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Article

Techno-Economic Assessment of Waste Heat Recovery Technologies for the Food Processing Industry †

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Abstract: The food manufacturing sector is one of the most dominant consumers of energy across the globe. Food processing methods such as drying, baking, frying, malting, roasting, etc. rely heavily on the heat released from burning fossil fuels, mainly natural gas or propane. Less than half of this heat contributes to the actual processing of the product and the remaining is released to the surroundings as waste heat, primarily through exhaust gases at 150 to 250 °C. Recovering this waste heat can deliver significant fuel, cost and CO_2 savings. However, selecting an appropriate sink for this waste heat is challenging due to the relatively low source temperature. This study investigates a novel application of gas-to-air low temperature waste heat recovery technology for a confectionary manufacturing process, through a range of experiments. The recovered heat is used to preheat a baking oven's combustion air at inlet before it enters the fuel-air mixture. The investigated technology is compared with other waste heat recovery schemes involving Regenerative Organic Rankine Cycles (RORC), Vapour Absorption Refrigeration (VAR) and hot water production. The findings indicate that utilising an oven's exhaust gases to preheat combustion air can deliver up to 33% fuel savings, provided a sufficiently large heat sink in the form of oven combustion air is available. Due to a lower investment cost, the technology also offers a payback period of only 1.57 years, which makes it financially attractive when compared to others. The studied waste heat recovery technologies can deliver a CO_2 savings of 28–356 tonnes per year from a single manufacturing site. The modelling and comparison methodology, observations and outcomes of this study can be extended to a variety of low temperature food manufacturing processes.

Keywords: waste heat recovery; baking; energy efficiency; food manufacturing; organic rankine cycle; vapour absorption cooling

1. Introduction

The food and drink sector involving processing, packaging, transportation, retail, consumption and disposal is heavily reliant on fossil fuel consumption, thereby making it one of the largest consumers of fossil fuels worldwide [1–4]. In the EU, the food sector accounted for 17% of the gross energy consumption in 2013, and around 79% of that energy came from fossil fuels [5]. A study on the US food system reported 13.8% energy consumption by the food sector of the total in the country from 2000 to 2010 [6]. It also indicated an average growth of 34% in energy consumption of the US food system in the last 60 years. With the rapid increase in the world population and consequent rising food demands, the energy consumption in the food manufacturing sector is expected to continue to rise in the future [3,7–9]. A study conducted by Paolo et al. [10] showed a 3- and 2.5-fold increase in global crop and animal production, respectively, in the past 50 years. The processing/manufacturing phase in the food chain has considerably higher fossil fuel consumption rates [11]. In the UK, the food and drink manufacturing sector consumed 60.5 TWh of energy compared to 12 TWh by agriculture and 12 TWh by retail in 2011 [12]. An article published by the European Commission [5] reported that 6.6 GJ of energy was consumed by the processing phase alone in the EU, which is 28% of the total energy consumption by the entire food chain.

The processing phase consists of food manufacturing operations such as baking, drying, frying, roasting, general heating, etc. These manufacturing processes rely on the direct heat released from burning fossil fuels, usually natural gas or propane, in specially designed equipment. A proportion of the heat supplied to these ovens contributes to the actual product processing and the rest is vented to the surrounding area with the exhaust gases as waste heat at 150 to 250 °C. In the UK alone, the food and drink manufacturing sector releases circa 2.8 TWh of recoverable waste heat into the atmosphere, annually [13]. Increasing the energy efficiency of modern manufacturing machinery by design improvement is extremely challenging, as it may already be operating at high efficiency according to the original design. However, an alternative option is to capture and recycle the waste heat back into the system to reduce the overall energy footprint of the manufacturing site. It is estimated that recovering waste heat from the UK food and drink manufacturing sector can potentially save £70 million and 500,000 tonnes of CO_2 emissions, annually [13]. In order to realise this huge opportunity for energy efficiency and carbon reduction, the Department for Business, Energy and Industrial Strategy (BEIS) of the UK government has launched several ambitious grant programmes for industry such the £18 million Industrial Heat Recovery Support (IHRS) [14] programme in 2018 and £315 million Industrial Energy Transformation Fund (IETF) [15] in 2020, especially targeting waste heat recovery from industrial processes.

Many mature technologies for waste heat recovery and utilisation are commercially available on the market, such as the Organic Rankine Cycle (ORC), to convert waste heat into electricity, Vapour Absorption Refrigeration (VAR), to produce a cooling effect, production of hot water or steam through an economiser, pre-heating combustion air through a recuperator and pre-heating the feedstock using a regenerator. Numerous studies on the application of ORC and VAR for waste heat recovery are available [16–28] in various industrial sectors. A few studies comparing ORC with VAR are available [29]. However, there is little information on the process of systematically selecting the best technical and economic solution from all the choices available, especially in food manufacturing processes where the waste heat leaves through the exhaust air at relatively low temperatures [29–31]. The quantity and quality of heat source available from a food manufacturing process determine the design operating conditions for ORC and VAR systems and have a direct influence on their performances. Therefore, the existing ORC and VAR models in the literature cannot be directly used for estimating their techno-economic feasibility against any other waste heat recovery solution such as combustion air preheating for food manufacturing processes. Additionally, the option of air-to-air heat recovery has not been adequately explored, especially for the food industry. Although the air-to-air heat recovery technology is fairly established for power generation cycles where the temperatures are comparatively higher, it is essential to assess its suitability for industrial baking, as the baking mechanism, machinery and conditions are different [32–36].

The focus of this work is not on the development of new technology or improving existing technology. Rather, the focus is on the development of a systematic approach for determining the best heat recovery solution based on technical, environmental and economic considerations. This work develops a systematic methodology for comparing various low grade waste heat recovery solutions for the industrial baking process based on fuel savings, operational cost savings, CO_2 savings and return on investment (ROI) using analytical and numerical models. It also carries out actual design, development and experimental testing of a novel low-grade gas-to-gas waste heat recovery solution for the baking sector for pre-heating the combustion air. The recovered waste heat from an industrial-scale baking oven at a UK-based confectionary manufacturing site was recycled to pre-heat the oven's combustion air. These experimental results were compared with analytical and modelling results for other heat recovery technologies mentioned above to develop the methodology of arriving at the most rewarding solution for heat recovery.

Not only the baking industry, but a variety of similar low temperature and energy-intensive food manufacturing processes can benefit from the observations and findings presented in this work.

2. Methodology

Six different types of waste heat recovery solution involving direct fuel/gas saving, electricity generation, cooling and hot water production have been investigated through modelling and experiments. A detailed description of the industrial baking machinery used for analysis is given in Section 2.1. A gas-to-gas low-grade waste heat recovery technology to preheat oven's combustion air using heat from exhaust gases was designed, developed and tested through experiments and modelling. Its performance was compared with other existing waste heat recovery technologies, ORC, VAR and gas-to-liquid heat recovery. Simulation models for ORC, VAR and gas-to-liquid heat recovery technologies were developed using experimentally derived inputs and existing literature. Sections 2.2–2.6 describe the experimental, modelling and techno-economic assessment methodology followed for the comparisons.

2.1. Baking Oven

A fully automatic wafer baking oven, shown in Figure 1, producing flat rectangular wafer sheets, was used for the experiments and analysis. A mixture of water, flour and flavouring ingredients was used to prepare the batter, which was then poured onto the baking plates fixed in tong frames. The tongs are fixed with graphite bearings and are revolved across the length of the oven using long chain drive powered by a 5 kW electric motor. The baking plates are heated to the desired temperatures as they are transported through the oven by burning a mixture of natural gas and ambient air (also called combustion or primary air) in the triangular burners located below the tong chains. The baking plate surface temperature, measured using a pyrometer, regulates the burner blower frequency and the fuel-air mix flow through a Zero Pressure Regulator.

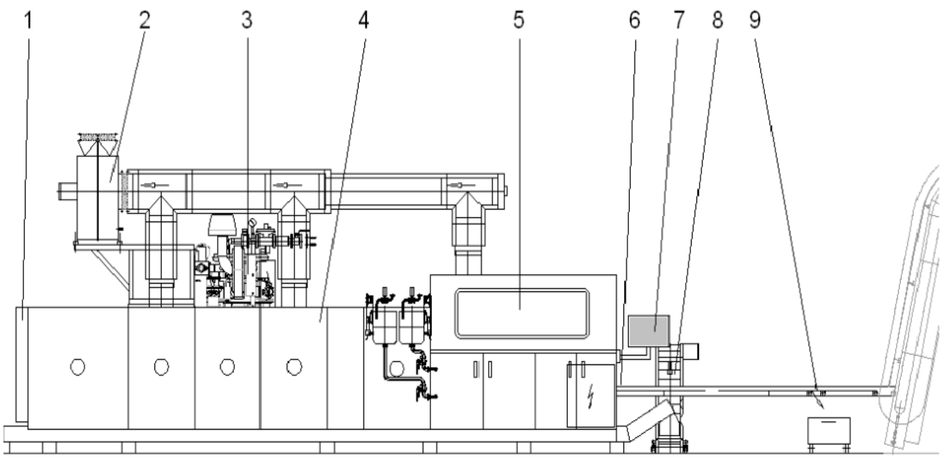

Figure 1. Schematic of a pilot-scale wafer baking oven highlighting the key components of the oven [37].

The Automatic Wafer Baking Machine consists of: 1. Service door. 2. Emission extraction unit. 3. Burner device. 4. Baking space. 5. Batter depositing station. 6. Wafer take-off station. 7. Control pane. 8. Waste scraper. 9. Wafer inspection device.

