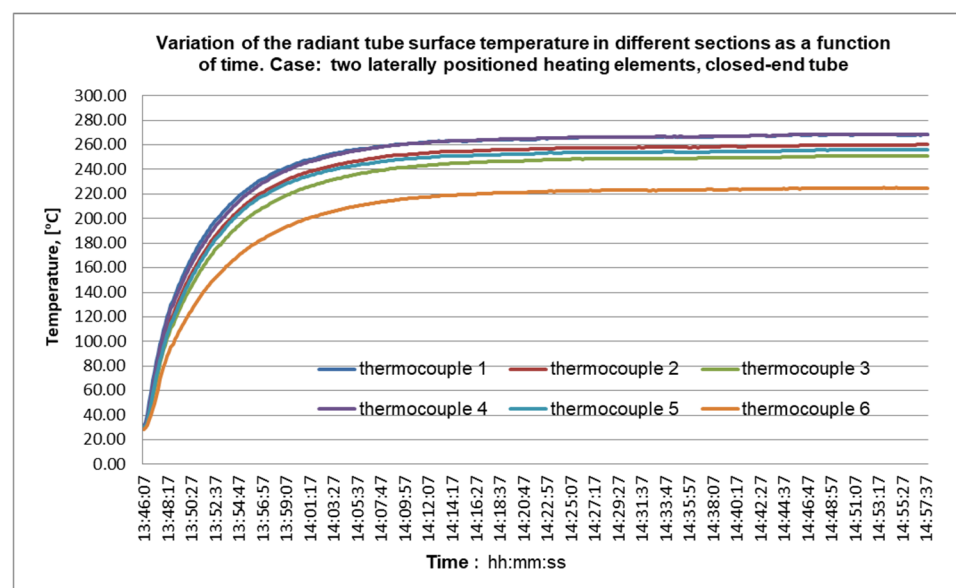


Figure 3. Temperature variation curves along the tube surface in different cross-sections (2 resistors, 3 April 2026).

4.2.2. Configuration with Two Resistors (~1.26 kW)—7 April 2026

A difference of approximately 16% was recorded between the first and sixth thermocouple readings. The ambient start temperature was 26.1 °C (the equipment having previously operated for another measurement set); the average tube temperature in steady state—reached in approximately 20 min—was 254 °C (Figure 4). Under these conditions, after reaching stable operation, the temperature recorded in the receiving plane reached 28.9 °C, with a relatively uniform temperature field in the receiving plane.

4.2.3. Configuration with One Resistor (~630 W)—8 April 2026

A difference of only approximately 3% was recorded between the first and sixth thermocouple readings—a markedly more uniform longitudinal distribution compared to the two-resistor configuration. The ambient start temperature was 24.1 °C; the average

tube temperature in steady state—reached in approximately 25 min—was 136 °C, closed and open-end tube (Figures 4 and 5).

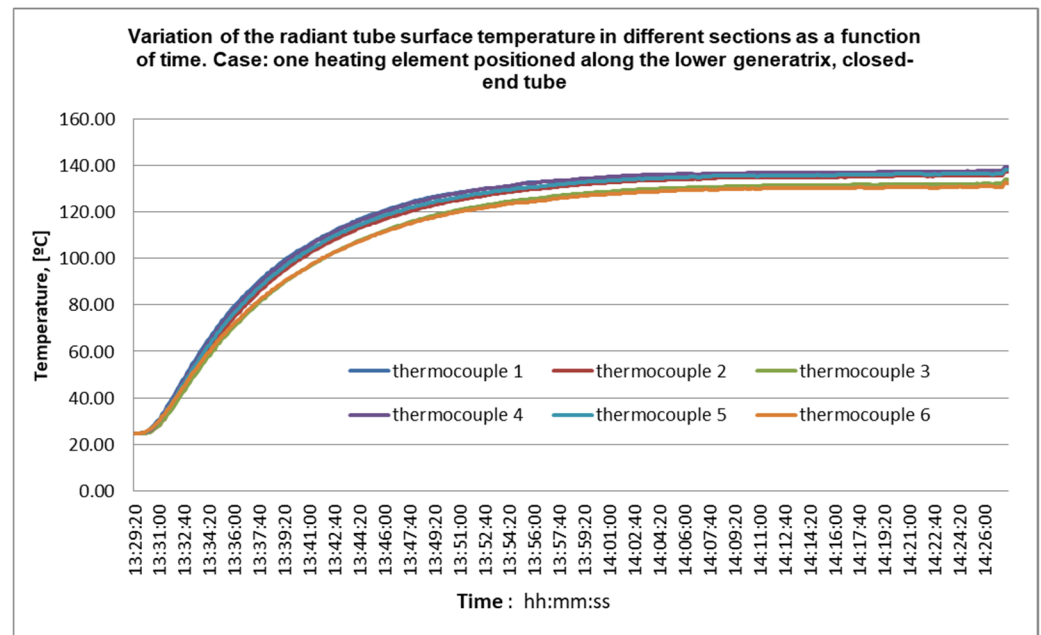


Figure 4. Temperature variation curves along the tube surface in different cross-sections (2 resistors, 7 April 2026).

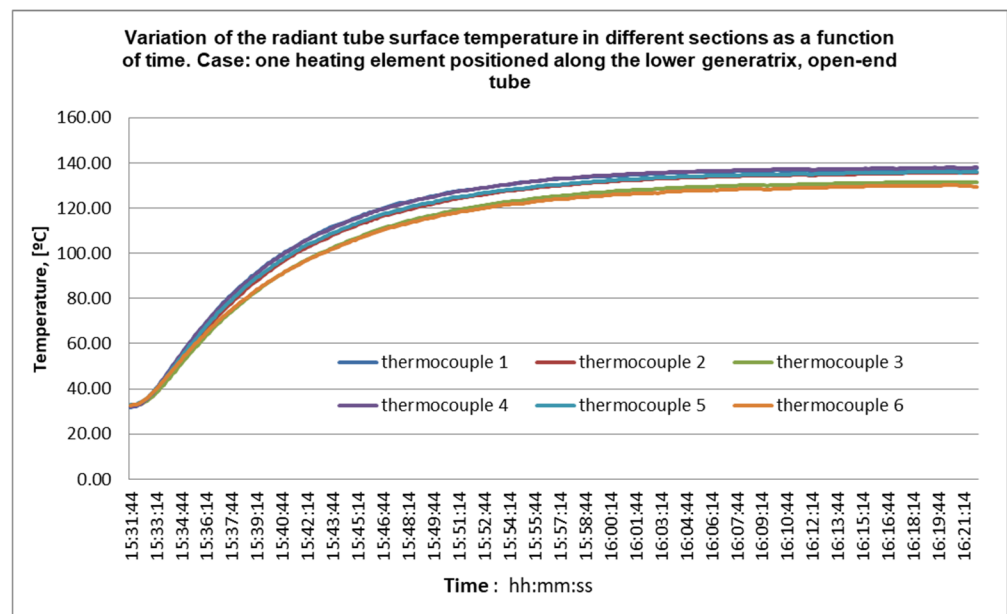


Figure 5. Temperature variation curves along the tube surface in different cross-sections (1 resistor, 8 April 2026).

