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Energy and Carbon Saving Potentials in a Bakery Plant

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ABSTRACT

This study investigated the energy consumption and CO_2 emission through the production process of a bakery plant. The study is conducted for Turkish pide oval bread products. The production process from the raw materials input to the final bread output is considered for the data collection. The existing energy consumption and CO_2 emission scenarios have been evaluated for the production process. Based on the existing scenarios the energy-intensive process has been identified and further analyzed to discover alternative strategies for potential savings. The analysis showed that natural gas is the dominant source of energy in the plant. The proofer and the stone-baked oven are energy-intensive processes that mostly consume steam and direct natural gas. The specific energy consumption and CO_2 emission found are 0.73 kWh/kg bread and 275 gm/kg bread respectively. Two alternative strategies such as "solar water heater" and "heat recovery system" have been proposed to reduce the energy consumption within the process. It is found that around 16% and 48% of energy savings are possible using solar water heaters and heat recovery strategies respectively whereas 8% and 25% CO_2 emission savings are possible for those strategies respectively. The comparative study showed that the specific energy consumption is a close agreement with the studies conducted in the available literature.

1. Introduction

Bakery foods are experiencing a rise in demand worldwide because of evolving lifestyles and easy-to-eat food. The global market size of bakery products is estimated at USD 621.58 billion in 2024 and is projected to reach 810.45 billion by 2029 with a growth rate is 5.45% [1]. Bread is the dominant bakery product and has been a fundamental part of diets worldwide. The mass manufacture of this product highlights the significant fossil energy consumption and greenhouse gas (GHG) emissions due to combustion. The UK, EU, and other countries worldwide are committed to reducing GHG emissions significantly from the atmosphere over the next forty years. Moreover, international legislation encourages industry to reduce fossil energy consumption [2] in the context of future fossil energy crises and environmental emissions due to combustion. The components for industrial baking are typically natural gas and electricity-powered systems which consume significant energy and emit harmful gas in the atmosphere. The need for comprehensive energy

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and emission assessment in such an industry is of greater interest to address the above issues.

The literature on energy and emission analysis is available online. Chowdhury et al., 2023 [3] investigated the impact of heat recovery on the UK bakery plant. They assessed the heat recovery performance, energy consumption, and emission reduction. The result showed that 286 kW of waste heat can be recovered, saving 161.93 t/year of natural gas and 412.5 tCO_2e/year emission. Rocha et al., 2023 [4] presented the environmental footprint of the bread industry in Portugal. The result showed that the CO_2 emission per kg of bread production was 368 gm. Weber et al., 2023 [5] assessed the climate change impact of bread transport in Sweden. The result showed that the CO_2 emission per kg of bread transport from the bakery gate to waste management was found 49 gm. Wang et al. 2019 [6] introduced a point energy technology to investigate energy consumption in the bakery production process in the UK. The electrical load allotment and voltage unbalance minimization techniques were investigated. The result showed that more than 800 kWh of energy-saving could be possible weekly. Papasidero et al. 2016 [7] showed an approach to optimize the energy consumption for bread baking in Italy. Their approach updated the control algorithm only. The optimization showed that the initial dough heating requires the highest energy. A 20% energy saving is possible by using the electric oven instead of a gas oven. Therkelsen et al., 2014 [8] examined the energy consumption in industrial baking in the USA. They found that fermentation, baking, cooling, freezing, and cleaning consume significant energy. The energy efficiency measures on the boiler, oven, chillers, freezer, and cleaning system can reduce energy consumption. Paton et al., 2013 [2] analyzed the energy consumption in a bread oven in the UK. The energy breakdown for the oven was investigated. The analysis for the potential energy savings was conducted by CFD. The result showed that the energy usage is reduced and bake time can be reduced by up to 10% using the proposed approach. Ekechukwu et al., 2011 [9] carried out the energy analysis for the bakery industry in Nigeria. The engineering and statistical tools were used to develop the empirical model for the optimization. The optimization technique could save energy consumption by 7.4%. Kannan and Boie, 2003 [10] introduced energy management strategies in a bakery plant in Germany. The result showed that a reduction of 6.5% in total energy consumption was expected by the given strategies. At the same time, the approach could be one answer to mitigate the CO_2 emission.