The batter is baked into wafer sheets in one revolution. These wafer sheets are carefully collected in the wafer sheet take-off station and sent to the processing line. The oven is also supplied with a cooling or secondary air flow through the sidewalls to protect the bearings from any damage resulting from overheating. The products of combustion, cooling air and moisture from the batter are extracted using an extractor fan operating at 40 Hz (1160 rpm). The fan speed is monitored using a differential pressure control device. The overall exhaust gases from the oven are vented through a rooftop exhaust duct. The temperature of the exhaust gases could vary from 130–205 °C depending on the batter recipe, oven design, ambient conditions, operative regime, fuel used, etc. The heat lost in the exhaust gas is not used in any other process downstream and is, hence, considered waste heat. The performance of the wafer baking oven is measured in terms of fuel consumption to produce the unit weight of the wafer product. This is also known as the oven productivity and is determined by Equation (1):

$$\mu_{baking} = \frac{\dot{Q}_{fuel}}{\dot{\omega}_{wafer}} \tag{1}$$

where $\dot{Q}_{fuel}$ is the energy supplied (in kWh) to the oven over a unit time and $\dot{\omega}_{wafer}$ is the wafer produced (in kilograms) in the same amount of time.

2.2. Combustion Air Preheating Experiments

The effect of combustion air temperature on the overall oven performance was determined through conducting a series of experiments on pilot-scale baking oven, which is a scaled-down version of the industrial oven explained in Section 2.1. At normal operating regime, combustion air is taken directly from inside the factory building, which is at around 30 °C, and is supplied to the oven's fuel-air mixer. However, in the preheating experiments, the combustion air supply was gradually heated up to 105 °C using a 25 kW electric resistance heater, shown in Figure 2a, to replicate the heat exchange with hot air recovered from the oven. In an actual heat recovery system, the combustion air will be preheated using the oven's hot exhaust gases through a gas-to-gas heat exchanger. A bespoke control system, shown in Figure 2b, was installed to control the electric heater, and hence, the combustion air temperature. The control system provides the upper limit cut out for the electric heater and ensures safe limits for differential pressure sensing for the extractor fan. The selection of the resistance heater was based on the design parameters shown in Table 1.

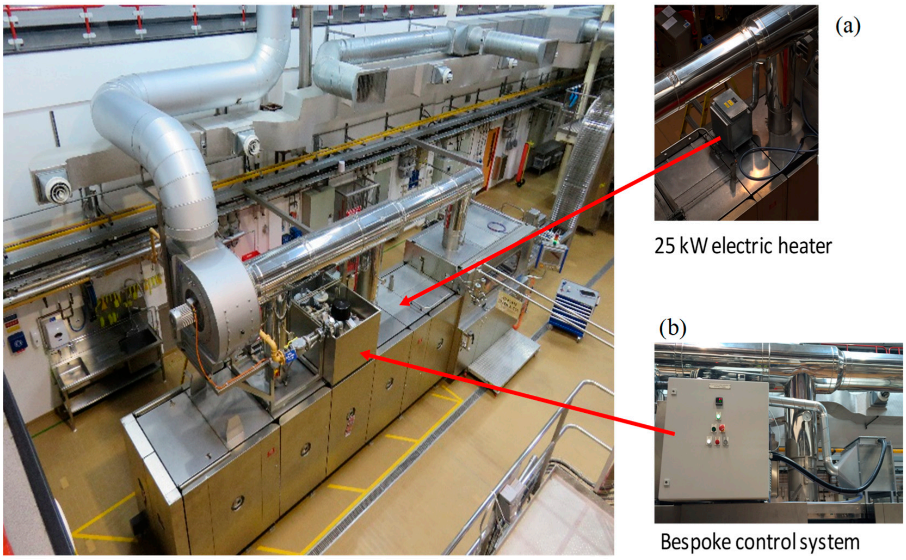

Figure 2. The pilot-scale baking oven with retrofitted bespoke electric resistance duct heater and its control system [38].

Table 1. Design parameters for a combustion air resistance heater.

Parameters	Unit	Value
Fuel (natural gas) consumption	Nm^3/hr	27
Primary air flow	m^3/s	0.14
Maximum temperature increase from ambient	°C	105
Combustion air connection duct diameter	mm	90

Pre-heating the combustion air would reduce the density of flow, thus, reducing the molar flow rate of oxygen per unit volumetric flow of combustion air causing incomplete combustion of the fuel. Therefore, the air regulator in the multi-flow valve of the fuel-air mixer needs resetting to maintain a suitable air-fuel ratio. The burner flame colour and quality were observed for every increment made in the combustion air temperature to ensure complete combustion of fuel. The parameters used to analyse the oven performance are fuel consumption rate, wafer quality (moisture, weight, size, colour), fuel conversion and temperatures in the oven. The effectiveness of the actual (with heat recovery) combustion air preheating system is determined by Equation (2):

$$n_{combustion\ air\ preheating} = \frac{\dot{Q}_{gas\ saved,\ Oven}}{\dot{Q}_{exhaust}} \tag{2}$$

where $\dot{Q}_{gas\ saved,\ Oven}$ is the reduction in oven's gas consumption rate in kW, and $\dot{Q}_{exhaust}$ is the rate at which the recoverable waste heat is released (in kW) from the exhaust of a single oven. Figure 3 shows a schematic of a baking oven with combustion air preheating process using the oven's exhaust gases.

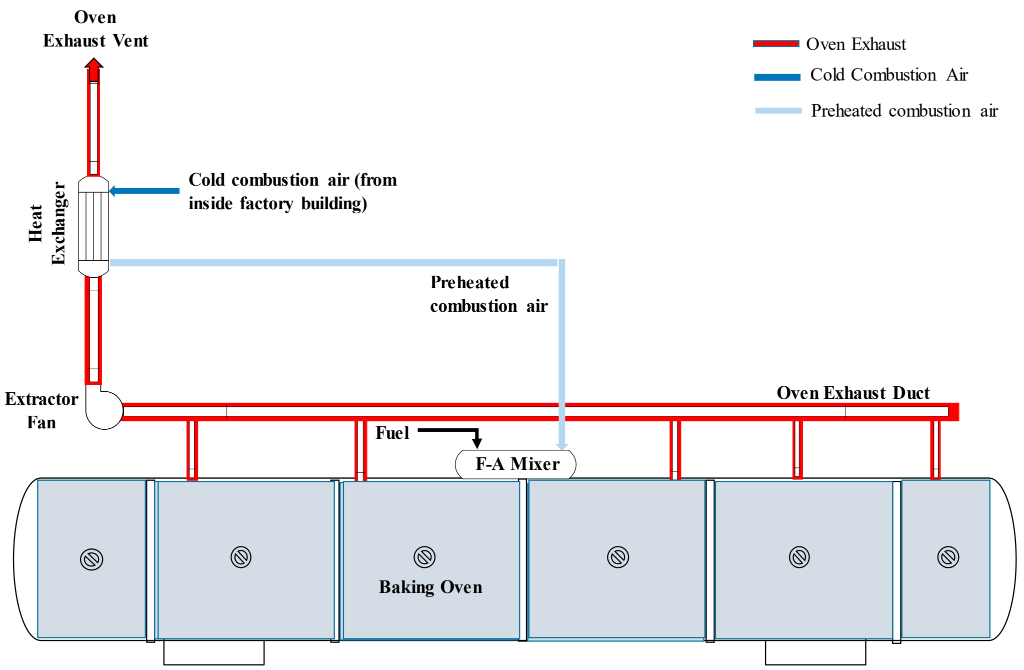

Figure 3. Schematic of combustion air preheating process using oven exhaust.

The combustion air preheating technology developed and discussed in this work can be applied to any other food manufacturing processes involving pre-mixed air-fuel combustion.

2.3. Hot Water Production System

Hot water is one of the key utilities in any industrial manufacturing process for a variety of applications, such as space heating, cleaning, showers, etc. The temperature requirements of hot water for the different types of applications are shown in Table 2.

Table 2. Hot water temperatures for industrial applications.

Parameters	Unit	Value
Industrial Processes	°C	70–95
Domestic or Industrial Space Heating	°C	55–65
Dish washing and Laundry	°C	40–60
Shower and Hand Wash	°C	40
Surgical Scrubbing	°C	43

The waste heat from the baking oven can be utilised in decentralised water heaters to heat the returning process waters. A schematic diagram of such a system is shown in Figure 4. Simulations of flowsheet models developed in Aspen Plus were conducted to analyse the system performance. A counter-current heat exchanger was used to recover the waste heat in the oven exhaust. The overall effectiveness of the heat recovery system reheating process water is determined by Equation (3):

$$n_{reheat\ process\ water} = \frac{\dot{Q}_{boiler\ gas\ saved}}{\dot{Q}_{exhaust}} \tag{3}$$

where $\dot{Q}_{boiler\ gas\ saved}$ is the rate of gas saving in a centralised hot water boiler system by offsetting the heating load by the recoverable waste heat from the oven, $\dot{Q}_{exhaust}$.

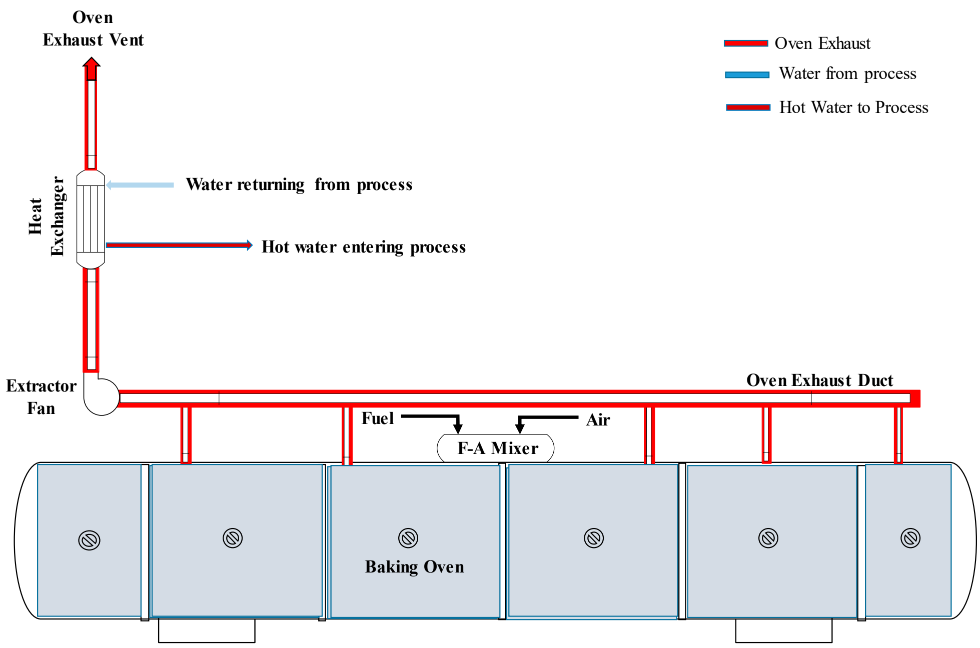

Figure 4. Schematic of the heating returning process water using oven exhaust.