4.3. Thermal Field in the Receiving Plane

Temperature measurements on the receiving surface were processed in MATLAB R2025b Trial to obtain temperature field maps through interpolation between grid node values. Measurements were performed both on the black-painted metallic squares (maximum absorption—theoretical model) and on the actual gray laboratory floor surface (real-world reference).

The results show a relatively uniform temperature distribution in the receiving plane, with a slight non-uniformity characterized by higher values beneath the lower

generator line of the radiant tube. This behavior is consistent with the directional nature of infrared radiation and the geometry of the reflective screen. Samples are presented in Figures 6–9.

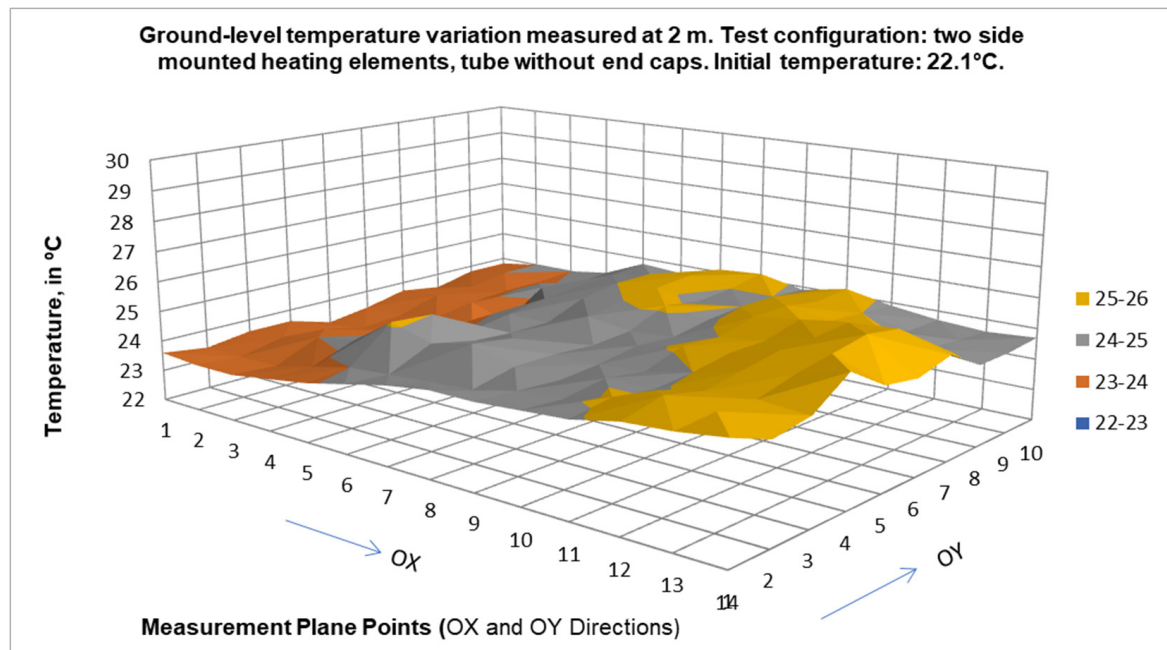


Figure 6. Temperature distribution on the receiving surface—infrared measurement. Two heated elements.

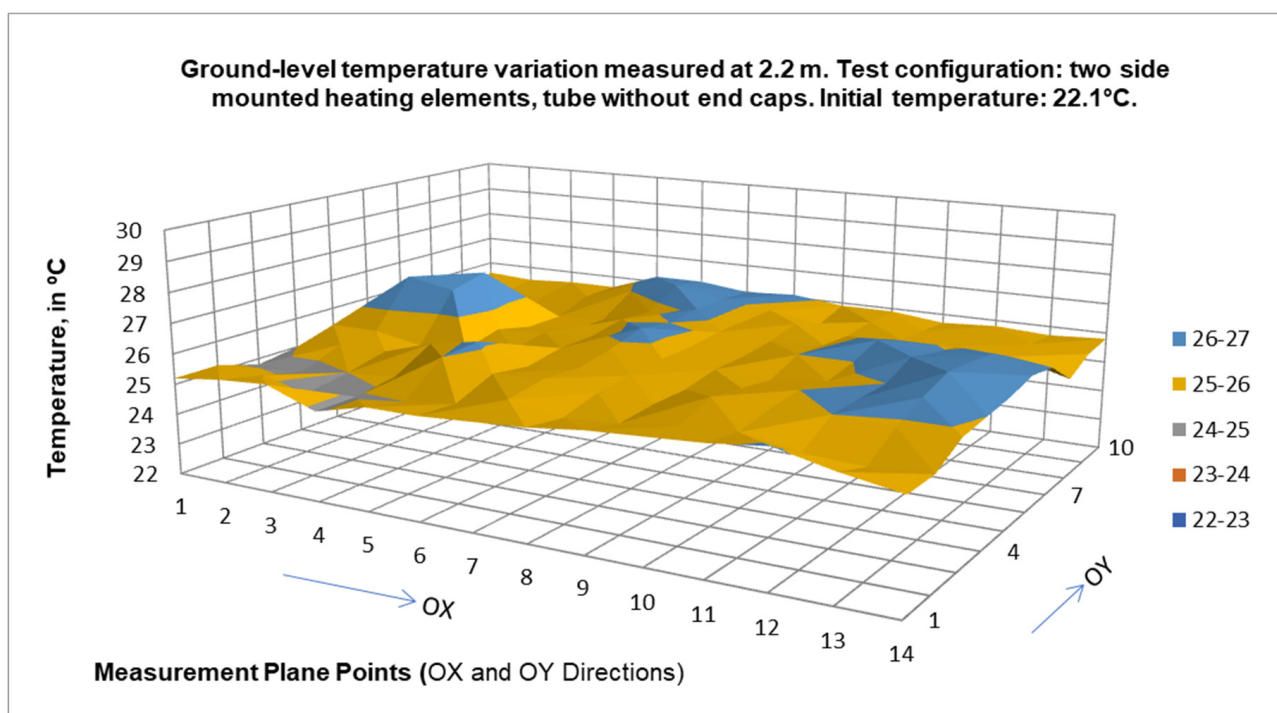


Figure 7. Temperature distribution on the receiving surface—infrared measurement. Two heated elements.

4.4. Thermovision Analysis

For qualitative evaluation, thermovision imaging was performed on both the receiving plane and the radiant tube. When using infrared optical systems, the measured temperature must be corrected for the emissivity of surfaces. Emissivity varies with temperature, radiation wavelength, and the angle relative to the surface normal; for precision measure-

ments, all these factors must be considered. Rough surfaces exhibit less angle-dependent emissivity variation than polished surfaces.

The thermovision images confirmed the temperature distributions obtained through thermocouple measurements and non-contact pyrometry, providing a qualitative spatial overview of the thermal field. They revealed a slightly higher temperature zone beneath the lower generator line of the tube, consistent with the expected directional radiation pattern (Figure 10).