The literature review reported the energy analysis for the UK, USA, Nigeria, Italy, and Germany bakery plants. Studies other than the USA and European countries are limited but they are important because the national energy mix and industrial performance vary from location to location. The literature studies mostly presented the management of electrical load, voltage, algorithm, CFD technique, and other optimization as energy-saving strategies. The integration of energy-saving technology and assessment in terms of values is limited. Where the different studies reported significant energy consumption, the report for carbon emission due to fossil energy consumption is limited. The salient feature of the present study is that it included those limited aspects stated above and reported the energy and carbon analysis of an Australian bakery plant and strategies for potential savings. This study aims to investigate the baseline energy consumption, and carbon emission, and evaluate the effect of energy-saving strategies for the selected bakery plant.

2. Methodology

This section describes the detailed methodology for the energy and carbon analysis of the bakery plant.

2.1 Overview of the Bakery Plant

The bakery plant was established in 2016 and is located in Australia. They are the market-leading wholesale bakery offering bread seven days per week delivery. Turkish pide oval bread is one of the popular bakery products of the plant and is considered for this study. The weight of the bread is 120 gm each. Natural gas and grid electricity are the energy sources of the bakery plant. Natural gas is used for producing steam and direct heating. The plant operates 24 hours per day.

2.2 Production boundary stages

The bread production stages consist of mixing, hoist, proofer, stone-baked oven, cooler, and freezer. The production boundary stages are shown in Figure 1.

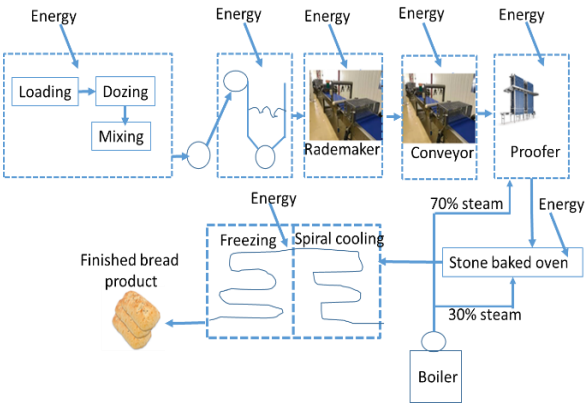


Figure 1. Production boundary stages

In the mixing stage, the number of ingredients used to develop the paste. The mixing unit consists of 2 mixers, 1 dosing station, an elevator, a washing system, a robot system, and a tank. The electric motor is the most energy-consuming equipment at this stage. The raw flour is supplied to the tank for pre-processing and storage to ensure no bacteria or other harmful substances with the flour. The pre-processed flour is sucked by a vacuum pump and brought to a silo to fill it with water and flour. The additional ingredient like gluten, oil, and drying flour is poured into the dosing station and then transferred to the mixing station. The mixing station starts to mix all the ingredients until the desired paste. Finally, the bowl with the desired paste is transferred to the elevator for discharge. The Rademaker receives the paste from the mixing zone and molds to shape the dough as per the desired bread type and size. Then the dough is compressed between two or more rollers to form the dough sheet. After this, the dough sheet is shaped into the desired product and passes through the conveyor.

Rademaker is driven by electrical appliances. The driving electrical motor is the main energy-consuming equipment in this sector. The time required to finish one bowl paste is 15 min with 67 boards of bread product measured. One board holds 32 pieces of bread measured on the conveyor. Belt conveyors are used to handle the products including fabric, rubber, plastic, wire mesh, etc wherever suitable. The conveyor is motor-driven. Many electrical motors have been installed to run the conveyor. In proofer, the product dough is allowed to rise and rest in the warming chamber before baking. The hydronic provides a heating effect by the electrical heater and has a control system to control the suitable humidity and temperature. The humidity is provided by supplying the steam. Fermentation of the dough by yeast through warm temperature and control humidity is undertaken in this stage. The warm temperature enhances the yeast which leads to the faster and higher rise of the dough. The proofing time is 90 min and the board capacity is 399. In stone stone-baked oven, there are two burners to burn the natural gas to release the required heat. The first burner is called a preheating burner and the second one is the heating burner.