2.4. Organic Rankine Cycle (ORC) Model

The ORC system works on the same principle as the steam Rankine cycle; however, it operates at comparatively lower source temperatures and uses organic fluids such as alkanes as the working fluid instead of water [39]. The organic fluids have lower boiling temperatures and higher molecular weights that create higher vapour pressures using low-grade heat (100–400 °C) and provide higher thermodynamic efficiencies than steam cycles [20]. The selection of organic fluid primarily depends on the operating temperatures and is very critical to the ORC performance. Many research activities on ORC have been carried out in the past to improve the performance by reducing complexity, selecting appropriate working fluid, improving system configuration, optimising operating conditions, etc. [40–45]. A two-loop Regenerative Organic Rankine Cycle (RORC), shown in Figure 5, has been modelled in this study after a thorough literature search [20,46–49].

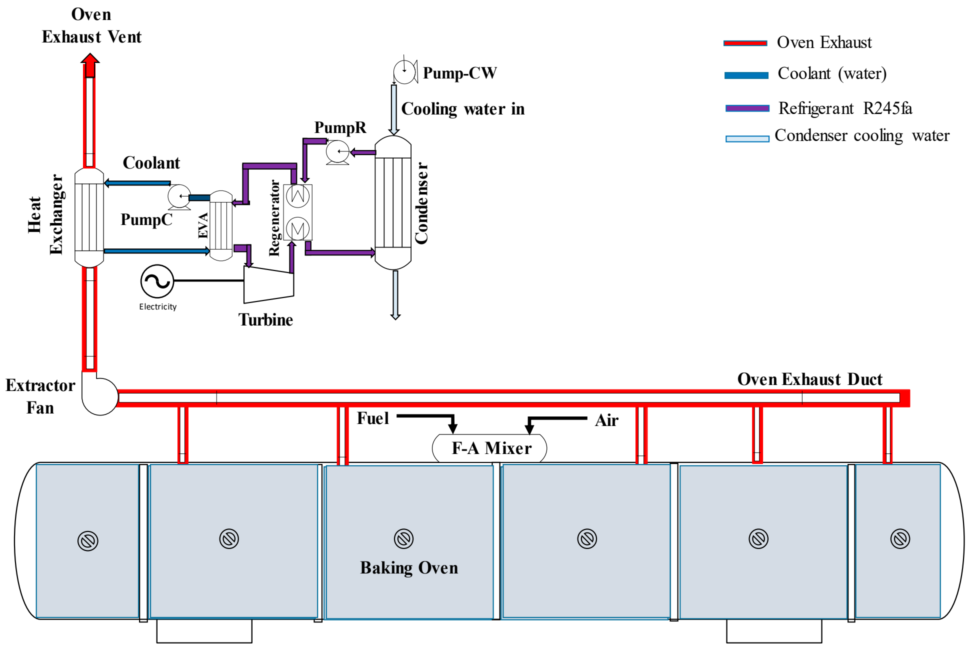

Figure 5. Schematic of a baking oven waste heat recovery system to produce electricity using the Regenerative Organic Rankine Cycle.

The primary loop circulates a coolant (water) that recovers waste heat from the oven exhaust gases and releases this heat into the evaporator of the RORC. In the secondary loop, an organic refrigerant R245fa (also called working fluid) is pressurised in the feed pump and fed to the regenerator, where it is preheated by the turbine exhaust [50]. It is then passed through the evaporator where it turns into superheated vapour after absorbing the heat released by the coolant, which is at 100 °C. The saturated pressurised refrigerant vapour is expanded in a turbine, which produces electricity through the generator unit. The vapour refrigerant, after preheating the liquid refrigerant in the regenerator, goes through a condenser, where it is re-condensed to liquid state. An Aspen Plus model of the heat recovery system using RORC was developed for simulations and performance analysis. The Peng-Robinson equation of state was selected to calculate the thermodynamic properties of the refrigerant [49,51]. The operating parameters and inputs, as shown in Table 3, were used to model RORC in Aspen Plus were obtained from literature [39,51–58]. The electrical efficiency of the RORC is determined by Equation (4):

$$n_{electrical,\ RORC} = \frac{\dot{W}_{net,\ RORC}}{\dot{Q}_{supply}} = \frac{\dot{W}_T - \dot{W}_{aux}}{\dot{Q}_{exhaust}} \quad (4)$$

where $\dot{W}_{net,\ RORC}$ is the net electrical output from the *RORC* system, $\dot{W}_T$ is the electrical power output of the *ORC* turbine and $\dot{W}_{aux}$ is the electrical power consumption by auxiliary equipment.

The effectiveness of the heat recovery system involving *RORC* is determined by Equation (5):

$$n_{ORC} = \frac{\dot{Q}_{gas\ saved,\ ORC}}{\dot{Q}_{exhaust}} \quad (5)$$

where $\dot{Q}_{gas\ saved,\ ORC}$ is the rate of gas used by a typical gas engine to produce same amount of electricity as produced by the *RORC* system using the recoverable oven waste heat $\dot{Q}_{exhaust}$.

Table 3. List of operating parameters to the Regenerative Organic Rankine Cycle (RORC) Aspen Plus model.

Parameter	Unit	Value
Oven exhaust temperature	°C	165
Evaporator pressure	bar	1.1
Condenser pressure	bar	10
Oven exhaust volumetric flow rate	m^3/s	3.72
Oven exhaust gas outlet temperature (after heat transfer)	°C	110
Refrigerant flow rate	L/min	30.9
Coolant flow rate	L/min	233.2
Turbine efficiency	%	85
Pump efficiency	%	80

2.5. Vapour Absorption Refrigeration (VAR) System Model

A VAR system, shown in Figure 6, is a closed loop cycle that produces a refrigeration or cooling effect using heat as primary energy input instead of electrical power, which is used for driving a vapour compression cycle [22]. The evaporation, expansion and condensation stages in a VAR system are the same as the vapour compression refrigeration (VCR) system. However, an absorber, generator and pump replace the compressor in a VCR system. A VAR model was developed in Aspen Plus using a mixture of ammonia and water as the working fluid [59–61]. In the generator, the rich ammonia/water mixture is heated to desorb the refrigerant. Hot water produced by extracting the waste heat from the oven exhaust gases is used as a thermal energy input to the generator. The refrigerant vapour then enters the rectifier, where it is cooled by the ammonia-rich solution. This preheats the ammonia-rich solution before it is sent to the generator. The refrigerant vapour flows to the water-cooled condenser, where it is completely liquefied. The liquefied refrigerant is further cooled in a refrigerant heat exchanger and flows through the expansion valve. After pressure reduction, the refrigerant flows to the evaporator unit, where heat from the chilled water evaporates the refrigerant. The refrigerant then moves to the absorber, where it mixes with the lean ammonia solution and forms a rich solution. This rich solution is then pumped back to the generator after some preheating in the rectifier.

Table 4 provides the detailed operating parameters and inputs used to model the VAR in Aspen Plus. A Peng-Robinson equation of the state property method was used in the Aspen model to calculate the thermodynamic properties of the working fluid.

Table 4. List of input parameters of the Vapour Absorption Refrigeration (VAR) system in the Aspen Plus model.

Parameter	Unit	Value
Evaporator pressure	bar	2.75
Generator pressure	bar	10
Turbine efficiency	%	85
Pump efficiency	%	80
Generator efficiency	%	98
Exhaust gas inlet temperature	°C	165
Minimum exhaust gas outlet temperature	°C	110
Exhaust gas volumetric flow rate	m^3/s	3.72

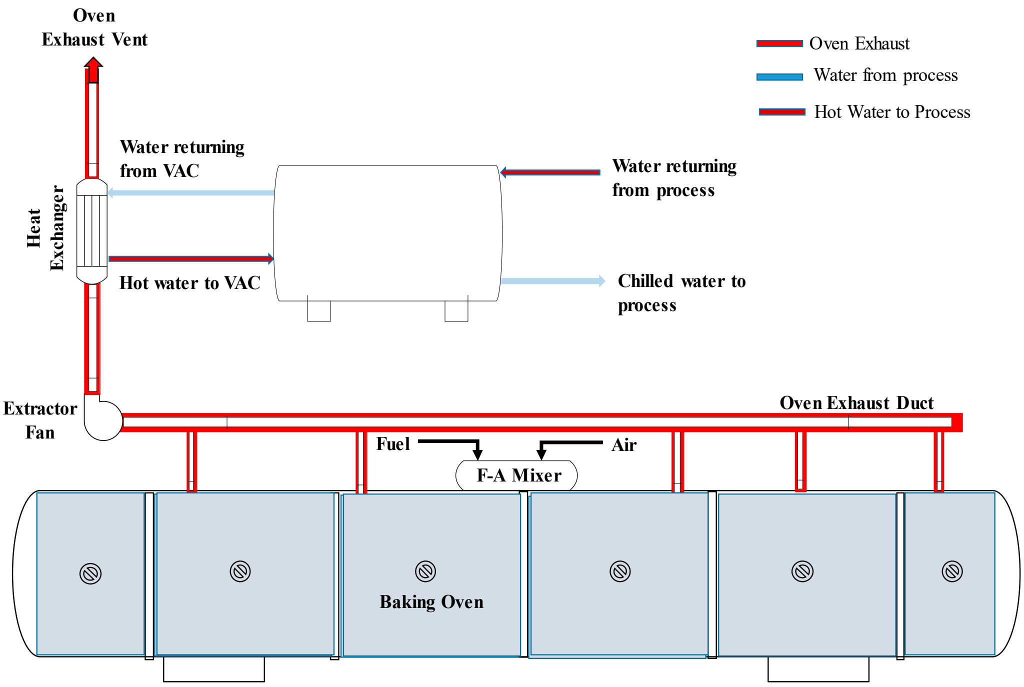

Figure 6. Schematic of a baking oven waste heat recovery system top produce chilled water using a vapour absorption system.