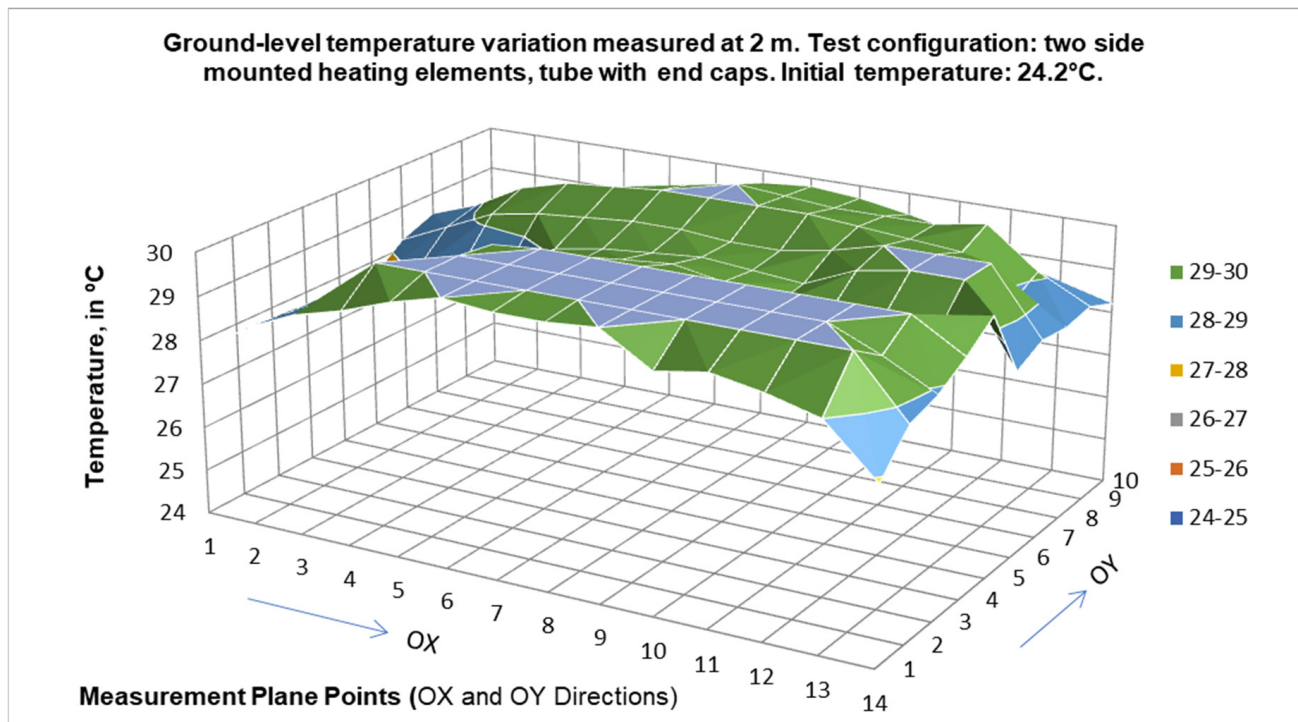


Figure 8. Temperature distribution on the receiving surface—infrared measurement. Two heated elements.

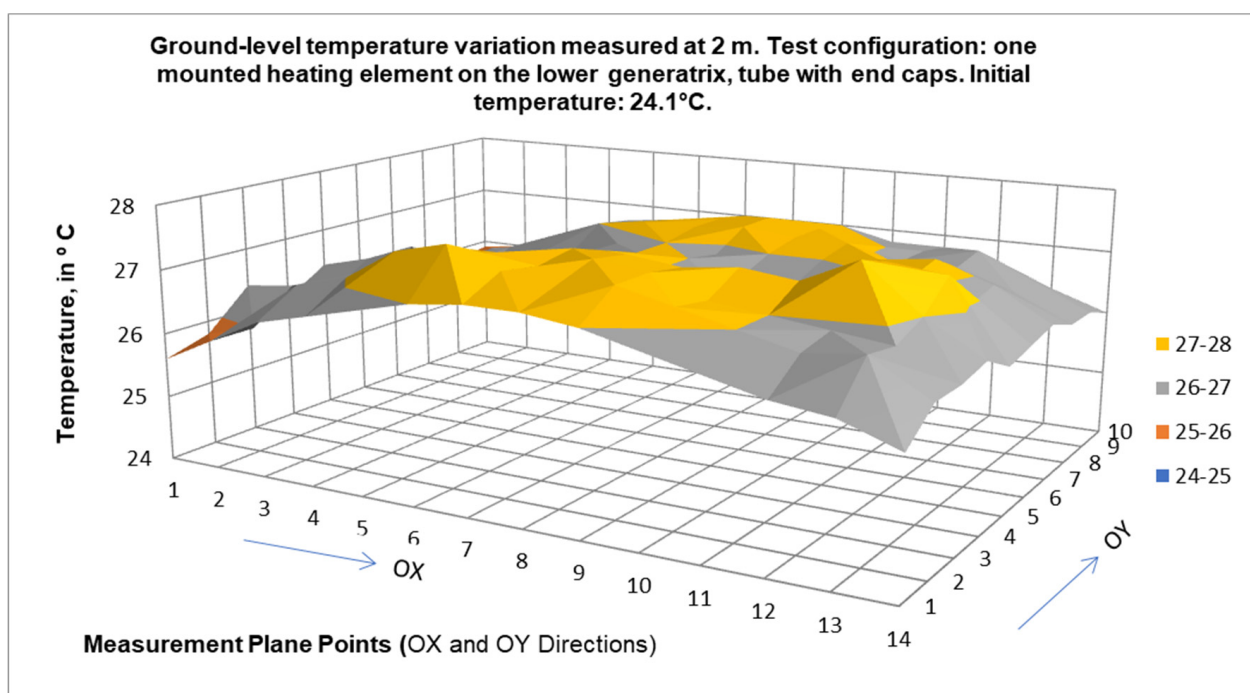


Figure 9. Temperature distribution on the receiving surface—infrared measurement. One heated element.