The steam is injected at the entry of the oven to ensure no cracking of the bread. The natural gas is burned in the chamber and the flue gas goes up to the atmosphere. The heat is generated by burning the gas which is spread over the entire oven to bake the bread. The spiral cooling ensures the bread is cool and simultaneously freezes in the freezer.

2.3 Data collection procedure

A data sheet was prepared contains the number of machines, power rating, running hours, energy, and raw materials for every production stage on a daily basis production before the collection of the data. The required data was then collected through factory visits. The annual report, walk-through, energy data books, and questionnaires were used to record the data wherever needed. The data collection time was from July to October of the year 2020. The energy consumption for the appliances not directly involved in production such as lighting, air conditioning, etc. are excluded. Then the raw data is checked for neutrality and consistency. The data is then recalculated per unit functional unit for the analysis.

2.3 Specification of the machinery surveyed

The detail of the machinery surveyed is shown in Table 1-6. The data are presented per functional unit. The functional unit is 1 bowl of 200 kg flour.

Table 1. Machinery surveyed for mixing unit

Stages	Components and power rating	Operating time (sec)
Dosing station	2 roller motor (1.1 kW) Dosing pump motor (1.1 kW) Survofan dosing motor (0.04 kW)	300
Mixer	Hydraulic unit motor (2 kW) 2 Bowl rotation motor (2.2 kW) Tools rotation motor (45 kW)	390
Elevator	Hydraulic unit motor (2.2 kW) Bowl rotation motor (0.75 kW) 2×Descent elevator motor (1.5 kW)	15 60 80
Robot unit	Longitudinal motor (2.2 kW) Cross direction motor (2.2 kW) Hydraulic unit motor (1.1 kW)	22 20 30
Tank	Impeller motor (22 kW) Scraper motor (3 kW)	300

Table 2. Machinery surveyed for the Rademaker unit

Stages	Components and power rating	Operating time (Sec)
1	Motor type 1 (27×115 W)	
2	Motor type 2 (3×0.55 kW)	
3	Motor type 3 (4×1.5 kW)	900
4	Motor type 4 (7×3 kW)	
5	Motor type 5 (1×0.37 kW)	

Table 3. Machinery surveyed for the conveyor unit

Stages	Component and power rating	Operating time (Sec)
Rademaker to D-oven	Bread conveyor motor type 1 (20×0.55 kW)	900

D-oven to Rademaker	Strawer conveyor motor type 2 (13×0.55 kW)	900
	Strawer sprayer motor type 3 (2×0.37 kW)	360

Table 4. Machinery surveyed for the proofer unit

Component and power rating	Proofing time (Sec)
Hydronic (66 kW) Motor type 1 (5.5 kW) Motor type 2 (inside lifter) (2×3 kW) Motor type 3 (inside lifter) (2×1 kW) Steam usage (308 kg/hr)	906

Table 5. Machinery surveyed for the stone-baked oven

Component and power rating	Baking time (Sec)
Burner: Panel fan motor and light (2×30 W+18W) Oven belt motor (4 kW) Forced ventilation motor (18.6 W) Venti. Preheating motor (5.5 kW) Venti. Heating motor (5.5 kW) Brush oven belt motor (0.55 kW) Unloader belt motor (0.25 kW) Preheating and heating burner Gas flow 7.24 m^3/hr Steam flow 132 kg/hr	1005

