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A Framework for Recovering Waste Heat Energy from Food Processing Effluent

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Abstract: Effluent water from food processing retains considerable heat energy after emission from treatment systems. Heat recovery technologies that may be appropriate for implementation in the food processing industry have been widely explored, and selection of the most suitable methodologies has been pursued. A four-stage framework is introduced in this paper to evaluate the potential recoverability of waste heat along with acceptor streams. The systematic approach utilizes thermal and temporal compatibility tools and cost–benefit analyses to determine the ideal heat-recovery equipment for food processing effluent. The applicability of this framework is demonstrated through an industrial case study undertaken in a vegetable canning processing facility. Based on the findings, the framework yields an efficient and optimized heat recovery approach to reducing the total energy demand of the facility.

Keywords: heat recovery; effluent water; decision support system; structured approach

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1. Introduction

The burning of fossil fuels releases carbon dioxide into the atmosphere, continuing to contribute to anthropogenic climate change. Global carbon dioxide emissions have increased dramatically since the turn of the 21st century. Carbon dioxide emissions rose by 40 percent worldwide between 2000 and 2019 [1]. Global greenhouse gas (GHG) emissions must be dramatically reduced to mitigate the effects of climate change. Many countries have officially committed to reducing their emissions under the 2015 Paris Agreement to attain a climate-neutral world by 2050 [2]. The latest UK government response to these pledges includes the Food 2030 strategy, which sets out goals for a sustainable food system for 2030 [3]. Reducing the food sector's energy use and GHG emissions are the most critical priorities for the UK's food processing industry.

As the UK's largest manufacturing sector and the country's fourth-largest industrial energy consumer, the food processing industry is an essential economic driver [4], consuming an estimated 117 PJ of energy in 2017 [5]. Although food processing facility layouts vary, the unit operations used to convert raw agricultural commodities into market-ready products are generally standard [6]. Figure 1 displays the energy consumption by end users in the food processing industry, indicating that 59 percent of energy consumption in the food processing industry is attributed to process heat [7]. For instance, boilers account for roughly 60 percent of the energy used in processing fruits and vegetables [8] and 83 percent of the energy used in wet milling corn is for dewatering, drying, and evaporation processes [6,9]. However, a significant amount of the processing heat, particularly low-grade waste heat (<200 °C) in the form of effluent, is ultimately wasted due to process inefficiencies and inadequate management of energy [10,11].

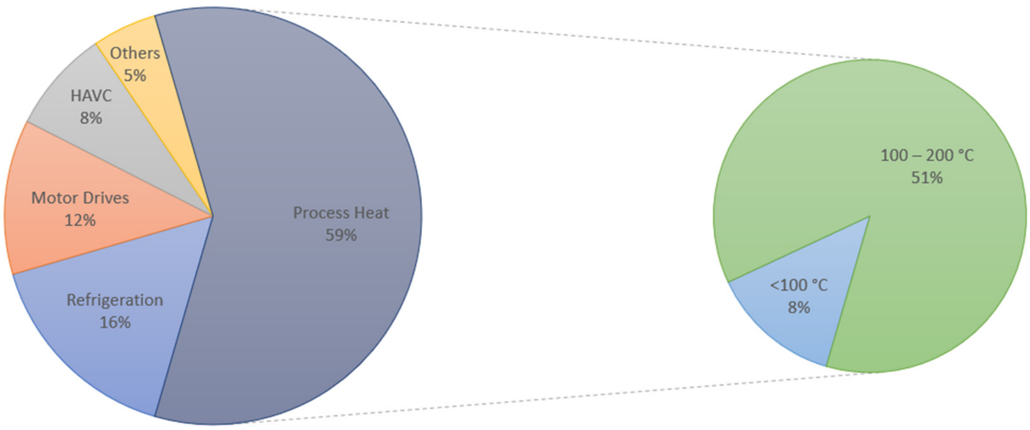

Figure 1. Typical energy consumption by end users in the food processing industry and temperature range, adapted from [12].

In food processing, discharged effluents may come from cleaning, boiler blowdown, condensate from indirect heating, refrigeration condensers and compressors. For example, when processing canned fruits or vegetables, the primary sources of wasted heat are blanching water, topping water, can-cooling water, clean-up hot water, and boiler blowdown (Figure 2a), while in dairy processing, the primary waste heat sources are pasteurization overflow, boiler condensate, clean-up hot water, and vapor from evaporators (Figure 2b).

