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Waste heat recovery integration options for commercial bakeries in a thermo-economic-environmental perspective

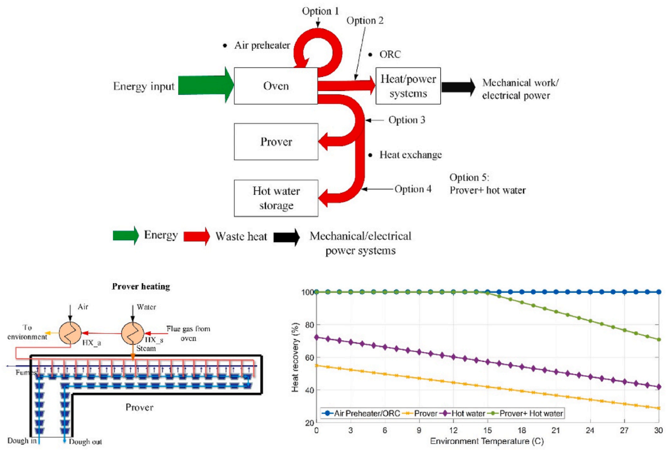
Jahedul Islam Chowdhury [a], Faisal Asfand [b,*], Mohammad Ja'fari [b], Sanjay Mukherjee [a], Nazmiye Balta-Ozkan [a]

[a] School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire, United Kingdom
[b] School of Computing and Engineering, University of Huddersfield, Huddersfield, United Kingdom

HIGHLIGHTS

- Investigating the potential of waste heat recovery in the bakery industry.
- Performance assessment of five potential waste heat recovery options in techno-economic-environmental perspective.
- Up to 286 kW of waste heat can be recovered using the proposed systems.
- Up to 161.93 t/year of natural gas and 412.5 $tCO_{2\ e}$/year can be saved using the air pre-heater option.
- Air preheating is the most energy-efficient and cost-effective option for waste heat recovery in bakeries.

GRAPHICAL ABSTRACT



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ABSTRACT

In commercial bakeries, a substantial amount of heat is exhausted which is not only a waste of useful resource, but also contributes to higher fuel consumption and carbon emissions, if not recovered. In this study, waste heat from a single oven is considered and five potential heat recovery options are investigated in a techno-economic-environmental perspective to provide essential results for integrating an appropriate technology for waste heat recovery in the commercial bakeries sector. Waste heat recovery options were selected considering the temperature

* Corresponding author.
E-mail address: f.asfand@hud.ac.uk (F. Asfand).

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profile, the waste heat source, quality and quantity of heat and the heat energy demand for the various processes in commercial bakeries. Thermodynamic, economic, and environmental models are developed to assess the heat recovery performance, cost savings and emission reduction at both design and off-design conditions. Results show that up to 286 kW of waste heat can be recovered and reused in the case of air pre-heater, which can save up to 161.93 t/year of natural gas and an equivalent cost and emission savings of $ 93,594/year and 412.5 tCO_2e/year, respectively. Moreover, the earliest payback period of 0.77 years was estimated for the air pre-heater option with an estimated capital investment cost of $71,631, whereas a maximum payback period of 4.59 years was estimated for the electricity generation by the organic Rankine cycle having an estimated capital investment cost of $304,040. These results reveal that air preheating is the most energy-efficient and cost-effective option to recover the waste heat from the ovens in the bakery industry.

Nomenclature

A	Area (m^2)
C_{BM}	Bare Module Cost ($)
C_{cap}	Total Capital Cost ($)
h	Specific Enthalpy (kJ/kg)
m	Mass (kg)
n	Number of Components
P	Pressure (bar)
Q	Heat (kW)
T	Temperature (^oC)
W	Work (kW)

Greek Symbols

ε	Emission Saving
τ	Payback Period
υ_f	Greenhouse Gas Conversion Factor
φ	Operation and Maintenance Cost Factor
η	Efficiency

Acronyms

CEPCI	Chemical Engineering Plant Cost Index
ES	Energy Saving
HE	Heat Exchanger
ORC	Organic Rankine Cycle
WHR	Waste Heat Recovery

Subscripts

a	Air
con	Condenser
evp	Evaporator
exh	Exhaust flue gas from oven
i	Inlet condition
is	Isentropic
o	Output conditions
recp	Recuperator
s	Steam
T	Turbine
w	Water
wf	Working Fluid
P	Pump
T	Turbine
ap	Air preheater
cp	Cooling pump
hw	Hot water
pr	Prover

1. Introduction

Industry accounted for 37 % (156 EJ) of the total global final energy use, and contributed to around 24 % (8.5 $GtCO_2$) of the global greenhouse gas emissions in 2017 [1]. Almost half of the total energy in the industry is used for the heating purposes, of which up to 50 % is left to the environment as waste heat [2]. If this waste heat is recovered, energy demand and greenhouse gas emissions can be reduced significantly. Industry sector consists of different sub-sectors including manufacturing sectors such as iron and steel, chemical, food and drink, etc. Food and drink industry is one of the largest manufacturing sub-sectors that plays significant roles in society and the economy around the world. For example, the EU food and drink industry employs around 24 million people across its supply chain, and has an estimated turnover of $1220 billion/year [3]. The UK alone employs 4 million people and secures an estimated turnover of around $135 billion/year [4]. Although its contribution to the society and economy is very positive, the use of fossil fuels such as natural gas and oil and non-renewable or high carbon electricity by this sector contributes to the environment negatively. To reduce the environmental impacts, it is therefore necessary to reconsider the methods by which energy is generated, managed, and used in the food and drink industry. Particularly, improving energy efficiency by reducing and reusing waste heat is seen as one of the several ways that can reduce CO_2 emissions and hence the environmental impacts [2,5–7].

Bakery industry is one of the heat intensive sectors within the food and drink industry that produces a variety of food products including breads, snacks, cookies, pies, etc. Among different products, bread manufacturing is the most energy intensive due to the requirement for a large amount of natural gas in baking ovens (590 kWh/tonne of bread for indirect ovens and 221 kWh/tonne for direct ovens [8]). Moreover, heating demand in other processes such as prover and hot water boiler is also significant and is further added up with the demand in ovens. Depending on the type of ovens, up to 50 % of heat input is wasted through flue gases and other media such as heat loss due to the lack of insulations, heat loss via baking tins and heat loss due to the combustion inefficiency [8]. The temperature of waste heat from the flue gases of bakery ovens can reach up to 336 °C [8]. The waste heat at this temperature provides many opportunities to recover and reuse the heat for on-site or over the fence heating and cooling or electricity generation purposes [2, 9–11]. The utilization of waste heat for heating purposes may include heating different low temperature sub-processes such as provers and generating hot water, or space heating. The waste heat can also be used in absorption chillers which can lead to a significant reduction of CO_2 and NOX emission and fuel consumption [12,13]. Moreover, waste heat at low (<250 °C) and medium (250–650 °C) grades are attractive to be used in different thermal power cycles such as organic Rankine cycle (ORC) [14,15], steam Rankine cycle (SRC), supercritical CO2 (s-CO2) cycle [16], etc. [9,11,17,18]. However, not all heat recovery options are best suited for all types of waste heat. Hence, to best utilise the waste heat from a plant (e.g., bakery), it is important to investigate different heat recovery integration options in techno-economic-environmental frameworks. Therefore, the objective of this research was to find a complete heat recovery integrated solution that, on the one hand, is techno-economically viable for the commercial bakery industry, and on the other hand, is the best option for the environment.

In April 2021, the Climate Law Regulation was introduced to implement the climate neutrality target into the binding EU law, so each member of the EU has been obliged to expand national legislation to reach the carbon neutrality target by 2050 [19]. The UK passed a net-zero emission law to reduce 100 % carbon dioxide emissions by 2050 [20]. This ambitious target has to be met by cutting emissions and reducing energy demand from all energy consuming sectors. In the UK, industrial energy use is responsible for 25 % of the total GHG emissions in 2016, which equates to 100 $MtCO_2e$, of which 8 % is from the food and drink sector [21]. The food and drink sector is a highly heat intensive and diverse sector that consists of many sub-sectors: grocery, bakery, meat and poultry, beverage, fish processing, etc. having high energy consumption. In 2007, the total energy demand was estimated to be 43.2 TWh, of which top two sub-sectors: bakery and meat/poultry sectors accounted for 5.5 TWh and 5.1 TWh, respectively, which collectively represented 25 % of the total industry demand. Other significant sub-sectors and their estimated demand can be seen in Fig. 1. Among them, bakery has the highest energy consumption (approx. 15 %) due to the extensive burning of natural gas for heat in ovens, which produces an estimated 4.1 billion units of bread, bakery snacks, and other bread products per year, and has an estimated market value of £3.6 billion/year [22]. The entire manufacturing process is a heat intensive process that is controlled carefully, particularly the baking process which takes place at a temperature of 230–270 °C for around 25 min [8]. A significant amount of heat from ovens ends up as waste with temperatures up to 250 °C [23]. The waste heat at this temperature provides an opportunity for waste heat recovery through in-process recovery, e.g., air preheating for combustors, sub-process recovery such as heat to prover, and heat to electricity conversion using thermodynamic power cycles [2].