Table 6. Machinery surveyed for the cooler and freezer

Components and power rating	Cooling/freezing time (Sec)
Ventilator panel fan for lifter (2×19 W) Heater air curtain (3×180 W) Heater ventilator evaporator (6×1260 W) Heater drain pipe (795 W) A panel of the heating evaporator (6×1940 W) Cooler lighting (464 W) Belt cooler (370 W) Drum cooler (300 W) Module input and output passage cooler (500 W) Cooler A/C fan motor (15000 W) Circulation pump cold water (2200 W) Freezer lighting (936 W) Heater door freezer (240 W) Belt freezer (370 W) Drum freezer (300 W) Module passage output freezer (250 W) Ventilation air curtain output freezer (3300 W) Evaporator Nos. 6 freezer for 12 lifter (4kW×12)	1020

3. Results and discussion

This section describes the energy analysis throughout the production process and the energy savings opportunities using the alternative strategies.

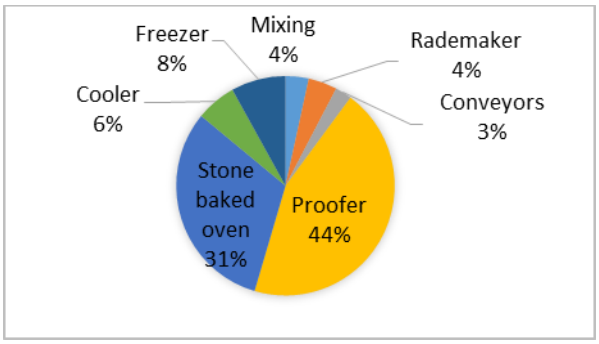
3.1 Energy consumption and carbon emission by production processes

The energy consumption and carbon dioxide (CO_2) emission values over the production process are shown in Table 7. The CO_2 emission per kWh of electricity generation in Australia is 656.4 gm [11] and the CO_2 emission per GJ natural gas combustion is 55 kg [12] are used to calculate the CO_2 emission. The electricity and primary energy was collected as per the procedure stated in section 2.3. It is seen that the proofer and stone-baked oven are dominated by primary energy. The total energy consumption including primary and secondary (electrical) form is 189.39 kWh and the corresponding CO_2 emission is 70.36 kg per functional unit. The specific energy consumption and CO_2 emission found are 0.73 kWh/kg bread and 275 gm/kg bread respectively.

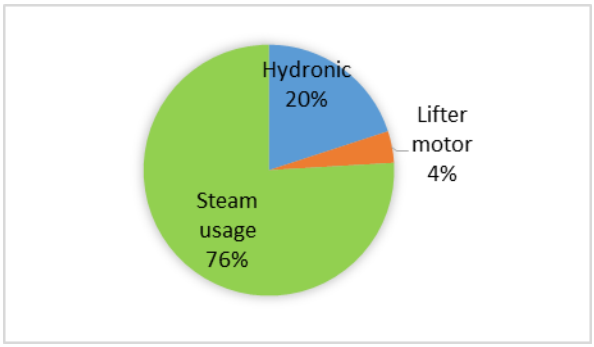
Table 7. The energy consumption and CO_2 emission breakdown

Production stages	Energy consumption (kWh) per functional unit (1 Bowl of 200 kg flour)		CO_2 emission (kg)
	Primary	Electrical	
Mixing unit	---	8.45	5.54
Rademaker unit	---	8.00	5.25
Conveyor	---	4.60	3.01
Proofer	63.21	20.02	25.65
Stone baked oven	54.40	4.43	13.67
Cooler	---	11.16	7.32
Freezer	---	15.12	9.92

The energy consumption share throughout the production process is shown in Figure 2. It is seen that the highest energy consumption share found in the proofer unit is 44% and the lowest energy consumption share found in the conveyor unit is 3% (Fig. 2a). The stone-baked oven is the second most intensive unit that shares the energy by 31%. The energy consumption by cooler and freezer is similar in magnitude likewise mixing and Rademaker are similar in magnitude. The proofer and stone-baked oven together energy share is 75% which is a significant share and their breakdown of energy consumption is shown in Figures 2 (a) and 2 (b) respectively. In the proofer unit (Fig. 2b), it is seen that steam usage contributed to the highest shear energy consumption of 76% and hydronic is the second highest share of 20%. The energy consumption by the lifter motor is insignificant. The hydronic components are electrical components. It is necessary to think about steam consumption as its contribution is significant. Such steam is the secondary form of energy supplied from burning the natural gas in the boiler. In the stone-baked oven (Fig. 2b), the steam and natural gas are consumed apart from the electrical equipment.