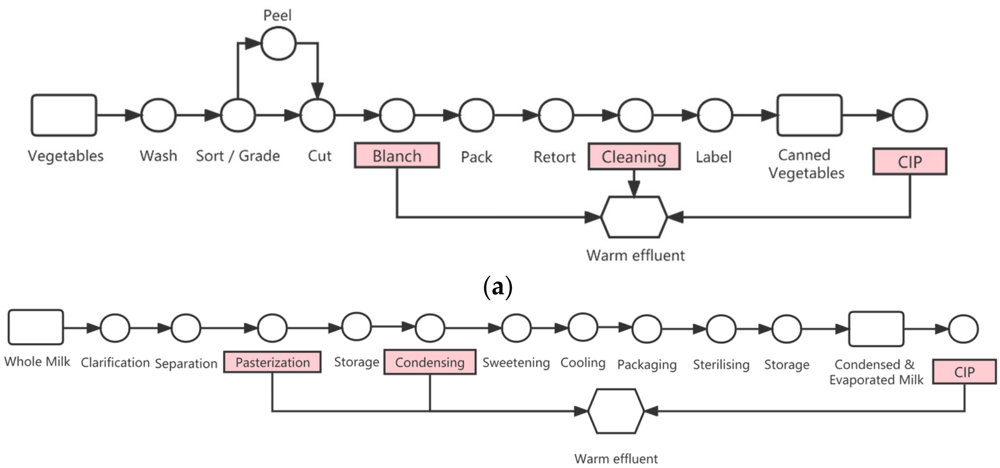

Figure 2. Process flow diagram for producing (**a**) canned vegetables and (**b**) condensed and evaporated milk.

To assess the potential for heat recovery from these streams, a few examples of the process-specific characteristics and temperature data are summarized in Table 1, based on unit of production. Proteins, sugars, and other soluble organic compounds, as well as inverse solubility salts (such as calcium and magnesium phosphates and sulphates) are common components of these waste streams that can interact with and potentially deposit on negatively charged heat exchanger surfaces, reducing heat transfer efficiency. While process and effluent temperature for various canning and dairy production are considered low-grade, the quantity produced is large. The waste heat potential in the UK's food manufacturing sector is estimated at 1.4 TWh per year [13]. It may be advantageous to recover and utilize the unavoidable heat energy loss from food processing effluent for process heating in order to minimize steam consumption and, by extension, the amount of natural gas combusted in boilers [14,15]. Substituting a portion of natural gas consumption with recovered waste heat decreases the quantity of purchased fuel required for processing, thus reducing GHG emissions and providing economic benefits to the food sector.

Table 1. Exemplified waste heat streams in the canning and dairy industries.

Food Processes	Heat Stream Medium	Temp, °C	Reference
Canned Vegetables—Steam Blanching			
Snap beans	Water/Steam	93–99	[12]
Kidney beans	Water/Steam	93–99	[13]
Lima beans	Water/Steam	93–99	[14]
Peas	Water/Steam	75–95	[14]
Clean-in-place	Water	66–80	[16]
Milk processing			
Pasteurisation overflow	Water	70	[17]
Boiler condensate	Water	93	[18]
Clean-in-place	Water	66–80	[19]

Clearly, there is a demand for improved energy efficiency in the food processing industry. At the same time, waste heat recovery strategies have been widely pursued, particularly for boilers, evaporators and dryers, where the recovered heat is reused in the same unit operations [20]. However, recovering and reusing low-grade waste heat from food processing effluent has proven to be challenging and is often done on an ad-hoc basis. Mukherjee et al. [21] reflected that, although there may be potential for energy efficiency improvement by integrating waste heat recovery technology into a baking process, the production schedule, fluctuations in heat source availability and sink demand should be carefully considered. In addition, the relative location of the heat source and sink may also influence the effectiveness of heat recovery [22], with a longer distance between waste heat source and sink being indicative of greater heat loss. Pantaleo et al. [23] investigated the applicability of the Organic Rankine Cycle system in the coffee roasting industry for intermittent waste heat recovery.

Techniques for conducting energy surveys for waste heat recovery have been established in process industries. Linnhoff et al. [24] first proposed the pinch analysis methodology for process heat integration and heat exchanger network design. The work was followed by extensive research and application, for example, incorporating genetic algorithms for optimizing heat exchanger networks [25], implementing waste heat integration for industrial symbiosis [26], industrial batch process [27], and energy storage integration [28]. However, there is a lack of research, in the selection of waste heat recovery equipment. The heat integration techniques may center around reusing waste heat from a specific type of heat exchanger, regardless of the specifics of the underlying process or the optimal design of the heat exchanger. Furthermore, the proposed methods could be seen as rather complex and inaccessible for certain prospective users within industry, hence, external consultants may often be required to carry out full analyses.

This work aims to establish a streamlined process for identifying and evaluating waste heat recovery opportunities within food manufacturing industry, selecting and performing preliminary costing of potential heat recovery equipment. The system is designed to provide a quick order of magnitude assessment, enabling the plant operating managers to make initial decisions for their waste heat recovery projects. A detailed design with full pinch analysis could be conducted following these preliminary results.

2. Methodology

Finding opportunities and establishing the sustainability of recovering waste heat from food processing wastewater may be difficult, particularly when the aim is to identify the solution with the greatest value, which may require combining energy savings, GHG reduction, and return on investment. Furthermore, due to the intricacy of food production, maximizing waste heat recovery may be difficult. Therefore, a systematic method is required to analyze and identify the optimal match between the waste heat and acceptor streams in order to maximize energy efficiency gain.

