


Decarbonisation of tunnel ovens for baking purposes: Review and future prospects

Hadi Tannous^{*} , Savvas A. Tassou, Geoffrey J. Rodgers

Centre for Sustainable Energy Use in Food Chains, College of Engineering and Physical Sciences, Brunel University of London, Uxbridge, Middlesex, UB8 3PH, UK

ARTICLE INFO

Keywords:

Tunnel ovens
Industrial baking
Electrification
Decarbonisation
Heat transfer
Waste heat recovery
Hydrogen combustion

ABSTRACT

Industrial tunnel ovens are among the most energy-intensive equipment in large-scale bakeries and a significant contributor to greenhouse gas emissions. This review synthesises experimental, computational, and industrial evidence on tunnel-oven performance and decarbonisation options, focusing on gas-fired, electric, and emerging heating technologies relevant to continuous baking. Studies were assessed with respect to thermal performance and product-quality outcomes. To enable consistent comparison across studies, thermal performance is interpreted using defined system boundaries. Supplied heat is taken as burner fuel input on a lower heating value basis for gas and hydrogen systems, or electrical power delivered to heating elements for electric systems. Useful heat absorbed by the product includes sensible heating of the dough and latent heat associated with moisture evaporation. Under these boundaries, reported product heat utilisation varies widely and can fall to around 16% in high-temperature direct-fired tunnel operation, indicating substantial losses through exhaust gases and heat transfer to the oven structure and surroundings. Electrification through resistance heating improves controllability and avoids combustion losses, although reduced radiative heat transfer can affect crust development. Hybrid concepts combining resistance heating with infrared or convection show potential to maintain surface quality while reducing energy use. Advanced electrothermal approaches, including induction, microwave, and ohmic heating, remain constrained by scale-up and control challenges and lack full-scale validation. Hydrogen combustion represents a possible longer-term pathway, but direct evidence for hydrogen-fired tunnel ovens in baking remains absent. Overall feasibility depends on grid carbon intensity, energy prices, and retrofit constraints.

1. Introduction

Industrial baking processes are commonly carried out in continuous tunnel ovens that enable large-scale production of breads, biscuits, and flatbreads under controlled thermal conditions. These systems operate as continuous thermal reactors in which products travel through multiple heating zones while undergoing simultaneous heat and mass transfer. Baking therefore involves a complex combination of mechanisms including conduction within the dough matrix, convective and radiative heat transfer from the surrounding air and heating surfaces, and moisture evaporation at the product surface [1]. The distribution of temperature and humidity within the oven directly influences key product attributes such as crust formation, colour development, texture, and crumb structure, making thermal control a critical design and operational parameter for industrial ovens [2]. As a result, tunnel ovens are not only food-processing equipment but also sophisticated

thermo-processing systems whose design, heating mode, and airflow configuration strongly affect both product quality and process performance [3,4].

Despite their importance for industrial food production, tunnel ovens are also among the most energy-intensive units in bakery operations because large amounts of thermal energy are required to heat the product, evaporate moisture, and maintain stable temperature conditions along the oven length. Most industrial tunnel ovens therefore rely on natural-gas-fired burners, which provide high heat fluxes and strong radiative heating that promote rapid crust formation and uniform baking [5]. However, combustion-based heating also produces direct carbon dioxide emissions, making industrial baking part of the broader challenge of decarbonising thermal processes in the food manufacturing sector. Recent studies on food-industry energy systems emphasise that electrification of industrial heat and improvements in process efficiency are key strategies for reducing greenhouse-gas emissions from food processing [5]. At the same time, optimisation studies of baking

^{*} Corresponding author.

E-mail address: Hadi.Tannous2@brunel.ac.uk (H. Tannous).

<https://doi.org/10.1016/j.rser.2026.117068>

Received 5 December 2025; Received in revised form 18 April 2026; Accepted 30 April 2026

Available online 13 May 2026

1364-0321/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Abbreviations

ER	Electric resistance
IR	Infrared
OH	Ohmic heating
WHR	Waste heat recovery
CFD	Computational fluid dynamics

processes have shown that oven operating conditions, heat-transfer mechanisms, and product moisture dynamics strongly influence energy use, indicating that any transition to low-carbon heating technologies must account for the complex thermo-physical behaviour of baking systems [1,6].

A substantial body of research has investigated the thermal behaviour and energy performance of tunnel ovens used in industrial baking. These studies have examined airflow patterns, heat-transfer mechanisms, and temperature distributions within ovens using both experimental measurements and computational fluid dynamics (CFD) modelling. For example, investigations of biscuit and bread tunnel ovens have analysed the influence of burner configuration, airflow recirculation, and baffle design on temperature uniformity and product heating [7,8]. Other studies have used combined experimental and numerical approaches to characterise radiative and convective heat-transfer contributions within baking chambers and to evaluate the impact of oven design on product heating rates [9,10]. More recent work has focused on improving the energy efficiency of tunnel ovens through optimisation of air-jet impingement systems, burner operation, and airflow management, demonstrating that modifications to oven operating conditions can reduce baking time and energy consumption [11–14]. While these studies have significantly improved understanding of oven thermodynamics, they are typically limited to specific oven configurations or products, which makes it difficult to compare different heating technologies within a unified framework.

In response to the need for lower-emission industrial heating, several alternative technologies have been explored as potential substitutes or complements to conventional gas-fired tunnel ovens. Electrification approaches include electric resistance heating, infrared emitters, air-impingement systems, induction heating, and microwave-based heating concepts. Experimental studies comparing gas and electric tunnel ovens have shown that electric resistance systems can achieve stable chamber temperatures and comparable baking performance for certain products, although differences in heat-transfer balance may affect crust colour and surface characteristics [15,16]. More recent pilot-scale investigations of resistance-heated conveyor ovens have demonstrated the feasibility of controlled baking under electrically heated conditions, supported by temperature monitoring and CFD analysis of airflow and heat transfer [17–19]. Other approaches, such as induction heating of baking plates and microwave-assisted tunnel systems, have also been investigated for specific products or laboratory-scale demonstrations [20,21]. In parallel, hydrogen combustion has been proposed as a potential pathway to maintain combustion-based heating while reducing carbon emissions, although its implications for burner design, heat-transfer characteristics, and baking performance remain largely unexplored [22,23].

Several review articles have examined baking technology, modelling, and specific bakery products; however, their scope differs from the system-level perspective required for evaluating tunnel-oven decarbonisation. General reviews of baking technologies and equipment have summarised machines, plants, and process-improvement strategies affecting final product characteristics [4], while modelling-oriented reviews have focused on CFD, heat and mass transfer, and measurement approaches during baking rather than on comparative technology assessment [1,24]. Product-specific reviews have addressed flatbread

formulation, quality, and innovation [25], and more recently flatbread qualities, oven design, energy consumption, and environmental conservation, particularly in balady-type systems [26]. Broader end-use and decarbonisation reviews have discussed electrification of heat in food manufacturing [5] and hydrogen-based cooking technologies [22], while technology-specific reviews have examined microwave baking as a separate processing route [27]. These studies provide valuable insights into baking processes, product characteristics, modelling tools, and selected low-carbon options, but they do not systematically analyse tunnel ovens as industrial thermal systems, nor do they compare conventional gas-fired operation with electrified, hybrid, and hydrogen-relevant pathways from the combined perspective of energy use, heat-transfer mechanisms, product-quality implications, and decarbonisation strategy. Consequently, a systematic synthesis of tunnel-oven research that integrates these aspects is still lacking in the literature.

In this context, the present review provides a systematic assessment of tunnel ovens used in industrial baking, with particular emphasis on heat transfer, product quality, and decarbonisation. The review first examines gas-fired tunnel ovens, focusing on the thermal mechanisms governing baking performance and the reported product-quality outcomes. It then evaluates electric tunnel ovens from the same perspective, assessing both heat-transfer behaviour and available evidence on baked-product quality. Emerging technologies that may contribute to tunnel-oven decarbonisation but have not yet been widely investigated in that context are subsequently reviewed with respect to their thermal characteristics and potential implications for baking performance. The evidence is further synthesised to compare product-quality outcomes across heating modes. Finally, the review discusses potential decarbonisation pathways for industrial tunnel ovens and identifies key research gaps and experimental needs required to support future low-carbon baking technologies.

2. Definitions and system boundaries

This review evaluates tunnel ovens primarily in terms of thermal performance and product quality. Heat and energy are used interchangeably in this manuscript, since the performance metrics discussed relate to thermal energy supplied to the oven and transferred within the baking process. The analysis focuses on heat supplied to the oven chamber, the fraction transferred to the baked product, and the principal thermal losses through exhaust gases and heat transfer to the surroundings. Electrical loads associated with conveyors, controls, and other auxiliary equipment are outside the core boundary unless explicitly included in a cited oven energy balance. Upstream processes across the baking line, such as mixing, proofing, and shaping, are also excluded.

Within this boundary, supplied heat denotes the primary thermal input to the oven. For gas and hydrogen systems, it is defined on a lower heating value basis for the fuel entering the burners. For electrically heated systems, it is taken as the electrical power delivered to heating elements. Upstream losses external to the oven, such as grid generation losses or boiler inefficiencies, are excluded. Accordingly, decarbonisation is treated as achievable when oven heating departs from fossil-fuel combustion. Electrification is therefore considered a direct step towards oven decarbonisation, while the wider sustainability of electricity supply is outside the scope of this review.

Useful heat absorbed by the product is defined as the sensible heating of the dough together with the latent heat associated with moisture evaporation during baking. Heat stored in oven walls, refractory and structural components, or discharged in exhaust gases is treated as loss within this boundary. In addition to thermal performance, product quality refers to the baked goods and is evaluated using reported measurable attributes, including moisture content, crust colour and browning indices, texture or crumb characteristics, volume or expansion, and sensory outcomes where available. Throughout the review,

efficiency comparisons, energy utilisation metrics, and quality trade-offs are interpreted within these defined boundaries to ensure consistency across heating technologies and study methodologies.

To ensure consistent interpretation of the evidence base, studies reviewed in this work are classified into four categories according to their level of industrial representativeness: (i) full-scale industrial tunnel ovens, (ii) pilot-scale tunnel ovens, (iii) compact conveyor or laboratory-scale systems, and (iv) adjacent non-tunnel systems (including batch ovens, burners, and non-bakery applications). This classification is used throughout the manuscript to distinguish evidence maturity and to avoid overgeneralisation across fundamentally different system configurations.

3. Current development of gas ovens

Gas-fired tunnel ovens remain the most common configuration in industrial bakeries worldwide, owing to their robustness, flexibility, and ability to handle high throughput. However, their reliance on fossil fuel combustion and their low overall efficiency make them a major contributor to energy use and carbon emissions in the baking sector. Research on gas-fired ovens has therefore focused on two broad themes. Firstly, the characterisation of oven operation through experimental measurement and computational modelling, in order to understand heat transfer, airflow, and product heating, and secondly the development of methodologies aimed at reducing energy consumption and emissions, including optimisation of operating parameters, innovations in burner and oven design, and integration of waste heat recovery (WHR) systems. Section 2.1 reviews the literature on oven operation, while Section 2.2 discusses strategies for improvement.

3.1. Operation

Gas-fired tunnel ovens have been extensively studied to better understand their thermal behaviour, airflow patterns, and heat transfer mechanisms. These ovens remain the standard in industrial bakeries due to their reliability and throughput, but their inherent inefficiencies make them a major focus of experimental and computational research, in order to identify causes of non-uniform baking and sources of heat loss.

A comprehensive example is the study by Mansour et al. [13], who developed and validated a three-dimensional CFD model of a

high-temperature laboratory scale tunnel oven used for Lebanese flatbread production. The oven, shown in Fig. 1, measured 1.5 m in length, 0.69 m in width, and 0.805 m in height, with an overhead burner supplying heat across three zones. Thermocouples and an IR camera provided detailed measurements of wall and surface future prospects temperatures, while an energy balance quantified heat transfer to the product. The model produced measured temperatures and heat fluxes with good agreement and revealed that only about 16% of the supplied heat was utilised in baking, with most lost to chimney gases (55% of heat supplied) and heated walls (28%). Radiation dominated the external heat transfer (66-73%), and strong spatial non-uniformities were observed, particularly near the burner, leading to uneven heating across the conveyor. Building on these findings, the authors performed a comprehensive experimental programme to characterise the thermal behaviour of the oven and dough expansion during baking. Flatbread discs of approximately 22 cm in diameter and 1.5 mm thickness were baked at between 450 and 650 °C with residence times of 10-12 s. Multiple thermocouples tracked air and surface temperatures, while high-speed imaging recorded bubble growth and puffing. The study reported oven thermal efficiencies between 16% and 21% depending on loading conditions, consistent with the earlier CFD results, and confirmed radiation as the dominant heating mode. Expansion measurements showed that dough volume increased rapidly within the first 7-11 s of baking, coinciding with vapour release and starch gelatinisation, before stabilising towards the end of residence. This work provided rare quantitative data on product deformation under conditions representative of industrial flatbread baking, complementing the earlier modelling results.

At industrial scale, Yi et al. [28] provided another perspective by modelling a forced-convection continuous industrial oven developed by Khatir et al. [29], shown schematically in Fig. 2. The oven consisted of a rectangular chamber measuring 12 m in length, divided into three 4 m heating zones, with nozzle arrays distributed across the upper and lower plates. A conveyor transported a 2 mm laminate product through the chamber, with exhaust vents positioned on the roof of each zone. CFD simulations were used to resolve velocity and temperature fields within the cavity. The results showed that nozzle design and spacing critically affected the uniformity of heat flux to the product surface. Recirculation zones formed near the walls and corners of the oven, producing local variations in convective heating. The study concluded that while forced

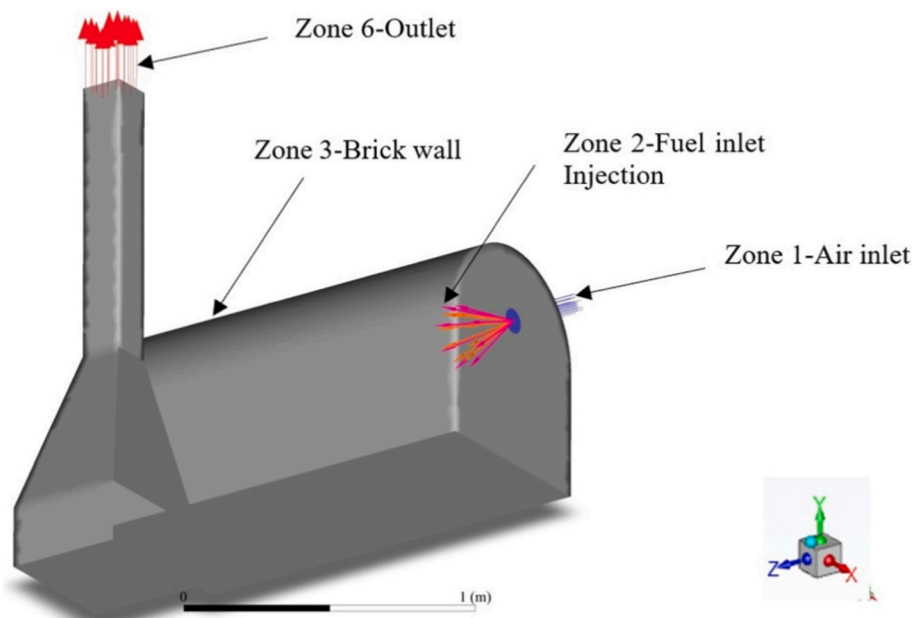


Fig. 1. Geometry of the high-temperature bread-baking oven [13].