(a)



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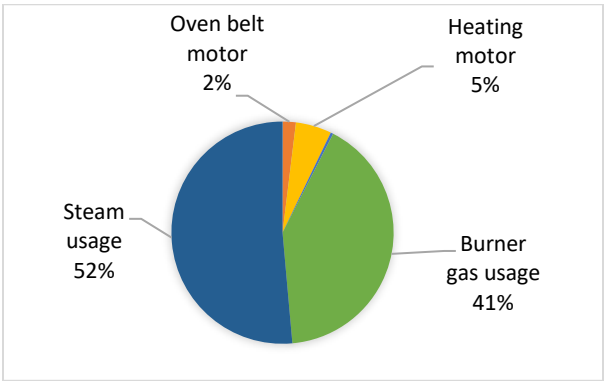

(c)

Figure 2. (a) Energy share throughout the production sub-process (b) Energy breakdown in the proofer (c) Energy breakdown in the stone-baked oven.

It is seen that the energy consumption from direct steam usage and gas usage gets a higher percentage shear compared to others. The share of energy consumption is around 52% from steam usage and 41% from natural gas usage. All other equipment share is negligible. Hence, potential alternative strategies can be developed based on the stem and natural gas usage to reduce energy consumption.

3.2 Energy consumption by energy sources

The above investigation shows that the production process has adopted many electrical appliances and are mostly operated by grid electricity. The natural gas is supplied in the stone-baked oven, and steam is supplied in the oven and proofer which is generated by burning the natural gas. Figure 3 shows the energy consumption by energy sources. It is seen that the contribution of natural gas consumption is 62% of total energy consumption of which direct natural gas usage is 13% and steam usage is 49%.

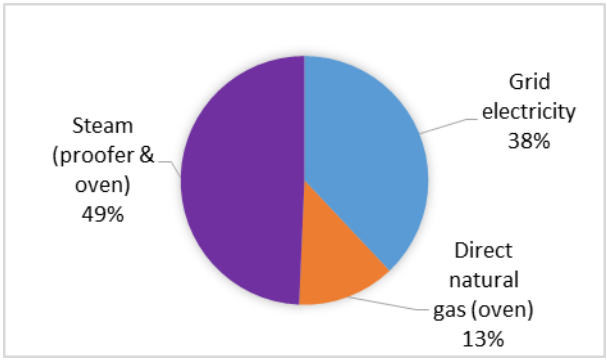

Figure 3. Energy consumption by energy sources

3.3 Proposed alternative strategies

The previous energy analysis shows that the stone-baked oven and proofer unit are the energy-intensive units in the production process. The energy consumption by the other process is insignificant and their share is around 10% of the total energy consumption throughout the production process. Hence, there is a scope to discover alternative strategies in the stone-baked oven and the proofer unit. In the stone-baked oven, steam and natural gas are used for the operation, and in the proofer unit, the electrical heater and steam are used for the operation. The steam is common for both units and is produced by the small boiler operating by the natural gas. In this regard, an alternative strategy can be applied to the boiler unit to minimize the natural gas consumption for steam production. On the other hand, the natural gas is burned in the stone-baked oven and the flue gas at high temperature goes out into the atmosphere. There is a heat recovery opportunity that can play an important role in generating the required steam. Hence, the following alternative strategies can be proposed for energy and carbon saving in the plant.