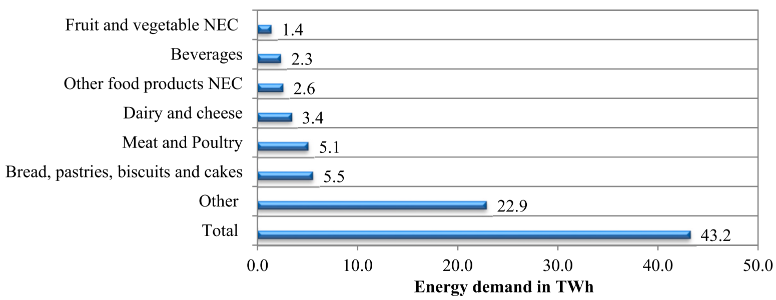

Fig. 1. Energy consumption in food and drink subsectors, UK 2007 [24].

Several technologies have been investigated by researchers to assess the waste heat recovery potential in energy intensive industries. Moreover, Jouhara et al. [25] have described in detail the functionality of waste heat recovery technologies and reviewed the potential waste heat recovery technologies and their applications in the iron and steel, ceramic and food industries. Valenti et al. [26] developed a cascade phase change regenerator to recover the exhaust air heat energy in a natural gas-fired batch dryer. They optimised the regenerator and performed economic analysis showing that 61.5 % energy could be recovered which accounts for net savings of 3340 €/year, achieving a payback period of less than 3 years. Liu et al. [27] developed a numerical model to investigate the performance evaluation of a waste heat recovery system from a bronze ingot casting mold via a thermoelectric generator. They assessed the effect of flue gas velocity and temperature on the performance of the thermoelectric generator and reported that the thermoelectric generator power increases with increase in inlet velocity and temperature. They achieved a maximum net power output of 18.83W at inlet flow velocities of 5 m/s. Bin et al. [28] investigated ORC to recover the waste heat in a hybrid electric vehicle. They used the GT-SUITE software to model and test the performance of the engine and ORC waste heat recovery system. They observed a maximum cycle efficiency of 5.4 % and reported that the ORC waste heat recovery system contributed 2.02 kW extra power, improving the fuel economy by up to 1.2 %. In another study, Zhar et al. [29] investigated the thermodynamic and economic performances of three different ORC configurations, including basic-ORC, reheating-ORC, and regenerative-ORC with open feedwater heater. Their results showed that regenerative-ORC can achieve better performance, achieving 13 % higher energy efficiency and 44 % lower exergy destruction compared to the basic-ORC at the same working conditions. The results showed that the payback period was less in the case of basic-ORC which has fewer heat exchangers. The cost of heat exchangers plays a critical role in defining the payback period and contributes to 70 % of the total cost [30]. Mukherjee et al. [23] developed a system level energy model of an industrial-scale baking oven with an integrated waste heat recovery unit and assessed the benefits of exhaust gas waste heat recovery for pre-heating the air. They reported that with the use of air-preheaters, 4 % savings in the oven fuel consumption can be achieved which can reduce the annual running costs by £4207 and CO_2 emissions savings of circa 43 tonnes per annum. In another study, Chowdhury et al. [9] investigated the waste heat recovery potential in industrial bakery ovens and its conversion into electricity using power cycles. They developed the thermodynamic models of recuperative-ORC, trilateral cycle, and supercritical CO_2 Brayton cycle, and investigated their performance for a range of heat source temperature. They reported that the ORC achieved the highest thermal efficiency of 26.5 % at a temperature of 250 °C, offering an annual electricity cost savings of approximately £23,000.

1.1. Overview and contribution

Though various waste heat recovery technologies have been investigated in the literature for different applications and energy intensive industries, there is still lack of comprehensive research in techno-economic-environment perspective for commercial bakeries. Moreover, a particular waste heat recovery technology may be efficient for one application, but the same may not be effective to recuperate waste heat in another case. The choice of waste heat recovery technology greatly depends on the type of heat source and fluid, temperature and pressure. Moreover, the on-site energy demand for various processes can also provide an opportunity to recuperate the waste heat through a particular technology. This study mainly focuses on the commercial bakeries sector and considering the type of heat source (flue gas), the quantity and quality of waste heat, and the on-site energy demand for various processes, potential heat recovery options are identified and assessed to minimise energy demand and maximise fuel savings. In commercial bakery ovens waste heat is available in the exhaust flue gas, and has a temperature of up to 330 °C. The heat at this profile provides various opportunities, including on-site recovery and the reuse of waste heat in the ovens, transfer of heat to other low temperature processes or conversion into electricity. In this study, we considered waste heat from a single oven and investigated five potential waste heat recovery integration options for a commercial bakery industry in a techno-economic-environmental framework. Moreover, this study aims to assess the heat recovery performance, cost savings and emission reduction of the selected options at both design and off-design conditions.

2. Materials and methods

2.1. System description

We investigated various waste heat recovery (WHR) integration options for the commercial bakery industry to identify the best solution that can offer the highest heat recovery and economic-environmental benefits. We particularly focused on a bread manufacturing line of a commercial bakery in the UK. The selected line produces around 2–2.5 tonne/h of bread weighing 800 gm each. Bread is made from dough, which is a mixture of flour and water, through baking. The processes involved in bread making are shown in Fig. 2. Among other processes, baking in ovens is the most energy intensive that uses natural gas for heating and generates a significant amount of waste heat. The second most energy intensive process is the proofing or proving process that requires both steam for humidity control and natural gas for heating at 40 °C. Besides these processes, bakery plants also need a substantial amount of hot water (at 70 °C) for cleaning tins and trays that are used for baking purposes. The hot water is conventionally supplied by a boiler.

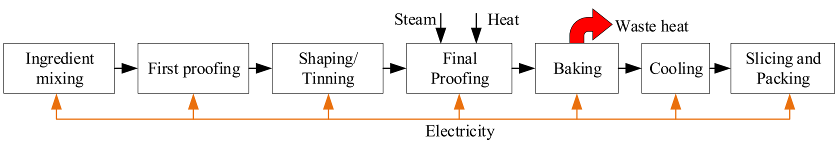

Fig. 2. Flowchart of commercial bread baking process.

Until now, only a few commercial bakeries in the UK recover the waste heat from bakery ovens for combustion air preheating, which reduces the fuel consumption and thus improves the efficiency. However, other options need to be investigated to assess their performance in terms of technical, economic and environmental benefits. These benefits can only be realised with the analysis of individual process-level integration against multi-process integrations of different heat recovery options. We considered five different waste heat integration options as can be seen in Fig. 3. These options include: (1) air preheating to preheat the combustion air for the oven, (2) heat to electricity generation using ORC, (3) prover heating (waste heat to supply both steam and hot air for prover), (4) water heating to replace hot water boiler, and (5) a combination of prover heating and hot water.

Indirect oven consists of two burners: a feed burner and a delivery burner. Waste heat from the oven could be used to preheat the combustion air for burners using a heat exchanger (HX-ap) in Option 1. The preheated air is then split to feed and deliver burners. Option 2 uses ORC for electricity generation which is to be consumed within the plant, and hence reduces the grid electricity demand. ORC works based on the Rankine principle [31] that converts heat into electricity. We used recuperated ORC with n-pentane as the working fluid, to maximise the heat recovery. N-pentane has no Ozone Depletion Potential (ODP) and has very low Global Warming Potential (GWP), and is considered to be an optimal fluid for an ORC with a medium grade waste heat recovery such as the heat from an oven in this research [18,19]. The ORC in this study comprises three heat exchangers (one evaporator, one recuperator and one condenser), two pumps (refrigerant and cooling water pump), and a turbine as shown in Fig. 4. Prover heating in Option 3 was designed with two heat exchangers (one for air heating (HX-a) and one for supplying steam (HX-s) for humidity control), while water heating in Option 4 was designed with one heat exchanger (HX-hw) and a pump. Option 5 is the combination of Options 3 and 4 that was designed with three heat exchangers (two for prover and one for hot water) and a pump.

2.2. Techno-economic-environmental modelling framework

In this study, thermodynamic, economic, and environmental models are developed and integrated to evaluate the techno-economic-environmental performance of various waste heat recovery options considered for the commercial bakery industry. Fig. 5 illustrates the systematic approach that we followed in developing these models. First of all, the thermodynamic models for each WHR option were developed in Aspen Plus based on the key input data from the oven, prover, boiler, and the design point ambient condition. Design data and parameters from the thermodynamic models such as, heat exchanger area, turbine work, pressure, temperature, etc., were then utilized to develop economic models, which estimated investment costs and payback period for each WHR option. Economic models were developed in MATLAB. Various economic constraints and assumptions which are described in Section 2.2.2 on the economic model were used. Finally, the technical parameters such as fuel savings or equivalent electricity savings were then used in environmental models, which were developed in MATLAB, to estimate the greenhouse gas savings by various WHR options.

2.2.1. Thermodynamic model

The thermodynamic models were developed using Aspen Plus™ modelling platform to design and simulate the components of the selected heat recovery options considered in this research. Mass and energy conservation equations were applied for the individual components (heat exchangers, pumps and turbine) to obtain a converged solution. Table 1 shows the thermodynamic models of different components in various WHR options considered in this article. The Peng-Robinson equation of state was used to calculate the thermophysical parameters for the simulation in the case of air-preheater, prover, and hot water options, whereas the REFPROP library was used for the thermodynamic and transport properties of n-pentane in the case of ORC system. A convergence criterion of 10^{-4} was set for the simulations in Aspen Plus tool.