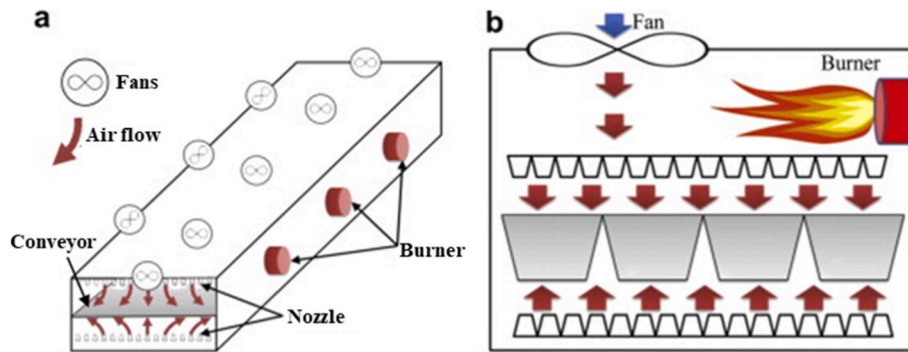


Fig. 2. Schematic of convection oven used by Khatir et al. [29].

convection improves bulk heat transfer rates, poorly designed nozzle systems can create significant differences in surface temperature distribution, leading to uneven product heating.

The work of Mirade et al. [7] remains an important reference for biscuit full-scale industrial tunnel ovens. Their study investigated a large industrial indirect gas-fired oven, the schematic of which is presented in Fig. 3. The baking chamber measured 50 m in length, 1 m in width, and 0.3 m in height, divided into 25 sections of 2 m each. Biscuits were conveyed on a wire-mesh band 0.82 m wide and 3 mm thick at 0.167 m/s, with the chamber heated by 56 gas burners distributed in two combustion chambers located above and below the baking space. Four extraction points connected to a common flue regulated airflow along the length. Using a $k-\epsilon$ turbulence model in combination with temperature and velocity measurements obtained with travelling thermocouples and hot-film anemometers, the authors characterised both temperature and airflow fields. Measured temperature profiles exhibited the bell-shaped curve typical of tunnel ovens, rising from 30 °C at the entrance to 240 °C mid-oven before falling to 120 °C at the exit. Air velocities were low, generally <0.5 m/s, with local fluctuations caused by the steel girders separating sections. CFD reproduced the overall temperature profile qualitatively but showed discrepancies in velocity predictions. The study demonstrated that even full-scale ovens exhibit strong spatial non-uniformities, confirming the complexity of airflow and heat transfer in industrial biscuit baking and the associated challenges for ensuring product uniformity.

Another important contribution is the work of Khatir et al. [10], who combined experimental measurements with CFD simulations to investigate airflow and temperature distribution in a three-zone direct-fired bread-baking tunnel oven (Fig. 4). The study used a pilot-scale tunnel oven (scaled-down industrial replica) measured 9 m in length, 1 m in

width, and 1.5 m in height, with three successive zones, each equipped with a burner and nozzle banks to direct hot-air jets above and below the conveyor. The CFD model was developed using a realisable $k-\epsilon$ turbulence approach and validated against thermocouple measurements taken throughout the chamber. Results showed that nozzle configuration and jet velocity had a strong influence on airflow distribution and temperature uniformity. Simulations reproduced the presence of recirculation zones and demonstrated that higher jet velocities reduced temperature deviations to within 2% of set-point values. The study demonstrated that oven nozzle design and operating conditions directly impact uniformity of baking conditions and provided a validated modelling approach for further optimisation studies. Other CFD studies reinforced this understanding. Boulet et al. [9] investigated a pilot-scale oven designed to reproduce one section of an industrial tunnel system. The chamber was divided into two halves, each 1.5 m wide, 1.4 m deep, and 0.2 m high, with heating provided by IR emitters through thin steel walls. Model validation used an h-monitor instrument fitted with thermocouples to record transient plate temperatures (Fig. 5), from which heat fluxes were calculated. Their simulations reproduced the measured temperature trends with good qualitative agreement and showed that radiation was the dominant heat-transfer mechanism, accounting for approximately 80% of the total heat flux on the upper plate and rising to nearly 99% on the lower plate over the course of baking (see Fig. 6).

Wong et al. [8] developed a CFD model of a full-scale industrial bread-baking oven with a U-turn conveyor configuration. The oven measured 16.5 m in length, 3.65 m in width, and 3.75 m in height, divided into four heating zones supplied by natural gas burners and hot-air circulation ducts. Using a two-dimensional sliding mesh model with discrete ordinate radiation, the study simulated bread motion along the 32.7 m track and compared predictions against data from travelling

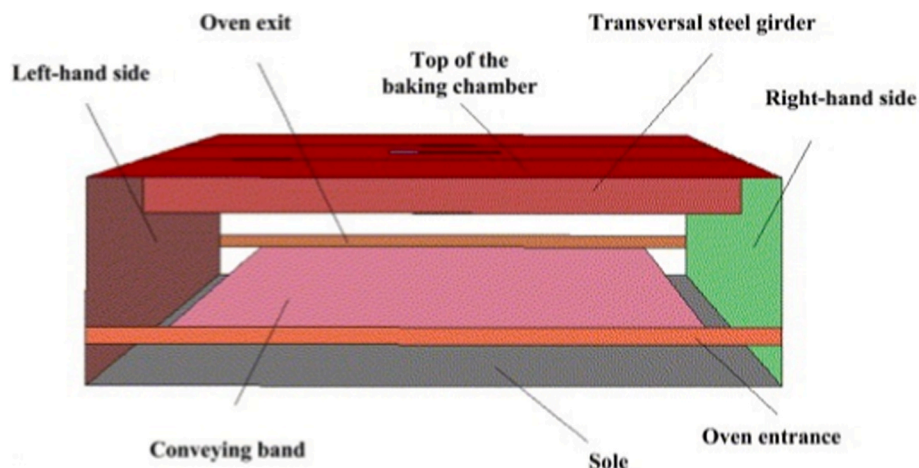


Fig. 3. Schematic of the forced convection oven [7].

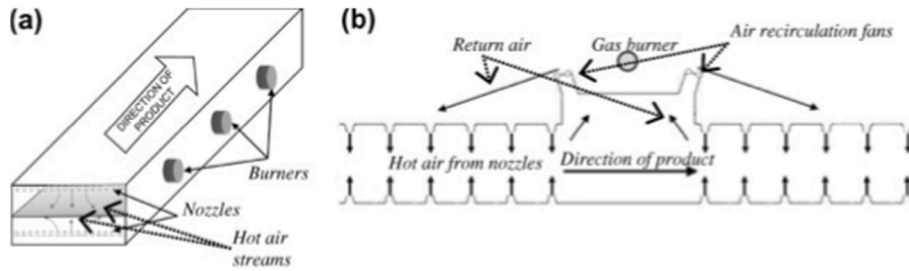


Fig. 4. Three-zone direct-fired oven. (a) Overview of the oven. (b) Simplified schematic showing the mechanism for distributing air through the nozzles for a single zone [10].

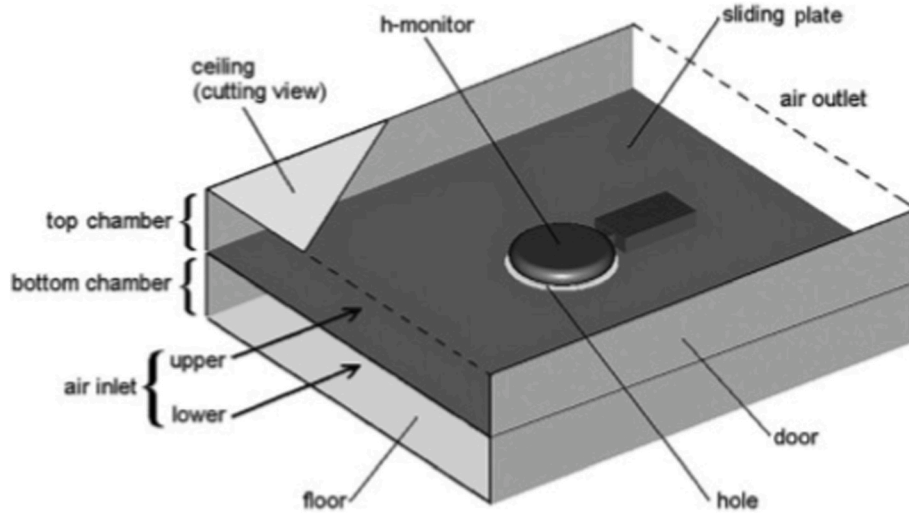


Fig. 5. Geometry of the oven and the h-monitor as used for CFD modelling by Boulet et al. [9].

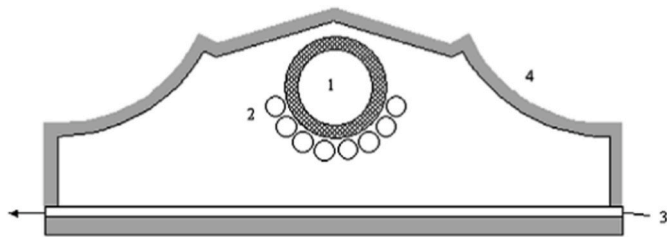


Fig. 6. Geometries for test apparatus of (1) combustion chamber; (2) radiant tubes; (3) plane of matt black coated tubes carrying flowing water; (4) thermal insulation. Williamson and Wilson [30].

thermocouples. Results showed that the model reproduced surface temperature profiles well, though discrepancies remained for dough centre temperature and air velocity. The analysis revealed that recirculating airflows and uneven heating persisted across zones, highlighting the role of oven geometry and burner balance in product uniformity.

Several experimental studies have provided valuable data for validating CFD models of bread baking. Al-Nasser et al. [31] developed and validated a CFD model of an industrial forced-convection bread non-tunnel oven with separate clean-air and flue-gas compartments. The product modelled was French baguette-type loaves, approximately 20 cm long, for which a new expansion model was implemented. Simulated surface and centre temperatures showed good agreement with experimental heating curves, and the model captured the interplay of evaporation, condensation, and volume growth during baking. This work demonstrated that CFD can reproduce bread heating and expansion

dynamics under realistic convection-oven conditions. Chhanwal et al. [1] reviewed CFD modelling of bread baking, examining turbulence models, radiation treatments, and product representations. They concluded that while CFD offers valuable insight for oven analysis, predictive accuracy is limited by assumptions such as steady state, simplified product properties, and omission of moisture transfer or dough expansion. They also highlighted the difficulty of scaling from pilot to industrial ovens because of differences in geometry, airflow, and loading.

Overall, the evidence base spans laboratory-scale tunnel systems, pilot-scale oven sections, and full-scale industrial tunnel ovens, with differences in geometry, airflow, and loading affecting direct comparability between studies.

In summary, studies of gas-fired tunnel oven operation consistently show that radiation dominates heat transfer under typical airflow conditions, while geometry and air-handling strongly influence uniformity. Overall thermal efficiency remains low, with substantial heat lost to exhaust gases and heated hardware. These findings establish the technical basis for the improvement strategies reviewed in the following section.

3.2. Improvement methods

While characterisation studies have demonstrated the inefficiencies of gas-fired tunnel ovens, a substantial body of research has focused on methods to improve their performance. These methods can be grouped into operational optimisation, burner and oven design innovations, and WHR systems. Each of these approaches has been explored at varying scales, including full-scale industrial tunnel ovens, pilot-scale rigs, and adjacent non-tunnel or cross-sector systems, and provide insights into

the achievable energy savings and emission reductions.

3.2.1. Operational optimisation

Operational optimisation of industrial ovens has received increasing attention as a cost-effective way to reduce energy use without major capital investment. Paton et al. [12] analysed a full-scale, three-zone direct-fired tunnel oven using a combined thermodynamic and CFD system-modelling framework. Their work quantified all major heat and mass flows, baking, moisture evaporation, tins, conveyor, flue gases, and wall losses and showed that approximately 19% of the input heat constituted unavoidable base losses through the structure and exhaust. By applying CFD-based optimisation of air-jet parameters and temperature uniformity, they demonstrated that bake time could be reduced by 5–10%, lowering specific energy required to bake each loaf by 2%. At the sector level, applying this reduction to the 2 TWh per year energy use of the UK bread-baking industry corresponds to savings of about £0.5 million and 5000 t CO₂ annually. Building on CFD-driven optimisation, Khatir et al. [29] introduced a multi-objective design optimisation framework for forced-convection bread ovens (generic or non-specific to tunnel configurations), coupling three-dimensional CFD (ANSYS FLUENT) with surrogate modelling and a genetic algorithm to optimise jet diameter, spacing ratio, and jet velocity for improved temperature uniformity. Their results indicate that reducing the temperature differential between the bread surface and oven air to approximately 10 °C can shorten effective baking time, yielding estimated energy savings of around 10% through reduced time-to-bake. In a complementary study, Khatir et al. [11] developed a combined experimental-computational optimisation framework for high-speed air-impingement bread ovens. Using a pilot-scale rig (4 m long, 3 m wide, 2 m high) with adjustable nozzle spacing and velocity, they measured local heat-transfer coefficients and validated a 3-D CFD model. The calibrated energy model identified an optimal convective heat-transfer coefficient of 35 W/m². K⁻¹, which could reduce overall energy use by 5% without compromising baking quality. The study confirmed that convection dominates (93% of heat transfer) and that improved air-jet design can deliver measurable energy savings and faster baking through higher uniformity of temperature and heat flux. Pask et al. [32] extended this line of work by applying a structured optimisation methodology to industrial ovens using the DMAIC cycle (Define, Measure, Analyse, Improve, Control). Their case study on a 1 MW festoon oven used for curing adhesives demonstrated that systematic optimisation of airflow, set-points, and exhaust controls could reduce gas use by 20–30% while also increasing throughput. Although not applied directly to bread ovens, the methodology illustrates the transferable potential of process optimisation for baking systems. El-Aldy et al. [33] also emphasised the role of operating parameters through experiments on Egyptian baladi industrial continuous ovens measuring 5 m × 2 m × 1.77 m with a belt width of 0.83 m. They showed that increasing belt speed reduced specific energy consumption from 3.57 to 1.93 kWh/kg for Magr bread and from 4.35 to 2.53 kWh/kg for Mawi bread. Their results confirmed that belt speed and product moisture content are major determinants of oven energy performance, and that careful adjustment of these parameters can deliver meaningful savings.

3.2.2. Burner and oven design innovations

Beyond operational control, burner and oven design innovations have been developed to improve heat transfer uniformity and efficiency. Williamson and Wilson [30] presented the development of a novel indirect gas-fired radiant burner intended for integration into tunnel ovens, demonstrating improved heat-flux uniformity at component scale rather than full tunnel-oven operation. The prototype was a 40 kW assembly sized for a 1.0 m wide conveyor, consisting of a central combustion tube feeding two parallel arrays of 6–8 radiant tubes. To characterise heat flux distribution, the burner was tested over a 1.245 m wide array of 83 water-cooled copper tubes positioned 0.12 m below the radiant surfaces, with tube surfaces coated matt black to provide high

emissivity. CFD simulations using a Monte-Carlo radiation model were validated against these measurements, with agreement within 10%. Results showed that the new burner achieved a much flatter radiative flux profile across the conveyor width compared to conventional single-tube burners, reducing the ratio of maximum to minimum flux from over 3.5:1 to around 2:1, and to below 1.3:1 in optimised configurations. This improvement in uniformity enables higher average radiation intensities without local overheating, thereby reducing oven length, lowering wall losses, and improving energy efficiency.