The cooling efficiency of the VAR system is determined by Equation (6):

$$n_{cooling,\ VAR} = \frac{\dot{Q}_{cooling,\ VAR}}{\dot{Q}_{exhaust}} \tag{6}$$

where $\dot{Q}_{cooling,\ VAR}$ is the cooling generation rate by the *VAR* system using the recoverable oven waste heat $\dot{Q}_{exhaust}$. The electrical efficiency of the *VAR* system is determined by Equation (7):

$$n_{electrical,\ VAR} = \frac{\dot{W}_{VCR}}{\dot{Q}_{exhaust}} \tag{7}$$

where $\dot{W}_{VCR}$ is the electrical power required by a *VCR* system to produce the same amount of cooling as produced by the *VAR* system using the waste heat from the oven $\dot{Q}_{exhaust}$.

The effectiveness of the heat recovery system involving *VAR* is determined by Equation (8):

$$n_{VAR} = \frac{\dot{Q}_{gas\ saved,\ VAR}}{\dot{Q}_{exhaust}} \tag{8}$$

where $\dot{Q}_{gas\ saved,\ VAR}$ is the rate of gas used by a gas engine to produce electricity $\dot{W}_{VCR}$. The *VAR* system produces the same amount of cooling as a *VCR* system would produce by consuming $\dot{W}_{VCR}$ amount of electrical power. Thus, the *VAR* system saves electrical power equal to $\dot{W}_{VCR}$.

2.6. Parameters for Economic Assessment

Detailed economic models for different waste heat recovery options investigated in this paper are developed. 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. [62] for estimating the equipment costs is used in this paper. The investment models are shown in Table 5. These are the standard economic models that are widely used for calculating capital and manufacturing costs, and predicting or assessing profitability or payback of chemical and process plant equipment. Firstly, we calculated the purchase cost of each component C_p, assuming the base conditions such as ambient operating pressure and carbon steel construction. However, in actual cases, the operating pressure and material types for the construction of components may not be the same as base conditions; rather, it can vary. Additionally, there are direct and indirect costs, which we need to consider. Hence, to calculate actual cost of a component, we calculated "bare module cost" C_{BM}, which represents the actual capital cost including both direct and indirect costs and material and pressure correction factors. The direct costs include labour, materials needed for installation such as piping, control management, insulations, structural supports, electrical work, etc., while the indirect costs comprise shipping of components, engineers and technicians salaries, etc. [63]. All the direct and indirect costs along with material and pressure corrections of a component are represented by a bare module cost factor, F_{BM}, which is multiplied with the purchase cost of a component.

Table 5. Investment model of each component in waste heat recovery options and their coefficient values (obtained from [64,65]).

Components	Investment Model *	Coefficient Values *
Pump (Centrifugal)	$\log C_{p,P} = K_{1,P} + K_{2,P} \log W_P + K_{3,P} (\log W_P)^2$ $\log F_{p,P} = C_{1,P} + C_{2,P} \log P_P + C_{3,P} (\log P_P)^2$ $F_{BM,P} = B_{1,P} + B_{2,P} F_{m,P} F_{p,P}$ $C_{BM,P} = C_{p,P} \times F_{BM,P}$	$K_{1,P} = 3.3892,\ K_{2,P} = 0.0536,\ K_{3,P} = 0.1538$ $C_{1,P} = 0\ C_{2,P} = 0\ C_{3,P} = 0$ $B_{1,P} = 1.89,\ B_{2,P} = 1.35$ $F_{m,P} = 1.6$ for carbon steel construction
Heat exchanger (Double pipe and spiral tube)	$\log C_{p,HE} = K_{1,HE} + K_{2,HE} \log A_{HE} + K_{3,HE} (\log A_{HE})^2$ $\log F_{p,HE} = C_{1,HE} + C_{2,HE} \log P_{HE} + C_{3,HE} (\log P_{HE})^2$ $F_{BM,P} = B_{1,HE} + B_{2,HE} F_{m,HE} F_{p,HE}$ $C_{BM,HE} = C_{p,P} \times F_{BM,HE}$	Double pipe (liquid to liquid), carbon steel : $K_{1,HE} = 3.3444,\ K_{2,HE} = 0.2745,\ K_{3,HE} = -0.0472$ $C_{1,HE} = 0,\ C_{2,HE} = 0,\ C_{3,HE} = 0$ for pressure < 40 barg $B_{1,HE} = 1.74,\ B_{2,HE} = 1.55,\ F_{m,HE} = 1$ Spiral tube (gas to liquid), 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 pressure < 150 barg $B_{1,HE} = 1.74,\ B_{2,HE} = 1.55,\ F_{m,HE} = 1$
Turbine (Radial)	$\log C_{p,T} = K_{1,T} + K_{2,T} \log W_T + K_{3,T} (\log W_T)^2$ $C_{BM,T} = C_{p,T} \times F_{BM,T}$	$K_{1,T} = 2.2476 K_{2,T} = 1.4965 K_{3,T} = -0.1618$ $F_{BM,T} = 3.5$ for carbon steel construction
Process vessels	$logC_{p,Ve} = K_{1,Ve} + K_{2,Ve} logV_{Ve} + K_{3,V} (logV_{Ve})^2$ $F_{P,Ve} = 1$ $F_{BM,Ve} = B_{1,Ve} + B_{2,Ve} F_{m,Ve} F_{P,Ve}$ $C_{BM,Ve} = C_{p,Ve} \times F_{BM,Ve}$	Horizontal vessels, carbon steel; $K_{1,Ve} = 3.5565,\ K_{2,Ve} = 0.3776,\ K_{3,Ve} = 0.0905$ $F_{P,Ve} = 1$ for vessel thickness t < 6.3 mm $B_{1,Ve} = 1.49,\ B_{2,Ve} = 1.52,\ F_{m,Ve} = 1$

* where $K_1,\ K_2, K_3, C_1,\ C_2, B_1$ and B_2 are coefficients in investment model, F_p and F_m are the pressure and material factor, respectively, W is the power of turbine in kW, V is the volume of pressure vessel in m^3, A is the area of a heat exchanger in m^2, P is the pump or pressure in bar, HE is the heat exchanger, T is the turbine and Ve is the pressure vessel.

All the correlations shown in Table 5 are for the base year 2001, and hence, we need to update the economic cost by taking the inflation into account for the year of investment, which is 2017 in this study. The CEPCI (Chemical Engineering Plant Cost Index) [4] is responsible for updating the cost index yearly. The CEPCI is an important tool for chemical-process-industry (CPI) professionals when adjusting process plant costs from one period to another. Based on the cost indexes for two different years, the bare module cost for the year 2017 is estimated as follows:

$$C_{BM,2017} = C_{BM,2001} \times \left(\frac{CEPCI_{2017}}{CEPCI_{2001}}\right)$$

where $C_{BM,\,2017}$ and $C_{BM,\,2001}$ are the bare module cost for the year 2017 and 2001, respectively. $CEPCI_{2017}$ and $CEPCI_{2001}$ are the cost index in 2017 and 2001 which are 567.5 and 397, respectively.

Total capital investment costs (C_{CI}) for investigated heat recovery options are calculated as follows:

Air preheater with one oven ($AP1$):

$$C_{CI,AP1} = C_{HE,BM,\,2017}$$

Air preheater with five ovens ($AP5$):

$$C_{CI,AP5} = C_{HE,BM,\,2017}$$

Water preheater (HW):

$$C_{CI,AP5} = C_{HE,BM,\,2017}$$

Air preheater + hot water ($APHW$):

$$C_{CI,APHW} = C_{HE,\,BM,\,2017} + C_{P,\,BM,\,2017}$$

Organic Rankine Cycle (ORC):

$$C_{CI,ORC} = C_{HE,\,BM,\,2017} + C_{P,\,BM,\,2017} + C_{T,\,BM,\,2017}$$

Vapour absorption refrigeration cycle ($VARC$):

$$C_{CI,VARC} = C_{HE,\,BM,\,2017} + C_{P,\,BM,\,2017} + C_{Ve,\,BM,\,2017}$$

where $C_{HE,\,BM,\,2017}$, $C_{P,\,BM,\,2017}$, $C_{T,\,BM,\,2017}$ and $C_{Ve,\,BM,\,2017}$ are the bare module cost for heat exchangers, pumps, turbines and process vessels in the year 2017, respectively.

Total investment cost (C_n) for different waste heat recovery options is the summation of capital cost and operation and maintenance cost:

$$C_n = C_{CI,n} + Cf_{OM} \times C_{CI,n}$$

where Cf_{OM}. is the operation and maintenance cost factor, which was assumed to be 1.5% of the total investment cost [62], n is the different waste heat recovery options.

The payback period is calculated by dividing the total cost by the fuel saving or cost avoided, CS_n, with a different option for one year as follows:

$$PB_n = \frac{C_n}{CS_n}$$

3. Results and Discussions

3.1. Pilot-Scale Combustion Air Preheating Experiments

The pilot-scale wafer baking oven was operated at normal conditions, as described in Table 5, at the beginning of the experiments to collect baseline data on key performance parameters such as fuel and energy consumption, exhaust temperatures and flow rate, wafer quality and fuel conversion, shown in Table 6. The average hourly fuel consumption without combustion air preheating was recorded as 27.69 Nm^3, indicating an energy consumption rate of 306.12 kW by the pilot oven. The oven produced 90 kg of wafer per hour with an energy consumption of 3.4 kWh per kg of wafer produced. The exhaust gases were released at 133 °C and 2.82 m^3/s.

Table 6. Baseline key performance indicators of pilot-scale baking oven.