Table 2 shows the input data for the simulations in Aspen Plus which includes the temperature, pressure and mass flowrate of the exhaust flue gas in a commercial bakery oven, the heat energy (steam) demand in prover and heat energy demand for hot water use. The design point input parameters such as temperature (T) and pressures (P) of individual components and the turbomachinery

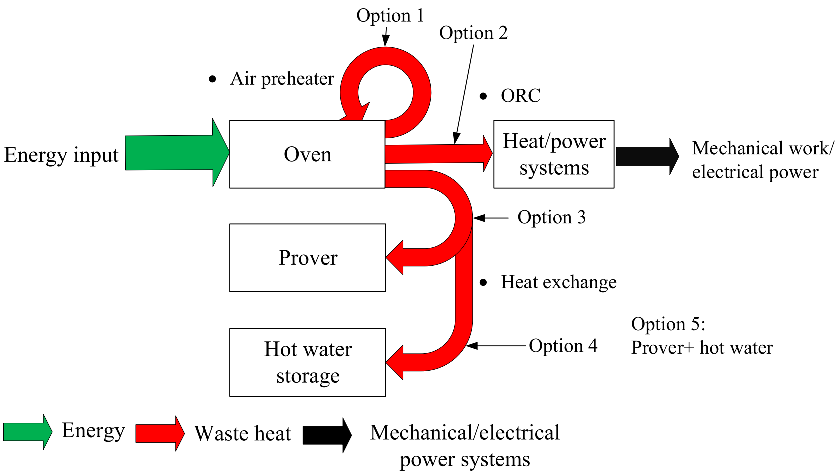

Fig. 3. Selected waste heat recovery options for commercial bakeries.

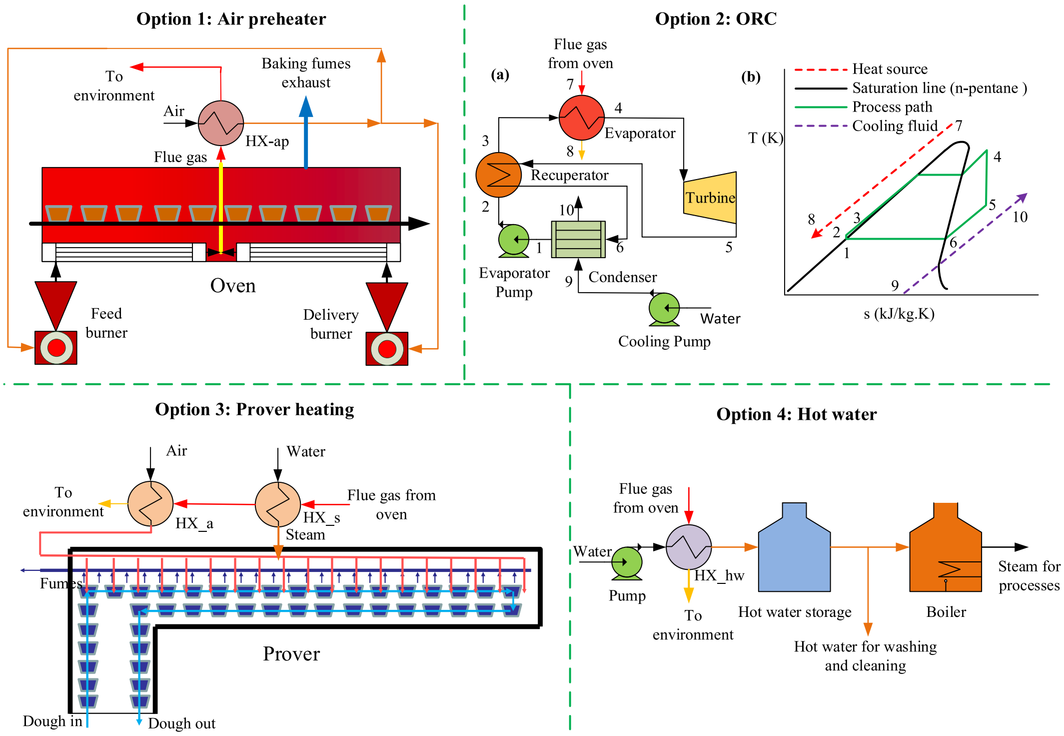

Fig. 4. Schematic diagram of waste heat recovery technology and their topologies in the commercial bakery plants. (Option 2: Recuperated Organic Rankine Cycle (ORC) configuration: (a) schematic design, (b) Temperature- Entropy (T–S) diagram).

efficiencies (η) for the baseline simulations are presented in Table 3. Based on the input data,the technical models were used to calculate the design point output parameters for heat exchangers, pumps, and turbines for different waste heat recovery options. The models were then integrated to estimate several output parameters including heat recovery potential, fuel or electricity savings, and power output. The design parameters such as heat exchange area and performance information such as the power input to pump and the power output from the turbine along with other technical parameters including pressure, temperature and fuel and electricity savings were fed to the economic model.

2.2.2. Economic model

The economic model of each option comprises of capital costs and operation and maintenance costs of individual and overall system components such as pumps, heat exchangers, turbines, etc. A set of correlations established by Turton et al. [32] for estimating equipment costs was used in this research. The investment models and corresponding coefficient values for different components are shown in Table 4. The economic models, developed in MATLAB environment, started with calculating the purchase cost of each equipment C_p assuming they were operating at ambient conditions and made of carbon steel. Then, it calculated the bare module cost (or actual cost) C_{BM} which includes all direct and indirect costs (e.g. transport, labour, installation, maintenance, piping, control management, etc.) and actual operating pressure and materials of the equipment [33].

Once we calculated the bare module cost which is based on the year 2001 [32], then we adjusted the cost for 2018 by taking into account inflation in Eq. (1). The CEPCI (Chemical Engineering Plant Cost Index) [34] is responsible for updating the cost index for inflation.

$$C_{BM,2018} = C_{BM,2001} \times \left(\frac{CEPCI_{2018}}{CEPCI_{2001}}\right), \tag{1}$$

where $C_{BM,2018}$ and $C_{BM,2001}$ are the bare module cost for the year 2018 and 2001, respectively. $CEPCI_{2018}$ and $CEPCI_{2001}$ are the cost index in 2018 and 2001 which are 603.1 and 397, respectively [35].

Total capital costs C_{cap,OP_x} for the investigated heat recovery options were calculated as follows:

$$C_{cap,OP_x} = \sum_{1}^{n} C_{BM,2018}, \tag{2}$$

where n is the number of components in each heat recovery option (for example in Option 2, the ORC has six components-see Table 3).

The total investment cost C_{IC,OP_x} for different options is the summation of capital cost and operation and maintenance cost:

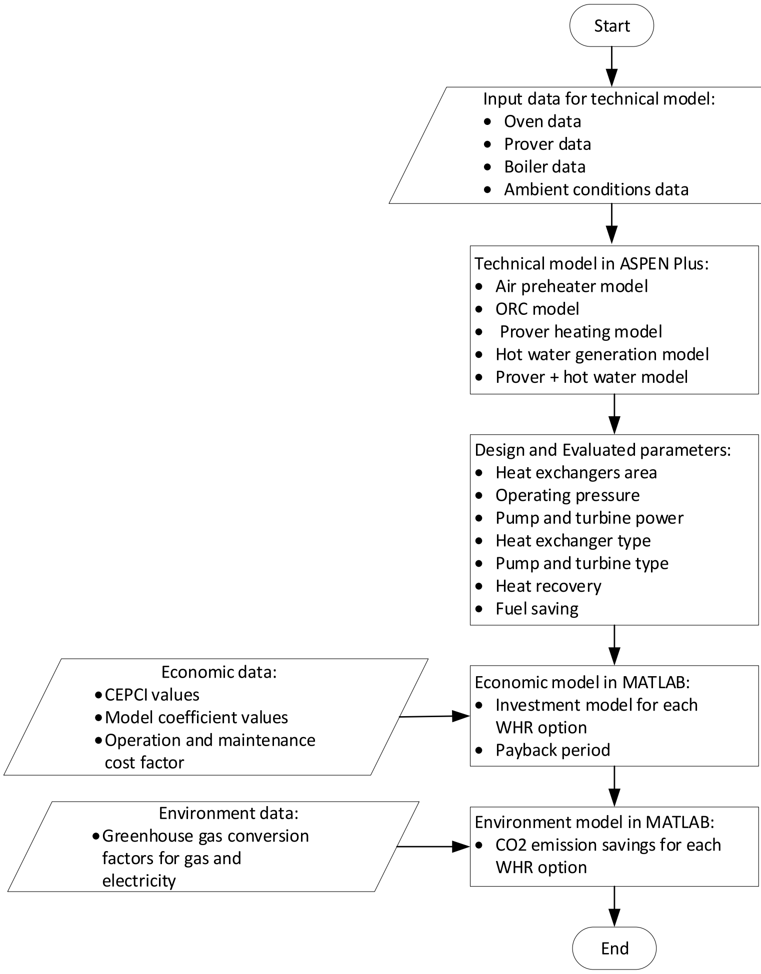

Fig. 5. Flowchart of the integrated techno-economic-environmental models.

Table 1
Energy relationship for each component for different waste heat recovery systems.