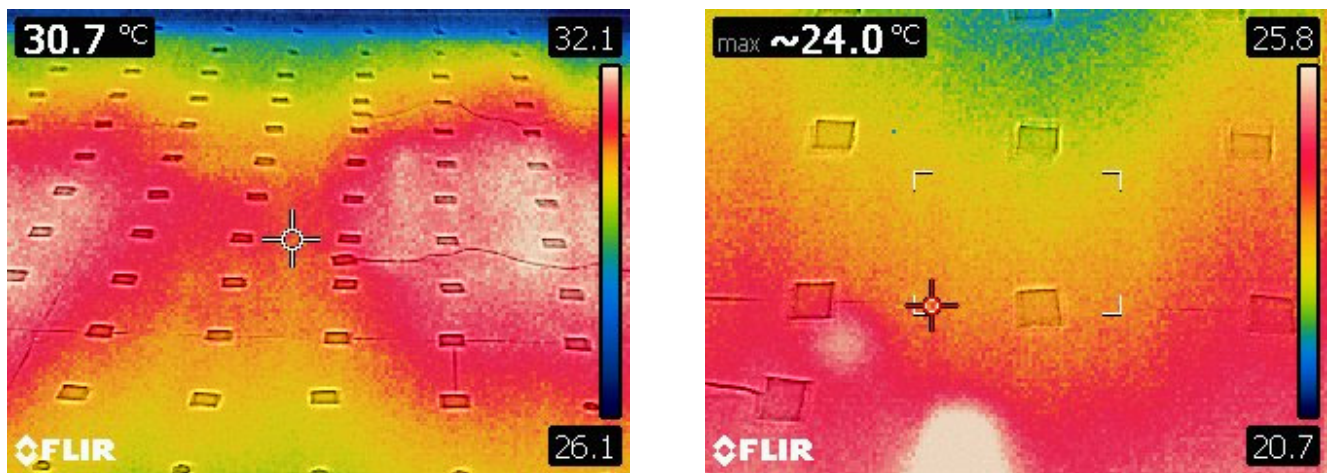


Figure 10. Thermovision image of the receiving surface—heating campaign.

5. Comparative Analysis of the Carbon Footprint

5.1. Assumptions and Input Data

To quantify the environmental benefits of transitioning from gas-fired to electric radiant heating, a comparative analysis of CO₂ equivalent emissions was carried out for six operating scenarios for an industrial workshop with a thermal load of 20 kW, operating 8 h per day, 150 days per year (standard heating season). The scenarios cover both electric solutions (grid-powered and photovoltaic-powered) and the progressive transition of natural gas networks towards hydrogen—in line with the European REPowerEU strategy and the Hydrogen Strategy (2020).

It should be noted that the two efficiency figures in Table 2 describe the fraction of input energy retained as heat within the workshop enclosure, not the radiant performance of the heater. The 92% value is the combustion efficiency of the gas-fired tube: 8% of the fuel's chemical energy leaves the building with the flue gases and never contributes to space heating. The 100% value reflects the fact that a purely resistive electrical load (unity power factor, $\cos \varphi = 1$) converts essentially all of its electrical input into heat inside the enclosure, with no analogous exhaust loss. Neither figure quantifies the *radiant efficiency* of the heater—i.e., the share of the retained heat that is emitted as directed infrared radiation to the target zone, as opposed to being lost via convection from the tube surface or conduction through end fittings and supports. Characterizing the radiant fraction of the prototype (through radiometric measurement or an energy balance separating convective and end losses) was outside the scope of the present experimental campaign and is identified as a direction for future work (Section 6). Accordingly, the CO₂ emissions calculated in Section 5.2 quantify the carbon intensity per unit of thermal energy retained within the enclosure for each energy vector; they are not a measure of the delivered radiant heating performance of the gas versus electric systems, which would additionally depend on their respective radiant fractions.

5.2. CO₂ Emissions Calculation per Scenario

Scenario A—Gas-fired radiant tube (100% CH₄, $\eta = 92\%$)

Annual thermal energy required and annual gas consumption (accounting for combustion efficiency of 92%):

$$Q_{\text{thermal}} = 20 \text{ kW} \times 8 \text{ h} \times 150 \text{ days} = 24,000 \text{ kWh/year}$$

$$Q_{\text{gas}} = 24,000 / 0.92 = 26,087 \text{ kWh/year}$$

$$E_A = 26,087 \times 0.202 = 5270 \text{ kg CO}_2/\text{year}$$

Scenario B—Gas-fired radiant tube on gas + 20% H₂ blend (no equipment modifications)

Table 2. Input data for the carbon footprint analysis.

Parameter	Value	Source
Heating system power	20 kW	—
Combustion efficiency of gas-fired radiant tube/gas+H ₂ (fraction retained after flue-gas losses)	92%	ISO 13790 [14]
Fraction of electrical input retained as heat within the enclosure (resistive load, $\cos \varphi = 1$)	100%	measured
Operating hours per day	8 h	assumption
Operating days per year	150 days	assumption
Emission factor—natural gas (100% CH ₄)	0.202 kg CO ₂ /kWh	IPCC 2021 [15]
Emission factor—gas + 20% H ₂ blend (vol.)	0.163 kg CO ₂ /kWh	IPCC/IEA 2023 [16,17]
Emission factor—Romanian national grid	0.294 kg CO ₂ /kWh	Eurostat 2023 [18]
Emission factor—photovoltaic system (life cycle)	0.025 kg CO ₂ /kWh	NREL 2021 [19]
Emission factor—photovoltaic + battery + inverter (life cycle)	0.080 kg CO ₂ /kWh	IEA PVPS Task 12, 2021 [20]
Emission factor—100% green hydrogen (life cycle)	0.010 kg CO ₂ /kWh	IRENA 2022 [21]

A blend of 20% hydrogen (by volume) in natural gas represents the maximum limit accepted by distribution networks and existing equipment without any modification, in accordance with European standard [22] and the REPowerEU objectives for 2030. Hydrogen has a lower heating value of 10.8 MJ/m³ compared to 35.9 MJ/m³ for methane, and the emission factor of the blend decreases proportionally with the H₂ fraction by volume:

$$f_{\text{emission_blend}} = 0.80 \times 0.202 + 0.20 \times 0.000 = 0.162 \text{ kg CO}_2/\text{kWh}$$

Note: hydrogen does not generate CO₂ upon combustion; residual emissions originate from H₂ production (grey or blue H₂). The IEA average factor for network H₂ in 2030 (blue H₂ with partial CO₂ capture) is used:

$$f_{\text{IEA_blend}} = 0.163 \text{ kg CO}_2/\text{kWh}$$

$$E_B = (24,000/0.92) \times 0.163 = 26,087 \times 0.163 = 4252 \text{ kg CO}_2/\text{year}$$

This represents a reduction of approximately 19% compared to Scenario A, without any equipment adaptation costs. The gas-fired radiant tube can operate on this blend without modifications to the burner, control system, or materials.

Scenario C—5 electric tubes (5×4 kW), powered from the national grid

$$Q_{\text{el}} = 20 \text{ kW} \times 8 \text{ h} \times 150 \text{ days} = 24,000 \text{ kWh/year}$$

$$E_C = 24,000 \times 0.294 = 7056 \text{ kg CO}_2/\text{year}$$

Grid-powered operation leads to a 34% increase in emissions compared to the pure gas scenario, due to the still significant share of fossil fuel-fired power plants in Romania's energy mix (2023). This situation will reverse as Romania decarbonizes its energy sector in accordance with the Energy Strategy 2025–2035, when the grid emission factor will fall below 0.17 kg CO₂/kWh—below the level of pure gas [2].