The aim is to provide plant managers with helpful information and feedback to make informed decisions about investing in heat recovery technologies. Therefore, a framework for collecting, organising, evaluating, and generating relevant data to support the implementation of waste heat recovery technology within food processing plants has been developed.

The effluent waste heat recovery framework comprises of four stages that, as shown in Figure 3, are intended to outline a process for identification and quantitative assessment of waste heat and acceptor streams for utilisation within food processing plants.

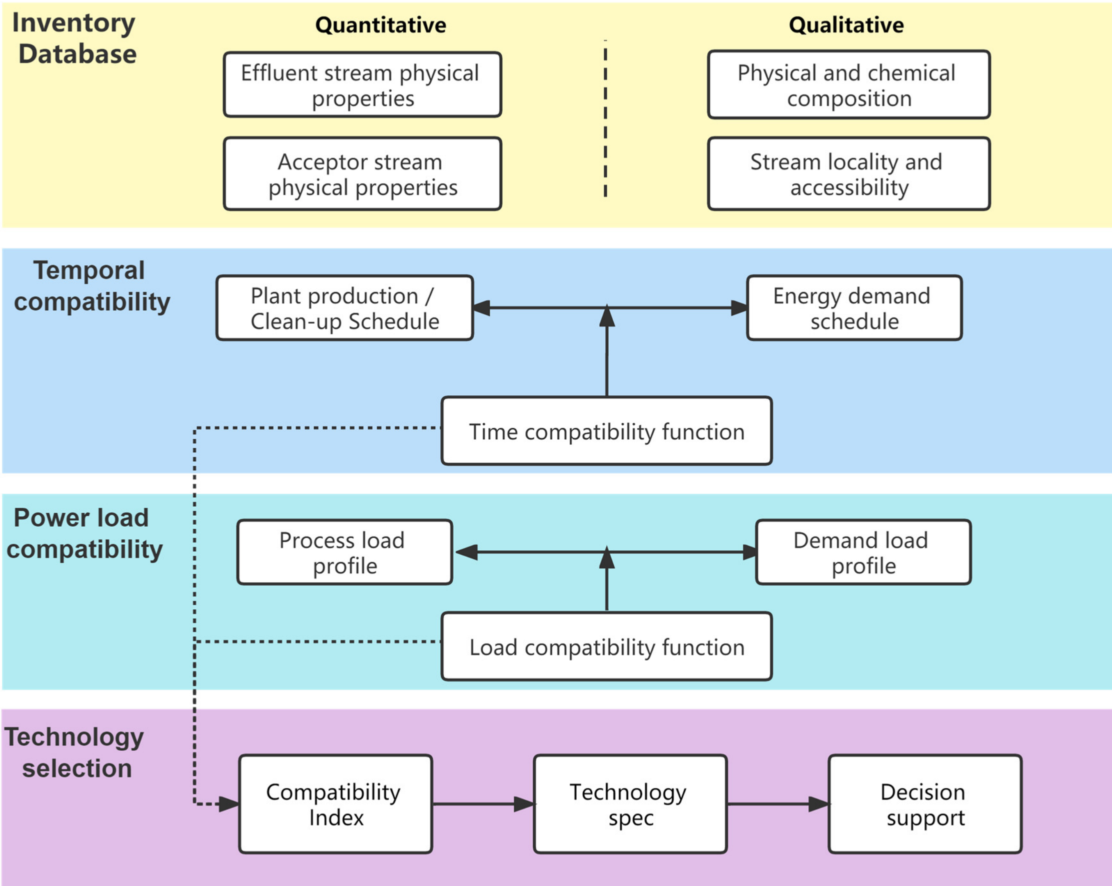

Figure 3. Decision support framework for food processing effluent heat recovery.

2.1. Inventory Database

Carrying out on-site energy audits is the preferable way to obtain accurate waste and acceptor stream data, using various invasive and non-invasive tools and techniques, such as flow meters, thermocouples, or infrared sensors. In the absence of measured data, supplier data sheets or process equipment studies may also be referenced. Theoretical calculation based on assumptions is practical when neither database nor empirical measurement is applicable. It is assumed that the production and cleaning schedules would be readily available to plant managers, from which a detailed time profile for both waste and acceptor streams can be determined. As shown in Table 2, the inventory data will produce both quantitative and qualitative outcomes. The numerical values will then be utilised in the computations of temporal and power load compatibility while a decision-support algorithm characterizes and interprets the descriptive data.

Table 2. Waste heat and acceptor stream physical properties.