Parameter	Units	Value
Gas consumption per hour	Nm^3/h	27.69
Calorific value of gas	kWh/m^3	11.0556
Load	kW	306.12
Combustion air inlet temperature	°C	30
Exhaust temperature	°C	133
Exhaust flowrate	m^3/s	2.82
Oven productivity	kWh/kg of wafer	3.40

After this, the combustion air was preheated from 30 °C to 105 °C with incremental steps of 20 °C, using the industrial electrical resistance heater described in Section 2.2. For every increment made, the key performance parameters were recorded. The effect of combustion air temperature on fuel consumption rate is shown in Figure 7. Preheating the combustion air increases the burner flame temperature, and consequently, also the baking oven plate temperature. The oven's control system that regulates the plate temperature responds instantly and brings down the temperature to the set point condition by reducing the fuel supply to the oven burners. It was observed from the experiments that the oven fuel consumption dropped by 1% for every 18.5–20 °C rise in combustion air temperature. An overall drop in average fuel consumption by the oven of circa 4% was obtained by raising the combustion air temperature by 75 °C (from 30 °C to 105 °C).

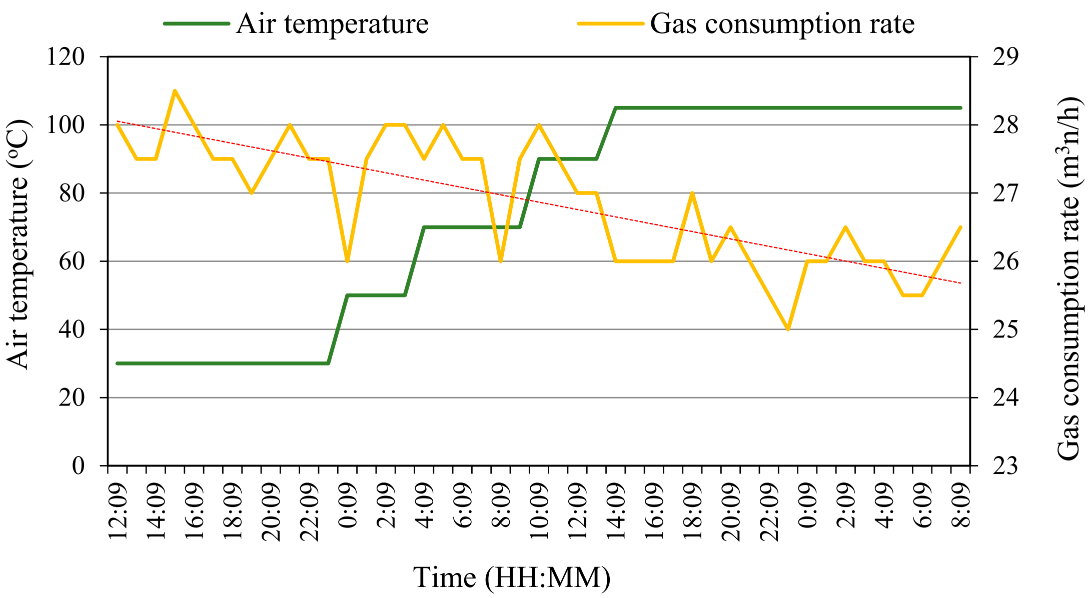

Figure 7. Effect of combustion air temperature on the oven fuel consumption rate.

Preheating the combustion air to higher temperatures reduces the air density, and hence, the oxygen mass flow rate. Any failure of the oven's control system to adjust to the preheated combustion air conditions could cause incomplete combustion of the gaseous fuel in the oven burners. This will lead to fuel wastage and formation of carbon monoxide (CO) and can negatively impact the wafer quality. Therefore, the burner flame colours were regularly observed during the experiments to check if the oven's control mechanism can precisely handle the variations in the operating conditions and if the fuel is being completely burned in the burners. A bluish flame with a yellow tip, as can be seen in Figure 8, indicates complete combustion of fuel in the burners. Moreover, the quality (moisture, weight, size, colour) checks performed on the wafer samples produced and collected during the experiments showed no negative impact on the wafer quality.

Figure 8. Flame colour before (**a**) and after (**b**) combustion air preheating.

3.2. *Savings for an Industrial-Scale Baking Oven*

The observations and findings from the pilot-scale experiments were applied on an industrial-scale baking oven, which is a scaled-up version of the pilot oven used in the experiments and has a similar design, construction and working principle. The baseline key performance parameters of the industrial-scale oven and the estimated changes after heat recovery are listed in Table 7. The average baseline fuel consumption of the industrial oven was 75.55 Nm^3/h, equating to an energy consumption rate of 835.25 kW. The oven produces 251.58 kg of wafer with a baseline productivity of 3.32 kWh per kg of wafer. The exhaust gases were released at 165 °C and 3.72 m^3/s.

Table 7. Key performance indicators of the industrial-scale baking oven before and after heat recovery to preheat combustion air of a single oven.

Parameter	Units	Baseline	After Heat Recovery
Gas usage	Nm^3/h	75.55	70.57
Load	kW	835	780
Exhaust temperature	°C	165	165
Combustion air inlet temperature	°C	30	155
Effectiveness of heat recovery system	%	-	32.96
Oven productivity	kWh/kg of wafer	3.32	3.10

The combustion air of the industrial oven can be preheated up to a temperature 10 °C below the exhaust temperature. Thus, in the current scenario where the exhaust is at 165 °C, the combustion air could be preheated up to 155 °C; 125 °C higher than the baseline temperature of 30 °C. Using the relation between the combustion air temperature and oven fuel consumption obtained from the pilot-scale experiments, it was estimated that a maximum fuel saving of ~6.6% i.e., 4.98 Nm^3/h or 55.05 kWh could be achieved for the industrial baking oven by preheating its combustion air. The new gas usage for the oven is calculated by subtracting the gas savings obtained due to heat recovery from the baseline gas consumption of 75.55 Nm^3/h. A 6.6% of fuel savings will reduce the energy consumption per kilogram of wafer production from 3.32 kWh to 3.10 kWh, thus making the oven more efficient.

Contamination of the product is one of the greatest risks in a food manufacturing plant. The exhaust gases contain moisture released from the batter and trace amount of sulphur oxides if the fuel used in the oven (natural gas) contains sulphur. In this study, the lowest possible temperature of the oven exhaust gas after heat recovery was set at 110 °C for all the heat recovery technologies, to avoid moisture and acidic vapour condensation in the heat recovery unit. However, using this condition limits the available heat for recovery per unit time in the exhaust to 167 kW. This is because most of the vapour in the exhaust gas does not condense thus losing the latent heat of vaporisation of water. This yields an effectiveness of 33%.

3.3. Heat Recovery for Hot Water Production

The industrial baking oven exhaust gases released at 165 °C and 3.72 m^3/s are a lucrative source of free waste heat that can be utilised to reheat process hot water streams. An Aspen Plus model was developed to reheat a returning process water using exhaust's heat. The simulation results indicate that heat can be recovered at a rate of 167 kWh from the exhaust gases by reheating 13.1 t/h of process hot water from 80 °C to 90 °C. To attain a similar output from an industrial gas boiler, 18.8 Nm^3/h or 207.84 kWh of natural gas will be required to burn, assuming an 80% efficiency for the overall gas-based hot water generation system involving boiler, pressure valves, calorifier, etc. [66,67]. This gas saving does not directly occur in the baking oven, but the overall energy consumption of factory can be saved. However, the factory's energy consumption savings were deducted from the oven's energy consumption for simplicity of the comparison with other heat recovery options. Table 8 provides a comparison of the oven's performance parameters before and after heat recovery. The new gas usage for the oven is obtained by subtracting the boiler gas savings of 18.8 Nm^3/h, achieved due to heat recovery, from the baseline gas consumption. The effectiveness (ratio of fuel consumed by an industrial boiler to generate a similar result as the heat recovery system and the recoverable heat from a single oven exhaust) achieved by the heat recovery system reheating the process water is 124.4%. Incorporating the savings accomplished from heat recovery into the baseline parameters indicates a 25% improvement in the oven productivity.

Table 8. Key performance indicators of the industrial-scale baking oven before and after heat recovery to reheat returning process water.

Parameter	Units	Baseline	After Heat Recovery
Gas usage	Nm^3/h	75.55	56.75
Load	kW	835.25	627.40
Effectiveness of heat recovery system	%	-	124.4
Oven productivity	kWh/kg of wafer	3.32	2.49

3.4. Preheating Combustion Air and Reheating Process Water

The experiments revealed that preheating the combustion air flow from 30 °C to 155 °C provides a relatively small heat sink due to a much lower flowrate of combustion air compared to the oven's exhaust gases. Hence, the waste heat in the exhaust gases are not recovered to the full potential due to the unavailability of sufficient heat sink or, in other words, a demand for the recovered heat in the form of oven's combustion air. This limitation of the combustion air preheating technology can be overcome by adding an additional heat exchanger downstream of the combustion air preheater to reheat the returning process water, as shown in Figure 9.