WHR options	Equations for component model	Subscripts
Air preheater		
Heater, HX-ap	$\dot{m}_{exh}(h_{exh,i} - h_{exh,o}) = \dot{m}_a(h_{a,o} - h_{a,i})$	*exh:* exhaust flue gas from oven;
ORC		*a* : air;
Pump	$W_p = \dot{m}_{wf}(h_{p,o} - h_{p,i}) = \dot{m}_{wf}(h_{p,o,is} - h_{p,i})/\eta_p$	*p*: pump;
Recuperator	$Q_{recp} = \dot{m}_{wf}(h_{recp,o} - h_{recp,i})$	*wf*: working fluid;
Evaporator	$Q_{evp} = \dot{m}_{wf}(h_{evp,o} - h_{evp,i})$	*is*: isentropic;
Expander	$W_T = \dot{m}_{wf}(h_{\exp,i} - h_{\exp,o}) = \dot{m}_{wf}(h_{\exp,i} - h_{\exp,o,i})/\eta_T$	*recp*: recuperator;
Condenser	$Q_{con} = \dot{m}_{wf}(h_{con,i} - h_{con,o})$	*evp*: evaporator;
Prover heater		*T*: turbine or expander; *con*: condenser;
Steam generator	$\dot{m}_{exh}(h_{exh,i,s} - h_{exh,o,s}) = \dot{m}_w(h_{w,o} - h_{w,i})$	*w*: water;
Air heater	$\dot{m}_{exh}(h_{exh,o,s} - h_{exh,o,a}) = \dot{m}_a(h_{a,o} - h_{a,i})$	*s*: steam.
Hot water		
Pump	$W_p = \dot{m}_w(h_{w,o} - h_{w,i})/\eta_p$	
Water heater	$\dot{m}_{exh}(h_{exh,i} - h_{exh,o}) = \dot{m}_w(h_{w,o} - h_{w,i})$	

$$C_{IC,OP_x} = C_{cap,OP_x} + \varphi \times C_{cap,OP_x}, \tag{3}$$

where φ is the operation and maintenance cost factor which was assumed to be 1.5 % of the total capital cost [36].

Finally, the payback period τ_{OP_x} was calculated based on the fuel or electricity savings ES_x and the total investment cost for each heat recovery option as follows:

Table 2
Oven waste heat and prover and boiler energy data.

Parameters	Values
Oven waste heat data	
Temperature (°C)	307.8 (average)
Flow rate (kg/s)	1.23
Pressure	Ambient @ 30 °C
Prover data	
Steam demand	60 kWth @ 105 °C and 1.2 bar
Gas demand	60 kWth
Boiler data	
Hot water demand	164 kWth @ 70 °C and 2 bar

Table 3
Design parameters for various WHR options.

WHR options	Design parameters (P = Pressure, T = Temperature, η = Efficiency)		
	Heat exchangers parameters	Pump parameters	Turbine parameters
Option 1: Air preheater for oven	P_{ap} = *ambient*		
1 heat exchanger	$T = 244^\circ C$		
Option 2: ORC	$P_{evp} = 30bar$	$P_{P,i} = 30bar$	$P_{T,i} = 30bar$
3 heat exchangers (evaporator, recuperator, and condenser); 2 pumps; 1 turbine	$P_{recp} = 30bar$	$P_{P,o} = 2bar$	$P_{T,o} = 2bar$
	$P_{con} = 2bar$	$P_{P,cp} = 2bar$	$\eta_T = 0.85$
	$T_{evp} = 215^\circ C$	$\eta_P = 0.80$	
Option 3: Prover heating	P_{air} = *ambient*		
2 heat exchangers (air and steam)	$P_s = 1.2bar$		
	$T_{air} = 40^\circ C$		
	$T_s = 105^\circ C$		
Option 4: Hot water	$T_{hw} = 70^\circ C$	$P_{hw} = 2bar$	
1 heat exchanger; 1 pump		$\eta_P = 0.80$	
Option 5: Prover heating + hot water	Prover:	$P_{hw} = 2bar$	
3 heat exchangers (air, steam, hot water); 1 pump	P_{air} = *ambient*, $P_s = 1.2bar$	$\eta_P = 0.80$	
	Hot water:		
	$T_{hw} = 70^\circ C$		

Table 4
Investment model of each component in the heat recovery integration options and their coefficient values (Ref. source [32]).

Components	Investment model	Coefficient values
Pump	$\log C_{p,P} = K_{1,P} + K_{2,P} \log W_P + K_{3,P}(\log W_P)^2$	For centrifugal pumps (carbon steel):
	$\log F_{p,P} = C_{1,P} + C_{2,P} \log P_P + C_{3,P}(\log P_P)^2$	$K_{1,P} = 3.3892$, $K_{2,P} = 0.0536$, $K_{3,P} = 0.1538$
	$F_{BM,P} = B_{1,P} + B_{2,P} F_{m,P} F_{p,P}$	$C_{1,P} = 0, C_{2,P} = 0, C_{3,P} = 0$ for P <10barg
	$C_{BM,P} = C_{p,P} \times F_{BM,P}$	$C_{1,P} = -0.3935, C_{2,P} = 0.3957, C_{3,P} = -0.00226$ for 10<P<100
		$B_{1,P} = 1.89$, $B_{2,P} = 1.35$, $F_{m,P} = 1.6$
Heat exchanger	$\log C_{p,HE} = K_{1,HE} + K_{2,HE} \log A_{HE} + K_{3,HE}(\log A_{HE})^2$	For double pipe heat exchanger (liquid to liquid, carbon steel)
	$\log F_{p,HE} = C_{1,HE} + C_{2,HE} \log P_{HE} + C_{3,HE}(\log P_{HE})^2$	$K_{1,HE} = 3.3444$, $K_{2,HE} = 0.2745, K_{3,HE} = -0.0472$
	$F_{BM,P} = B_{1,HE} + B_{2,HE} F_{m,HE} F_{p,HE}$	$C_{1,HE} = 0$, $C_{2,HE} = 0$, $C_{3,HE} = 0$ for P <40barg
	$C_{BM,HE} = C_{p,P} \times F_{BM,HE}$	$B_{1,HE} = 1.74$, $B_{2,HE} = 1.55$, $F_{m,HE} = 1$
		For spiral tube heat exchanger (gas to liquid/gas, carbon steel):
		$K_{1,HE} = 3.9912$, $K_{2,HE} = 0.0668, K_{3,HE} = 0.2430$
		$C_{1,HE} = 0$, $C_{2,HE} = 0$, $C_{3,HE} = 0$ for P <15barg
		$B_{1,HE} = 1.74$, $B_{2,HE} = 1.55$, $F_{m,HE} = 1$
Turbine (radial type)	$\log C_{p,T} = K_{1,T} + K_{2,T} \log W_T + K_{3,T}(\log W_T)^2$	$K_{1,T} = 2.2476, K_{2,T} = 1.4965, K_{3,T} = -0.1618$
	$C_{BM,T} = C_{p,T} \times F_{BM,T}$	$F_{BM,T} = 3.5$

$$\tau_{OP_x} = \frac{C_{IC,OP_x}}{ES_x}, \tag{4}$$

2.2.3. Environmental model

The environmental model evaluated the CO_2 emission saving ε_{CO_2e} from the UK government greenhouse gas conversion factors [37] and the amount of energy saving *ES* (either gas saving in kg or electricity saving in kWh) as follows:

$$\varepsilon_{CO_2e} = \upsilon_f \times ES, \tag{5}$$

where υ_f is the greenhouse gas conversion factor which was estimated by BEIS [37] that 1 kg of natural gas combustion causes to emit 2.54 kg CO_{2e} and 1 kWh of electricity generation at grid level emits 0.255 kg CO_{2e}.

3. Results and discussions

3.1. Base case analysis

The numerical models to assess the technical, economic and environmental impacts of different waste heat recovery options for a commercial bakery were simulated in the Aspen Plus and MATLAB environment. The output parameters, such as the area of the heat exchangers (A), turbine and pumps thermodynamic works (W) for the different heat recovery options are presented in Table 5. Heat exchangers areas and heat duties, and the pumps and turbine thermodynamic works are determined from the baseline simulations at design point conditions. These results were used in the economic and environmental models to assess the costs and emissions reductions of the selected technologies. The heat exchangers areas calculated from the baseline simulations and the design point parameters were fixed in the off-design calculations. Moreover, full load conditions were considered in the off-design conditions and as only the ambient temperature was varied, the turbomachinery efficiencies were assumed constant.

Results in Table 5 show that the heat exchanger sizes vary significantly, depending on the heating and pressure requirements of the simulated systems as well as the type of fluids used. For example, an air preheater with a preheating temperature of 244 °C needs a heat exchanger with a surface area of 4.81 m^2. On the other hand, an evaporator in the ORC option needs 9.06 m^2 heat transfer area for an evaporation temperature of 215 °C at a pressure of 30 bar. Condenser area requirement is the largest ($A = 12.48\ m^2$) among all the heat exchangers sized for different WHR options considered in this study. This is due to the large amount of cooling needed to cool the working fluid from the saturated vapour to the saturated liquid (see ORC T-S diagram in Fig. 4), which is essential for pumping the fluid back to the evaporator. Heat exchanger sizes for other WHR options are relatively smaller due to low heating temperature requirements for their intended use in either prover (for heating and steam it needs 40 °C and 105 °C) or for hot water production (temperature requirement is 70 °C). The ORC in the design mode could generate up to 61 kW of electricity from the waste heat provided by the Oven. Apart from the high working pressure in the ORC, all other WHR options are designed to be operated at ambient or near ambient pressure conditions. Low working pressure is desirable as the pump used in WHR systems consumes a small amount of electricity in these systems (see Table 5).