Physical Properties	**Units**
Waste heat stream temperature	T_w (°C)
Waste heat stream mass flow	m_w (kg/t material)
Waste heat stream density	p_w (kg/m^3)
Waste heat stream specific heat capacity	$c_{p,w}$ (kJ/kg·K)
Waste heat stream pressure	P_w (bar)
Waste heat stream viscosity	μ_w (kg/m·s)
Acceptor stream temperature	T_a (°C)
Acceptor stream mass flow	m_a (kg/t material)
Acceptor stream density	ρ_a (kg/m^3)
Acceptor stream specific heat capacity	$c_{p,a}$ (kJ/kg·K)
Acceptor stream pressure	P_a (bar)
Acceptor stream viscosity	μ_a (kg/m·s)

2.2. Temporal Compatibility

Maximum effluent heat recovery is achieved when the availability of the waste heat stream aligns exactly with acceptor stream demands. For example, Figure 4 shows the relative load intensity of a fruits and vegetables canning process operation. The demand for clean-up water is typically out-of-phase with waste-heat streams, whereas the demand for boiler feedwater is in-phase, making it the primary acceptor stream for waste heat.

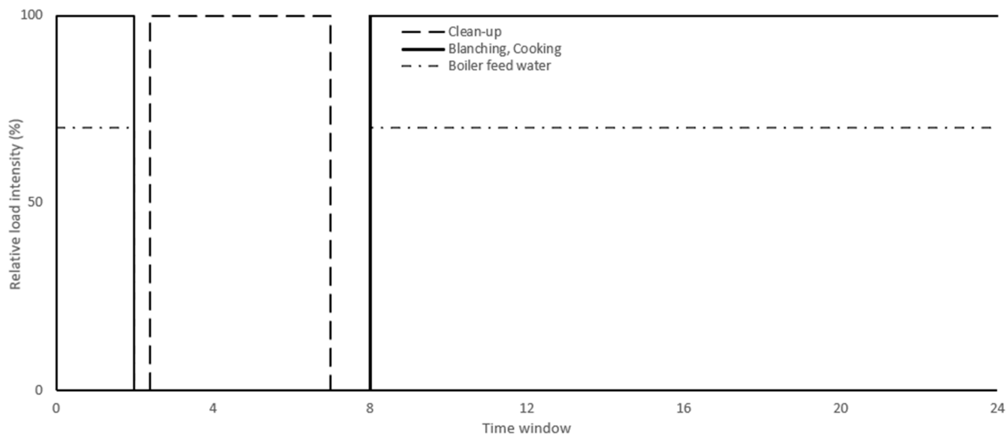

Figure 4. Time profile of a typical vegetable canning operation.

$Power_w$ and $Power_a$ are the load profile for waste heat and acceptor stream, respectively:

$$\mathrm{Power_w}(t) = \sum_{i=1}^{x} \dot{m}_i(t) \cdot c_{p.i} \cdot \Delta T_i(t) = \sum_{i=1}^{x} \dot{m}_i(t) \cdot c_{p,i} \cdot (T_{h,in,i}(t) - T_{h,out,i}(t)) \quad (1)$$

$$\mathrm{Power_a}(t) = \sum_{j=1}^{y} \dot{m}_j(t) \cdot c_{p,j} \cdot \Delta T_j(t) = \sum_{j=1}^{y} \dot{m}_j(t) \cdot c_{p,j} \cdot (T_{c,out,j}(t) - T_{c,in,j}(t)) \quad (2)$$

Following the plotting of the potential waste heat stream and acceptor stream profiles, the temporal compatibility function between the effluent stream and acceptor stream is computed, which is defined as:

$$\mathrm{Temporal_{w,a}}(t) = \begin{cases} \mathrm{Power_a}(t), & \mathrm{Power_a}(t) < \mathrm{Power_w}(t) \\ \mathrm{Power_w}(t), & \mathrm{Power_a}(t) \geq \mathrm{Power_w}(t) \end{cases} \quad (3)$$

The maximum recoverable energy is the integral of the temporal compatibility function over a specific time frame [0, t], for a given waste heat and acceptor stream combination:

$$\mathrm{Recoverable\ Energy_{w,a}} = \int_0^T \mathrm{Temporal_{w,a}}(t)dt \quad (4)$$

The recovery Index, $RI_{w,a}$, is used to reflect on the overall quality of temporal and power load compatibility between waste heat and acceptor streams:

$$0 < RI_{w,a} = \frac{\text{Recoverable Energy}_{w,a}}{\text{Total waste heat}_{w}} < 1 \tag{5}$$

The computation of $RI_{w,a}$ is based on temporal and heat load compatibility between potential waste source and acceptor streams. The process is repeated for all possible combinations and ranking of RI can be carried out. For example, if the user identified three waste heat sources and four sinks in a facility, that would mean a total of twelve combinations. Obviously, not all the combinations are likely to warrant further analysis, because lower values of $RI_{w,a}$ are indicative of relatively poor heat recovery efficiency. In these circumstances, a threshold would be set, for example, $RI_{w,a} \geq 0.5$, to eliminate low quality heat source and acceptor stream matchups.