Scenario D—5 electric tubes, powered 100% by photovoltaics

$$E_D = 24,000 \times 0.025 = 600 \text{ kg CO}_2/\text{year}$$

The photovoltaic emission factor (0.025 kg CO₂/kWh) includes emissions from the manufacturing, installation, and decommissioning of PV panels over the full life cycle (LCA). This represents an 88.6% reduction compared to natural gas.

Scenario E—Gas-fired radiant tube on 100% green hydrogen

Green hydrogen is produced through electrolysis powered exclusively from renewable energy sources (wind, solar). Hydrogen combustion does not generate CO₂; residual emissions are exclusively of industrial origin (manufacture of the electrolyser, storage vessels, and distribution infrastructure), assessed through life cycle analysis at ~0.010 kg CO₂/kWh (IRENA, 2022) [21].

This scenario does, however, require significant equipment modifications: the burner (injector) must be replaced or recalibrated, the air-to-fuel ratio control system must be adapted for the much higher combustion velocity of H₂ (3.2 m/s vs. 0.4 m/s for CH₄), seals and gaskets must be replaced with materials compatible with the small H₂ molecule, and leak detection systems require dedicated sensors. Consequently, the transition cost of Scenario E is substantially higher than that of Scenario D (electric + PV).

$$E_E = (24,000/0.92) \times 0.010 = 26,087 \times 0.010 = 261 \text{ kg CO}_2/\text{year}$$

The reduction compared to Scenario A (natural gas) is 95%, placing this scenario at a level comparable to the photovoltaic scenario in terms of emissions, but with significantly higher adaptation and fuel costs at the current stage of the energy transition.

Scenario F—5 electric tubes, powered by photovoltaics with battery storage and inverter (no grid backup)

Scenario D assumes PV electricity is consumed directly, without storage—realistic only if heating operates strictly during daylight hours. Continuous or evening/night operation, as implied by an industrial workshop with a fixed 8 h/day schedule, requires battery storage sized to bridge the gap between solar generation and load, together with the associated charge/discharge inverter.

Including the battery and inverter within the life-cycle boundary raises the emission factor of the PV-supplied electricity from 0.025 kg CO₂/kWh (panels and grid-tied inverter only, as used in Scenario D) to approximately 0.080 kg CO₂/kWh, based on life-cycle assessments of residential/C&I PV-battery systems with 10–20 kWh Li-ion storage (IEA PVPS Task 12).

$$Q_{el} = 20 \text{ kW} \times 8 \text{ h} \times 150 \text{ days} = 24,000 \text{ kWh}_{el}/\text{year}$$

$$E_F = 24,000 \times 0.080 = 1920 \text{ kg CO}_2/\text{year}$$

This corresponds to a 63.6% reduction in emissions compared to Scenario A (natural gas), smaller than the 88.6% reduction in Scenario D, because the manufacturing footprint of the battery adds materially to the life-cycle emissions of the electricity supplied. Scenario F is retained alongside Scenario D throughout this section as the more conservative, operationally realistic estimate for a fully photovoltaic-powered solution.

5.3. Comparative Summary

The comparative analysis of the scenarios analyzed, maps a coherent decarbonization trajectory for industrial heating, with differentiated options across three time horizons: short-term (2025–2030), medium-term (2030–2035), and long-term (2040–2050). Each scenario is characterized by a distinct profile of CO₂ emissions, transition cost, and degree of technical intervention on existing equipment (Figure 11, Table 3).

5.4. Discussion of Environmental Impact and Decarbonization Pathway

Short-term (2025–2030)—Partial hydrogenation of the gas network (Scenario B)

Blending natural gas with 20% hydrogen (by volume) is the measure with the lowest transition cost: it requires no modification to heating equipment, is compatible with

the existing distribution network in accordance with standard EN 16726, and is already targeted by the REPowerEU strategy and by Transgaz through commitments for 2030. The reduction achieved—from 5270 to 4252 kg CO₂/year (−19%)—remains modest relative to European climate targets (carbon neutrality by 2050) and is insufficient as a standalone decarbonization measure.

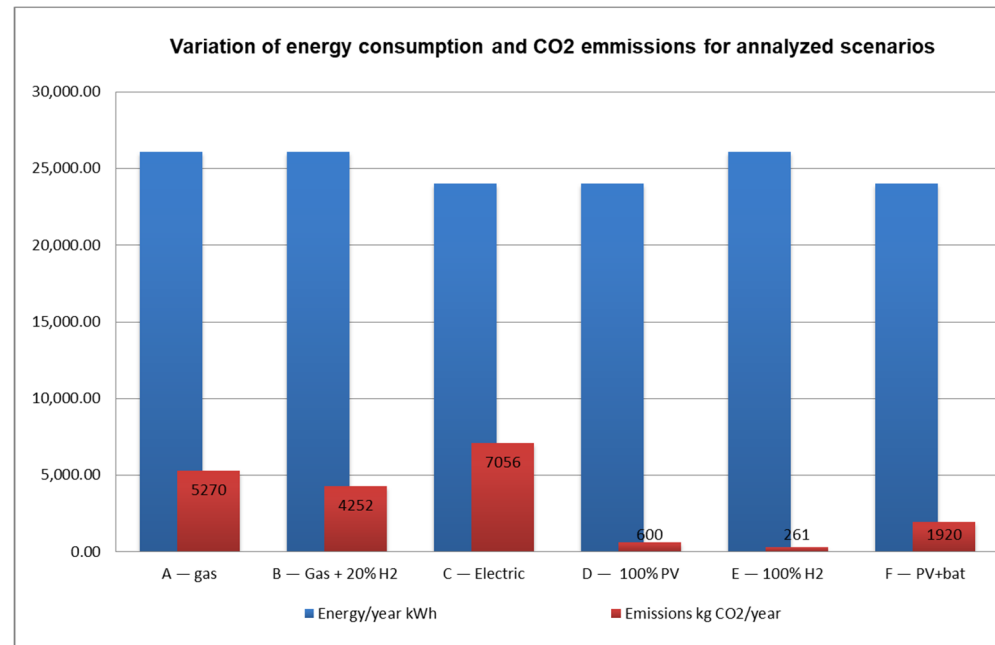


Figure 11. Annual energy consumption (kWh) and CO₂ emissions comparison for the scenarios (A–F). Decarbonization trajectory runs left to right: from natural gas (A) through gas/H₂ blending (B), grid electricity (C), photovoltaic electricity without battery (D) and with battery (F), to 100% green hydrogen (E).

Table 3. Comparison of annual CO₂ emissions across industrial heating decarbonization scenarios.