3.2.3. Waste-heat recovery systems

A third category of improvement focuses on recovering waste heat from the exhaust gases of gas-fired ovens, which typically leave the chamber at 250–336 °C. Henderson et al. [34] reported on a Percotherm direct-contact heat recovery unit installed on a commercial tunnel oven in Brooklyn, USA. The system transferred heat from flue gases into a water loop, which was then used to preheat boiler feedwater and makeup air. Monitoring over one year showed annual recovery of about 765 MMBtu, equivalent to 9600 therms of natural gas, although net economic savings were modest at \$4500–8000 per year once parasitic electricity use was included. Qu et al. [35] proposed three configurations of absorption heat pumps (AHPs) integrated with gas boilers for high-temperature WHR. Their models showed that an exhaust-gas-driven AHP improved boiler efficiency from 78.4% to 83.9%, while hot-water-driven and direct-fired AHPs reached 88.4%, representing up to a 10% efficiency gain. Reported heating COPs were in the range of 1.6–1.75, with payback periods of 1.7–3.6 years depending on configuration. Erdoğan and Acar [36] performed an energy and exergy analysis of an industrial tunnel biscuit oven (1.2 m belt width, 61.5 m length, 1850 kg/h capacity) and assessed waste-heat recovery from the chimney stream of temperature 503.15 K. They proposed integrating an Organic Rankine Cycle to utilise this exhaust heat and reported a net electrical output of 58.62 kW, increasing the oven's reported thermal efficiency from 3.90% to 11.04% (and exergy efficiency from 0.5% to 6.22%) [36].

Recent research has explored the use of high-temperature mechanical heat pumps to recover and reuse waste heat from bakery ovens. Mukherjee et al. [37] analysed WHR technologies across the food sector, including bakeries, and emphasised the low cost of systems that use exhaust gasses to preheat combustion air can save 33% fuel saving and 28–365 tonnes of CO₂ with a payback period of only 1.57 years. The Danish Technological Institute [38] developed and tested a prototype water-vapour heat pump designed specifically for tunnel ovens and spray dryers. The system employed a spindle-type steam compressor (capacity ≈ 130 kW) operating between 105 °C and 230 °C, using water as the working fluid. The project demonstrated the mechanical feasibility of achieving supply temperatures up to 230 °C and projected coefficients of performance between 1.8 and 2.6, depending on the heat-source temperature (60–80 °C). Although the prototype compressor performed reliably, further optimisation of spindle geometry and water-injection sealing was required to reach the intended pressure ratios. The authors concluded that such heat pumps could replace gas-fired heating in tunnel ovens once compressor efficiency and cost targets are met. Chowdhury et al. [39] extended this concept through a techno-economic assessment of high-temperature heat-pump integration in industrial bakeries. Using process simulations (system-level modelling) for exhaust-gas recovery and space heating, they estimated energy-use reductions of 20–25% and CO₂-emission savings of 30–40% compared with conventional gas systems, with typical supply temperatures of 150–200 °C. The study highlighted that economic viability depends strongly on electricity pricing and capital cost but showed that payback periods below three years are achievable under favourable market conditions.

The evidence base for improvement methods spans full-scale tunnel ovens, pilot-scale studies, and adjacent non-tunnel or cross-sector systems, which should be considered when interpreting the reported

performance improvements.

Collectively, these studies illustrate that both “software” and “hardware” improvements are available for gas-fired tunnel ovens. Operational optimisation of zone set-points, belt loading, and exhaust control can reduce energy use by 10-30% with minimal investment. Burner redesign, can also improve heat flux uniformity and reduce excess heating. WHR systems, whether through direct-contact exchangers, absorption cycles, or high-temperature heat pumps, can reclaim a significant fraction of exhaust losses and achieve meaningful reductions in fossil fuel demand. However, even with these improvements, the fundamental limitation of gas-fired ovens remains their reliance on fossil combustion. This provides the rationale for exploring electric tunnel ovens and alternative heating technologies, which are discussed in subsequent sections.

Table 1 summarises the main contributions on gas-fired tunnel ovens, bringing together oven configurations, methodologies, and key results. This synthesis provides a clear basis for comparison and establishes the foundation for the subsequent evaluation of electric ovens and alternative heating methods.

4. Advances in electric tunnel ovens

While gas-fired tunnel ovens remain the backbone of industrial baking, their fundamental reliance on fossil combustion constrains long-term decarbonisation. As grids decarbonise and regulatory pressure on industrial CO₂ emissions intensifies, electric heating is emerging as a key alternative to gas heating. Electrification reduces flue-gas losses, offers finer process control, and enables direct integration with renewable energy [4,5]. However, industrial deployment of electric tunnel ovens is still limited, and the literature remains sparse compared to gas systems. Importantly, the available evidence is not uniform in scale or system type, spanning application-specific industrial systems, pilot-scale tunnel configurations, compact conveyor ovens, and laboratory or proxy-product studies. These differences should be considered when interpreting reported performance, as they reflect varying levels of industrial representativeness and evidence maturity. The following section reviews the state of development of electric tunnel ovens, beginning with the configurations currently offered by major manufacturers, before analysing the research evidence for resistance, induction, microwave, and hybrid designs.

4.1. Industrial offerings and classification

Commercial oven suppliers in Europe and North America now market a variety of tunnel ovens that combine gas, electric, or hybrid heating. Fully electric resistance (ER) ovens use heating elements to provide both convective and radiative transfer, and are positioned as zero-emission alternatives where electricity supply is decarbonised. These ovens are typically promoted for biscuits, crackers, and pastries, where chamber uniformity is critical and process times are relatively short [6]. Hybrid gas-electric ovens are also available, offering bakeries the flexibility to operate in either mode depending on energy prices and carbon intensity. Such designs are often viewed as transitional technologies that can reduce fossil gas use without requiring a full switch to electric infrastructure [5,40].

Additional specialised configurations highlight the diversity of industrial practice. Indirect radiant ovens employ heated tubes to deliver uniform thermal fields suitable for artisan breads, while impingement ovens use high-velocity nozzle jets to accelerate convective transfer for products like pizza bases and flatbreads. IR modules are sometimes installed as optional zones in industrial tunnel ovens to enhance surface browning or caramelisation, and hydrogen-ready burners have been developed as a long-term low-carbon option [4,41].

These configurations show that industry offerings extend beyond a simple gas-electric dichotomy. Electric resistance ovens are commercially established, hybrid ovens provide transitional flexibility, and

complementary technologies such as impingement, IR, and hydrogen heating are already marketed [41]. Yet academic research has focused almost exclusively on resistance and, more recently, induction heating. Despite the availability of these technologies at industrial level, the supporting academic evidence is uneven and often derived from pilot-scale, compact conveyor, or laboratory systems rather than full-scale tunnel-oven operation. The following subsections review the evidence available in the literature for these technologies, while highlighting limitations compared with the breadth of industrial offerings.

4.2. Electric resistance tunnel ovens

ER heating is the most established method for electrifying tunnel ovens. In this configuration, energy is supplied directly by heating elements embedded in the chamber walls or ceiling, providing both convective and radiative flux to the product surface. Unlike gas burners, resistance elements avoid combustion losses and allow more precise zoning.

Baik et al. [15,16] compared two full-scale industrial cake ovens: a gas-fired band oven measuring 21.34 m in total length with three 7.11 m zones (bandwidth 0.9 m, chamber height 0.5 m), and an electric mould oven measuring 27.97 m with four zones of approximately 7 m each (Figs. 7 and 8). Both ovens were instrumented with wall and air thermocouples and humidity probes, and the authors quantified the partitioning of heat transfer to the product. In Part I [16], they showed that radiation dominated the heat delivered to the product's top surface in both ovens, while the electric mould oven exhibited a larger conductive share via the pans compared to the gas band oven. In Part II [15,16], they reported that cake moisture and texture outcomes were broadly comparable between the two ovens, but crust colour was paler in the electric oven, consistent with its lower effective radiative contribution and the absence of combustion products. The papers did not calculate an overall thermal-efficiency advantage for electric over gas, and the often-quoted efficiency percentages originate from a handbook range cited for typical tunnel ovens rather than measurements in these trials. Overall, these studies establish that ER tunnel systems can reproduce industrial cake quality with a different heat-transfer balance (more pan conduction, relatively less flame-radiation effect) that tends to yield lighter surface colour than direct gas firing.

Pereira et al. [17] reported one of the first systematic evaluations of an ER pilot-scale tunnel oven designed for baking traditional Brazilian baked food at lab scale. The oven (Fig. 9), had an internal dimensions of 0.4 × 0.4 × 2.0 m³, divided into four independently controlled heating zones along a conveyerised chamber. Resistance elements of 1.2 kW each were mounted above and below the band to provide combined convective and radiative heating. The system was instrumented with thermocouples at multiple points along the length and on the product surface, as well as a camera, enabling detailed monitoring of thermal profiles. Trials showed that temperature readings across the conveyor width were consistent, confirming uniform heating laterally. The embedded temperature sensor revealed a steady internal temperature increase through the preheating and baking zones. Browning analysis showed that crust colour matched the reference for optimal baking when the process was properly tuned. The combination of internal temperature monitoring and digital imaging allowed for comprehensive evaluation of bake quality. The study concluded that the system enabled accurate, real-time assessment of baking performance, and highlighted the potential for wireless sensor networks and vision systems to enhance control and product quality in electric tunnel ovens. Reddy et al. [42] estimated transient heat flux into bread during baking by solving an inverse heat conduction problem using experimental surface temperatures from pan bread baked at 200 °C in a laboratory non-tunnel oven with top and bottom electric coils. The dough was baked in a rectangular loaf mould, giving loaves of 16 × 5 cm or 18 × 8.5 cm with a domed pan-bread top. Inverse modelling was used to reconstruct the time-dependent heat flux. The results showed that total flux decreased

Table 1
Summary on gas ovens.

Reference	Oven type/ Configuration	Scale/dimensions	Methods	System boundary	Energy metric type	Product- quality metrics measured	Key findings
Henderson et al. [34]	Full-scale industrial bakery tunnel oven (Percotherm) with direct-contact heat recovery	Industrial installation	Experimental	Exhaust-to-water heat recovery loop; not oven-to-product	Heat recovered; gas displaced; net savings	No	765 MMBtu/yr recovered; 9574 therms/year displaced; net savings \$4.5k-8k/yr
Mirade et al. [7]	Full-scale industrial biscuit tunnel oven, indirect gas; 56 burners; multi-point extraction	Industrial, 50 × 1 × 0.3 m, 25 sections	CFD + experimental	Oven air environment only; no energy balance	Temperature and velocity field metrics	No	Bell-shaped air-temperature profile; air velocities mostly below 0.5 m/s; extraction/section geometry drives non-uniformity; CFD matches temperature trend but not velocities well.
Wong et al. [8]	Full-scale industrial bread tunnel, U-turn conveyor; four heating zones with hot-air supply/return ducts and burners	Industrial, 16.5 × 3.65 × 3.75 m, 4 zones	Two-dimensions CFD + experimental	Oven cavity plus tin and dough temperature histories; no energy balance	Temperature and velocity agreement metrics (correlation; root mean square error)	No	Tin surface temperatures predicted well (correlation about 0.94–0.96; root mean square error about 12–16 °C); weaker agreement for air temperature/velocity (correlation about 0.35 and 0.30)
Williamson and Wilson [30]	Component-scale indirect gas-fired Radiant gas burner for tunnel ovens	Prototype, 40 kW burner, 1.0 m conveyor; two parallel radiant-tube arrays (6- and 8-tube variants)	CFD + experimental	Burner and near-field radiation environment at a target plane; no oven energy-to-product balance	Heat-flux uniformity; burner efficiency	No	Heat-flux non-uniformity reduced from ≥3.5:1 to about 2:1 and below 1.3:1 (optimised); burner efficiency about 60%, up to about 80% with exhaust-heat recovery
Boulet et al. [9]	Pilot-scale tunnel oven section; two chambers heated by infrared emitters	Pilot, 1.5 × 1.4 × 0.2 m (per chamber)	CFD + experimental	Chamber heat-transfer environment to an inert target; conditioning represented by boundary conditions	Heat flux and radiative fraction (from plate-temperature transients)	No	Radiation dominates: about 80% (upper plate) and about 85% rising to near 99% (lower plate); top-plate temperatures matched well, lower plate overpredicted
Khatir et al. [10]	Pilot-scale direct-fired jet impingement forced-convection bread-baking tunnel oven (3-zone)	Pilot/industrial, 9 × 1 × 1.5 m	CFD + experimental	Oven cavity airflow and air-temperature fields; no energy balance	Temperature/velocity accuracy metrics; temperature uniformity	No	Average relative temperature error about 3.5%; correlation about 0.90–0.92; root mean square error about 2.8–4.2%; recirculation zones identified and influenced by jet velocity
Khatir et al. [11]	High-speed air-impingement bread pilot-scale oven design framework	Pilot experimental rig 4 m long, 3 m wide, 2 m high	CFD + experimental	Thermal input plus fan electricity versus ambient heat losses; not a tunnel-oven energy-to-product balance	Optimum heat-transfer coefficient; specific energy change	No	Optimum convective heat-transfer coefficient 35 W/m ² ·K; total energy saving >5% (example: +2.9 kJ/kg fan electricity to save 44.7 kJ/kg ambient losses); convection about 93% and radiation about 7%
Khatir et al. [29]	Forced-convection air-impingement bread-baking model-based oven design optimisation (multi-objective; jet arrays)	Generic commercial bread-oven model (dimensions not specified)	CFD	CFD + optimisation (ANSYS FLUENT; surrogate model; genetic algorithm)	Oven cavity thermal environment and jet design/operation; objective based on temperature uniformity and baking time reduction (no full oven energy balance)	No	Oven cavity thermal environment and jet design/operation; objective based on temperature uniformity and baking time reduction (no full oven energy balance)
Paton et al. [12]	Full-scale industrial bread direct fire tunnel oven with jet impingement and recirculation	Industrial oven, 3 zones, dimensions unspecified	Modelling + optimisation	Oven-level heat and mass flows (dough heating, evaporation, tins/lids, conveyor, flue gases, wall/roof losses)	Heat split (kJ/kg and %); bake-time reduction; specific energy change	No	Heat split: dough heating 25.8%, evaporation 28.1%, gelatinisation 1.4%, wall/roof 16.7%, tins/lids 6.5%, conveyor 8.9%, flue gases 12.5%; baseload losses about

(continued on next page)

Table 1 (continued)