2.3. Technology Selection and Ranking

A summary of heat exchanger types considered for the decision support framework and their respective technical specifications have been tabulated below (Table 3). Although not comprehensive, the list does contain the more common types. The following should be checked off the list in the table for the specific application under consideration:

1. Maximum pressure—Since many exchanger types only function at low pressure, they can be immediately discounted from consideration for a given application;
2. Temperature range—Many exchanger types can only be used in a narrow temperature range, which, once more, eliminates several types;
3. Fluid restrictions—Compatibility between the fluid and the building materials is emphasized most in this case;
4. Size range available—By connecting several heat exchangers in parallel, the issue of maximum size limitation can always be solved;
5. Complexity with fouling—Fouling can be caused by a variety of mechanisms, which has an impact on the heat exchanger of choice. For instance, suspended solids may make it impossible to use passageways that are too small. Therefore, filtration prior to suspended solids removal can occasionally be cost-effective.

2.4. Decision Support

The ability to assess and visualize the effects of choices is important for the waste heat recovery project. In order to compare the technology options providing the same level of service, a simplified techno-economic analysis is conducted. The analysis can produce data on the annualised net economic benefit and overall payback time for energy savings.

The heat energy load $\dot{Q}$ is calculated based on the heat balance between the waste heat and acceptor streams:

$$\dot{Q} = \dot{m}_h \cdot C_{p,h} \cdot (T_{h,in} - T_{h,out}) = \dot{m}_c \cdot C_{p,c} \cdot (T_{c,in} - T_{c,out}) \tag{6}$$

Using the Logarithmic Mean Temperature Difference (LMTD) method, the mean temperature difference, ΔT_m, is given by

$$\Delta T_m = F_T \cdot \Delta T_{lm} = F_T \cdot \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\log_e \frac{(T_{h,in} - T_{c,out})}{(T_{h,out} - T_{c,in})}} \tag{7}$$

Table 3. Summary of heat recovery technology and technical specification, adapted from [19].

Heat Recovery Tech	Maximum Pressure (Bar)	Temperature Range (°C)	Normal Size Ranges	Special Features	Corrosion Resistance	Advantages	Limitations
Brazed-plate	16	<200	1–10 m^2	Modular construction; not easily cleaned.	Protected by coating	Wide range of operating temperatures; compact design; good heat transfer.	Limited working pressure range; low fouling resistance.
Double-pipe (plain and finned tubes)	300 (shell) 1400 (tube)	−100–600	0.25–200 m^2 Multiple unit combination possible	High thermal efficiency; standard modular construction.	Protected by coating	Offers true counter-current flow (F_T = 1.0); low capital and maintenance costs.	Not available in crossflow design; possibilities of fluid leakage.
Graphite	20	−50–165	0.2–60 m^2	High corrosion resistance	Protected by coating	Highly tolerant to corrosive chemicals.	Monitoring and regular maintenance of coating required.
Plate-and-frame	25	−25–175	1–2500 m^2	Modular construction; stainless steel or titanium often used.	Protected by coating	Corrugated plate design to give efficient heat transfer; can increase in size with little cost.	Limited range of operating temperatures and pressures; integrity of sealing.
Plate-fin	100 (aluminum) 200 (stainless steel)	−273–150 (aluminum) −273–600 (stainless steel)	<9 m^3 volume	Can accommodate small ΔT.	Protected by coating	Highly compact; possibility of multi-stream operation.	Limited temperature and pressure range; intolerant to excessive cyclic stresses.
Printed circuit heat exchanger (PCHE)	1000	<800	1–1000 m^2	Large surface area per unit volume; stainless steel or other alloys used for construction.	Protected by coating	Highly compact; wide range of pressure and temperature.	Not suitable for duties with any significant amount of fouling.
Shell-and-tube	300 (shell) 1400 (tube)	−25–600	10–1000 m^2 Multiple shells can be used	Very adaptable and widely applicable to almost all applications.	Protected by coating	Full range of pressures and temperatures.	Requires more space for cleaning and maintenance; limited tube cooler capacity.
Welded plate	60	>650	>1000 m^2	Differential pressure should be less than 30 bar.	Protected by coating	Wide range of operating temperatures and pressures; large areas are feasible.	Higher cost; limited differential pressure between the two fluids; chemical cleaning of the plates needed.

The heat exchanger industry developed the *C*-value method [19] to perform an order-of-magnitude assessment for heat exchanger sizing and costs. The cost of the heat exchanger is a function of its effective heat transfer area, *A*, which is directly proportional to the overall cost for a particular heat exchange duty specified in terms of $(\dot{Q}/\Delta T_m)$.

$$A = \frac{1}{U}\left(\frac{\dot{Q}}{\Delta T_m}\right) \tag{8}$$

From Tables 3 and 4 [19] provided for each exchanger type, for a particular duty and configuration, values of *C* may be estimated and given in addition to *U* values in the tables. The cost of the heat exchanger may be estimated by simply multiplying *C* by $\dot{Q}/\Delta T_m$. *C* has the units £/(W/K).

$$C = \exp\left\{ \ln C_1 + \frac{\ln(C_1/C_2)\ln\left[(\dot{Q}/\Delta T_m)/(\dot{Q}/\Delta T_m)_1\right]}{\ln\left((\dot{Q}/\Delta T_m)_1/(\dot{Q}/\Delta T_m)_2\right)} \right\} \tag{9}$$

Table 4. U and C values for shell-and-tube heat exchangers (adopted from [19].)