Scenario	Energy/Year	CO ₂ Emissions/Year	Reduction vs. Gas	ETS Carbon Cost *	Equipment Changes
A—Natural gas (100% CH ₄ , η = 92%)	26,087 kWh _{gas}	5270 kg CO ₂	reference	~€369/yr	No
B—Gas + 20% H ₂ (EN 16726)	26,087 kWh _{blend}	4252 kg CO ₂	−19% reduction	~€298/yr	No
C—Electric, national grid (5 × 4 kW)	24,000 kWh _{el}	7056 kg CO ₂	+34% increase	~€494/yr	No
D—Electric, powered 100% by photovoltaics (5 × 4 kW 100% PV)	24,000 kWh _{el}	600 kg CO ₂	−88.6% reduction	~€42/yr	No
E—100% Green hydrogen	26,087 kWh _{H₂}	261 kg CO ₂	−95% reduction	~€18/yr	Yes (significant)
F—Electric, photovoltaic + battery + inverter (5 × 4 kW + PV + BESS)	24,000 kWh _{el}	1920 kg CO ₂	−63.6% reduction	~€134/yr	No

* Carbon cost calculated at the average ETS (EU Emissions Trading System) price of ~€70/tonne CO₂ (2024). Scenario E does not include the additional cost of equipment adaptation, nor the fuel price differential (green H₂ currently costs 3–5 times more than natural gas). Scenario F does not include the additional capital cost of the battery and inverter themselves, only the resulting change in the electricity life-cycle emission factor.

In the same time horizon, grid-powered electric heating (Scenario C) is disadvantageous in terms of emissions (+34% compared to gas), due to the still significant share of

fossil fuel power plants in Romania's energy mix (grid emission factor: 0.294 kg CO₂/kWh in 2023). Consequently, simple electrification of industrial heating without coupling to own renewable sources does not constitute a viable decarbonization strategy in the short term.

Medium-term (2030–2035)—Electrification with on-site photovoltaic sources (Scenario D)

The photovoltaic-powered electric scenario represents, in the current context and on a medium-term horizon, the most efficient combination of carbon footprint reduction and techno-economic feasibility. The 88.6% reduction in CO₂ emissions (from 5270 to 600 kg CO₂/year) is achieved without any modification to the fuel distribution infrastructure and without investment in adaptation of the heating equipment. A further advantage stems from the fact that a purely resistive electrical load ($\cos \varphi = 1$, experimentally demonstrated within the INFRAEL project) retains all of its input energy as heat within the enclosure, whereas 8% of the fuel input to the gas tube is lost with the flue gases; for the same 24,000 kWh/year of thermal energy retained in the workshop, this corresponds to an input-energy saving of 2087 kWh/year relative to the gas tube. This saving concerns the energy retained within the space, not the radiant fraction of the two systems, which has not yet been characterized (see Section 5.1).

As the emission factor of the national electricity grid falls below 0.17 kg CO₂/kWh (projected by 2035, according to the Energy Strategy 2025–2035 [2]), Scenario C will also become advantageous over gas—further expanding the decarbonization potential of the electric solution, even in the absence of an own PV system.

Long-term (2040–2050)—100% Green hydrogen (Scenario E)

The 100% green hydrogen scenario achieves the greatest emissions reduction in all scenarios analyzed (−95%, from 5270 to 261 kg CO₂/year), placing it at a level comparable to the photovoltaic scenario in terms of carbon footprint. However, this scenario requires significant modifications to the combustion equipment—replacement or recalibration of the burner, adaptation of the air-to-fuel ratio control system for H₂'s much higher combustion velocity (3.2 m/s vs. 0.4 m/s for CH₄), replacement of seals and gaskets with H₂-compatible materials, and installation of dedicated leak detection sensors. Furthermore, the cost of green hydrogen is currently 3–5 times higher than natural gas, making this scenario cost-competitive only after 2040, once electrolysis production is scaled to industrial levels.

Comparative Synthesis and Energy Policy Implications

In terms of ETS carbon cost (~€70/tonne CO₂ in 2024), the ranking of scenarios in ascending order of annual carbon cost is:

- Scenario E—100% green H₂: ~€18/year (lowest carbon cost, but highest total transition cost)
- Scenario D—Electric, powered 100% by photovoltaics: ~€42/year (best ratio of emissions reduction to transition cost)
- Scenario F—Photovoltaic 100% + battery + inverter: ~€134/year (more realistic PV configuration once storage is included)
- Scenario B—Gas + 20% H₂: ~€298/year (modest reduction, minimal transition cost)
- Scenario A—Natural gas 100% CH₄: ~€369/year (current baseline)
- Scenario C—Electric from national grid: ~€494/year (currently disadvantageous, favorable after 2035)

The results indicate that, in the current context and on the 2025–2035 horizon, the electric solution powered 100% by photovoltaics (Scenario D) represents the optimal decarbonization pathway for industrial workshop heating: it offers the greatest immediately available emissions reduction (−88.6%), requires no modifications to fuel infrastructure or heating equipment, and is technically demonstrated—as confirmed by the experimental results of the INFRAEL project. In the long term, 100% green hydrogen (Scenario E) remains a viable option for completing decarbonization in sectors where direct electrification is

difficult, but requires substantial investment in equipment adaptation and a reduction in green H₂ production costs. It should be noted that Scenario D assumes PV electricity consumed directly, without storage, which is realistic only for daylight-hours operation; for the fixed 8 h/day schedule considered here, Scenario F—the same PV-electric configuration but with battery storage and inverter included in the system boundary—offers a more operationally realistic estimate, still achieving a 63.6% emissions reduction versus Scenario A while accounting for the additional life-cycle footprint of the storage system.

These conclusions are fully consistent with the objectives of the European Green Deal, the REPowerEU strategy, and Romania’s Energy Strategy 2025–2035, which recognize both photovoltaic energy and green hydrogen as key vectors of industrial decarbonization [2].

5.5. Unit Cost of Thermal Energy (€/kWh_t)

To complement the carbon footprint assessment, the final unit cost of the thermal energy delivered to the industrial workshop (€/kWh_t) was estimated for each scenario, combining the price of the energy carrier with the ETS carbon cost already presented in Table 3. Reference 2024 prices for the Romanian market (Eurostat, non-household consumers, and the national photovoltaic support auction) were used, as summarized in Table 4.

Table 4. Reference unit prices of energy carriers (Romania, 2024).

Parameter	Value	Source
Natural gas price (industrial, non-household)	0.047 €/kWh	Eurostat, Q4 2024 [23]
Electricity price (national grid, industrial, non-household)	0.140 €/kWh	Eurostat, Dec 2024 [23]
Electricity price (photovoltaic, LCOE/CfD auction)	0.050 €/kWh	RO renewables auction, Dec 2024 [24]
Green hydrogen price (3–5× natural gas, this study)	0.190 €/kWh	derived (Table 3 note)
Gas + 20% H ₂ blend price (80% gas + 20% H ₂ , weighted)	0.076 €/kWh	calculated
Electricity price (photovoltaic + battery storage + inverter, LCOE)	0.090 €/kWh	Fraunhofer ISE, 2024 [25]
Emission factor—photovoltaic + battery + inverter (life cycle)	0.080 kg CO ₂ /kWh	IEA PVPS Task 12, 2021 [20]

The unit thermal cost for each scenario was computed as the sum of the energy-carrier cost (fuel or electricity price divided by system efficiency η) and the ETS carbon cost per unit of useful thermal energy ($Q_{\text{thermal}} = 24,000$ kWh/year, constant across all scenarios):

$$C_{\text{unit}} = (p_{\text{energy}}/\eta) + (\text{Cost}_{\text{carbon,year}}/Q_{\text{thermal}}) \text{ [€/kWh}_t\text{]}$$

Applying this formula with the reference prices of Table 4 and the annual carbon costs of Table 3 yields the unit thermal costs summarized in Table 5.