Reference	Oven type/ Configuration	Scale/dimensions	Methods	System boundary	Energy metric type	Product-quality metrics measured	Key findings
El-Aldy et al. [33]	Continuous industrial Egyptian bread oven; diesel-fired burners	Industrial, 5 × 2 × 1.77 m, belt 0.83 m	Experimental	Baking-stage energy accounting at different belt speeds (thermal, electrical, human)	Specific energy (kWh/kg); productivity; cost	Yes: moisture content	19%; bake time reduced up to 10% and specific energy reduced about 1.9–2% Specific energy decreased with belt speed: Magr 3.57 to 1.93 kWh/kg, Mawi 4.35 to 2.53 kWh/kg (1.18 to 3.55 m/s); moisture content increased with belt speed (Magr 24.32 to 29.25%, Mawi 34.25 to 41.66%)
Yi et al. [28]	Full-scale industrial forced-convection continuous impingement oven (hot-air jets)	Industrial, 12 m length, 3 zones	CFD	Oven cavity and product-surface flow/thermal fields; no energy balance	Temperature/velocity fields; heating uniformity indicators	No	Nozzle spacing governs heating uniformity; recirculation near walls/corners drives non-uniformities; target heating 170 °C for 60 s
Pask et al. [32]	Direct gas-fired industrial Festoon oven (adhesives curing)	Industrial, 1 MW system	Experimental + modelling + optimisation	Oven operability and fuel use (airflow, infiltration, thermal mass); not oven-to-product	Fuel reduction; downtime reduction	Yes (non-food): colour; dynamic mechanical analysis	Gas consumption reduced 20–30%; cooling time reduced 87.5% (about 202 h/year downtime saving)
Mansour et al. [13]	Direct-fired Laboratory-scale tunnel oven (flatbread); overhead swirl burner (diesel), rated 130 kW	Industrial prototype, 1.5 × 0.69 × 0.805 m	CFD + experimental	Oven-level balance: input split into baking, exhaust, and environmental losses	Energy-to-product utilisation; specific energy input; loss fractions; radiative share	No	Thermal efficiency 16.5% (12.5% including preheating); 3.15 MJ/kg; chimney about 55% and base-load about 28%; radiation share about 66–73%
Mansour et al. [14]	Same as above; flatbread; 450–650 °C; residence 10–12	Industrial prototype, 1.5 × 0.69 × 0.805 m	Experimental	Oven-level efficiency with and without preheating; useful baking energy from product heating and evaporation	Energy-to-product utilisation; useful baking energy (kJ/kg)	Yes: mass loss; expansion/puffing	Useful baking energy about 667 kJ/kg; thermal efficiency 21% (16% including preheating); rapid expansion during baking

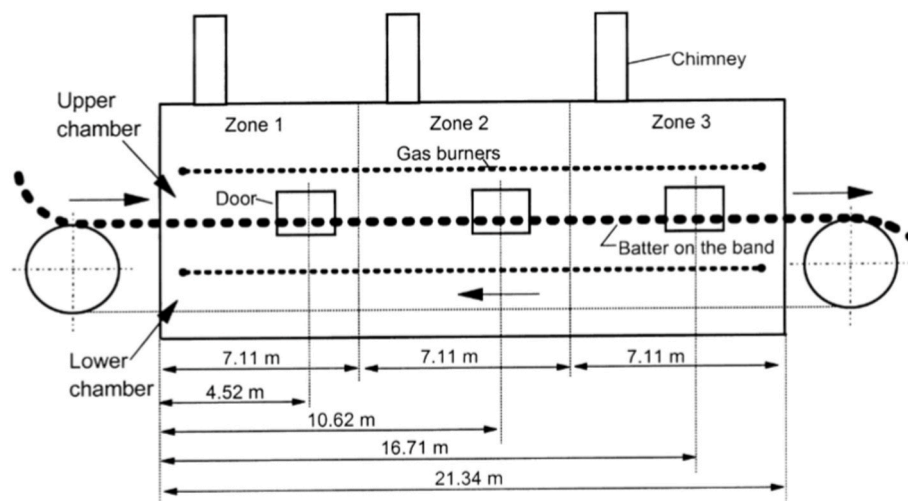


Fig. 7. Gas-fired band oven [16].

from about 9000 W/m² at the start of baking to around 1300 W/m² at the end, with radiation contributing 70% under natural convection and 62–65% under forced convection. These detailed flux profiles provide benchmark data that can be used to validate CFD predictions.

Wu et al. [19] developed and validated a pilot-scale three-zone ER tunnel oven designed for naan baking, integrating experimental trials

with CFD simulation. The oven had an external shell measuring 4 m in length, 0.85 m in width, and 0.65 m in height, enclosing a conveyerised chamber divided into three independently controlled heating zones (Fig. 10). Numerically, they used a steady-state temperature-field simulation to examine heat distribution within the baking chamber and identify dominant heat-loss locations, reporting pronounced losses at

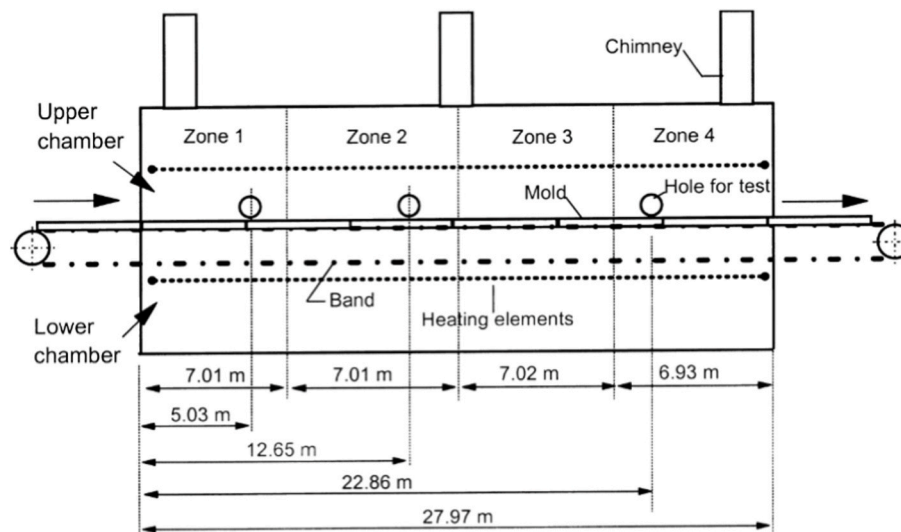


Fig. 8. Electric powered oven [16].

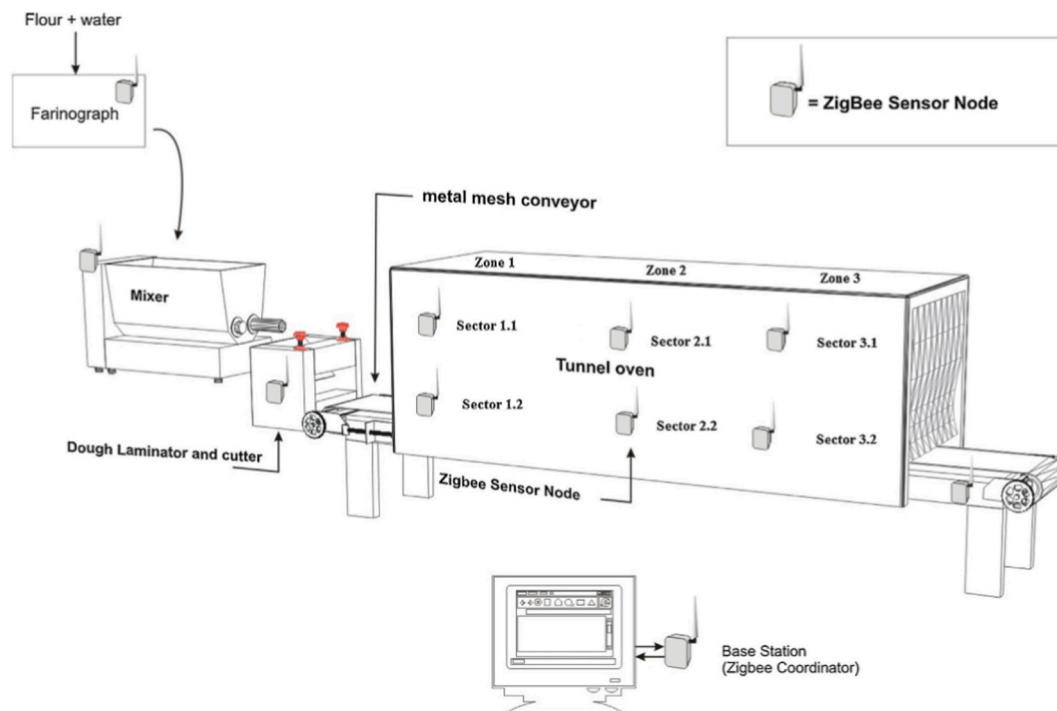


Fig. 9. Schematic representation of the pilot-scale oven used by Pereira et al. [17], showing the arrangement of the sensor nodes and zones.

the inlet and outlet and showing that reducing the spacing between the upper and lower heating tubes improved the uniformity and intensity of heating in the product region. Experimentally, they baked naan under different conveyor speeds and heating-tube set temperatures and evaluated product quality using a sensory scoring scheme covering colour and lustre, form, internal structure, taste, and aroma. The highest overall score was obtained at a conveyor speed of 6 m/h, while the best score under heating-tube temperature variation was reported at 260 °C. These results indicate that, for this pilot configuration, optimisation was driven primarily by balancing heating intensity and residence time to achieve favourable sensory outcomes rather than by efficiency metrics or transient CFD validation.

Constantin et al. [18] investigated airflow and thermal behaviour in a compact ER conveyor oven using CFD and experimental validation. The study employed a Zanolli Synthesis 06/40V E oven (Fig. 11), with

an internal conveyor chamber 1.2 m long and 0.4 m wide [43]. Heating was provided by two electrical resistance elements positioned above the conveyor (Fig. 12), while a pair of fans circulated hot air across the band to enhance convective transfer. Air and product temperatures were measured with thermocouples at multiple points in the chamber, and CFD simulations were performed to model airflow and temperature distributions. Validation against experimental data showed deviations of less than 7.6%, confirming the model's predictive reliability. Results indicated that recirculation zones formed near the sidewalls, generating lateral non-uniformities, while central regions of the band received more consistent heating. Baking trials on the flatbread discs confirmed that dough reached starch gelatinisation and expansion temperatures within expected residence times, reproducing typical baking curves. The study demonstrated that compact resistance conveyor ovens can be effectively analysed with CFD, providing a framework for design optimisation.

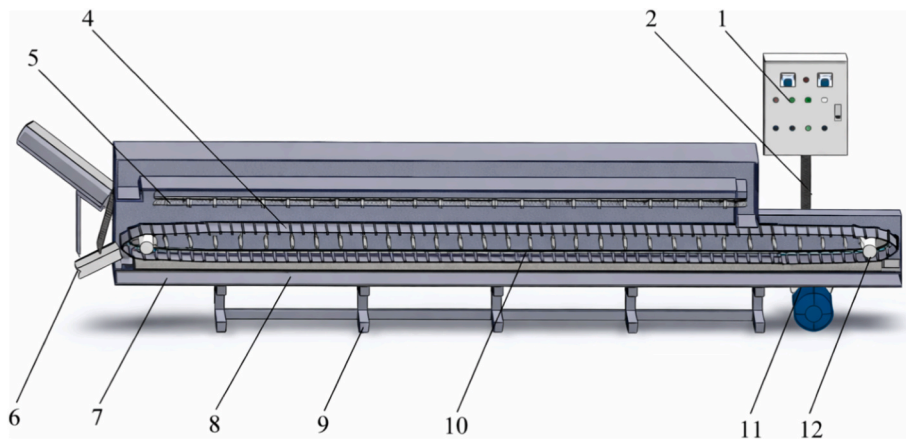


Fig. 10. Tunnel type naan baking stove by Wu et al. [19]: 1. Distribution box 2 Power lead 3. Conveying plate 4. Heating tube support frame 5. Outlet high temperature baffle 6. Outlet guide plate 7. Naan oven housing 8. Baking slag collection box 9. Body support frame 10. Heating tube 11. Motor 12. Gear shaft.



Fig. 11. Zanolli Synthesis 06/40V E compact electric conveyor oven used by Constantin et al. [18], developed by [43].

However, the oven scale was limited and the findings cannot be directly extrapolated to full scale industrial tunnel ovens.

Research on ER tunnel ovens demonstrates clear advantages over gas systems, with improved thermal performance and more stable chamber conditions reported across industrial cake ovens [15,16], pilot bread ovens [17], compact conveyor rigs [18], and modern flatbread systems [19]. However, limitations are consistent: crust browning is weaker due to reduced radiative input, studies remain product-specific, and most trials are confined to pilot or compact systems rather than full industrial

lines. This uneven evidence base highlights the need for larger-scale validation and motivates investigation of alternative electro-heating methods, such as induction, which are reviewed in the next section.

4.3. Alternative electric tunnel ovens

While resistance heating dominates the literature on electric tunnel ovens, a few studies have explored alternative electro-heating methods. These include induction, microwave, and hybrid gas-electric systems.

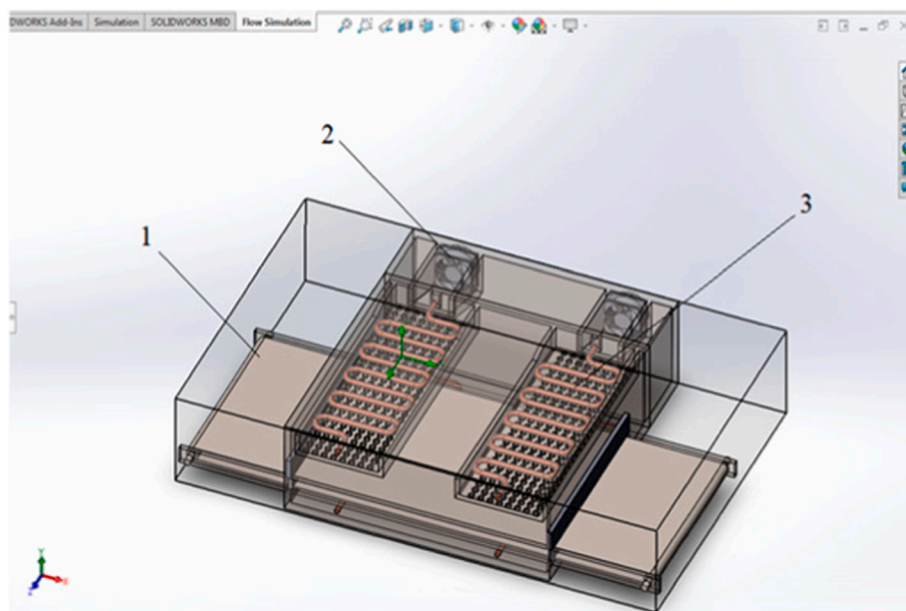


Fig. 12. The assembly used in airflow analysis by Constantin et al. [18]: 1. conveyor; 2. fan; 3. electrical resistance for heating.

Although promising in principle, the available work is very limited and often restricted to narrow product categories or small-scale rigs.

Steinbach et al. [20] investigated induction heating in a continuous industrial wafer tunnel oven (application-specific system). The system used steel baking plates mounted on a circulating conveyor, with induction coils positioned above and below to raise plate temperatures. Target conditions were reached within 30–60 s, significantly faster than with resistance or gas systems. Energy savings were achieved because coils were energised only when plates were loaded. Wafer quality, measured by moisture and surface colour, matched that from gas ovens. However, no chamber dimensions were reported, and the application was limited to thin wafers, leaving scalability to breads or cakes untested, and not representative of general tunnel-oven baking conditions.

Methlouthi et al. [21] developed a continuous conveyorised microwave oven powered by six 1.2 kW magnetrons at 2.45 GHz, arranged in quincunx over the tunnel. The applicator belt carried agar gel samples at speeds of 0.61–1.09 m/min through a treatment zone a few tens of centimetres wide, with water traps at inlet and outlet. Fibre-optic probes and infrared imaging showed that product centre heating was rapid, but surface maps revealed strong lateral non-uniformities and edge over-heating, confirming electromagnetic field heterogeneity and highlighting the limitations of directly extrapolating these results to industrial baking applications. The authors concluded that hybridisation with IR or convection would be required for practical baking.