Strategy 1: Steam generation by solar water heating system during the peak load

Strategy 2: Flue gas heat recovery from the stone-baked oven unit

3.3.1 Steam generation by solar water heater (Strategy 1)

The steam generator delivered steam normally at 0.7-0.75 bar (70 kPa) pressure. At this pressure the steam temperature read from the saturated steam table is 90^0C. This temperature is manageable using the solar thermal technology established today. The solar water heater is well recognized and one of the renewable energy technologies in the world by which hot water is produced. The natural circulation-based solar water heater has an extensive application in hotels, hospitals, guest houses, residential buildings, etc [13]. The solar water heater can supply water at a temperature above 90^0C to 110^0C. There are two basic types of solar water heaters such as flat plate and evacuated tube water heaters. The evacuated tube type is more efficient (less heat loss) than that of the flat plate type system. Evacuated tube type uses two layers of glass with a vacuum in between (Figure 4).

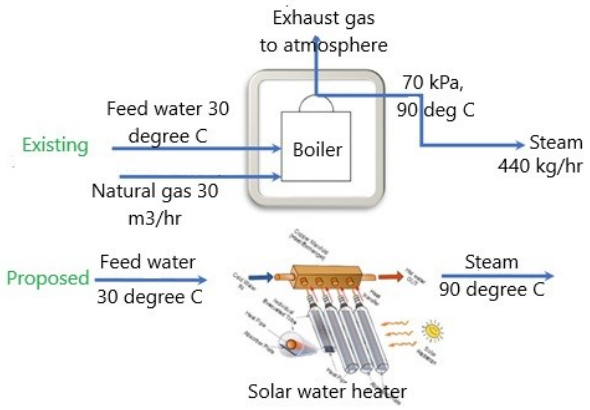

Figure 4. The existing and proposed steam generation strategies

The outer glass is very pure and does not become hot and allows all the solar radiation to pass through it. The vacuum acts as an insulator that does not allow the heat to escape again. The inner glass has coatings of heat absorption with integrated transfer material which takes the radiation and becomes hot. Then it transfers heat to the copper heat pipe contains phase change liquid inside. The phase change liquid gets vaporized and pressurized which allows going to the header water. In the header manifold, the vapor exchanges heat with ambient water and condenses. The condensed liquid returns to the bottom of the heat pipe and the cycle starts again. Each tube works independently and is over 93% efficient [14]. The size of the solar water heater will be defined based on the demand for the steam needed per hour. A typical solar hot water panel is 2 square meters and can supply 150 liters per day which is 18 liters per hour based on the average sunshine hour is 8 for the studied location [15-16]. In this regard, one-third of the existing consumption amount in 24 hours can be saved using solar water heaters. The peak hour energy and carbon saving potential for the solar water heating system is shown in Table 7.

3.3.2 Flue gas heat recovery (Strategy 2)

The waste heat from the stone-baked oven released into the atmosphere can be recovered through the heat exchanger to heat the water. This will exchange the heat to feed water and the temperature of feed water is 150-180^0C possible to rise using the recovery of flue gas [17]. The result is boiler can be 100% replaced by the appropriate heat exchanger result is the amount of existing energy use saved. The conceptual schematic is shown in Figure 5. Typical flue gas temperature ranges from 230^0C to 340^0C. The common practice is to recover sensible heat from flue gas until the flue gas temperature reaches 150^0C [18]. Hence the energy and carbon saving potential for the heat recovery system is shown in Table 8.

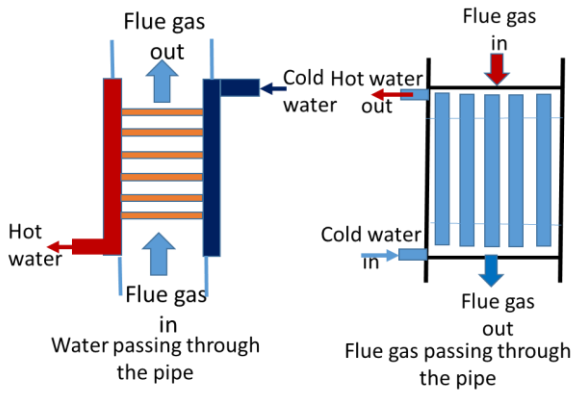

Figure 5. Example of heat recovery system

Table 8. Energy and carbon saving potential for the proposed strategies

Strategies and section	Steam supplied (kg/hr)	Power from the steam (kW)	Operating time (hr)	Existing energy from steam (kWh)	Proposed energy use (kWh)	Energy Savings (kWh/day)	CO_2 emission savings (kg/day)
Solar water heating system: Stone baked oven	132	108.37	24	2,600	1,733	867	172
Proofer	308	251		6,024	4,016	2,008	397
Flue gas							

heat recovery system:						
Stone baked oven	132	108.37	2,600	0.00	2,600	514
Proofer	308	251	6,024	0.00	6,024	1,192