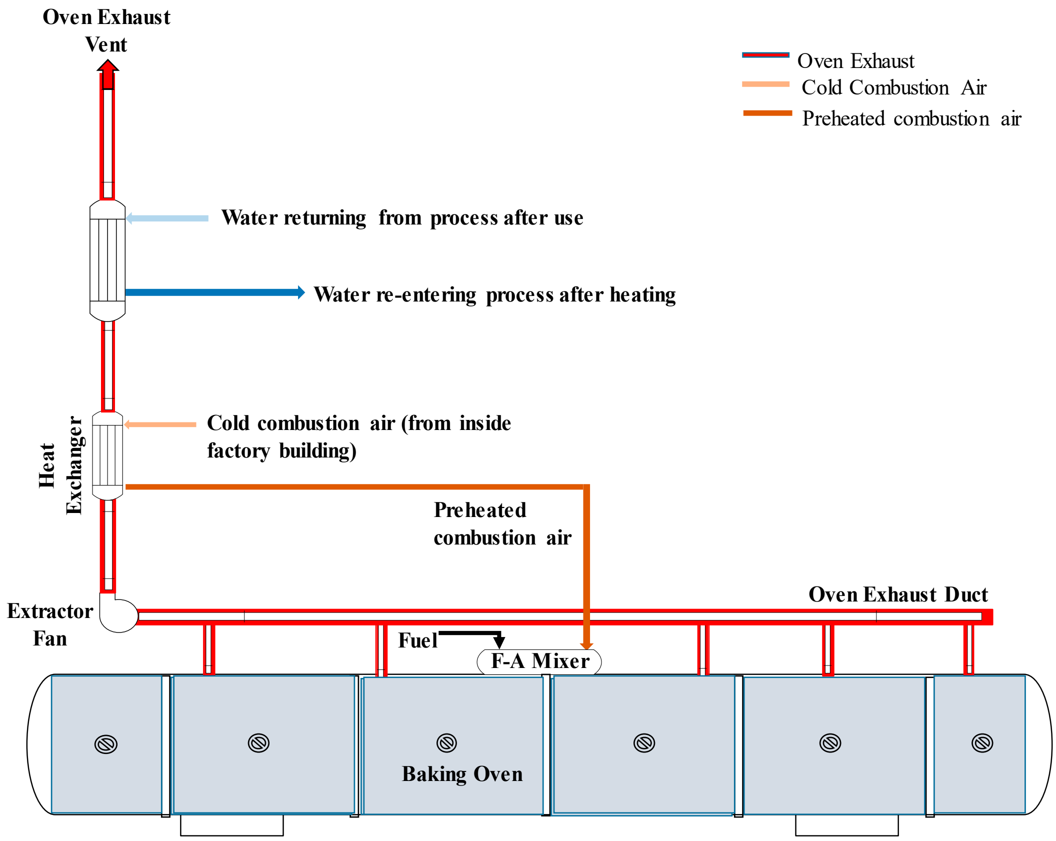

Figure 9. Schematic of combustion air preheating combined with reheating process water using oven exhaust gases.

An Aspen Plus model of a heat recovery system combining preheating combustion air and reheating returning process water was developed to evaluate the system performance. The simulation results indicate that the combustion air preheating technology utilises only 19.08% of the total recoverable heat from the exhaust that is available by cooling the exhaust to 110 °C. The remaining heat is recovered by integrating an additional heat sink in the form of returning process water, after the combustion air preheating system. The exhaust gases, after preheating combustion air, reheat a returning process hot water stream flowing at 10.6 tonnes/h from 80 °C to 90 °C. The heat recovery rate obtained by the process water reheating system from the oven's exhaust gases is 135.02 kW. A typical industrial gas boiler with an efficiency of 80% would require burning 15.26 Nm^3 or 168.7 kW of natural gas to achieve a similar output. The fuel savings by the combined preheating and reheating system is 20.24 Nm^3/h or 223.76 kW. The new gas usage for the oven is obtained by subtracting the overall gas savings of 20.24 Nm^3, delivered after heat recovery in one hour, from the baseline gas consumption. The overall system combining preheating combustion air and reheating process water achieves an effectiveness of 134%. Incorporating the savings as shown in Table 9, accomplished from the combined heat recovery technologies into the baseline parameters delivers a 26.8% improvement in the oven productivity.

Table 9. Key performance indicators of the industrial-scale baking oven before and after heat recovery to preheat combustion air and reheat returning process water.

Parameter	Units	Baseline	Savings/Preheating Air	Savings/Reheating	Combined Savings
Gas usage	Nm^3/h	75.55	70.57	60.29	55.3
Load	kW	835.25	780.19	666.54	611.37
Effectiveness of heat recovery unit	%	-	32.96	101	134
Oven productivity	kWh/kg of wafer	3.32	3.10	2.65	2.43

3.5. Preheating Combustion Air of Multiple Ovens

As discussed in Section 3.4, the heat recovery system with preheating combustion air does not fully recover the heat available in the exhaust due to having a smaller heat sink than the available heat. An alternative solution for maximising the heat recovery is preheating combustion air of multiple ovens by using exhaust heat from a single oven. Large confectionary manufacturing sites typically operate more than one baking ovens simultaneously. These ovens are placed in parallel and close to each other to facilitate batter supply from a common batter preparation unit, thus avoiding additional equipment costs. Aspen Plus models of preheating combustion air were developed with gradual increments in the number of combustion air streams with each stream representing a different oven. It was assumed that all ovens have identical designs, sizes and operational parameters. The findings from the Aspen Plus simulation models are shown in Figure 10.

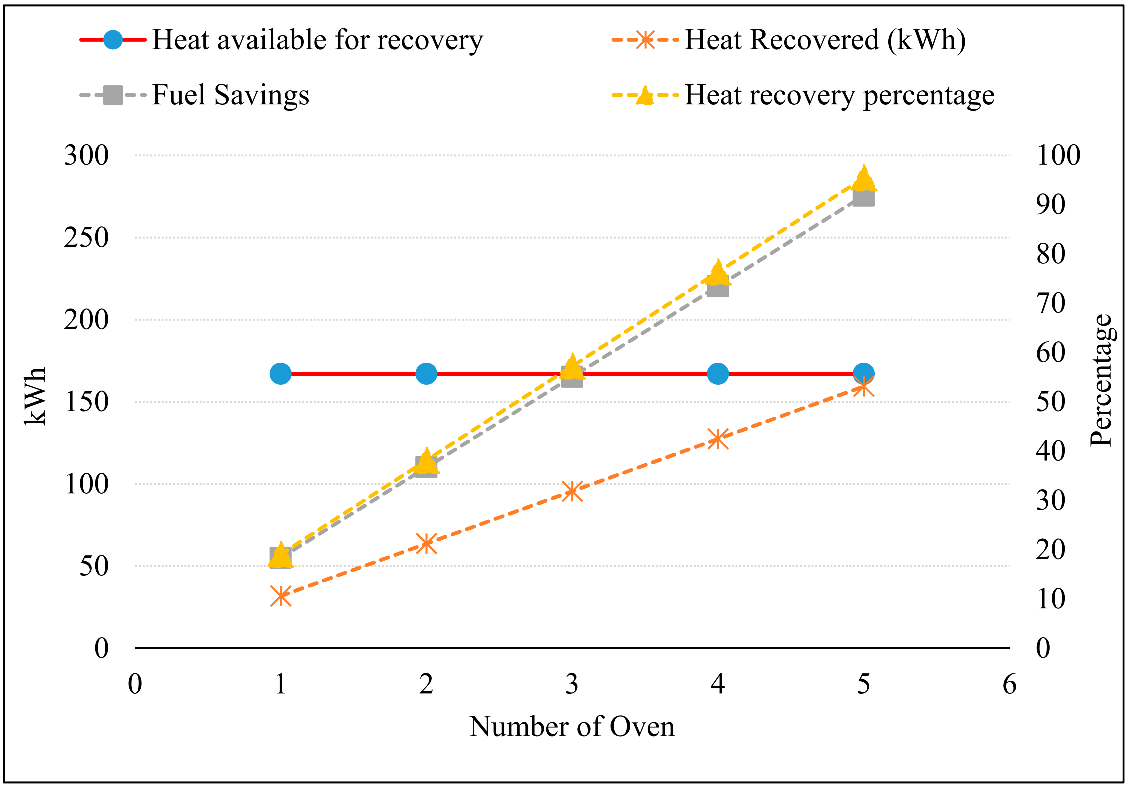

Figure 10. Savings obtained by preheating combustion air of multiple ovens.

It can be seen from the figure that a total of five combustion air streams or five baking ovens are required to extract maximum recoverable heat from exhaust of a single oven. The five combustion air streams manage to extract 95.4% of the 167 kW of recoverable heat available in the exhaust. The cumulative gas savings achieved from all five ovens is 24.9 Nm^3/h or 275.28 kW. This cumulative gas saving has been transferred to a single oven for the simplicity of performance evaluation. Table 10 provides a comparison of the oven's key performance parameters before and after the heat recovery. An overall system effectiveness, which is the ratio of gas savings from all five ovens and recoverable heat from a single oven exhaust, of 164.8% was achieved by the heat recovery system. A 33.1% improvement in the productivity of the oven used as heat source (exhaust gas) has been achieved after the heat recovery.

Table 10. Key performance indicators of the industrial-scale baking oven before and after heat recovery to preheat combustion air of five ovens.

Parameter	Units	Baseline	After Heat Recovery
Gas usage	Nm^3/h	75.55	50.65
Load	kW	835.25	559.96
Effectiveness of heat recovery system	%	-	164.8
Oven productivity	kWh/kg of wafer	3.32	2.22

3.6. RORC for Oven Heat Recovery

The key performance parameters obtained from Aspen Plus simulation model for the proposed RORC system generating electricity using the heat extracted from baking oven's exhaust gases are summarised in Table 11. A hot water stream at 2 bars and 90 °C is fed to a heat exchanger, where it is heated to 100 °C by cooling the oven's exhaust gases down to 110 °C and extracting 167 kW of heat. This hot water, at 100 °C, is used in the evaporator to vaporise 3.9 litres of liquid refrigerant every minute. The vapourised refrigerant at 90 °C and 10 bars is expanded to 1.1 bar in an expander, producing 23.99 kW of electricity. The refrigerant stream exiting the expander at 38 °C and 1.1 bar is sent to the regenerator to extract heat by preheating the liquid refrigerant before the refrigerant is fed to the evaporator. The parasitic power consumed by the three pumps (refrigerant, condenser cooling water and coolant; see Figure 5) is 0.97 kW. The RORC system delivers a net electrical output of 23.02 kW with a net thermal efficiency of 13.78%, which is comparable to the efficiency range reported in literature [20,24–26,56].

Table 11. Results of the RORC Aspen Plus simulation.

Parameter	Units	Value
Heat available in the exhaust	kW	167
Gross electricity generated by the turbine	kW	23.99
Parasitic electrical power consumption	kW	0.97
Net electrical output	kW	23.02
RORC system efficiency (electrical)	%	13.78

The key performance parameters of the oven before and after the heat recovery involving RORC are summarised in Table 12. The RORC system converts waste heat into electrical output. However, to maintain uniformity and continuity in the key performance parameters used for evaluation of the studied heat recovery technologies, the electrical output was converted or represented in the form of gas savings. A gas engine with an efficiency of 45% would require to burn 4.62 Nm^3/h or 51.15 kWh of natural gas to generate 23.02 kW of electricity [68]. Therefore, the effectiveness achieved by the heat recovery system involving RORC is 30.6%. A 6% improvement in the oven productivity was achieved after the heat recovery using the RORC system.