In summary, induction and microwave offer alternative approaches to tunnel baking, with potential advantages in start-up time, volumetric heating, and flexibility. However, the supporting evidence is limited and uneven, with industrial validation restricted to application-specific systems (e.g. wafer baking), while most studies are based on laboratory or proxy-product investigations. As a result, their applicability to general tunnel-oven baking remains unproven. Systematic trials on full-scale bread or biscuit production are absent, underscoring a critical gap in the development of non-resistance electro-heating tunnel ovens.

Table 2 summarises the main contributions on electric tunnel ovens, bringing together oven configurations, methodologies, and key results. This synthesis provides a clear basis for comparison and establishes the foundation for the subsequent evaluation of electric ovens and alternative heating methods.

4.4. Product-quality synthesis across heating modes

Decarbonisation pathways for tunnel ovens cannot be ranked on energy performance alone because baking outcomes depend strongly on how heat is delivered to the product surface and how moisture is removed during baking. In practice, electrification can improve controllability and temperature stability, but changes in the balance between radiative, convective and conductive heating may alter browning, moisture gradients and texture development. For this reason, a technology comparison that omits product quality can lead to misleading conclusions about feasibility for industrial adoption. Table 3 consolidates the available evidence on quality outcomes reported for continuous baking and conveyor-oven heating modes and, where direct quality metrics are not reported, summarises mechanism-relevant findings that are expected to influence quality. This synthesis helps the reader identify which decarbonisation options have demonstrated acceptable product outcomes, where evidence is limited to thermal behaviour only, and where targeted experimental validation is required to support scale-up.

5. Potential decarbonisation pathways

5.1. Electric resistance heating

ER heating is the most established electric alternative to fossil fuel combustion in tunnel ovens and therefore a central pathway for decarbonisation. In ER ovens, electrical current passes through heating elements positioned above and below the conveyor, producing convective and radiative fluxes without generating combustion gases. This eliminates flue-gas losses, simplifies exhaust management, and removes on-site CO₂ and NO_x emissions. As national grids incorporate more renewable energy, ER ovens can align directly with decarbonised electricity supply, offering bakeries a scalable route to reduce emissions [4, 5].

The technical literature on ER tunnel ovens, reviewed in section 3, demonstrates that they are generally more efficient than gas ovens and provide tighter thermal control. Studies on full industrial systems [15, 16], pilot bread tunnels [17], and compact flatbread ovens [19] all reported energy conversion advantages and good zone stability. However, across these scales the results were consistent in showing lighter crust colour and reduced combustion-derived flavour compared to

Table 2
Summary on electric ovens.

Reference	Oven type/ configuration	Scale/dimensions	Methods	System Boundary	Energy metric type	Product-quality metrics measured	Key findings
Baik et al. [16]	Full-scale industrial tunnel cake ovens: Direct gas vs electric resistance	Gas oven: 21.34 m long, 3 zones (7.11 m each), 0.9 m wide, 0.5 m high. Electric oven: 27.97 m long, 4 zones (7.01-7.02 m each).	Industrial trials, measurements of heat flux, temperatures, humidity	Baking-chamber conditions and heat-transfer pathways to product (radiation, convection, conduction); no full oven energy balance	Heat-transfer to product surfaces	No	Radiation dominated top-surface heating in both ovens (gas about 79.5–81.5%; electric about 66.2–72.4%, noting element radiation was not fully incorporated). Conduction share was higher in the electric mould oven (about 78–84%) than the gas band oven (about 44–56%).
Baik et al. [15]	Same ovens as above	Same as above	Industrial trials with quality measurements	Product quality evolution in multi-zone oven; not an oven energy-balance study	No	Yes: texture; surface colour; moisture; density; pH	Most colour change occurred between one-quarter and three-quarters of baking time; position effects were generally not critical for several texture and colour outcomes (with exceptions such as moisture).
Methlouthi et al. [21]	Laboratory-scale microwave conveyor tunnel oven	Six magnetrons at 1.2 kW each, belt speed 0.61-1.09 m/min; applicator dimensions not fully reported	Experimental (agar gel models, fibre-optic probes, infrared imaging)	Applicator electromagnetic heating behaviour inferred from product thermal response; no oven energy balance and no baking metrics	Thermal-field metrics (internal temperature histories; infrared surface temperature maps)	No	Rapid internal heating but strong lateral non-uniformity with higher heating near boundaries, indicating electric-field heterogeneity; mitigation suggested via added infrared/conductive heating or generator power control.
Pereira et al. [17]	Pilot-scale electric resistance tunnel oven	Internal chamber: $0.4 \times 0.4 \times 2.0 \text{ m}^3$, 3 zones, 6 heating elements (1.2 kW each)	Experimental	In-oven temperature profiling and baked-food evaluation/control; no oven energy balance/efficiency	Thermal profiles; image-based classification metrics	Yes: surface appearance (image histogram); internal temperature history	Sensors enabled consistent temperature profiling across belt positions; image histograms distinguished raw/correct/burnt states and supported control of oven temperature and belt velocity.
Reddy et al. [42]	Laboratory electric oven (top and bottom coils); pan-bread baked under natural and forced convection	Loaf size: $16 \times 5 \text{ cm}$ and $18 \times 8.5 \text{ cm}$; oven set to $200 \text{ }^\circ\text{C}$	Experimental + inverse modelling	Product-level heat transfer boundary (surface heat flux inferred from measured temperatures); not an oven energy balance	Transient total heat flux (W/m^2) and radiative fraction (%) derived from inverse heat conduction	No	Total heat flux decreases strongly during baking (example: $9009.1 \rightarrow 1329.9 \text{ W}/\text{m}^2$ under forced convection, larger loaf, undeformed); radiation contribution about 70–71% (natural convection) and 62–65% (forced convection).
Constantin et al. [18]	Compact conveyor oven, resistance-heated (Zanolli Synthesis 06/40V E)	Chamber: 1.2 m long, 0.4 m wide. Two resistance heaters above conveyor with fan circulation	CFD + experimental	Internal baking-chamber airflow and temperature field (openings treated as closed to external environment); no overall oven energy balance	Thermal-field metrics (airflow patterns; temperature distribution; local heat-transfer coefficient patterns)	No	CFD matched product heating within 7.6%, recirculation zones caused lateral non-uniformities.
Steinbach et al. [20]	Industrial induction wafer tunnel oven	Industrial wafer tunnel, induction coils above and below baking plates (dimensions not reported)	Experimental/Industrial trial,	Plate heating and operation during production (loaded versus idle); no oven-to-product energy balance reported	Warm-up time (seconds); qualitative idle-loss reduction (load-dependent energisation)	Yes (wafer moisture; surface colour)	Target plate temperatures reached within about 30–60 s; reduced idle heating by energising coils only when plates are loaded; wafer moisture and surface colour comparable to gas-baked reference wafers (shown for thin wafers).
Wu et al. [19]	Pilot-scale electric resistance tunnel	Outer shell: $4000 \times 850 \times 665 \text{ mm}$; 3 zones	CFD + experimental	Oven temperature field and heat-loss locations (inlet/outlet) plus	Thermal-field metrics (temperature)	Yes: sensory evaluation (colour and	Simulation indicates pronounced heat loss at inlet/outlet and improved <i>(continued on next page)</i>

Table 2 (continued)

Reference	Oven type/ configuration	Scale/dimensions	Methods	System Boundary	Energy metric type	Product-quality metrics measured	Key findings
	oven for flatbread (naan)			operating trials; not an oven energy balance	distribution; qualitative heat- loss locations)	lustre; form; inner structure; taste; smell/ flavour)	heating with reduced upper-lower tube spacing; best sensory scores reported at conveyor speed 6 m/h and heating- tube temperature 260 °C.

Table 3

Synthesis of reported product-quality outcomes and mechanistic drivers across electric heating modes.

Heating mode	Study	Product type	Quality metrics reported	Heat transfer mechanism
Electric resistance (pilot conveyor oven; sensing/ vision control)	Baik et al. [15]; heat-transfer context: Baik et al. [16]	Cakes	Colour; moisture; texture (hardness and related parameters); density; pH	Heat-transfer balance differs top-surface heating more radiation-dominant in gas, and conduction share higher in the electric mould configuration
Electric resistance (pilot conveyor oven; sensing/ vision control)	Pereira et al. [17]	Baked filled dough product (biphasic)	Surface appearance classification (image histogram); internal temperature history	Quality evaluation is linked to internal temperature trajectories and image-based surface-state classification used for control actions
Electric resistance (compact conveyor oven; forced convection)	Constantin et al. [18]	Flatbread discs (heating curves)	No direct product-quality metrics reported	Recirculation near sidewalls produces lateral thermal non- uniformity, implying spatial variation in heating rate (quality not quantified)
Electric resistance (tunnel- type naan oven)	Wu et al. [19]	Naan	Sensory evaluation: colour and lustre; form; inner structure; taste; smell/flavour	Thermal simulation highlights inlet/outlet heat loss and sensitivity to tube spacing; experimentally, quality optimum reflects heating-intensity vs residence-time trade-off
Induction (wafer baking plates; industrial line)	Steinbach et al. [20]	Wafers	Not reported	Study focuses on temperature observation/control in an inductively heated wafer baking process; product-quality metrics are not quantified in the paper
Microwave (conveyor applicator; proxy product)	Methlouthi et al. [21]	Agar gel (proxy)	Not reported (proxy thermal maps only)	Infrared maps show lateral non-uniformity linked to electric- field heterogeneity; mitigation proposed via hybridisation with infrared/convection or generator control
Electric coil laboratory oven (pan bread; benchmark heat flux)	Reddy et al. [42]	Pan bread	Not reported (heat-flux history and radiation fraction only)	Provides benchmark transient heat flux and radiative fraction under natural/forced convection, relevant for crust- development mechanisms in models (quality not measured)

direct-fired gas ovens. These limitations underline that while ER ovens are technically viable, their application to bread and biscuit production still faces quality-related challenges.

Beyond tunnel-scale studies, ER ovens have long been used as controlled laboratory systems for investigating baking processes. Early work by Shelke et al. [44] employed an ER oven combined with viscometry to study cake batter dynamics, showing that resistance heating provided uniform temperature fields and reduced gradients compared with conventional gas ovens. More recently, Masure et al. [45] used an ER oven to analyse gluten-free bread structure, demonstrating that crumb development could be monitored under well-controlled thermal conditions. These studies emphasise the value of ER ovens as research tools, allowing process variables such as gelatinisation, expansion, and crumb setting to be examined with fewer confounding factors from combustion gases or unstable airflow. Chukwunke et al. [46] reported the design of a small dual-fuel oven combining electric coils and a gas burner in a single rectangular chamber. The oven measured 460 × 400 × 750 mm with an internal volume of 0.14 m³ that could bake up to 12 loaves per batch. Maximum chamber temperature with the electrical system was 220 °C, reached in about 30 min. While intended for domestic use in Nigeria where power supply is unreliable, the design demonstrates hybridisation as a strategy to improve resilience and flexibility in baking. Its small capacity and batch operation, however, limit its direct applicability to industrial tunnel systems.

Product-specific trials further illustrate both the versatility and the constraints of ER heating. A study on biscuits baked in ER ovens reported that products retained higher moisture and lighter surface colour relative to gas-fired counterparts, while textural and sensory quality remained acceptable [47]. Rana et al. [48] developed a small ER oven for cakes and biscuits, with a chamber volume of 0.056 m³ powered by 2 kW elements. Specific energy consumption was measured between 0.53

and 0.88 kWh/kg (1.9–3.2 MJ/kg), which is lower than values typically reported for gas ovens. Their results confirmed energy efficiency advantages but again highlighted lighter crusts and subtle textural differences. Together, these findings suggest that ER ovens can bake a variety of products effectively, but systematic evaluations across bread, biscuits, and pastries at industrial throughput are still lacking.

Operational parameters also play a key role in determining ER oven performance. Kulishov et al. [49] reviewed ER baking as a method for producing toast bread and noted that, despite promising laboratory demonstrations, industrial uptake remains very limited. This under-utilisation reflects several well-documented barriers. As highlighted in broader electrification reviews, the high capital cost of ER equipment, combined with electricity prices that remain elevated relative to gas, makes commercial deployment economically unattractive for many bakeries. Risk aversion and a lack of process understanding further inhibit adoption, particularly given the dominance of gas-fired systems and the limited number of validated, full-scale demonstrations. Industrial concerns about achieving consistent crust colour and structure when using electrically driven heating systems also contribute to hesitation. Collectively, these factors explain why ER ovens are widely recognised in research settings but remain sparsely applied in commercial bakeries.

From a decarbonisation perspective, the strengths of ER ovens are clear. They remove on-site fossil fuel use, offer higher end-use efficiency, and integrate readily with renewable electricity. Industrial suppliers already market fully electric tunnel ovens for biscuits and crackers, highlighting precise zone control, rapid start-up, and low flue-gas losses as advantages. Case studies suggest 10–20% reductions in energy use compared with equivalent gas systems, though peer-reviewed industrial data are limited.

Yet significant gaps remain. Published research is concentrated on cakes, biscuits, and pan breads, with little systematic data on other high-

volume bakery products such as flatbreads, wraps, or enriched doughs. Quality issues, particularly paler crusts and weaker Maillard development, are consistent across scales. Infrastructure constraints, including electrical capacity and operating costs, also limit widespread adoption. Furthermore, most detailed studies remain confined to laboratory or pilot ovens, with limited validation under true industrial production conditions.

5.2. Infrared and infrared hybrid heating

IR heating has been widely explored as a means of improving energy efficiency and accelerating surface quality development in bakery products. Unlike resistance elements that heat chamber air, IR emitters deliver radiant energy directly to product surfaces, which can shorten baking times and enhance browning. Because IR energy is absorbed within the outer millimetres of the dough, it is particularly effective for crust formation, though its shallow penetration depth limits its ability to bake thicker products without assistance from other heat transfer modes. This has led to growing interest in hybrid IR systems, where infrared is combined with convection, microwave, or resistance heating to achieve both surface quality and rapid internal structure development.

Plateau et al. [50] provided one of the most detailed experimental and modelling studies of IR-dominant ovens. Their batch oven measured $0.62 \text{ m} \times 0.85 \text{ m} \times 0.26 \text{ m}$ high, and incorporated resistive vault and sole heaters with a cement slab floor to deliver combined radiative, convective, and conductive transfer. Thermocouple and fluxmeter measurements, together with a two-dimensional FEM model, showed that radiation accounted for more than 80% of the total heat transfer, with convection contributing less than 20%. Radiative fluxes reached up to 15 kW/m^2 during transient heating, while conduction from the slab influenced the early stages of baking. The study confirmed that IR is the dominant mechanism in electrically heated ovens, and that modelling approaches can capture coupled conduction-radiation-convection effects with reasonable accuracy. However, the setup was static rather than continuous, highlighting the lack of tunnel-scale demonstrations of IR systems.

Nicolas et al. [51] combined experiments and multiphysics modelling to analyse bread dough baked under controlled IR and convection conditions. Their experimental setup allowed simultaneous measurement of temperature, mass loss, moisture content, deformation, and gas pressure within the dough. The model predicted heat and mass transfer during baking and was validated against these measurements. Results showed that IR accelerated surface heating and moisture removal, leading to earlier crust setting compared with convection alone. However, penetration depth was insufficient to complete crumb baking, confirming that IR must be complemented by volumetric or convective modes for thick products.