Table 6 shows the techno-economic performances of different WHR options considered in this research. Results show that the air preheater, ORC, and combined prover and hot water could recover the maximum amount of waste heat from an oven, which is around 285 kW. However, the energy or fuel saving from these options are significantly different from each other. For example, the air preheater could save up to 161.9 tonne/year of fuel if it was integrated with the oven. Combined prover and hot water could save slightly lower than the air preheater (149 tonne/year). The ORC, which converts heat into electricity, could generate around 429 MWh/year of electricity from the waste heat from the oven. Although ORC is among the largest heat recovery options found in this research, its annual cost saving is much lower than the air preheater and combined prover and hot water options (cost saving for ORC is $66k/year in compared to $93k/year for air preheater and $86k/year for combined prover and hot water). The reason for the lower cost saving in ORC is because of the low heat to work conversion efficiency, which was found to be around 21 % in this research. That means, it converted only 21 % of the recovered waste heat into electricity due to the thermodynamic limitation of the cycle, and the rest of the heat was lost during the conversion processes. It is worth noting that it was assumed in the simulation that the oven and the heat recovery systems were running 7500 h/year, which is normal in the commercial bakery industry. Prover heating and hot water production using the waste heat, could recover much less amount of waste heat and hence save much lower amount of fuel (120 tonne/year for prover heating and 164 tonne/year for hot water) as well as costs, as the requirement for heating in these sub-systems are much less than the former set of options. The investment costs are also different for each WHR option due to the size, number of components and working pressure of equipment used in each option. Results from Table 6 demonstrate that the hot water option requires the least investment costs, $65k, followed by the air preheater, $71k, Prover heater, $104k, combined prover heater and hot water, $173, and ORC, $304k. Although the air preheater is not the least expensive option, the payback period was found to be the

Table 5
Estimated parameters for various WHR options in base case scenarios.

WHR options	Estimated parameters (A = Area, W=Power)		
	Heat exchangers parameters	Pump parameters	Turbine parameters
Option 1: Air preheater for oven 1 heat exchanger	$A_{ap} = 4.81m^2$		
Option 2: ORC 3 heat exchangers (evaporator, recuperator, and condenser); 2 pumps; 1 turbine	$A_{evp} = 9.06m^2$ $A_{recp} = 1m^2$ $A_{con} = 12.48m^2$		$W_P = 2.68kW$, $W_T = 60.8kW$ $W_{cp} = 0.93kW$
Option 3: Prover heating 2 heat exchangers (air and steam)	$A_{air} = 0.33m^2$, $A_s = 0.38m^2$ $P_{air} = ambient$, $P_s = 1.2bar$ $T_{air} = 40^\circ C$, $T_s = 105^\circ C$		
Option 4: Hot water 1 heat exchanger; 1 pump	$A_{hw} = 0.96m^2$	$W_{p,hw} = 0.083kW$	
Option 5: Prover heating + hot water 3 heat exchangers (air, steam, hot water); 1 pump	Prover: $A_{pr,air} = 0.33m^2$, $A_{pr,s} = 0.38m^2$, Hot water: $A_{hw} = 1.78m^2$	$W_{p,hw} = 0.21kW$	

Table 6
Techno-economic performances of different waste heat recovery options in base cases.

WHR options (Integration options)	Heat recovery	Fuel or electricity[a] saving/ year		Investment cost (WHR options only)	Payback period
	kW	(tonne or MWh)	($/year[b])	($)	(years)
Option 1: Air preheater (Oven + Air preheater)	286	161.93 t	93,594	71,631	0.77
Option 2: ORC (Oven + ORC)	286	428.93 MWh	66,157	304,040	4.59
Option 3: Prover heating (Oven + Prover heating)	120	61.10 t	35,317	104,000	2.94
Option 4: Hot water (Oven + Hot water)	164	87.57 t	50,613	64,886	1.28
Option 5: Prover heating + hot water (Oven + Prover heating + Hot water)	284	148.85 t	86,032	172,810	2

Currency conversion rate 1 £ = 1.28 US$.
[a] gas price £0.029/kWh, **Electricity price £0.1205/kWh for medium sized industry (source BEIS [38]).
[b] Yearly operation time: 7500 h.

lowest (less than 1 year) due to its higher fuel savings. Hot water production option is also an attractive choice as it can return the investment cost in only 1.3 years. However, the drawback of this stand-alone option is that it cannot recover all the useable heat from the oven. The combined option of prover heating and hot water production at the same time could utilise most of the waste heat and return the investment within a reasonable time of 2 years. The ORC, on the other hand, has the highest payback period of 4.6 years. Together with low conversion efficiency, higher number of components and their costs, and high operating pressure (30 bar for ORC compared to other options at ambient or 2 bar (see Table 3)), affected the payback period of the ORC. Although the economic indicators suggest that the ORC is least preferable among other options, one must realise that the electricity generated from the ORC is of high-grade energy, compared to heat. Therefore, it is possible that the electricity generated on-site can bring more economic benefits by storing and reusing it during the peak time.

Fig. 6 illustrates the emission savings resulting from various WHR options considered in this study. It is obvious that the greater the extent of fuel savings achieved, the lower the associated CO_2 emissions. As anticipated, the air preheater not only stands out as the most economically viable choice but also offers the highest emission savings, thereby positioning it as the most environmentally friendly option. Specifically, the air preheater option is estimated to save approximately 412.5 tCO_2/year, surpassing the emission savings of 376.8 tCO_2/year offered by the combined prover heating and hot water option (option 5). The third best performer from an environmental point of view is the hot water production option, which can save 223.1 tCO_2/year followed by the stand-alone prover heating option which can save 153.90 tCO_2/year. In contrast, the ORC (option 2) lags behind with a relatively modest emission savings of 110.20 tCO_2/year. This is attributed to the fact that the ORC cycle also utilizes fuel in the conversion process, thereby contributing to CO_2 emissions.

From the technical-economic-environmental perspectives, the air preheater has the shortest payback period, the highest heat recovery potential and offers the most substantial reduction in emissions savings, making it the best option for the commercial bakery industry. Nonetheless, this study shows that integrating more than one option together (such as options 3 and 4) for waste heat recovery can bring more technical (higher heat recovery) and environmental (higher CO_2 saving) benefits, even though these options may not necessarily have the lowest payback periods due to higher investment costs. This implies that the combined heat recovery integration options will have more benefits in the longer term than that of a single integration option.

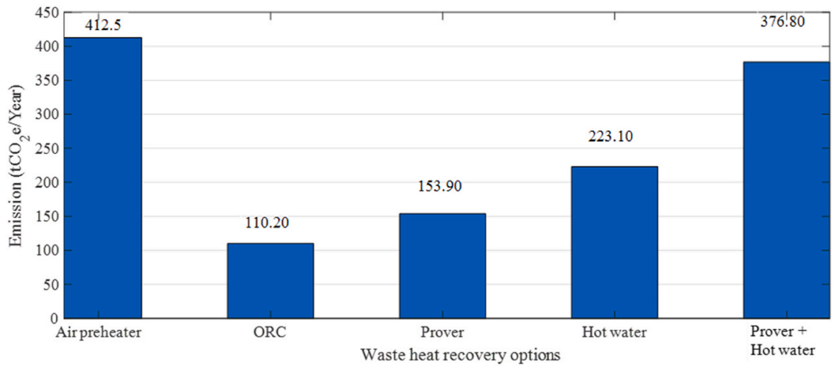

Fig. 6. Emission savings with different waste heat recovery options.

3.2. Design sensitivity

In this section the effect of ambient temperature on the heat recovery, fuel saving, carbon emission and the payback period has been evaluated for the air preheater, ORC, prover, hot water, and a combined prover and hot water systems. The ambient temperature is varied from 0 °C to 30 °C to investigate its impact on the performance of the chosen technologies in the design mode.

3.2.1. Change in environment temperature

Figs. 7 and 8 show the excess heat available after the recovery and the percentage of waste heat recovered for the range of ambient temperatures between 0 °C and 30 °C. Results show that the air-preheater and ORC systems can utilise all the waste heat available at any ambient temperature within this range. Whereas a linear decrease in the waste heat recovery is observed for the prover, hot water and a combined prover and hot water system when the ambient temperature is varied from 0 °C to 30 °C. At lower ambient temperatures, the available waste heat is less than the required amount for the combined prover and hot water system and therefore all the waste heat is recuperated up to a temperature of about 15 °C. However, a steep increase in the excess waste heat is observed in the case of combined prover and hot water system when the ambient temperature increases, reaching a value of 83 kW at 30 °C, recuperating only 71 % of the waste heat. Similarly, at 0 °C an excess heat of 129 kW and 79 kW is available in the case of prover and hot water systems which linearly increases to a value of 203 kW and 166 kW at 30 °C, respectively. Thus, a decrease of 47.5 % and 41.9 % in the recuperated heat is observed in the case of prover and hot water systems, respectively.

Fig. 9 shows the impact of ambient temperature on fuel saving considering different heat recovery technologies. The maximum fuel saving is achieved in the case of air-preheating whereas minimum fuel saving is observed in the case of prover. The air preheating and ORC systems can recuperate all the waste heat, therefore a maximum of 21.6 kg/h fuel (gas) saving can be achieved in the case of air-preheating whereas an electricity saving of 57.2 kWh is achieved in the case of ORC system. The combined prover and hot water system is able to recuperate all the waste heat at lower ambient temperatures therefore a maximum fuel saving of 19.8 kg/h is realised up to an ambient temperature of 15 °C and thereafter a linear decrease in the fuel saving is observed, reaching a minimum value of 14.3 kg/h at a temperature of 30 °C. In the case of prover and hot water systems, the fuel saving linearly decreases from 10.6 kg/s and 14.9 kg/h at 0 °C to a value of 5.7 kg/h and 8.5 kg/h at 30 °C, respectively.