Table 12. Key performance indicators of the industrial-scale baking oven before and after heat recovery.

Parameter	Units	Baseline	After Heat Recovery
Gas usage	Nm^3/h	75.55	70.93
Load	kW	835.25	784.17
Effectiveness of heat recovery system	%	-	30.6
Oven productivity	kWh/kg of wafer	3.32	3.11

3.7. VARC for Oven Heat Recovery

The simulation results summarised in Table 13 for the proposed heat recovery system involving VAR indicates that cooling can be generated at a rate of 55.5 kW by recovering 167 kW of waste heat available from the oven exhaust. The heat recovery system attains a cooling efficiency of 33.2%. The parasitic power consumed by the auxiliary equipment is 1.03 kW. A VCR system with a coefficient of performance (COP) of 3.5 [69,70] will consume 15.85 kW of electricity to produce the same cooling effect as produced by the VAR. Thus, the VAR system saves 15.85 kW of electricity by recovering waste heat and yields a net thermal efficiency of 9.49%.

Table 13. Aspen Plus simulation results of heat recovery system using VAR.

Parameter	Units	Value
Heat available in the exhaust	kW	167
Cooling produced by the system	kW	55.5
Cooling efficiency	%	33.2
Parasitic power consumption	kW	1.03
Net electricity saved	kW	15.85
Electrical efficiency of VAR	%	9.49

The cooling effect produced by VAR is first converted into electrical savings and then to gas savings to maintain uniformity in comparison to the key performance parameters of the heat recovery systems studied. A typical gas engine with an efficiency of 45% would require to burn 3.18 Nm^3/h or 35.22 kW of natural gas to generate 15.85 kW of electricity. The key performance parameters of the oven before and after the heat recovery involving VAR are summarised in Table 14. The effectiveness achieved by the heat recovery system is 21.08%. The results also indicate an improvement of 4.2% in the oven productivity.

Table 14. Key performance indicators of the industrial-scale baking oven before and after heat recovery.

Parameter	Units	Baseline	After Heat Recovery
Gas usage	Nm^3/h	75.55	72.37
Load	kW	835.25	800.09
Effectiveness of heat recovery system	%	-	21.08
Oven productivity	kWh/kg of wafer	3.32	3.18

3.8. Comparison of Heat Recovery Technologies

The performances of the heat recovery technologies discussed in Sections 3.1–3.7 are evaluated against each other based on four key criteria: (i) oven gas consumption, (ii) oven productivity, (iii) effectiveness of heat recovery system and (iv) cost savings payback period. Figure 11 illustrates the graphical comparison of the heat recovery technologies based on the first three criteria, whereas the fourth criteria is compared in Tables 15 and 16. The heat recovery system involving VAR technology incurs the least gas savings of 4.2%, yielding a gas consumption rate of 72.37 Nm^3/h against the baseline consumption of 75.55 Nm^3/h. The VAR technology is followed by RORC technology and preheating technology for single oven with a gas consumption reduction by 6.11% and 6.59%, respectively.

The heat recovery technology involving preheating combustion air of multiple ovens shows the most promising outputs, with a 33% reduction in hourly gas consumption followed by combined preheating and reheating technology with a 26.8% reduction. The process water reheating technology stands third with fuel savings of 24.88%. A similar performance trend was observed for the other two comparison criteria—productivity and effectiveness.

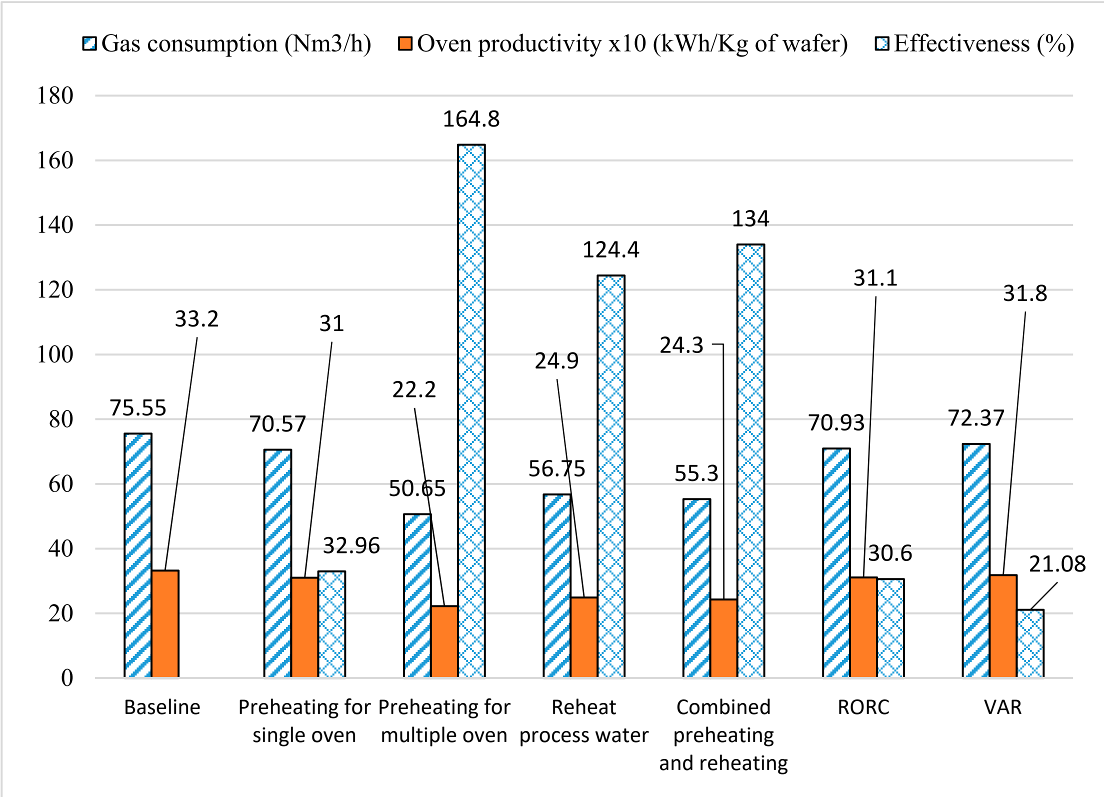

Figure 11. Comparison of heat recovery technologies based on oven's gas consumption, productivity and effectiveness. Note: the oven productivity values have been multiplied by 10 to fit the graph.

Table 15. Annual energy, operational cost and CO_2 savings for the studied heat recovery technologies based on 7000 h of operation per year.

Recovery Technology \ Parameters	Fuel Saved	Energy Savings (MWh/yr)	Operational Cost Savings (£/yr)	CO_2 Emissions Reduction (t/yr)
Preheating for single oven	Gas	385	6938	71
Preheating for multiple oven	Gas	1927	34,687	356
Reheating process water	Gas	1455	26,189	269
Combined preheating and reheating process water	Gas	1567	28,209	290
RORC *	Electricity	161 #	9668	41
VAR	Electricity	111 #	6657	28

* Feed in Tariffs for exporting the electricity to the grid have not been considered here. # MWH Electrical.

Table 16. Annual energy, operational cost and CO_2 savings for the studied heat recovery technologies based on 7000 h of operation per year.

Components	Component	Parameters Value	Cost of Investment (£)	Fuel/Electricity Saving (£/Year)	Payback Period (Years)
Preheating for single oven	One heat exchanger	$A = 0.8261$ m^2, $P = ambient$	35,616	6938	5.13
Preheating for multiple oven	One heat exchanger	$A = 5.461$ m^2, $P = ambient$	54,557	34,687	1.57
Reheating process water	One heat exchanger, one pump	$A = 3.99$ m^2, $P = 2$ bar $W_P = 0.023$ kW	59,346	26,189	2.26
Combined preheating and reheating process water	Two heat exchangers, one pump	$A_{HE,\,1} = 0.8261$ m^2, $A_{HE,2} = 3.52$ m^2 $P_{HE,1} = ambient$, $P_{HE,2} = 2$ bar , $P_{P,1} = 2$ bar $W_P = 0.0188$ kW	92,914	28,209	3.25
RORC	Four heat exchangers, three pumps, one turbine	$A_{HE,\,1} = 5$ m^2, $A_{HE,2} = 0.674$ m^2, $A_{HE,\,3} = 0.657$ m^2, $A_{HE,4} = 5.14$ m^2 $P_{HE,1} = 10$ bar, $P_{HE,2} = 10$ bar , $P_{HE,3} = 1.5$ bar, $P_{HE,4} = 2$ bar $P_{P,1} = 10$ bar, $P_{P,2} = 1.5$ bar, $P_{P,3} = 2$ bar $W_{P,1} = 0.584$ kW, $W_{P,2} = 0.35$ kW, $W_{P,1} = 0.0247$ kW $P_T = 10$ bar, $W_T = 23.02$ kW	152,335	9668	15.75
VARC	Three pumps, five heat exchangers (including two air coolers with fans), two process vessels (generator and absorber)	$P_{P,1} = 2$ bar, $P_{P,2} = 10$ bar, $P_{P,3} = 4$ bar $W_{P,1} = 0.27$ kW, $W_{P,2} = 0.38$ kW, $W_{P,3} = 0.22$ kW $A_{HE,\,1} = 5.15$ m^2, $A_{HE,2} = 9.26$ m^2, $A_{HE,\,3} = 3.6$ m^2, $A_{HE,4} = 7.8$ m^2, $A_{HE,5} = 12.56$ m^2 $P_{HE,1} = 2$ bar, $P_{HE,2} = 10$ bar , $P_{HE,3} = 10$ bar, $P_{HE,4} = 4$ bar , $P_{HE,5} = 1$ bar $P_G = 10$ bar, $P_A = 1$ bar , $V_{Ve,G} = 0.1$ m^3, $V_{Ve,A} = 0.1$ m^3	217,824	6657	32.72

Although some technologies provide higher savings than other, all the technologies discussed in this work can be used for waste heat recovery in a food manufacturing site in a certain scenario. The performances of all these technologies could vary with the production scales and the seasonal variations. For instance, the heat recovery potential of the gas-to-liquid heat recovery technology producing hot water highly depends on the hot water demand in the factory. The hot water demand may fluctuate or drop due to changes in production level, thus, varying or reducing the heat recovery system's output. The system output will also vary with the ambient temperature if the hot water produced is used for space heating. These irregularities in production level and ambient temperatures can make the design of heat recovery system producing hot water challenging. In addition to that, the distance between the heat source (ovens) and sink (processes with hot water demand) is also an important factor for consideration. This is because the capital cost of the heat recovery system and operational heat losses are directly proportional to the distance. Moreover, in some factories, the whole hot water demand is supplied by Combined Heat and Power systems. Therefore, there may be no requirement for installing an additional hot water generation system.