Gokmen et al. [52] investigated IR-assisted baking of Gelveri sourdough bread in a hybrid oven. They found that breads baked with IR treatment exhibited extended microbial shelf life and reduced staling rates, highlighting potential sustainability benefits through waste reduction. However, sensory evaluation revealed harder textures, lower pH, and sourer taste than breads baked in traditional stone ovens, indicating that, while IR can improve microbial stability and energy use, consumer acceptance may be affected by changes in texture and flavour.

Several studies examined IR in hybrid configurations with convection or microwave heating. Work on convective-IR ovens demonstrated that combining radiant and convective fluxes reduced baking times and energy demand while achieving acceptable crust development [53]. Hybrid microwave-IR ovens have been tested at laboratory scale, where IR was used to counteract the common microwave limitation of weak crust formation. For instance, trials reported by Sumnu et al. [54] and later by Turabi et al. [55] showed that microwave-IR systems achieved faster internal heating and acceptable crust colour compared with microwave-only baking. These findings suggest that IR can compensate

for the deficiencies of microwave heating, though non-uniformity in volumetric heating still limits product consistency.

Chhanwal et al. [40] evaluated a hybrid ER-IR oven equipped with quartz halogen IR lamps and electric coils. Bread baked under hybrid conditions required only 18 min at $220 \text{ }^\circ\text{C}$, compared to 25 min in a conventional electric oven, corresponding to a 28% reduction in baking time. Loaf volume, crumb softness, and overall quality scores were higher under the hybrid regime, while crust colour was slightly darker due to the IR contribution. The study concluded that hybridisation of IR with resistance heating can enhance both energy efficiency and product quality, although the small batch oven used limits, direct extrapolation to tunnel systems.

Across these studies, a consistent theme emerges that IR is best suited as a complementary technology within hybrid ovens. As a standalone method it accelerates crust development but cannot bake thicker products evenly. When integrated with convection, microwave, or resistance systems, IR improves surface browning and reduces baking times, while other modes provide the volumetric heating required for crumb structure. From a decarbonisation standpoint, IR offers the potential to reduce process times and energy use, thereby lowering emissions when powered by renewable electricity. Its main limitations are shallow penetration, sensitivity to product geometry, and the absence of industrial tunnel-scale demonstrations.

In summary, IR and hybrid IR ovens represent a promising pathway for reducing baking energy demand and improving surface quality in electric tunnel ovens. However, current evidence is confined to laboratory and pilot-scale rigs, with limited validation for bread and biscuit production at industrial throughputs. Further research is needed to scale IR technologies into continuous tunnel systems and to establish their effects on a wider range of bakery products.

5.3. Ohmic heating

OH, also known as Joule heating, generates heat volumetrically as electric current passes through the food. Because energy is dissipated internally, it can raise temperature rapidly and uniformly in pumpable products, and theoretical conversion efficiencies above 80% have been reported in laboratory systems [56]. The method therefore appears attractive for energy-intensive operations, yet its use in bread baking remains experimental. Electrode contact with solid dough is unstable, crust formation is weak, and no continuous or tunnel-scale system has been demonstrated (Fig. 13).

Gally et al. [56] characterised bread dough during OH and observed abrupt changes in electrical conductivity at starch-gelatinisation and protein-denaturation temperatures, confirming the strong coupling

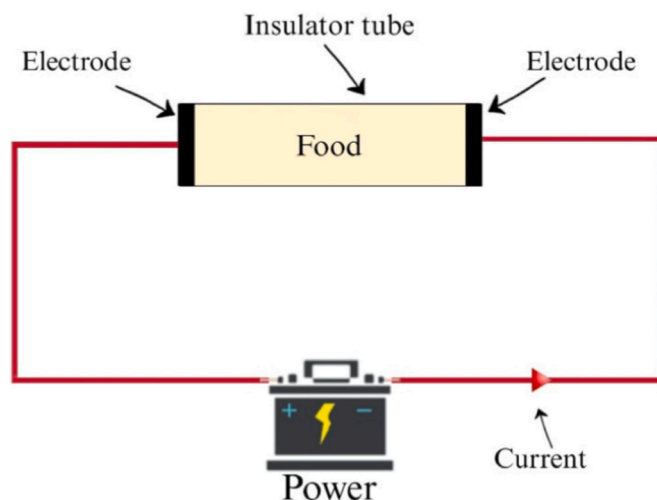


Fig. 13. Schematic diagram of an ohmic heater [57].

between electrical and thermal properties. Heating was rapid but spatially non-uniform. In a follow-up study [58], applied the technique to dough proofing: fermentation time was shortened by roughly half, yet local overheating and uncontrolled thermal gradients occurred at higher current densities. Bender et al. [59] reported that OH accelerated crumb setting and improved internal porosity compared with conventional baking, though crust development remained incomplete [60,61]. obtained similar outcomes for flatbread and small dough pieces, acceptable internal texture but pale, uneven surfaces. Recent laboratory prototypes confirm these findings [62]. observed good dough expansion in thin flatbreads but limited browning [63,64]; achieved soft, open crumbs yet reported electrode fouling and surface cracking. Waldert et al. [65,66] found non-uniform heating near electrode contacts that caused inconsistent expansion and local drying. Collectively, these studies demonstrate that ohmic baking of bread is technically possible at small scale but constrained by contact, control, and quality issues.

Panirani et al. [67] reviewed combined electro-heating systems and concluded that, among solid foods, bread remains the most demanding application because it requires simultaneous volumetric heating and high surface flux for crust formation, conditions difficult to realise with electrodes.

Outside bakery products, OH is far more mature. Continuous systems for milk pasteurisation achieve uniform heating and microbial inactivation without quality loss; liquid egg processing has shown stable, controllable operation under flow; meat cooking experiments report faster heating and reduced drip loss; apple pre-treatments shorten drying times; and oil extraction yields higher recovery than conventional methods. These examples confirm that OH performs reliably in continuous liquid or semi-solid operations where electrical contact is consistent, but the same principles cannot be transferred directly to viscoelastic doughs.

Overall, the literature portrays OH as a high-efficiency method with clear advantages for uniform internal heating, yet one that is unsuitable for conventional bakery ovens. Its key weaknesses are electrode-contact instability, uneven temperature fields in solid doughs, and lack of crust formation. No pilot- or industrial-scale tunnel oven using OH has been reported. At present, the technology serves primarily as a research tool for studying thermal and rheological behaviour of dough rather than as a practical decarbonisation route. Substantial innovation in electrode design or hybridisation with complementary surface-heating techniques would be required before it could contribute meaningfully to tunnel-oven electrification.

5.4. 4Hydrogen

5.4.1. Direct tunnel-oven baking evidence

No peer-reviewed studies were identified in the present review that report hydrogen-fired tunnel ovens used for baking, including measurements of oven thermal performance, emissions, or baked-product quality under hydrogen combustion. The available literature relevant to hydrogen therefore does not provide direct tunnel-oven baking trials, and the discussion in the following subsections is based on adjacent industrial burner and combustion evidence and on broader conceptual and techno-economic analyses that are informative but not tunnel-oven specific. These sources provide only indirect insight and cannot be assumed to represent tunnel-oven baking conditions, where coupled heat transfer, moisture removal, and product quality requirements introduce additional constraints.

5.4.2. Adjacent industrial burner evidence

Adjacent burner studies show that hydrogen combustion presents a coupled stability-NO_x (Nitrogen oxides) design problem because high burning velocity and high adiabatic flame temperature can promote instability and thermal-NO_x formation, so mitigation focuses on controlling fuel-air mixture formation, lowering peak temperatures, and expanding stable operating windows [68,69]. Schmidt et al. [68]

developed a partially premixed single-nozzle hydrogen burner and combined non-reactive CFD (Star-CCM+) with flame diagnostics and exhaust-gas analysis to show that improving mixture homogeneity through geometric changes can reduce temperature peaks and thereby reduce NO_x under lean operation; they also report that humidifying combustion air decreases NO_x, particularly near stoichiometric operation, consistent with a temperature-reduction mechanism. Complementing this, Kikuchi et al. [70] experimentally evaluated hydrogen firing in a practical industrial diffusion burner and showed that NO_x increased to around twice the level of city-gas operation when hydrogen was burned in a nozzle-mixed burner, but that increasing combustion-air velocity reduced NO_x; importantly, they found that modifying the number of air nozzles (rather than only reducing nozzle diameter) increased furnace recirculation and enabled NO_x reduction of up to 51%, indicating the effectiveness of exhaust-gas self-recirculation as an in-furnace dilution strategy. At larger capacity and with hydrogen-natural gas blending, Kim et al. [69] proposed an oblong flame-port design with orthogonal fuel-air injection and used CFD together with tests on a commercial-scale multi-port burner to demonstrate stable flame attachment and NO_x below 40 ppm across 20%, 75% and 100% hydrogen blends when the equivalence ratio (and residual oxygen) was appropriately controlled, highlighting the role of flame segmentation, internal recirculation, and ultra-lean operation for meeting emissions constraints. Finally, where strict NO_x limits must be met, the evidence base also indicates that downstream treatment performance can be sensitive to the high water-vapour environments associated with hydrogen combustion, since Keller et al. [71] show that steam significantly decreases NO oxidation activity and affects NO_x storage and reduction behaviour in NO_x storage-reduction catalyst systems, implying that burner-only optimisation may not be sufficient where aftertreatment is part of compliance strategy. While these studies provide valuable insights into hydrogen combustion behaviour, their applicability to tunnel ovens remains uncertain, as they do not capture the coupled heat transfer, airflow, and product-oven interactions characteristic of continuous baking systems.

5.4.3. Adjacent point-of-use appliance evidence

Evidence from hydrogen blending trials in boilers and other point-of-use combustion devices indicates that emissions outcomes cannot be assumed to scale linearly with blend fraction and are strongly conditioned by burner design, excess air, and control strategy. Wright et al. [72] synthesise available experimental evidence on hydrogen blending and report substantial variability in nitrogen oxides response across appliance and burner types, with studies showing increases, decreases, or limited change depending on how blending alters flame temperature, mixing, and residence time. This variability is important for bakery applications because it implies that a given hydrogen fraction does not guarantee regulatory emissions compliance without site-specific burner optimisation and verification testing. Glanville et al. [73] similarly examine hydrogen addition in practical combustion equipment and highlight that operational constraints such as derating, altered aeration requirements, and control retuning (recalibration of fuel-air ratio control and burner operating parameters) can become necessary as hydrogen fraction increases, with emissions behaviour sensitive to the resulting changes in flame structure and local equivalence ratio. In addition to emissions and operability, appliance-focused reviews emphasise that safety and deployment considerations (for example, leak detection, ventilation, ignition management, and public acceptance) become increasingly salient as hydrogen fractions rise, reinforcing that conversion of natural-gas combustion systems to hydrogen operation is not purely a combustion problem but a broader system integration issue. However, these findings are derived from non-tunnel systems and should not be directly extrapolated to industrial baking without dedicated validation under tunnel-oven operating conditions.

5.4.4. Conceptual and system-level framing for hydrogen adoption

At the conceptual and system level, the literature emphasises that hydrogen deployment in existing combustion-based thermal equipment is expected to be constrained by fuel interchangeability, infrastructure compatibility, and the limited decarbonisation impact of low hydrogen to natural gas blending fractions. Franco and Rocca [23] review blended natural gas–hydrogen combustion for industrial thermal users and show, using interchangeability indicators and mass–energy balance reasoning, that maintaining equivalent thermal input requires increased volumetric flow as hydrogen fraction rises, while practical constraints linked to Wobbe index and heat-rate ratio can limit the level of blending ratio depending on natural gas composition and regulatory considerations; they therefore position blending as a medium-term decarbonisation route and note that higher fractions typically require burner and infrastructure redesign rather than “drop-in” substitution. They further highlight that hydrogen’s higher flame speed and broader flammability ratio increase flashback risk, while higher flame temperature tends to elevate thermal NO_x, suggesting that any transition strategy would likely need to consider both operability and emissions compliance at the system level rather than assuming carbon benefits alone. Complementing this system framing from another end-use sector, Mukelabai et al. [22] review hydrogen cooking and conclude that hydrogen can be used safely in principle, but that large-scale uptake depends on robust safety and regulatory frameworks and on techno-economic assumptions that vary widely across modelling studies, reinforcing the argument that adoption is shaped by infrastructure readiness and economics as much as by combustion feasibility.

5.4.5. Tunnel-oven-specific unknowns and research needs

In the absence of direct evidence for hydrogen-fired tunnel ovens in baking (Section 5.4.1), several tunnel-oven-specific uncertainties must be addressed before hydrogen can be considered a practical decarbonisation pathway. Firstly, zone control and temperature uniformity are critical in continuous baking, yet it remains unknown how hydrogen firing would affect longitudinal zone balance and cross-belt uniformity under typical recirculation and extraction arrangements, particularly given the sensitivity of hydrogen flames to mixing and flow-field design observed in adjacent burner studies [68,69]. Secondly, hydrogen combustion is expected to modify the radiation–convection balance and the moisture trajectory in the baking chamber because of differences in flame characteristics and elevated water vapour in the baking products of combustion, creating uncertainty in browning behaviour and surface quality development compared with methane firing [23]. Thirdly, although low-nitrogen-oxide strategies have been demonstrated in adjacent industrial burners through geometric design, recirculation, humidification, and lean operation, it is unclear whether these approaches can meet nitrogen oxide compliance requirements in tunnel ovens operating across diverse product loads and duty cycles, and whether downstream control would be required given the sensitivity of nitrogen-oxide conversion and storage chemistry to steam-rich exhaust [71,74,75]. Fourth, hydrogen conversion introduces safety and retrofit constraints, including leak detection and ventilation, flashback and ignition management, and the feasibility of integrating new burners and control schemes within existing ducting and extraction systems; these system-level constraints are consistently highlighted as adoption barriers in broader hydrogen end-use reviews [22,23]. Overall, these gaps indicate that tunnel-oven demonstration studies are required that couple burner development with oven-scale measurements of heat-transfer uniformity, emissions, and baked-product quality under representative industrial operating conditions. These uncertainties cannot be resolved through extrapolation from existing combustion or appliance studies and require direct experimental investigation in tunnel-oven configurations.

Therefore, hydrogen should be considered a promising but currently unvalidated decarbonisation pathway for tunnel ovens, with its feasibility dependent on future experimental evidence at pilot and industrial

scale.

6. Future prospects

This section synthesises the forward-looking implications of the reviewed evidence for decarbonising industrial tunnel ovens. Section 6.1 frames pathway selection as scenario-dependent, highlighting the emissions and cost sensitivities that govern technology ranking under different electricity, fuel-price, and retrofit conditions. Section 6.2 then converts the identified evidence gaps into a prioritised research roadmap, specifying the validation datasets, transferable design parameters, and pilot-to-industrial scaling requirements needed to support reliable technology comparison and deployment.

6.1. Scenario sensitivity for pathway ranking

Decarbonisation pathway ranking for tunnel ovens is inherently scenario-dependent because both emissions and operating costs vary strongly with local electricity carbon intensity and energy prices, while feasibility is constrained by retrofit capital expenditure and downtime. In addition, pathway suitability is product-dependent, since different baked goods require different surface heat flux levels and moisture trajectories to achieve target browning and internal structure, so electrification and hybridisation options should be interpreted alongside the product-quality evidence synthesised in Section 4.4. For emissions, the greenhouse-gas emission intensity of electricity generation differs markedly across European countries and is changing over time; therefore, the emissions benefit of electrifying tunnel ovens depends on the location-specific electricity mix rather than a single universal value [76]. Under lower-carbon electricity, electrification pathways (ER and hybrid electric concepts) tend to rank higher for emissions reduction, whereas under higher-carbon electricity the relative advantage narrows and near-term measures such as operational optimisation and waste-heat recovery can provide lower-regret progress while electricity supply continues to decarbonise [76].