As expected, the carbon emission savings in the case of all proposed heat recovery technologies show a similar trend to that of fuel saving. As fuel combustion directly leads to carbon emissions, higher fuel saving will consequently lead to lower carbon emissions. Again, a maximum emission savings at a steady rate of 54.8 kg (CO_2)/h is achieved in the case of air-preheater whereas a minimum emission savings at a steady rate of 14.6 kg (CO_2)/h is noticed in the case of ORC system (as shown in Fig. 10). This is because of the

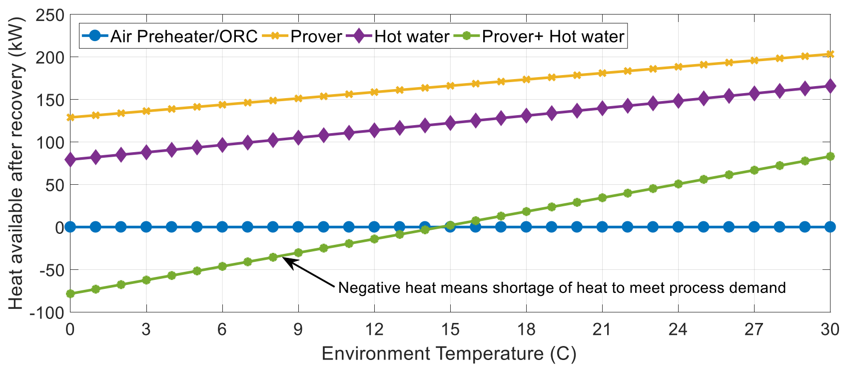

Fig. 7. Post-recovery excess heat at various design temperatures.

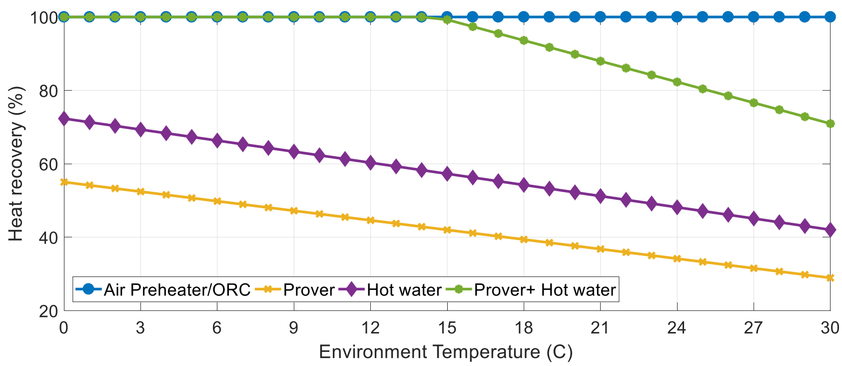

Fig. 8. Heat recovery using selected technologies at various design temperatures.

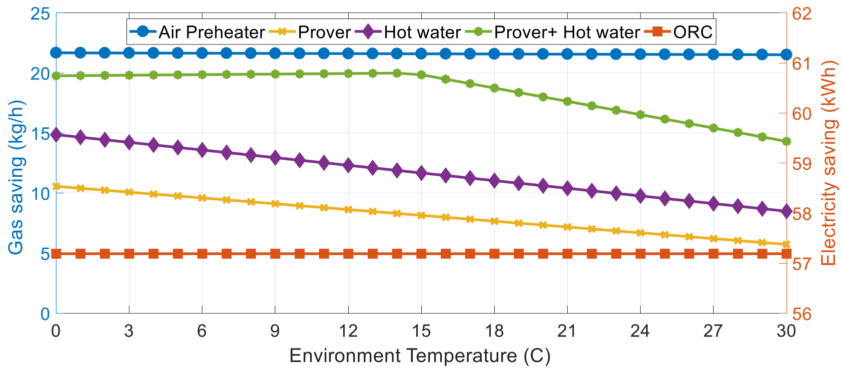

Fig. 9. Fuel savings using selected technologies at various design temperatures.

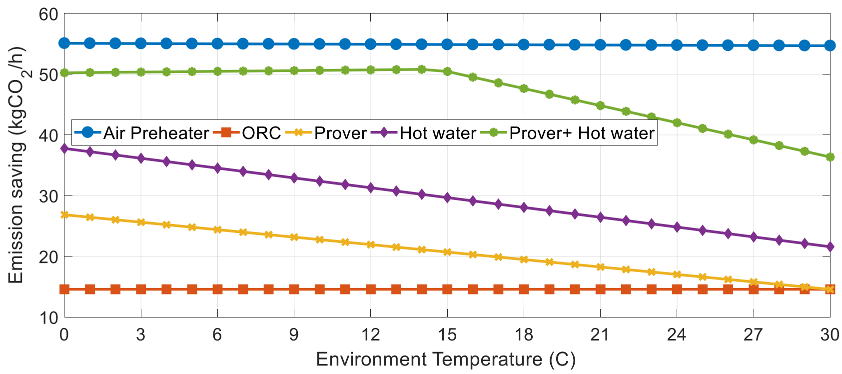

Fig. 10. Emission savings using selected technologies at various design temperatures.

fact that more fuel is required to drive the ORC cycle in addition to the available waste heat, and therefore its contribution to carbon emission is high. Fig. 10 shows that the carbon emission savings in the case of prover and hot water systems linearly decreases by 45.8 % and 42.9 %, respectively, when the ambient temperature increases from 0 °C to 30 °C. This is because of the lower waste heat recovery and consequently less fuel savings in the case of hot water and prover at higher ambient temperatures.

While both the air-preheater and ORC systems are capable of recovering all available waste heat, their payback periods differ significantly. The payback period is lowest for the air-preheater, attributed to its lower capital cost compared to the ORC system. Interestingly the payback period of the combined prover and hot water system is lower than the only prover system which is because of the higher heat recovery capability of the combined prover and hot water system. Moreover, it can be noticed in Fig. 11 that the effect of ambient temperature is negligible on the payback period at lower temperatures for all the heat recovery technologies. However, at higher temperatures the payback period increases especially for the prover and ORC cases. In the case of the ORC system, the higher payback period at 27 °C and above is because of the lower condenser efficiency of the ORC system which leads to a lower efficiency of the overall cycle, hence lower power generation and higher payback period. At an ambient temperature of 18 °C, the payback period

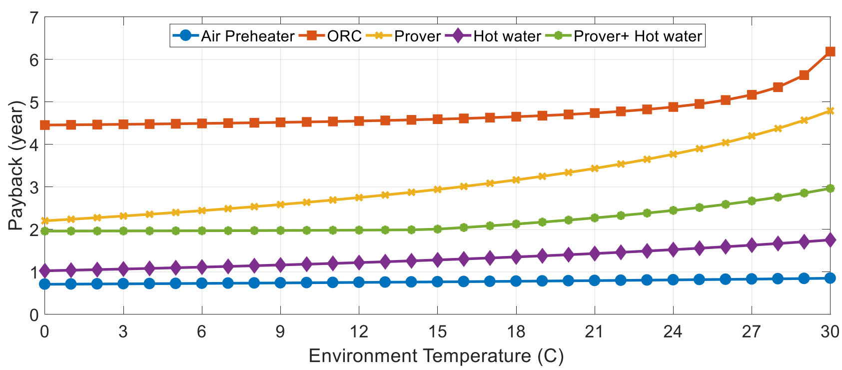

Fig. 11. Payback period of selected technologies for waste heat recovery in bakeries at various design temperatures.

for air-preheater, only hot water system, combined prover and hot water system, prover, and ORC system was estimated to be 0.78, 1.35, 2.13, 3.17, and 4.65 years, respectively, and an increase of 9 %, 30 %, 40 %, 50 %, and 33 %, respectively, was noticed when the ambient temperature was increased to 30 °C.

3.3. *Off-design sensitivity*

In this section the influence of selected environment temperatures on the performance of air preheater, ORC, prover, hot water and the combined prover and hot water systems are investigated in the off-design mode. The environment temperature was varied in the range of 0–30 °C with a temperature interval of 5 °C.

3.3.1. *Performance variation against fixed component size*

3.3.1.1. Air preheater. The off-design performance of the air preheater option for the selected environment temperatures is represented in Fig. 12. As it is seen, the air preheater option utilizes the maximum heat of 282.3 kW at the environment temperature of 0 °C, the results show that the performance of the system negligibly changes in the environment temperature range of 0–15 °C. However, the performance of the system changes for the environment temperatures beyond 15 °C, where a maximum reduction of 5% in the performance of the system occurs at the environment temperature of 30 °C. The amount of the utilized heat by the system decreases by increasing the environment temperature in the off-design mode, hence the reduction of fuel and emission savings at higher environment temperatures.