$\dot{Q}/\Delta T_m$ (W/K)	Cold Side Fluid	Parameter	Hot Side Fluid				
			Process Water	Low Viscosity Organic Liquid	High Viscosity Liquid	Condensing Steam	…
1000	Treated cooling water	*U* (W/m^2 K) *C* (£/(W/K))	938 3.77	714 3.85	142 4.59	1607 3.61	…
	Low viscosity organic liquid	*U* (W/m^2 K) *C* (£/(W/K))	600 3.91	500 3.97	130 4.67	818 3.81	…
	High viscosity liquid	*U* (W/m^2 K) *C* (£/(W/K))	161 4.46	153 4.51	82 5.16	173 4.42	…
	…	…	…	…	…	…	…
5000	Treated cooling water	*U* (W/m^2 K) *C* (£/(W/K))	938 0.88	720 0.91	142 1.41	1607 0.83	…
	Low viscosity Organic liquid	*U* (W/m^2 K) *C* (£/(W/K))	600 0.95	500 0.99	130 1.46	818 0.89	…
	High viscosity liquid	*U* (W/m^2 K) *C* (£/(W/K))	161 1.36	153 1.38	82 1.71	173 1.32	…
	…	…	…	…	…	…	…
30,000	Treated cooling water	*U* (W/m^2 K) *C* (£/(W/K))	938 0.23	714 0.25	142 0.56	1607 0.19	…
	Low viscosity Organic liquid	*U* (W/m^2 K) *C* (£/(W/K))	600 0.27	500 0.38	130 0.59	818 0.24	…
	High viscosity liquid	*U* (W/m^2 K) *C* (£/(W/K))	161 0.52	153 0.53	82 0.83	173 0.50	…
	…	…	…	…	…	…	…

If the recovered waste heat is reused within the same process or back into the food processing plant, an equivalent amount of purchased energy is offset. As a result, the expected annual cost saving, C_{as}, is calculated by multiplying the unit power load of heat recovery equipment by the annual service hours and cost per unit energy consumption:

$$C_{as} = (\text{unit kW})\cdot(\text{hrs/yr})\cdot\text{£/kWh} \tag{10}$$

The payback time can be estimated based on the ratio of initial investment capital costs, which include heat exchanger equipment costs, $C_{equipment}$, auxiliary costs, C_{aux}, and cost-saving, C_{as} in terms of purchased fuel replaced:

$$\text{Payback} = \frac{C_{equipment} + C_{aux}}{C_{as}} = \frac{(\dot{Q}\cdot C) + C_{aux}}{\Delta T_m \cdot C_{as}} \tag{11}$$

Thus, industrial decision-makers can use the results of this systematic approach to support investment decisions on heat recovery projects. It may also be utilized beyond the food processing industry to applications in other manufacturing sectors.

3. Case Study

An industrial case study is presented to illustrate the effectiveness and application of the waste heat recovery system described. The investigation is performed utilizing a local vegetable canning processing company that processes 13 tonnes of raw peas per hour during operation. The data in this study comprises actual data supplied by the food manufacturer and references to existing studies when the data provided was inadequate. For this study, it is assumed that the process operation was at steady state with constant properties and unchanged production plans.

The heat recovery framework is implemented to assess the potential for waste heat recovery in the food processing situation. An on-site survey identified that several waste heat streams, as previously illustrated in Figure 2a, present some potential for waste heat recovery. In the thermal process, steam is condensed on the outside of cans to heat the product to a temperature in the range of 120 °C, and after the scheduled process, heat is extracted from the container and its contents by using cold water as a heat sink. This process generates a number of waste heat streams (Table 5):

(1) Condensate from the heating process, which is under pressure and at the corresponding condensing temperature;
(2) Can-cooling water, which is at about 55 °C;
(3) Blanching overflow also presents another source of waste heat, as direct stream heating of blanching water at 88 °C;
(4) Can-topping water at 94 °C.

Table 5. Waste heat recovery inventory data for a canned food processing plant.

Waste Heat Stream(s)	T_{in} (°C)	T_{out} (°C)	Mass Flow m (kg/ton)	Density p (kg/m^3)	Pressure P (bar)	Specific Heat c_p (kJ/kg·K)	Viscosity μ (kg/m·s)
Can-cooling water	55	38	2585	1000	1.0	4.2	1.01
Blanching overflow	90	55	110	1000	1.0	4.2	1.01
Can-topping water	93	59	156	1000	1.0	4.2	1.01
Cooker condensate	122	68	102	1000	1.0	4.2	1.01
Blowdown	168	83	145	1000	8.6	4.2	1.01
Acceptor stream(s)							
Boiler feedwater	15	45	3200	1000	1.0	4.2	1.01

The temporal and energy compatibility assessment indicated that boiler feedwater demand is in-phase in the canning process operation, meaning that the potential sink was pre-heating boiler feedwater for the processing plant. A unique characteristic of both acceptor and effluent streams is that they are essentially an on/off stream. The plan generally runs on an average of 6 days per week.