**The energy content of steam is 2.9 MJ/kg*

A summary of the energy consumption and carbon emission savings potential is shown in Table 9. It is seen that the proposed alternative strategies offer the possibility of the energy consumption reduction magnitude of 2,873 kWh/day and 8,622 kWh/day for the solar system and heat recovery system respectively. Around 16% and 48% of energy savings are possible using solar water heaters and heat recovery strategies respectively whereas 8% and 25% carbon savings are possible for those strategies respectively.

Table 9. Summary of the energy consumption analysis

Sections	Existing demand (kWh/day)	Proposed demand (Solar system) (kWh/day)	Proposed demand (Heat recovery) (kWh/day)	Total energy savings kWh/day (% of total)		Total CO_2 emission savings, kg/day (% of total)	
				Solar system	Heat recovery	Solar system	Heat recovery
Proofer	7,990	5,982	1,966				
Stone baked oven	5,648	4,781	3,048	2875 (16%)	8624 (48%)	569 (8%)	1706 (25%)
Sub-total	13,638	10,763	5,014				

3.4 Comparative analysis

The results of the present study are compared with the available literature shown in Table 10. The energy consumption (kWh) per unit of production is considered for the comparison. It should be noted that,

- The study was undertaken in different countries of the world
- The country's energy mix, industrial performance, policies, and management are different
- Energy assessment methods are different
- The production industry is in a different capacity
- The size of the products is different

Table 10. Comparative analysis

Sources	Location	Energy consumption (kWh/kg bread)	CO_2 emission (gm/kg breadd production)
Kannan et al., 2003 [10]	Germany	1.37	----
Rocha et al, 2023 [4]	Portugal	----	368
Leon et al., 2021 [19]	Spain	0.186	----
Carbon Trust, 2010 [20]	UK	0.590	----
Present study	Australia	0.73	275

It is seen that the energy consumption for Germany-manufactured products [10] is higher and for Spain-manufactured products [19] is lower. They both have utilized the field survey data but the variation is due to the national energy mix in the electricity generation, industrial performance and the types of other energy sources used during the operation are different. The UK-manufactured product shows a little higher energy consumption per unit of bread product. The specific energy consumption for the Australia-manufactured (present study) product is 0.73 kWh/kg. The CO_2 emission per kg bread production for Portugal [4] was found to be 368 gm whereas the present study showed the value is 275 gm. Hence the present study has a close agreement when compared with the available literature studied.

4. Conclusion

The assessment of energy consumption and CO_2 emission throughout the production process of a bakery plant has been conducted in this study. The existing evaluation and alternative strategies for the potential savings are investigated. The result shows that the proofer and stone-baked ovens are energy-intensive processes within the production chain. Natural gas is the dominant energy source found in the bakery plant mostly used for steam generation. Solar water heaters and heat recovery strategies are proposed to reduce energy consumption within the production process. The specific energy consumption and CO_2 emission found are 0.73 kWh/kg bread and 275 gm/kg bread respectively. The alternative strategies showed that around 16% and 48% of energy savings are possible using solar water heaters and heat recovery systems respectively whereas 8% and 25% CO_2 emission savings are possible for those strategies respectively. The results of this paper will be useful for the production manager, policy maker, designer, and environmental regulatory team to optimize the production chain and to create an environmental benchmark in national and international contexts. Hence, the energy efficiency of the bakery plant can improve through the proposed strategies and contribute to the national and global energy crisis challenge as well.

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