3.3.1.2. ORC. Fig. 13 represents the effects of environment temperature on the selected parameters in off-design mode for the ORC system. It can be seen that the ORC system exhibits complete waste heat recovery across the entire range of environmental temperatures. The other parameters of the study including the net output work, the electricity saving, and the emission saving are almost uniform for the environment temperature $\geq 15^{\circ}C$, while they experience small changes at lower environment temperatures. It's important to highlight that despite the comprehensive utilization of waste heat by the ORC system, the net-work achieved across the entire temperature range is approximately 57 kW, yielding an efficiency of around 21 %. This efficiency value is relatively low due to inherent thermodynamic limitations of the ORC cycle. The working fluid is a crucial parameter that affects the overall efficiency of the system. The proper selection of the working fluid is greatly dependent on the temperature of the waste heat because the thermodynamic efficiency of the ORC system increases by increasing the temperature of the waste heat based on the Carnot cycle. Therefore, the working fluid with higher critical temperature is preferred for the waste heats with higher temperature to enhance the thermodynamic efficiency of the system. The critical temperature of n-pentane is 196.45 °C which is lower than the temperature of waste heat from the

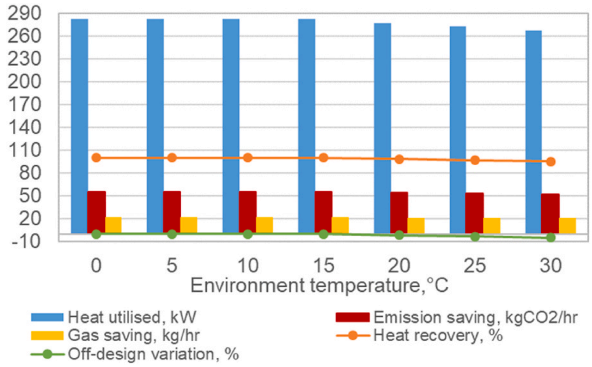

Fig. 12. Off-design performance of air preheating option at various ambient temperatures.

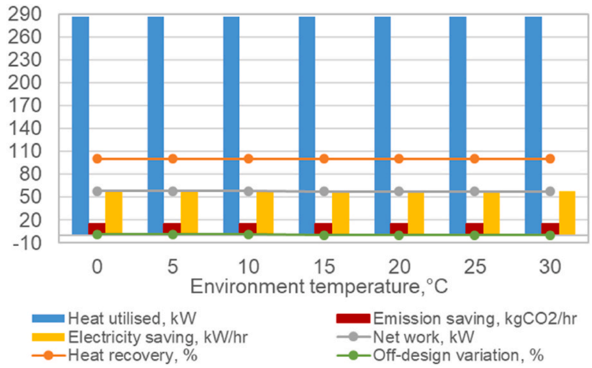

Fig. 13. Off-design performance of ORC option at various ambient temperatures.

oven which is 307.8 °C, therefore, selecting working fluid with critical temperature closer to the temperature of waste heat from oven can be helpful to increase the electricity production using the ORC system. Unlike the air preheater option, the ORC system demonstrates remarkable temperature independence, maintaining consistent performance beyond 15 °C ambient temperatures.

3.3.1.3. Prover. Fig. 14 shows the performance of the prover system in off-design mode in terms of the heat recovery, the utilized heat and the gas/emission savings parameters at different environment temperatures. As it can be seen, the waste heat is not sufficient to meet the process demand for the environment temperature range of 0–10 °C for the prover option. The performance of the system decreases by about 22.25 % in terms of the heat utilization for process demand at an ambient temperature of 0 °C. Although, the fuel and emission savings at this temperature is about 48 % more than the corresponding values at the maximum environment temperature. The lower temperature demand in the prover option allow smaller heat recovery in comparison with the other heat recovery options.

3.3.1.4. Hot water. Fig. 15 depicts the performance of the hot water option in off-design mode in terms of the heat recovery, the utilized heat, and gas/emission savings at different environment temperatures. Similar to the prover option, the waste heat is not sufficient to meet the process demand for the environment temperature range of 0–10 °C for the hot water option. The performance of the system reduces by about 18.31 % in terms of the utilizing heat for the process demand at an ambient temperature of 0 °C. Although the heat recovery for the hot water option is higher in this environment temperature range compared to the prover option as the hot water temperature demand is higher. The fuel and emission savings for the hot water option is averagely enhanced by about 39 % compared to the prover option as can be seen in Figs. 14 and 15.

3.3.1.5. Combined prover and hot water. Fig. 16 illustrates the performance of combined hot water and prover options in off-design mode in terms of the heat recovery, the utilized heat and the gas/emission savings parameters at different environment temperatures. Although similar to both the individual prover and hot water options, the waste heat is not enough to meet the process demand for the ambient temperature range of 0–10 °C, the heat recovery for the combined system is considerably enhanced compared to prover or hot water options. The higher heat recovery capacity of the combined system translates into notable gains in fuel savings and emission reduction. On average, the combined system exhibits an impressive 138.3 % increase in fuel savings and a 71.5 % increase in emission reductions when compared to the prover and hot water options separately. The emission savings offered by the combined system are on par with the values attained by the air preheating option, making it as the second-best option, followed by hot water, prover and ORC options. The lower contribution of the ORC system to emission reduction can be attributed to its increased fuel consumption required to operate the ORC.

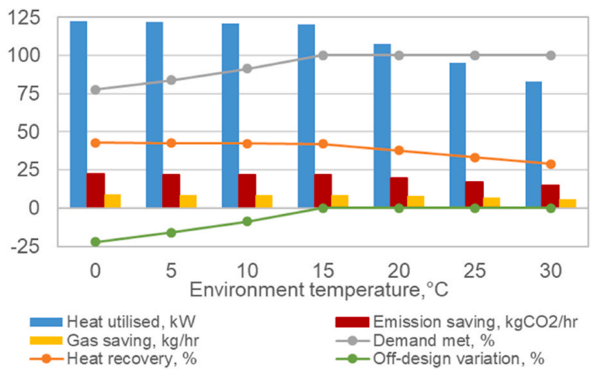

Fig. 14. Off-design performance of Prover option at various ambient temperatures.

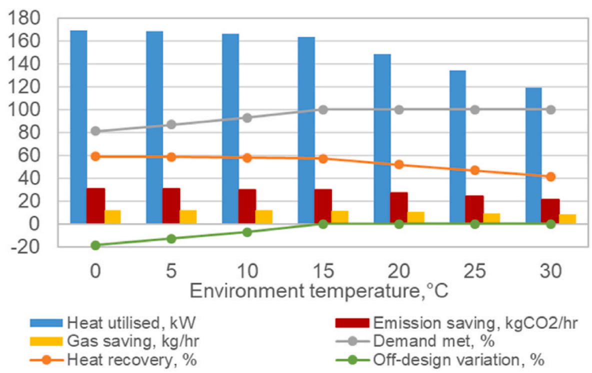

Fig. 15. Off-design performance of hot water option at various ambient temperatures.

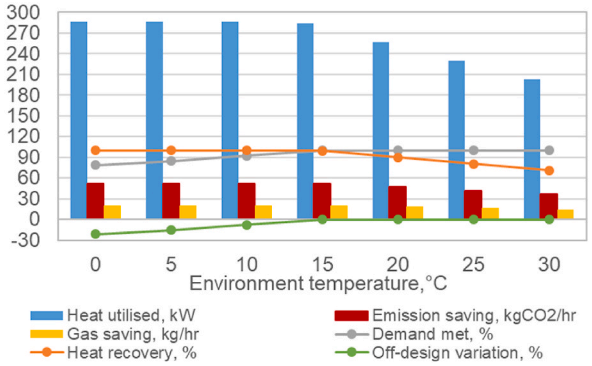

Fig. 16. Off-design performance of combined prover and hot water option at various ambient temperatures.

3.3.2. Oven operation time variation

This section provides an overview of the performance of waste heat recovery technologies, taking into account variations in oven operation time (operational hours per annum). As in actual scenario, the oven operational time can fluctuate due to factors such as end-product requirements, maintenance, equipment faults, and lockdowns. Consequently, the benefits of chosen waste heat recovery options are subject to variability. Fig. 17 shows a linear correlation between cost savings and oven operation time, ranging from 3500 h to 8500 h annually, across all waste heat recovery technologies. Moreover, the higher cost savings is pivotal in reducing the payback period which reduces proportionally when the operation time of the oven increases as demonstrated in Fig. 18. It can be noticed from the results that doubling the operation time can lead to a two-fold increase in the cost savings and a 50 % reduction in the payback period for all the waste heat recovery technologies studied in this paper. This emphasises the significant financial advantages and rapid return on investment potential associated with extending oven operation hours.

A similar trend is observed in the case of carbon emission savings where increasing the operation time results in a linear increase in the carbon emission savings. As expected, during longer operation more fuel saving is possible as a result of heat recovery technologies which consequently helps in lower carbon emissions. Fig. 19 depicts that a two-fold increase in the carbon emission savings can be

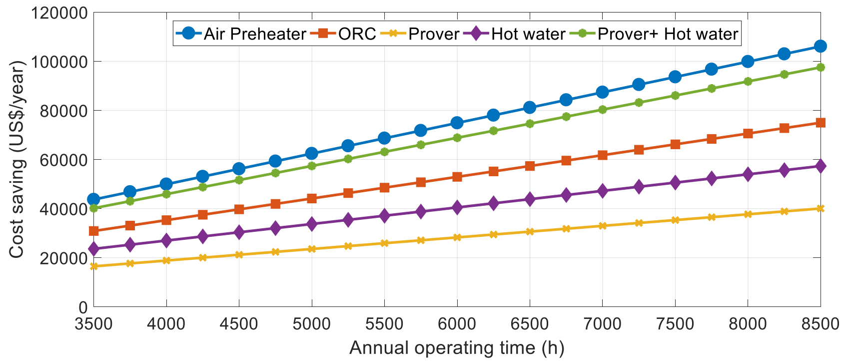

Fig. 17. Change in annual cost savings of the selected waste heat recovery technologies with respect to change in annual operating hours.