In this situation, the net results are pre-heating the boiler feedwater from 15 °C to 60 °C by indirect exchange with the waste heat streams. While most processing operations generate condensate at a higher temperature than boiler feedwater, the temporal and energy compatibility algorithm computes the waste and acceptor stream combination based on the Recovery Index ($RI_{w,a}$). As can be seen from Table 6, there are five potential options for waste heat recovery. With an $RI_{w,a}$ value of 0.62, the predominant waste heat energy is encapsulated in the can-cooling water, which is discharged as effluent. Hence, solution #1 is considered to benefit most from implementing a waste heat recovery technology, while #2–#5 are discarded due to lower values of heat recovery efficiency between the match-ups.

Table 6. Ranking of the waste heat and acceptor stream based on $RI_{w,a}$.

Solution #	Waste Heat Stream (s)	Acceptor Stream (s)	$RI_{w,a}$
1	Waste steam 1	Acceptor 1	0.62
2	Waste steam 5	Acceptor 1	0.18
3	Waste steam 3	Acceptor 1	0.08
4	Waste steam 4	Acceptor 1	0.08
5	Waste steam 2	Acceptor 1	0.05

The proposed heat transfer $\dot{Q}$ and ΔT_m is calculated using Equations (6) and (7), respectively, based on the hot inlet, $T_{h,in}$, and outlet, $T_{h,out}$ temperature of the waste heat stream, i.e., can-cooling water, and the cold inlet, $T_{c,in}$, and outlet, $T_{c,out}$, temperature of the acceptor stream, i.e., boiler feedwater.

A list of potential heat recovery technology for the waste and acceptor streams can, therefore, be populated, as seen in Table 7.

Table 7. Potential heat exchanger types with costs based on the C-value method.

Heat Exchanger Types	C_1 £/(W/K)	C_2 £/(W/K)	C £/(W/K)	Total Cost £	Heat Transfer Area (m^2)	Payback Time
Shell and tube	0.88	0.23	0.47	28,795	1206	2 y 3 m
Double pipe	0.5	0.19	0.32	19,606	1054	1 y 5 m

The cost of such a heat recovery project largely depends on the specific unit process, locality and how well the waste heat stream integrates with the acceptor stream. All plant operators need to account for all costs, such as the heat recovery equipment, extra pipework required for longer distances, installation auxiliaries and control systems. The payback period for implementing the heat recovery project is evaluated by returning the number of years necessary to repay the original investment and subsequent operational costs.

The case study conducted on the operations of a canned vegetable processing plant demonstrates the usefulness and applicability of a systematic approach to an industrial problem. By identifying the waste heat hotspots in the plant and evaluating the potential for energy recovery, plant operators are empowered to make informed and optimized decisions based on types of technology to implement and financial payback.

4. Conclusions

The study demonstrates significant potential low-grade waste heat recovery in the food processing industry, particularly from processing effluent that is otherwise discharged without utilization. A four-stage framework has been developed to provide a structured approach to support the plant operators' decision-making on the most suitable heat recovery technology. This is accomplished by understanding the plant energy flows, the availability, compatibility and recoverability of waste heat and acceptor streams and technology selection based on a user-defined criterion.

The case study shows that the system provides a valuable assessment of waste energy flows in the plant, generating beneficial results from temporal and heat load compatibility analysis and allowing comparisons between various waste and acceptor streams and technology options. Furthermore, the framework is relevant to existing and future facilities, as it gives a means of rapidly costing and sizing to determine if energy recovery is a beneficial investment and which technologies are most suited to particular circumstances.