Operating-cost ranking is similarly sensitive to energy-price conditions. Eurostat reports substantial variation in non-household electricity prices across EU Member States and over time, and the same is true for non-household natural gas prices. Accordingly, economic conclusions should be tested against at least “high electricity-to-gas price ratio” and “low electricity-to-gas price ratio” scenarios rather than a single assumed tariff [77,78]. Hydrogen pathways are additionally conditioned by hydrogen cost and supply context. The European Hydrogen Observatory shows that production costs vary by pathway and location, so hydrogen retrofit should be treated as a conditional option whose competitiveness depends on the availability of low-carbon hydrogen at acceptable cost [79]. Finally, retrofit capital expenditure and downtime constraints often determine what is implementable in practice, and industrial electrification studies emphasise the importance of testing options against site constraints rather than assuming immediate, full-system replacement [80].

Based on these sensitivities, three qualitative scenarios are used to interpret pathway ranking. (i) Under lower-carbon electricity with moderate electricity prices relative to gas, electrification (ER and hybrids) ranks highest for emissions and can be economically favourable depending on the electricity-to-gas price ratio [76–78]. (ii) Under higher-carbon electricity and/or high electricity prices relative to gas, near-term optimisation and waste-heat recovery rank higher as lower-regret options, with electrification remaining a longer-term option as grids decarbonise and relative prices evolve [76–78]. (iii) If low-carbon hydrogen becomes competitive and available, hydrogen retrofit may become more plausible, subject to both cost competitiveness and the resolution of the substantial technical uncertainties identified in Section 5.4 [79,80].

6.2. Research roadmap and validation priorities for low-carbon tunnel ovens

To translate the reviewed evidence into decision-relevant guidance, pathway ranking is framed as scenario-dependent. The following subsection summarises the key sensitivities that determine emissions and cost outcomes.

6.2.1. Priority validation datasets for comparable assessment

Progress towards low-carbon tunnel-oven technologies is currently limited by the scarcity of consistent, comparable datasets that link oven heat delivery, moisture trajectory, emissions, and baked-product quality across heating modes. To enable reproducible comparison and model validation, future experimental studies, including pilot-scale rigs designed to test multiple heating technologies under identical loading and residence-time conditions are required. At the oven level, these should include zone-resolved air temperatures and cross-belt uniformity, airflow or jet conditions where relevant, and exhaust extraction conditions, together with humidity or moisture indicators that characterise the chamber moisture trajectory. At the product level, datasets should include surface and internal temperature histories, mass-loss measurements as a moisture proxy, and, where feasible, surface heat-flux information or heat-transfer partitioning that distinguishes radiative and convective contributions. Finally, product-quality outcomes should be quantified using consistent metrics appropriate to the product class, including colour indices, moisture content, texture or crumb characteristics, volume or expansion measures, and sensory outcomes where possible. Reporting these datasets alongside a clearly stated energy-accounting boundary (supplied heat definition and included losses/auxiliaries) would establish a common benchmark for model validation and transition of laboratory findings to industrial tunnel-oven conditions.

6.2.2. Generalisable non-dimensional parameters and heat-flux ratios

To translate case studies into transferable design guidance, future work should prioritise the development of a small set of non-dimensional descriptors that enable comparison across heating modes and scales. A practical starting point is non-dimensional heat-flux ratios. The top-to-bottom heat-flux ratio captures heating asymmetry relevant to crust development and differential expansion, while the radiative-to-convective heat-flux ratio characterises the dominant external heating mode and provides a mechanism-based link to browning sensitivity and surface drying when comparing direct-fired, ER and hybrid configurations. Uniformity should be reported using dimensionless measures, such as normalised variation in surface heat flux or surface temperature across belt width and along the baking direction, to allow objective comparison between nozzle layouts, recirculation patterns and frame extraction strategies.

For scale-up and model validation, classical transport groups should be reported in forms meaningful for baking. A Biot number based on an effective surface heat-transfer coefficient indicates whether internal conduction limits heating, and a Fourier number based on residence time indicates the extent of thermal penetration relative to product thickness. Where impingement convection is used, jet Reynolds number, nozzle-to-product spacing ratio and nozzle pitch-to-diameter ratio should be reported as they govern heat-transfer coefficients and recirculation behaviour. Finally, since baking couples heat and mass transfer, the moisture trajectory should be captured using normalised mass-loss measures or latent-to-sensible demand ratios where feasible, enabling humidity and extraction effects to be compared consistently.

6.2.3. Pilot-to-industrial scaling and transferability

A central requirement for accelerating decarbonisation of tunnel ovens is a clearer basis for translating pilot-scale results into industrial performance. Scale-up should not be treated as a geometric enlargement alone, because industrial ovens differ in loading density, residence-time

distribution, recirculation and extraction architecture, and the balance between radiation and convection. Transferability is improved when pilot and industrial systems are compared using similarity targets rather than absolute dimensions. In practice, this means preserving the key non-dimensional descriptors introduced above, particularly heat-flux ratios (top-to-bottom and radiative-to-convective), uniformity metrics across belt width, and residence-time conditions that define the product heating trajectory.

For forced-convection and impingement designs, similarity should preserve jet Reynolds number and nozzle geometry ratios (spacing and stand-off distance), since these govern local heat-transfer coefficients and recirculation zones. For radiant-dominant systems, scaling should preserve the radiative view factors and the effective radiating temperature seen by the product, since these determine surface heating rate and browning tendency. Because moisture loss couples strongly to crust formation and energy demand, the exhaust extraction rate and chamber humidity trajectory should also be treated as scale-defining variables rather than secondary operating details. Finally, pilot-to-industrial translation requires consistent reporting of loading patterns (product spacing, belt coverage fraction, and product-to-oven thermal mass ratio), since these strongly affect both thermal efficiency and uniformity.

To support generalisable conclusions, future studies should explicitly test scaling hypotheses by reproducing industrial target conditions in pilot rigs, reporting the similarity metrics achieved, and then validating against at least one industrial dataset. Such a structure would allow the field to move from isolated demonstrations toward validated design rules for electrified, hybrid and alternative-heating tunnel ovens.

6.2.4. Model validation and benchmarking requirements

Because many decarbonisation options rely on numerical tools for design and control, progress depends on validation datasets that are sufficiently rich to test both oven-scale heat-transfer predictions and product responses. Validation should be defined in terms of measurable quantities that are comparable across heating modes. At the oven level, models should reproduce zone-resolved air temperatures and their cross-belt non-uniformity, together with the dominant flow features that drive uneven heating (for example, recirculation regions in forced-convection systems). Where radiation plays a major role, benchmarking should include the ability to predict radiating-surface temperatures and net radiative heat flux to the product or to a calibrated target.

At the product level, validation should go beyond surface temperature alone. Minimum benchmarks should include surface and internal temperature histories, mass-loss or moisture-loss trajectories, and at least one representative quality indicator appropriate to the product class. For breads and flatbreads, this should include quantitative colour indices and moisture outcomes, with texture or crumb metrics where feasible. Agreement criteria should be reported transparently, including sensor uncertainty, repeatability across runs, and performance across a range of operating set-points and loading conditions. Finally, studies should report the energy-accounting boundary used for any efficiency metric to avoid comparisons between incompatible definitions. Establishing these benchmarks would enable models to be used credibly for pathway comparison, optimisation of hybrid heating strategies, and pilot-to-industrial scaling.

6.2.5. Prioritised research questions

To make progress towards efficient, low-carbon continuous baking systems, future work should prioritise research questions that are measurable and transferable across heating modes.

1. Which non-dimensional heat-flux ratios best predict product outcomes? Identify whether top-to-bottom and radiative-to-convective heat-flux ratios correlate most strongly with browning indices, moisture retention and texture development across products and heating technologies.

2. What is the minimum validation dataset required for reliable oven and product modelling? Define a standard measurement set that enables benchmarking of oven fields (temperature, humidity, extraction) and product trajectories (surface/core temperature, mass loss) with quantified uncertainty.
3. How should pilot rigs be scaled to preserve industrial baking trajectories? Establish similarity targets for residence time, heat-flux ratios, humidity trajectory, and loading density that allow pilot-scale systems to reproduce industrial baking behaviour for defined product classes.
4. How do humidity control and exhaust extraction affect energy use and quality across heating modes? Quantify the coupling between extraction rate, chamber moisture trajectory, latent heat demand and surface colour development, particularly in electrified and hybrid ovens.
5. What hybrid configurations most effectively recover surface quality while maintaining electrification benefits? Identify when IR assist, impingement convection, or other surface-heating augmentation is required to achieve industrial browning targets under ER heating.
6. What techno-economic and operational constraints dominate pathway choice at bakery scale? Develop reporting templates that include retrofit downtime assumptions, boundary-consistent efficiency metrics, and sensitivity to electricity, gas and hydrogen prices.
7. What tunnel-oven demonstration studies are required to establish the feasibility of hydrogen, given the current absence of direct experimental evidence?
8. Define tunnel-scale test protocols that simultaneously measure uniformity, emissions compliance and product quality, enabling credible comparison with established gas and electric systems. Addressing these questions through integrated experimental rigs and shared reporting standards would provide a practical foundation for validating models, developing generalisable design parameters, and accelerating deployment-ready decarbonisation pathways.

7. Conclusions

This review evaluated industrial tunnel ovens with emphasis on decarbonisation options and the experimental infrastructure needed to validate emerging heating concepts. Under the thermal system boundaries defined in this paper, published energy balances and modelling studies show that gas-fired tunnel ovens can exhibit low product heat utilisation, with large losses to exhaust gases and heated structures, while thermal uniformity is strongly influenced by burner arrangement, extraction, and recirculation. Operational optimisation and waste-heat recovery can reduce fuel use, but combustion remains the dominant source of on-site emissions.

Electrification is the most immediate route to eliminate on-site combustion, but the quality evidence base remains product-specific. Direct industrial comparisons show that ER systems can deliver stable thermal conditions and comparable product outcomes for some products, while differences in heat-transfer partitioning can alter surface colour development. Across other electric conveyor and tunnel-type studies, evidence is often limited to thermal-field characterisation and control performance, with fewer studies reporting quantitative product-quality metrics, highlighting the need for systematic validation of hybrid electric concepts across multiple product classes. Induction and microwave conveyor systems have been demonstrated for specific applications or proxy products, but their generalisation to diverse bakery products remains insufficiently evidenced.

For hydrogen, no peer-reviewed tunnel-oven baking studies were identified; the hydrogen assessment therefore relies on adjacent burner evidence and tunnel-oven-specific unknowns. As a result, conclusions regarding hydrogen remain inherently uncertain and should be interpreted as exploratory and low in evidence maturity when compared with electrification pathways supported by direct experimental data. This limitation also affects its positioning within pathway ranking, which

remains scenario-dependent and varies with electricity carbon intensity, energy prices, hydrogen costs, and retrofit constraints. To support reliable future use of these findings, the paper provides consistent definitions and boundaries for efficiency reporting, updates summary tables to make system boundaries and metric types explicit, and presents a decision-oriented scenario framework together with a prioritised research roadmap specifying the minimum validation datasets and scaling requirements needed for technology comparison and industrial translation.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to find and analyse relevant peer-reviewed papers, and proofread this manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Funding

This work is supported by the Engineering and Physical Sciences Research Council (EPSRC, UK Research and Innovation (UKRI), through grant; EP/Y023846/1, Place Based Impact Acceleration Account (PBIAA), Park Royal Net Zero Food Supply Chains.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hadi Tannous reports financial support was provided by Engineering and Physical Sciences Research Council (EPSRC). Savvas Tassou reports financial support was provided by Engineering and Physical Sciences Research Council (EPSRC). Geoff Rodgers reports financial support was provided by Engineering and Physical Sciences Research Council (EPSRC). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

- [1] Chhanwal N, Tank A, Raghavarao KSMS, Anandharamakrishnan C. Computational fluid dynamics (CFD) modeling for bread baking Process-A review. *Food Bioprocess Technol* 2012;5:1157–72. <https://doi.org/10.1007/s11947-012-0804-y>.
- [2] Saberi F, Kouhsari F, Abbasi S, Rosell CM, Amini M. Effect of baking in different ovens on the quality and structural characteristics of saltine crackers. *Int J Food Sci Technol* 2021;56:6559–71. <https://doi.org/10.1111/ijfs.15372>.
- [3] Broyart B, Trystram G. Modelling of heat and mass transfer phenomena and quality changes during continuous biscuit baking using both deductive and inductive (neural network) modelling principles. *Food Bioprod Process: Transactions of the Institution of Chemical Engineers, Part C* 2003;81:316–26. <https://doi.org/10.1205/096030803322756402>.
- [4] Cappelli A, Lupori L, Cini E. Baking technology: a systematic review of machines and plants and their effect on final products, including improvement strategies. *Trends Food Sci Technol* 2021;115:275–84. <https://doi.org/10.1016/j.tifs.2021.06.048>.
- [5] Atuonwu J, Tassou S. Decarbonisation of food manufacturing by the electrification of heat: a review of developments, technology options and future directions. *Trends Food Sci Technol* 2021;107:168–82. <https://doi.org/10.1016/j.tifs.2020.10.011>.
- [6] Purlis E. Baking process design based on modelling and simulation: towards optimization of bread baking. *Food Control* 2012;27:45–52. <https://doi.org/10.1016/j.foodcont.2012.02.034>.
- [7] Mirade PS, Daudin JD, Ducept F, Trystram G, Clément J. Characterization and CFD modelling of air temperature and velocity profiles in an industrial biscuit baking tunnel oven. *Food Res Int* 2004;37:1031–9. <https://doi.org/10.1016/j.foodres.2004.07.001>.