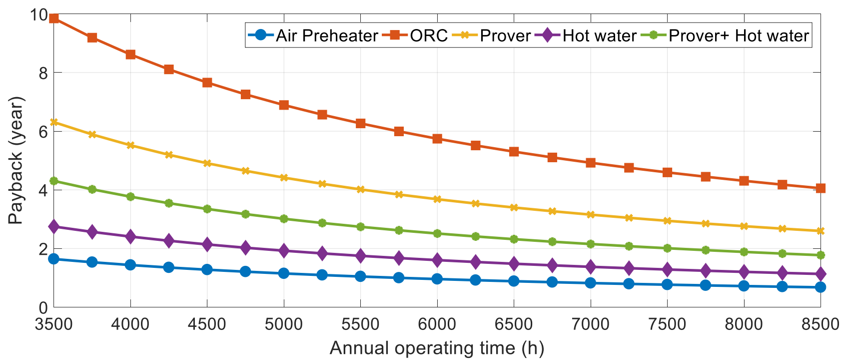

Fig. 18. Change in payback period of the selected waste heat recovery technologies with respect to change in annual operating hours.

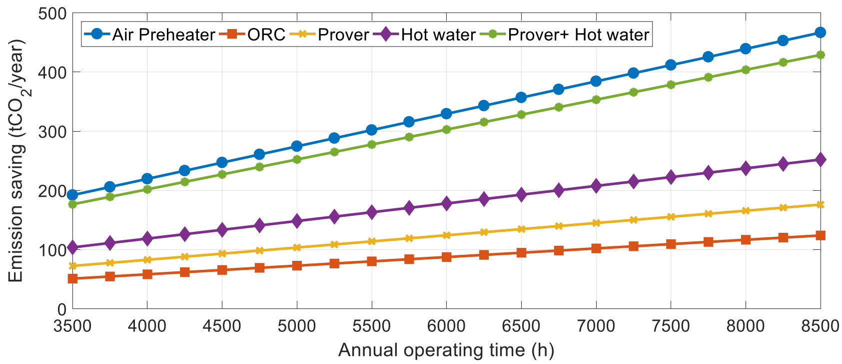

Fig. 19. Change in annual emission savings of the selected waste heat recovery technologies with respect to change in annual operating hours.

achieved when the oven operation time is doubled. Result shows that a maximum of 466, 429, 252, 176, and 124 tons of carbon emission savings is achievable in a year when either air-preheater, combined prover and hot water system, only hot water system, prover, or ORC system, respectively, is integrated into a bakery oven which operates for 8500 h in a year. As discussed in the previous sections, these findings clearly indicate that the greater the extent of waste heat recovery, the higher the resulting emission savings. As air-preheater can recover higher amount of waste heat compared to other options, the resulting emissions savings are also higher.

3.3.3. Fuel price variation

In the previous sections, the analyses were carried out assuming the baseline value of fuel cost in all scenarios throughout the life period. However, in the actual scenario the fuel cost is a variable that can increase or decrease depending on the international market. This section evaluates the impact of fuel cost on the cost saving and payback period considering higher and lower values of fuel cost with respect to the baseline value.

A higher fuel cost can lead to a higher cost saving when a waste heat recovery technology is implemented as it helps in reducing fuel consumption by recuperating the waste heat. Fig. 20 shows a linear increase in the cost saving for all the heat recovery options when the fuel cost is increased. In addition, it can be noticed that the maximum cost saving is achievable in the case of air-preheating as it can recuperate all the waste heat available. Though the ORC system is capable of recovering all waste heat, it requires additional fuel to operate, which can negatively impact overall cost savings, and hence a lower value of cost saving is achieved in the case of ORC compared to air preheating. Moreover, the fuel and electricity prices also play a critical role in dictating the cost savings. Results show that the cost saving increases by a factor of 3 in all the studied cases when the fuel cost increases from a 50 % baseline value to 150 % baseline value. Moreover, the fuel cost impact can also be seen on the payback period which reduces when the fuel cost increases as a result of higher cost savings. Fig. 21 shows that the payback period decreases at a steeper rate below the baseline fuel cost because at lower fuel cost, the capital cost of the heat recovery technology is the dominant factor. Results reveal a consistent threefold reduction in the payback period across all studied cases as fuel costs escalate from 50 % to 150 % of the baseline value.

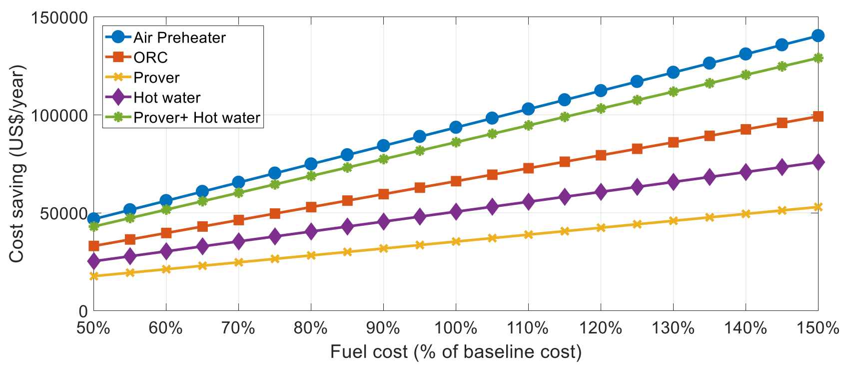

Fig. 20. Change in annual cost savings using the selected waste heat recovery technologies with respect to change in fuel cost.

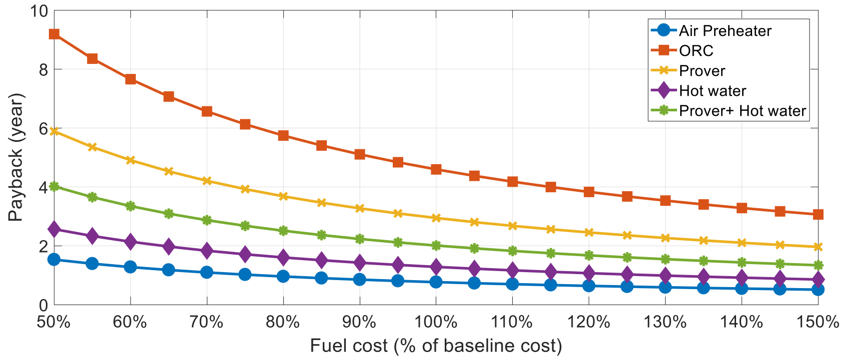

Fig. 21. Change in payback period of the selected waste heat recovery technologies with respect to change in fuel cost.

4. Conclusions

This paper investigates the potential of waste heat recovery in commercial bakeries, which is one of the heat intensive sectors within the food and drink industry that uses an extensive amount of natural gas, primarily in ovens and some in the provers. Five different waste heat recovery integration options, including, (1) air preheating for the oven combustors; (2) electricity generation via the organic Rankine cycle; (3) prover heating; (4) hot water; and (5) combined prover and hot water were considered and their heat recovery performance, cost savings and emission reduction were assessed at both design and off-design conditions. The following conclusion is drawn from the results.

- Air pre-heater and ORC systems can offer 100 % waste heat recovery for a range of design point ambient temperatures, whereas the least amount of waste heat was recovered in the case of prover only option. However, designing a system to recover waste heat through both the prover and hot water options can increase the amount of total heat recovered.
- Air pre-heating option can account for 21.5 kg/h of gas saving, maximum amongst the other options, whereas 57.2 kWh of electricity can be saved in the case of ORC system.
- Maximum emission savings of approximately 55 $kgCO_{2\ e}$/h can be achieved in the case of air pre-heating compared to other options, with the least emission savings of approximately 15 $kgCO_{2\ e}$/h observed in the case of ORC.
- The earliest payback period of 0.77 years was estimated for the air preheater option whereas a maximum payback period of 4.59 years was estimated for the organic Rankine cycle at a design point ambient temperature of 15 °C.
- The maximum off-design variation of 22 % was observed in the case of prover, whereas the ORC system showed negligible variation in off-design mode compared to the corresponding ambient condition in design mode.

This study provides essential results for integrating an appropriate technology for waste heat recovery in the commercial bakeries sector. The analysis leads to the conclusion that air preheating is the most energy efficient method for the waste heat recovery in the bakery industry. It not only maximises waste heat recovery, but also proves to be a cost-effective solution with a minimal payback period. However, it is worth to note that the techno-economic-environmental indicators presented in this study are sensitive to change in operating conditions of different heat recovery options, variations in waste heat output from the ovens, shifts in operational schedules, and fluctuations in fuel and electricity costs.

CRediT authorship contribution statement

Jahedul Islam Chowdhury: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft.
Faisal Asfand: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.
Mohammad Ja'fari: Writing – review & editing.
Sanjay Mukherjee: Methodology, Formal analysis.
Nazmiye Balta-Ozkan: Project administration, Funding acquisition.

Declaration of competing interest

The authors 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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2023.103714.

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