Scenario F—Unit Cost of the PV + Battery + Inverter Configuration

As established in Section 5.2, Scenario F retains the same PV-electric configuration as Scenario D but includes the battery and inverter within the life-cycle boundary, raising the emission factor to 0.080 kg CO₂/kWh and giving $E_{\text{F}} = 1920$ kg CO₂/year—a 63.6% reduction versus Scenario A, smaller than the 88.6% reduction in Scenario D because of the battery’s

manufacturing footprint. At the ETS reference price of ~€70/tonne CO₂, the annual carbon cost of Scenario F is:

$$\text{Cost}_{\text{carbon},F} = 1920 \times 0.070 = \sim\text{€}134/\text{year}$$

For the energy cost component, the price of PV-generated electricity increases substantially once battery storage is added: Fraunhofer ISE (2024) [25] reports an LCOE of €0.06–0.225/kWh for PV-plus-battery systems in Germany (versus €0.041–0.144/kWh for PV alone), reflecting the added capital cost of the storage system. A representative mid-range value of €0.090/kWh is used here for an industrial-scale system. Applying the C_{unit} formula ($\eta = 100\%$) gives an energy cost of €0.090/kWh_t and a carbon cost of €0.0056/kWh_t ($1920 \times 0.070/24,000$), for a total unit cost of ~€0.096/kWh_t—included as Scenario F in Table 5.

Table 5. Final unit cost of thermal energy per scenario (D and F distinguish PV without vs. with battery storage).

Scenario	Energy Cost (€/kWh _t)	Carbon Cost (€/kWh _t)	Total Unit Cost (€/kWh _t)
A—Natural gas (100% CH ₄ , η = 92%)	0.0511	0.0154	0.0665
B—Gas + 20% H ₂ (EN 16726)	0.0822	0.0124	0.0946
C—Electric, national grid (5 × 4 kW)	0.1400	0.0206	0.1606
D—Electric, powered 100% by photovoltaics (5 × 4 kW + PV)	0.0500	0.0018	0.0518
E—100% Green hydrogen	0.2065	0.0008	0.2073
F—Electric, powered 100% by photovoltaic + battery + inverter (5 × 4 kW + PV + BESS)	0.0900	0.0056	0.0956

Prices are indicative 2024 references for the Romanian market (Eurostat non-household tariffs; national photovoltaic support auction, December 2024) and for the German market for storage-coupled PV (Fraunhofer ISE, 2024 [25]), as no equivalent Romanian LCOE data for PV + battery systems was identified; the green hydrogen price is derived from the 3–5× natural-gas ratio already noted in Table 3. Scenario F assumes a battery sized in the 10–20 kWh class, sufficient to shift part of the daytime PV generation to cover the remaining hours of the 8 h/day operating schedule; larger or smaller storage capacities, or a different battery chemistry, would shift both the emission factor and the LCOE. Where contracted tariffs and system specifications specific to the INFRAEL project are available, they can be substituted directly into the C_{unit} formula above.

The unit-cost ranking corroborates the emissions-based ranking for Scenario D—in which the electric tubes are powered 100% by photovoltaics, with no grid backup and no storage—which combines the lowest energy-carrier price (self-generated photovoltaic electricity) with a minimal carbon surcharge, resulting in the lowest final cost of thermal energy (~€0.052/kWh_t) among all six original scenarios. Scenario E, despite achieving the lowest carbon emissions of all scenarios, carries by far the highest unit cost (~€0.207/kWh_t), driven almost entirely by the current price premium of green hydrogen; this confirms that the scenario becomes cost-competitive only in the long term, as electrolysis costs decline towards industrial scale. Scenario C remains the least favorable option under present Romanian grid conditions, combining a comparatively high electricity price with the highest emission factor of the six scenarios.

Scenario F—the more realistic PV configuration once battery storage and its associated inverter are included in the system boundary—sits between Scenarios D and B, both in

emissions (1920 vs. 600 kg CO₂/year for D, still well below the 5270 kg CO₂/year of Scenario A) and in unit cost (~€0.096/kWh_t, close to Scenario B and roughly 85% higher than Scenario D). This gap illustrates that the very low unit cost attributed to Scenario D depends on an optimistic assumption—PV electricity consumed without storage—that is unlikely to hold for a workshop operating on a fixed daily schedule irrespective of solar availability. Reporting both D (idealized, no storage) and F (with battery and inverter) gives a more complete picture of the achievable decarbonization and cost range for a fully photovoltaic-powered solution, and is recommended as the basis for any techno-economic conclusions drawn from this analysis. These findings reinforce, from an economic perspective, the conclusion already drawn from the carbon footprint analysis: an electric pathway powered by photovoltaics—with or without storage—offers the best combination of decarbonization and cost-effectiveness on the 2025–2035 horizon, with Scenario F representing the more conservative, operationally realistic estimate.

6. Conclusions

The experimental results demonstrate the technical feasibility of the proposed electric radiant tube concept. At a total power of approximately 1.2 kW (two resistors in parallel), the tube surface reaches temperatures exceeding 250 °C, placing it in the medium-wave infrared radiation domain (wavelength ~4 µm). With a single 630 W resistor, surface temperatures of approximately 136–160 °C are achieved, corresponding to low-temperature infrared emission.

The temperatures obtained are consistent with the applied electrical power level, confirming correct operation of the assembly. The unity power factor ($\cos \varphi = 1$) demonstrates the purely resistive character of the system, with electrical energy converting entirely into thermal energy without reactive losses. This ensures that no electrical input is dissipated as reactive power, which is favorable from an electrical-efficiency standpoint; it does not by itself establish the radiant efficiency of the heater, which depends additionally on the fraction of that thermal energy emitted as directed infrared radiation rather than lost to convection and end conduction.

This paper presents the experimental development and characterization of an innovative electric radiant tube prototype for sustainable industrial heating. The following key conclusions are drawn:

- At a total power of ~1.2 kW (two resistors in parallel), the electric radiant tube achieves surface temperatures exceeding 250 °C, corresponding to medium-wave infrared emission (~4 µm), confirming the technical viability of the concept.
- With a single 630 W resistor, surface temperatures of ~136–160 °C are achieved, with markedly improved longitudinal temperature uniformity (variation of ~3%).
- The system exhibits a purely resistive character ($\cos \varphi = 1$), ensuring complete conversion of consumed electrical energy into thermal energy, with no reactive losses.
- The temperature field on the receiving plane ($h = 2$ m) is relatively uniform, with a slight concentration of thermal flux beneath the lower generator line of the tube.
- The comparative analysis of six decarbonization scenarios (natural gas, gas + 20% H₂, grid electricity, photovoltaic electricity, 100% green hydrogen) maps a coherent trajectory across three time horizons. In the short term (2025–2030), the gas + 20% H₂ blend offers an immediate 19% reduction without equipment modification. In the medium term (2030–2035), the photovoltaic electric solution with battery (a realistic scenario) reduces emissions by 63.6% (from 5270 to 1920 kg CO₂/year) with the best reduction-to-transition-cost ratio. In the long term (2040–2050), 100% green hydrogen can reduce emissions by 95% (261 kg CO₂/year), but requires significant equipment modifications and a reduction in green H₂ cost.