On the other hand, the heat recovery technology involving preheating of combustion air is independent of the hot water demand of the manufacturing site. However, for the preheating technology to perform better than others, there should be adequate heat sinks (combustion air flow rate or multiple ovens) available in the factory. This technology will deliver the best possible results if there is more than one oven in the factory. In the absence of hot water demand and sufficient combustion air sink, an RORC or VAR system can be considered to generate direct electrical savings, perhaps more valuable form of energy than natural gas and can be exported to the grid.

Some heat recovery technologies perform notably better than others. However, in general, all exhibit their own merits when energy and operating cost savings are considered, as shown in Table 15. A wholesale price of £1.8 per MWh of gas and £6 per MWh of electricity taken from Ofgem UK has been considered to calculate operational cost savings. While the electricity price is three times more than the gas price, the RORC and VAR does not save enough electricity to be an attractive option for operational (fuel) cost saving compared to gas saving cases. Implementing these heat recovery technologies in food manufacturing will also reduce considerable amount of CO_2 emissions (see Table 15), thus, making the food producers more complacent with the legislation.

A comparison of payback period for all the heat recovery options are given in Table 16. The combustion air preheating technologies with single and multiple ovens used only one heat exchanger, and therefore, were found to have the lowest investment cost of £35,616 and £54,557, respectively. The reheating process water technology requiring a heat exchanger and a pump has the third lowest investment cost of £59,346. The investment calculations considered that the heat sink (water to be heated) is close to the oven. Hence, the cost of laying out long piping is not taken into account. The same assumption is taken for the combined preheating and reheating process water technology. It is found that air preheating using multiple ovens has the lowest payback period, of 1.57 years, followed by reheating process water technology with 2.26 years and combined preheating combustion air and reheating process water technology with 3.25 years. This is mainly because a high operational saving was obtained on a nominal investment from these three technologies. The RORC and VAR has a payback period of 15.75 and 32.72 years, respectively. Both these processes use several units, such as heat exchangers, pumps, turbine and process vessels, and hence, have a significantly high investment cost. In addition to that, the operational/fuel cost savings were also low, which ultimately resulted in high payback periods.

3.9. Route to Election of Heat Recovery Technology

Figure 12 shows the systematic methodology or the process map for selecting a suitable waste heat recovery technology for the baking process discussed in this work. It is recommended to operate the baking oven at a fully optimised condition ahead of selecting a heat recovery system. This will provide an accurate estimation of the available waste heat from the oven exhaust. Therefore, initially, an optimisation study should be conducted to investigate the scope of the operational improvements. Additionally, historical data on the oven performance accounting for the changes in production scales, operational hours, cleaning and maintenance schedules should be obtained. This will help in understanding the variations in the waste heat production by the oven and selecting a suitable heat sink. Once the technical feasibility of a heat recovery solution is affirmed, it should be investigated further for economic viability before proceeding with the construction and installation of the heat recovery system. As understood from the results discussed above and indicated by the process map in Figure 12, the heat recovery solution involving combustion air preheating is investigated first, followed by hot water production (or combined hot water and combustion air preheating). The process map recommends investigating VAR before ORC, although the results shown in Figure 11 and Table 14 indicate higher energy savings for ORC compared to VAR. This is because a single VAR system can fulfil two purposes, i.e., produce cooling and recover waste heat. On the other hand, an ORC system will only recover waste and a separate VCR system will still be required to produce cooling. This may increase the capital investment and require more installation space.

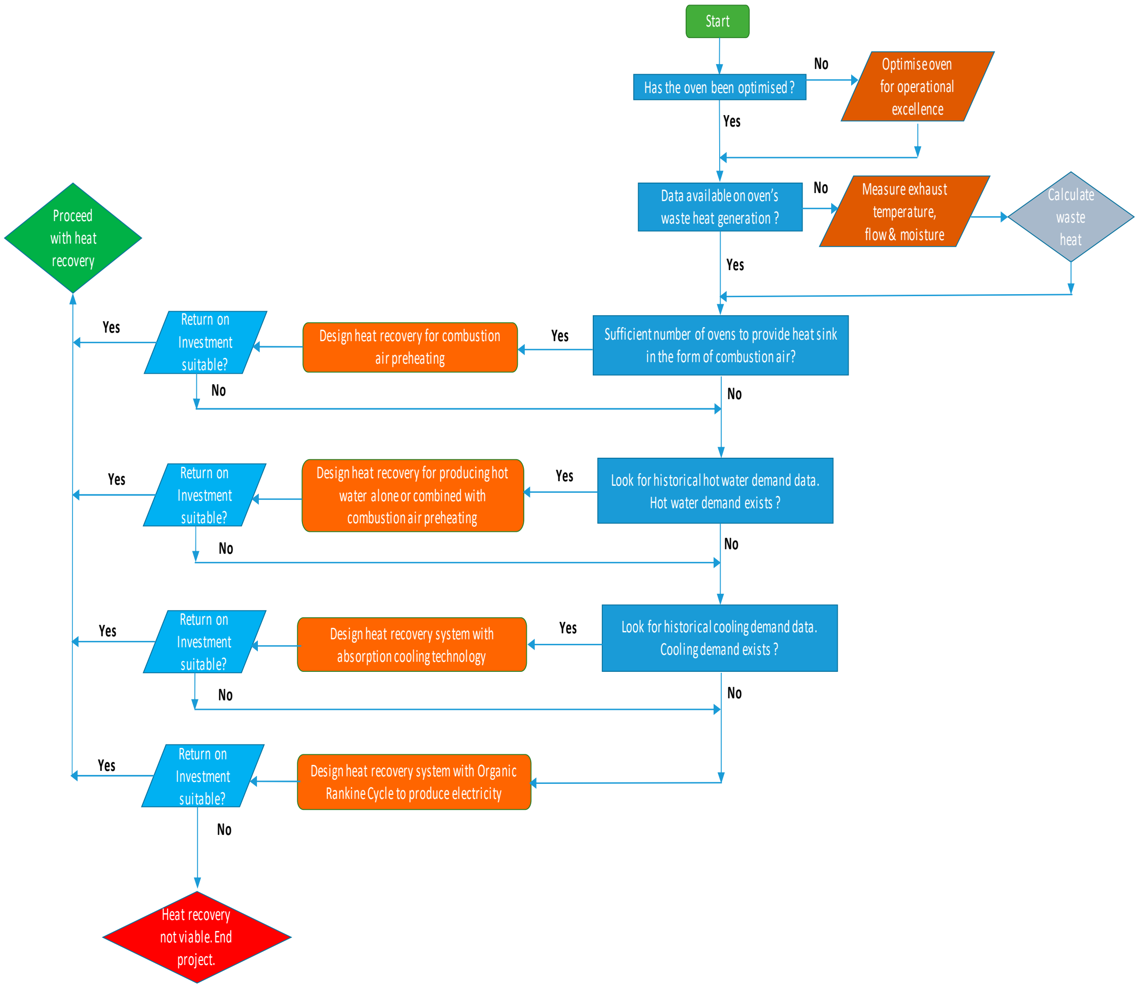

Figure 12. Process map for the selection of suitable heat recovery technology.

4. Conclusions

Worldwide, the food manufacturing sector is an energy-intensive sector using fossil fuels which is expected to grow in line with population growth. More than half of the heat supplied to food manufacturing processes, such as baking, drying, frying, roasting, heating, etc. is vented to the surroundings, with the exhaust gases as waste heat, without contributing to the processing of the product. The UK food and drink manufacturing sector emits circa 2.8 TWh of recoverable waste heat into the environment annually. This represents a significant opportunity for waste heat recovery.

This study investigated the performance of a novel low-grade gas-to-gas waste heat recovery technology, to preheat combustion air, applied to wafer baking ovens. It also compared the newly developed technology with other existing technologies, such as waste heat to hot water, organic Rankine cycle and vapour absorption refrigeration, based on technical feasibility and energy savings. The work presents a systematic methodology for developing and comparing low grade waste heat recovery models for the food manufacturing sector. It also highlighted the key parameters that should be used to evaluate the performance of manufacturing processes with integrated heat recovery systems.

The findings revealed that the energy efficiencies of existing wafer baking processes and equipment used in industry can be improved by ~33% by integrating them with a waste heat recovery unit. The most promising results were obtained by recycling the waste heat back into the baking process, i.e., by preheating the oven's combustion air, which reduces the oven fuel consumption rate. Factors such as production scales and fluctuations in heat sink should be carefully monitored and considered while designing heat recovery systems. Apart from these two factors, the capital and installation costs also have a significant role in the selection of an appropriate heat recovery technology. The study found that the preheating combustion air technology has a payback period of 1.57 years, which is the lowest among all by a fair margin, making it a financially attractive option. To conclude, the heat recovery technology involving preheating combustion air is the most advantageous, provided a sufficiently large heat sink is available.

Author Contributions: S.M. was a postdoctoral researcher who led the experiments, modelling and analysis along with writing the manuscript. A.A. was Co-Investigator and the academic supervisor who also contributed to the planning, analysis and writing and reviewing of the manuscript. M.H. was the Principal Investigator who provided the overview of the research programme and contributed to writing the manuscript. J.I.C. performed the financial analysis and also contributed to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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