- [8] Wong SY, Zhou W, Hua J. CFD modeling of an industrial continuous bread-baking process involving U-movement. *J Food Eng* 2007;78:888–96. <https://doi.org/10.1016/j.jfoodeng.2005.11.033>.
- [9] Boulet M, Marcos B, Dostie M, Moresoli C. CFD modeling of heat transfer and flow field in a bakery pilot oven. *J Food Eng* 2010;97:393–402. <https://doi.org/10.1016/j.jfoodeng.2009.10.034>.
- [10] Khatir Z, Paton J, Thompson H, Kapur N, Toropov V, Lawes M, et al. Computational fluid dynamics (CFD) investigation of air flow and temperature distribution in a small scale bread-baking oven. *Appl Energy* 2012;89:89–96. <https://doi.org/10.1016/j.apenergy.2011.02.002>.
- [11] Khatir Z, Paton J, Thompson H, Kapur N, Toropov V. Optimisation of the energy efficiency of bread-baking ovens using a combined experimental and computational approach. *Appl Energy* 2013;112:918–27. <https://doi.org/10.1016/j.apenergy.2013.02.034>.
- [12] Paton J, Khatir Z, Thompson H, Kapur N, Toropov V. Thermal energy management in the bread baking industry using a system modelling approach. *Appl Therm Eng* 2013;53:340–7. <https://doi.org/10.1016/j.applthermaleng.2012.03.036>.
- [13] Mansour Y, Rouaud O, Slim R, Rahmé P. Thermal characterization of a high-temperature industrial bread-baking oven: a comprehensive experimental and numerical study. *Appl Therm Eng* 2024;236. <https://doi.org/10.1016/j.applthermaleng.2023.121467>.
- [14] Mansour Y, Rahmé P, El Hajj N, Rouaud O. Thermal and expansion analysis of the Lebanese flatbread baking process using a high-temperature tunnel oven. *Appl Sci* 2025;15. <https://doi.org/10.3390/app15158611>.
- [15] Baik OD, Marcotte M, Castaigne F. Cake baking in tunnel type multi-zone industrial ovens part II. Evaluation of quality parameters 2000.
- [16] Baik OD, Marcotte M, Castaigne F. Cake baking in tunnel type multi-zone industrial ovens part I. Characterization of baking conditions; 2000.
- [17] Pereira LAM, Piza LV, Vicente M, Arce AIC, Silva AC de S, Tech ARB, et al. Construction of an experimental pilot-scale electric oven using wireless sensor instrumentation for baked food evaluation. *Food Bioprod Process* 2016;100:214–20. <https://doi.org/10.1016/j.fbp.2016.07.004>.
- [18] Constantin GA, Munteanu MG, Voicu G, Paraschiv G, Ștefan EM. An analysis of air flow in the baking chamber of a tunnel-type electric oven. *Computation* 2023;11. <https://doi.org/10.3390/computation11120236>.
- [19] Wu Y, Rusuli A, Zhao D, Li X. Design and test of tunnel-type naan baking stove. *Advances in Transdisciplinary Engineering* 2024;51:142–51. <https://doi.org/10.3233/ATDE240069>. IOS Press BV.
- [20] Steinbach J, Jadachowski L, Steinboeck A, Kugi A. Modeling and observer design of an inductive oven with continuous product flow. *Mechatronics* 2023;95. <https://doi.org/10.1016/j.mechatronics.2023.103041>.
- [21] Methlouthi A, Rouaud O, Boillereaux L. High speed industrial heat treatment by conveyorised microwave applicators. 2011.
- [22] Mukelabai MD, Wijayantha KGU, Blanchard RE. Hydrogen for cooking: a review of cooking technologies, renewable hydrogen systems and techno-economics. *Sustainability* 2022;14. <https://doi.org/10.3390/su142416964>.
- [23] Franco A, Rocca M. Industrial decarbonization through blended combustion of natural gas and hydrogen. *Hydro* 2024;5:519–39. <https://doi.org/10.3390/hydrogen5030029>.
- [24] Chakraborty S, Dash KK. A comprehensive review on heat and mass transfer simulation and measurement module during the baking process. *Applied Food Research* 2023;3. <https://doi.org/10.1016/j.afres.2023.100270>.
- [25] Boukid F. Flatbread - a canvas for innovation: a review. *Applied Food Research* 2022;2. <https://doi.org/10.1016/j.afres.2022.100071>.
- [26] Ammar ASM, Hegab KK. Flat breads qualities and attributes — ovens design, energy consumption, and environmental conservation: a review. *Food Systems* 2024;7:612–9. <https://doi.org/10.21323/2618-9771-2024-7-4-612-619>.
- [27] Chavan RS, Chavan RS. Microwave baking in food industry: a review. *Int J Dairy Sci* 2010;5:113–27.
- [28] Yi Y, Salonitis K, Tsoutsanis P, Litos L, Patsavelas J. Improving the curing cycle time through the numerical modeling of air flow in industrial continuous convection ovens. *Proced CIRP* 2017;63:499–504. <https://doi.org/10.1016/j.procir.2017.03.167>. Elsevier B.V.
- [29] Khatir Z, Thompson H, Kapur N, Toropov V, Paton J. Multi-objective computational fluid dynamics (CFD) design optimisation in commercial bread-baking. *Appl Therm Eng* 2013;60:480–6. <https://doi.org/10.1016/j.applthermaleng.2012.08.011>.
- [30] Williamson ME, Wilson DI. Development of an improved heating system for industrial tunnel baking ovens. *J Food Eng* 2009;91:64–71. <https://doi.org/10.1016/j.jfoodeng.2008.08.004>.
- [31] Al-Nasser M, Fayssal I, Moukalled F. Numerical simulation of bread baking in a convection oven. *Appl Therm Eng* 2021;184. <https://doi.org/10.1016/j.applthermaleng.2020.116252>.
- [32] Pask F, Lake P, Yang A, Tokos H, Sadhukhan J. Industrial oven improvement for energy reduction and enhanced process performance. *Clean Technol Environ Policy* 2017;19:215–24. <https://doi.org/10.1007/s10098-016-1206-z>.
- [33] El-Adly IF, Bahnasawy AH, Ali SA, Khater E-SG. Process engineering bread baking process energy requirements as affected by oven belt speed and type of breads *process engineering*, vol. 33; 2016.
- [34] Henderson HL, Ciolkosz D, Guerrero P. Measured performance of a direct-contact heat recovery system installed at a commercial bakery. 2001.
- [35] Qu M, Abdelaziz O, Yin H. New configurations of a heat recovery absorption heat pump integrated with a natural gas boiler for boiler efficiency improvement. *Energy Convers Manag* 2014;87:175–84. <https://doi.org/10.1016/j.enconman.2014.06.083>.
- [36] Erdoğan M, Acar MŞ. Thermodynamic analysis of a tunnel biscuit oven and heat recovery system. *WAPRIME* 2024;1:1–15. <https://doi.org/10.5281/zenodo.14930792>.
- [37] Mukherjee S, Asthana A, Howarth M, Chowdhury JI. Techno-economic assessment of waste heat recovery technologies for the food processing industry. *Energies* 2020;13. <https://doi.org/10.3390/en13236446>.
- [38] Danish Technological Institute. High-temperature heat pump for tunnel oven. n.d.
- [39] Chowdhury JI, Asfand F, Ja'fari M, Mukherjee S, Balta-Ozkan N. Waste heat recovery integration options for commercial bakeries in a thermo-economic-environmental perspective. *Case Stud Therm Eng* 2023;52. <https://doi.org/10.1016/j.csite.2023.103714>.
- [40] Chhanwal N, Ezhilarasi PN, Indrani D, Anandharamakrishnan C. Influence of electrical and hybrid heating on bread quality during baking. *J Food Sci Technol* 2015;52:4467–74. <https://doi.org/10.1007/s13197-014-1478-4>.
- [41] AMF Bakery Systems. Presentation on AMF bakery systems. 2025.
- [42] Reddy RS, Arepally D, Datta AK. Estimation of heat flux in bread baking by inverse problem. *J Food Eng* 2020;271. <https://doi.org/10.1016/j.jfoodeng.2019.109774>.
- [43] Dr. Zanolli srl. SYNTHESIS. 2022.
- [44] Shelke K, Faubion JM, Hosney RC. The dynamics of cake baking as studied by a combination of viscometry and electrical resistance oven heating. *Cereal Chem* 1990;6:575–80.
- [45] Masure HG, Wouters AGB, Fierens E, Delcour JA. Electrical resistance oven baking as a tool to study crumb structure formation in gluten-free bread. *Food Res Int* 2019;116:925–31. <https://doi.org/10.1016/j.foodres.2018.09.029>.
- [46] Chukwunke JL, Nwuzor IC, Anisiji EO, Digitemie IE. Design and fabrication of a dual powered baking oven. *Adv Res* 2018;16:1–8. <https://doi.org/10.9734/air/2018/43219>.
- [47] Dogan IS. Effect of oven types on the characteristics of biscuits made from refrigerated and frozen doughs. *Food Technol Biotechnol* 2005;1:117–22.
- [48] Rana M, Yasmin S, Mahomud MS, Noor F, Sarker MSH. Development and performance evaluation of an improved electric baking oven for baked products. *Food Sci Nutr* 2023;11:3057–66. <https://doi.org/10.1002/fsn3.3287>.
- [49] Kulishov BA, Soboleva EV, Sergacheva ES, Novoselov AG. Electric resistance baking as a method for production of toast bread. *IOP Conf Ser Earth Environ Sci* 2021;640. <https://doi.org/10.1088/1755-1315/640/7/072007>. IOP Publishing Ltd.
- [50] Ploteau JP, Nicolas V, Glouannec P. Numerical and experimental characterization of a batch bread baking oven. *Appl Therm Eng* 2012;48:289–95. <https://doi.org/10.1016/j.applthermaleng.2012.04.060>.
- [51] Nicolas V, Glouannec P, Ploteau JP, Salagnac P, Jury V. Experiment and multiphysics simulation of dough baking by convection, infrared radiation and direct conduction. *Int J Therm Sci* 2017;115:65–78. <https://doi.org/10.1016/j.ijthermalsci.2017.01.018>.
- [52] Gokmen S, Erdem N, Kocabas A, Yetim H. Using a hybrid technology to produce traditional sourdough Gelveri bread: infrared cooking assisted with traditional method. *J Food Sci Technol* 2021;58:962–7. <https://doi.org/10.1007/s13197-020-04610-3>.
- [53] El-Mesery HS, Mwithiga G. Performance of a convective, infrared and combined infrared-convective heated conveyor-belt dryer. *J Food Sci Technol* 2015;52:2721–30. <https://doi.org/10.1007/s13197-014-1347-1>.
- [54] Sumnu G, Sahin S, Sevimli M. Microwave, infrared and infrared-microwave combination baking of cakes. *J Food Eng* 2005;71:150–5. <https://doi.org/10.1016/j.jfoodeng.2004.10.027>.
- [55] Turabi E, Sumnu G, Sahin S. Optimization of baking of rice cakes in infrared-microwave combination oven by response surface methodology. *Food Bioprocess Technol* 2008;1:64–73. <https://doi.org/10.1007/s11947-007-0003-4>.
- [56] Gally T, Rouaud O, Jury V, Le-Bail A. Bread baking using ohmic heating technology; a comprehensive study based on experiments and modelling. *J Food Eng* 2016;190:176–84. <https://doi.org/10.1016/j.jfoodeng.2016.06.029>.
- [57] Dos Santos IF, Pimentel TC, Da Cruz AG, Stringheta PC, Martins E, Campelo PH. Ohmic heating in food processing: an overview of plant-based protein modification. *Processes* 2024;12. <https://doi.org/10.3390/pr12091800>.
- [58] Gally T, Rouaud O, Jury V, Havet M, Ogé A, Le-Bail A. Proofing of bread dough assisted by ohmic heating. *Innov Food Sci Emerg Technol* 2017;39:55–62. <https://doi.org/10.1016/j.ifset.2016.11.008>.
- [59] Bender D, Gratz M, Vogt S, Fauster T, Wicki B, Pichler S, et al. Ohmic Heating—A novel approach for gluten-free bread baking. *Food Bioprocess Technol* 2019;12:1603–13. <https://doi.org/10.1007/s11947-019-02324-9>.
- [60] Khodeir M, Rouaud O, Ogé A, Jury V, Le-Bail P, Le-Bail A. Study of continuous cake pre-baking in a rectangular channel using ohmic heating. *Innov Food Sci Emerg Technol* 2021;67. <https://doi.org/10.1016/j.ifset.2020.102580>.
- [61] Norouzi S, Fadavi A, Darvishi H. The ohmic and conventional heating methods in concentration of sour cherry juice: quality and engineering factors. *J Food Eng* 2021;291. <https://doi.org/10.1016/j.jfoodeng.2020.110242>.
- [62] Mattioli NG, Olivera DF, Salvadori VO, Marra F, Goñi SM. Ohmic baking of gluten free sponge cake: analysis of technological and quality characteristics. *Lebensm Wiss Technol* 2024;203. <https://doi.org/10.1016/j.lwt.2024.116357>.
- [63] Asamoah EA, Le-Bail A, Oge A, Queveau D, Rouaud O, Le-Bail P. Exploring the influence of ohmic heating on the action of baking powders and pound cake textural properties. *Applied Food Research* 2025;5. <https://doi.org/10.1016/j.afres.2025.100896>.
- [64] Sutrisno A, Hutasoit JP, Murtini ES, Effendi FD, Prakash S. Evaluation and analysis of transglutaminase-modified gluten-free soybean bread processed using ohmic heating with varied voltage levels. *Innov Food Sci Emerg Technol* 2025;100. <https://doi.org/10.1016/j.ifset.2024.103904>.

- [65] Waldert K, Bittermann S, Martinović N, Schottruff F, Jäger H. Ohmic baking of wheat bread – effect of process parameters on physico-chemical quality attributes. *J Food Eng* 2025;392. <https://doi.org/10.1016/j.jfoodeng.2025.112493>.
- [66] Waldert K, Martinović N, Bittermann S, Schottruff F, Jäger H. Impact of specific power input and treatment chamber design on product-process-interactions during ohmic baking of wheat bread. *J Food Eng* 2025;396. <https://doi.org/10.1016/j.jfoodeng.2025.112569>.
- [67] Panirani PN, Darvishi H, Hosainpour A, Behroozi-Khazaei N. Comparative study of different bread baking methods: combined ohmic – infrared, ohmic – conventional, infrared – conventional, infrared, and conventional heating. *Innov Food Sci Emerg Technol* 2023;86. <https://doi.org/10.1016/j.ifset.2023.103349>.
- [68] Schmidt N, Müller M, Preuster P, Zigan L, Wasserscheid P, Will S. Development and characterization of a low-NOx partially premixed hydrogen burner using numerical simulation and flame diagnostics. *Int J Hydrogen Energy* 2023;48:15709–21. <https://doi.org/10.1016/j.ijhydene.2023.01.012>.
- [69] Kim YB, Sohn CB, Jeong YS. Development of a low-NOx hydrogen combustion burner with an oblong flame port and orthogonal fuel-air injection. *Appl Therm Eng* 2025;279. <https://doi.org/10.1016/j.applthermaleng.2025.127714>.
- [70] Kikuchi K, Hori T, Akamatsu F. Fundamental study on hydrogen Low-NOx combustion using exhaust gas self-recirculation. *Processes* 2022;10. <https://doi.org/10.3390/pr10010130>.
- [71] Keller K, Wan S, Borchers M, Lott P, Suntz R, Deutschmann O. Treating NOx emission of hydrogen fueled combustion engines by NOx storage and reduction catalysts: a transient kinetic study including PLIF measurements. *Proc Combust Inst* 2023;39:4247–56. <https://doi.org/10.1016/j.proci.2022.07.027>.
- [72] Wright ML, Lewis AC. Emissions of NOx from blending of hydrogen and natural gas in space heating boilers. *Elementa* 2022;10. <https://doi.org/10.1525/elementa.2021.00114>.
- [73] Glanville P, Fridlyand A, Sutherland B, Liszka M, Zhao Y, Bingham L, et al. Impact of hydrogen/natural gas blends on partially premixed combustion equipment: NOx emission and operational performance. *Energies* 2022;15. <https://doi.org/10.3390/en15051706>.
- [74] Cantiani A, Viggiano A, Fanelli E, Cornacchia G, Braccio G, Magi V. CFD analysis of biodiesel combustion applied to industrial burners. *Modelling. Meas Control C* 2018;79:61–9. <https://doi.org/10.18280/mmc.c.790301>.
- [75] Kikuchi K, Hori T, Akamatsu F. Fundamental study on hydrogen Low-NOx combustion using exhaust gas self-recirculation. *Processes* 2022;10. <https://doi.org/10.3390/pr10010130>.
- [76] European Environment Agency. Greenhouse gas emission intensity of electricity generation in Europe. 2025.
- [77] Eurostat. Electricity price statistics. 2025.
- [78] Eurostat. Natural gas price statistics. 2025.
- [79] European Hydrogen Observatory. Cost of hydrogen production. 2024.
- [80] International Energy Agency. Renewables for industry: electrification of low-temperature heat and steam. 2025.