- In the current context, the photovoltaic solution with battery (Scenario F) represents the optimal decarbonization pathway: the greatest immediately available reduction, without interventions on fuel infrastructure, technically confirmed by the experimental results of the INFRAEL project. These results are fully consistent with the objectives of the European Green Deal, REPowerEU, and Romania's Energy Strategy 2025–2035.
- The main identified optimization directions are: improvement of resistor geometry, use of high-emissivity materials for the tube surface, reduction in convective end losses, and coupling with a solar-tracked PV system. A further priority for future work is the direct characterization of the radiant efficiency of the prototype (the fraction of input energy emitted as directed infrared radiation to the target zone, as distinct from the enclosure-level retention efficiency reported in Section 5), through radiometric measurement or an energy balance separating radiant, convective, and end-conduction losses, to allow a like-for-like comparison with the radiant efficiency of gas-fired tubes.

The planned future integration of the electric radiant tube with a photovoltaic power supply system—including solar tracking to maximize energy production throughout the year—represents a logical next step towards a fully sustainable, zero-carbon industrial heating solution. As noted in the literature, photovoltaic production is seasonal, making intelligent energy management or hybrid backup systems necessary for year-round operation [3,12].

Author Contributions: Conceptualization, N.T. and M.S.T.; methodology, N.T. and M.S.T.; experimental model construction and measurements, N.T. and M.S.T.; data processing and analysis, M.S.T. and N.T.; writing—original draft, M.S.T.; writing—review and editing, T.C.; supervision, N.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the INFRAEL research grant. The APC was funded by the Technical University of Civil Engineering of Bucharest (ctr.13714/10 October 2025)

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Parliament. Renewable Energy Sources. Available online: <https://www.europarl.europa.eu> (accessed on 10 March 2026).
2. Bejan, M.; Bologa, O. *Energia Regenerabilă*; Univers Ingineresc: Bucharest, Romania, 2007.
3. Romanian Government. *Romania's Energy Strategy 2025–2035, with a Perspective to 2050*; Ministry of Energy: Bucharest, Romania, 2024. Available online: <https://energie.gov.ro> (accessed on 10 March 2026).
4. Cannava, L.; Dadras Javan, F.; Najafi, B.; Perotti, S. Green warehousing practices: Assessing the impact of PV self-consumption enhancement strategies in a logistics warehouse. *Sustain. Energy Technol. Assess.* **2024**, *72*, 104054. [CrossRef]
5. Hussein, H.M.S.; Ahmad, G.E.; El-Ghetany, H.H. Performance evaluation of photovoltaic modules at different tilt angles and orientations. *Energy Convers. Manag.* **2004**, *45*, 2441–2452. [CrossRef]
6. Lucía, O.; Maussion, P.; Dede, E.J.; Burdío, J.M. Induction heating technology and its applications: Past developments, current technology, and future challenges. *IEEE Trans. Ind. Electron.* **2014**, *61*, 2509–2520. [CrossRef]
7. Rudnev, V.; Loveless, D.; Cook, R.L. *Handbook of Induction Heating*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2017.
8. Sarbu, I.; Tokar, A. Numerical modelling of high-temperature radiant panel heating system for an industrial hall. *Int. J. Adv. Appl. Sci.* **2018**, *5*, 1–9. [CrossRef]
9. Ahanj, M.D.; Rahimi, M.; Alsairafi, A.A. CFD modeling of a radiant tube heater. *Int. Commun. Heat Mass Transf.* **2012**, *39*, 432–438. [CrossRef]
10. Dudkiewicz, E.; Jeżowiecki, J. Measured radiant thermal fields in industrial spaces served by high intensity infrared heater. *Energy Build.* **2009**, *41*, 27–35. [CrossRef]

11. Toropoc, S.M.; Frunzulică, R. Economical considerations concerning radiant heating systems. *Sci. Bull. UPB* **2011**, *73*, 83–92.
12. International Energy Agency. Economic and Demographic Trends to Create Opportunities for Solar. *PV Tech*, 12 November 2025. Available online: <https://www.pv-tech.org/economic-demographic-trends-create-opportunities-solar-world-becomes-thirsty-for-energy/> (accessed on 17 March 2026).
13. Silva, K.A.E.; Carrasco, L.M.; Hogan Almeida, R.; Narvarte, L.; Lorenzo, E. Sizing Photovoltaic Self-Consumption Systems for Sustainable Decision-Making: A Novel Techno-Economic Approach Using Performance Metrics and Real Consumption Data. *Sustainability* **2026**, *18*, 2991. [CrossRef]
14. ISO 13790:2008; Energy Performance of Buildings—Calculation of Energy Use for Space Heating and Cooling. International Organization for Standardization: Geneva, Switzerland, 2008.
15. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; ISBN 978-1-009-15789-6.
16. IPCC. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023.
17. International Energy Agency. *World Energy Outlook 2023*; IEA: Paris, France, 2023. Available online: <https://www.iea.org/reports/world-energy-outlook-2023> (accessed on 17 March 2026).
18. Eurostat. *Renewable Energy Statistics*; Statistical Office of the European Union: Luxembourg, 2023. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics (accessed on 17 March 2026).
19. Ramasamy, V.; Feldman, D.; Desai, J.; Margolis, R. *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021*; Technical Report NREL/TP-7A40-80694; National Renewable Energy Laboratory: Golden, CO, USA, 2021.
20. Raugei, M.; Frischknecht, R.; Olson, C.; Sinha, P.; Heath, G. *Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity*, 2nd ed.; IEA-PVPS Task 12, Report T12-20:2021; International Energy Agency: Paris, France, 2021; ISBN 978-3-907281-18-5.
21. IRENA. *Renewable Power Generation Costs in 2021*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022; ISBN 978-92-9260-452-3.
22. EN 16726:2025; Gas Infrastructure—Quality of Gas—Group H. European Committee for Standardization (CEN): Brussels, Belgium, 2025.
23. Eurostat. *Electricity Price Statistics*; Statistical Office of the European Union: Luxembourg, 2024. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (accessed on 17 March 2026).
24. Ministerul Energiei. *Rezultatele Primei Licitații CfD pentru Capacități Noi de Producere a Energiei Electrice din Surse Regenerabile*; Ministerul Energiei: Bucharest, Romania, 2024.
25. Fraunhofer ISE. *Photovoltaics Report*; Philipps, S., Warmuth, W., Eds.; Fraunhofer Institute for Solar Energy Systems ISE: Freiburg, Germany, 2024. Available online: <https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf> (accessed on 17 March 2026).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.