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References

1. IEA. The Future of Cooling in China Delivering on Action Plans for Suistainable Air Conditioning. 2019. Available online: https://iea.blob.core.windows.net/assets/9212903b-e310-48d4-96fa-3eaf7ddf56d9/The_Future_of_Cooling_in_China.pdf (accessed on 12 October 2022).
2. UK Export Finance. Climate Change Strategy 2021 to 2024. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1019141/UKEF_Climate_Change_Strategy_2021.pdf (accessed on 12 October 2022).
3. Government of Ireland. Food Vision 2030: A World Leader in Sustainable Food Systems. 2020. Available online: https://www.gov.ie/en/publication/c73a3-food-vision-2030-a-world-leader-in-sustainable-food-systems/#food-vision-2030 (accessed on 13 October 2022).
4. FDF. Our Industry At a Glance. 2021. Available online: https://www.fdf.org.uk/globalassets/resources/public/general/industry-at-a-glance-april2020.pdf (accessed on 14 October 2022).
5. Department of Business UK. Digest of United Kingdom Energy Statistics 2018. 2018. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf (accessed on 15 October 2022).
6. Jagtap, S.; Rahimifard, S.; Duong, L.N.K. Real-time Data Collection to Improve Energy Efficiency: A Case Study of Food Manufacturer. *J. Food Process. Preserv.* **2022**, *46*, e14338. [CrossRef]
7. Sims, R.; Flammini, A.; Puri, M.; Bracco, S. *Opportunities For Agri-Food Chains To Become Energy-Smart*; FAO: Rome, Italy; USAID: Washington, DC, USA, 2015.
8. Galitsky, C.; Worrell, E.; Ruth, M. *Energy Efficiency Improvement and Cost Saving Opportunities for the Corn Wet Milling Industry: An ENERGY STAR Guide for Energy and Plant Managers*; Lawrence Berkeley National Lab.(LBNL): Berkeley, CA, USA, 2003.
9. Papapetrou, M.; Kosmadakis, G.; Cipollina, A.; la Commare, U.; Micale, G. Industrial Waste Heat: Estimation of the Technically Available Resource in the EU per Industrial Sector, Temperature Level and Country. *Appl. Therm. Eng.* **2018**, *138*, 207–216. [CrossRef]
10. Amón, R.; Maulhardt, M.; Wong, T.; Kazama, D.; Simmons, C.W. Waste Heat and Water Recovery Opportunities in California Tomato Paste Processing. *Appl. Therm. Eng.* **2015**, *78*, 525–532. [CrossRef]
11. Luo, Y.; Andresen, J.; Clarke, H.; Rajendra, M.; Maroto-Valer, M. A Decision Support System for Waste Heat Recovery and Energy Efficiency Improvement in Data Centres. *Appl. Energy* **2019**, *250*, 1217–1224. [CrossRef]
12. Bomben, J.L. Effluent generation, energy use and cost of blanching. *J. Food Process. Eng.* **1977**, *1*, 329–341. [CrossRef]
13. Featherstone, S. Canning of Vegetables. In *A Complete Course in Canning and Related Processes*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 3–84.
14. Featherstone, S. Canning with Pulses and Pasta. In *A Complete Course in Canning and Related Processes*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 169–197.
15. Woolley, E.; Luo, Y.; Simeone, A. Industrial Waste Heat Recovery: A Systematic Approach. *Sustain. Energy Technol. Assess.* **2018**, *29*, 50–59. [CrossRef]
16. Thomas, A.; Sathian, C.T. Cleaning-In-Place (CIP) System in Dairy Plant- Review. *IOSR J. Environ. Sci. Toxicol. Food Technol.* **2014**, *8*, 41–44. [CrossRef]
17. Panchal, H.; Patel, R.; Chaudhary, S.; Patel, D.K.; Sathyamurthy, R.; Arunkumar, T. Solar Energy Utilisation for Milk Pasteurisation: A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2018**, *92*, 1–8. [CrossRef]
18. Law, R.; Harvey, A.; Reay, D. Opportunities for Low-Grade Heat Recovery in the UK Food Processing Industry. *Appl. Therm. Eng.* **2013**, *53*, 188–196. [CrossRef]
19. Hewitt, G.F.; Pugh, S.J. Approximate Design and Costing Methods for Heat Exchangers. *Heat Transf. Eng.* **2007**, *28*, 76–86. [CrossRef]
20. Jagtap, S.; Trollman, H.; Trollman, F.; Garcia-Garcia, G.; Parra-López, C.; Duong, L.; Martindale, W.; Munekata, P.E.S.; Lorenzo, J.M.; Hdaifeh, A.; et al. The Russia-Ukraine Conflict: Its Implications for the Global Food Supply Chains. *Foods* **2022**, *11*, 2098. [CrossRef] [PubMed]

21. Mukherjee, S.; Asthana, A.; Howarth, M.; Chowdhury, J.I. Techno-Economic Assessment of Waste Heat Recovery Technologies for the Food Processing Industry. *Energies* **2020**, *13*, 6446. [CrossRef]
22. Legorburu, G.; Smith, A.D. Energy Modeling Framework for Optimizing Heat Recovery in a Seasonal Food Processing Facility. *Appl. Energy* **2018**, *229*, 151–162. [CrossRef]
23. Pantaleo, A.M.; Fordham, J.; Oyewunmi, O.A.; De Palma, P.; Markides, C.N. Integrating Cogeneration and Intermittent Waste-Heat Recovery in Food Processing: Microturbines vs. ORC Systems in the Coffee Roasting Industry. *Appl. Energy* **2018**, *225*, 782–796. [CrossRef]
24. Linnhoff, B.; Hindmarsh, E. The Pinch Design Method for Heat Exchanger Networks. *Chem. Eng. Sci.* **1983**, *38*, 745–763. [CrossRef]
25. Ravagnani, M.A.S.S.; Silva, A.P.; Arroyo, P.A.; Constantino, A.A. Heat Exchanger Network Synthesis and Optimisation Using Genetic Algorithm. *Appl. Therm. Eng.* **2005**, *25*, 1003–1017. [CrossRef]
26. Kapil, A.; Bulatov, I.; Smith, R.; Kim, J.-K. Process Integration of Low Grade Heat in Process Industry with District Heating Networks. *Energy* **2012**, *44*, 11–19. [CrossRef]
27. Krummenacher, P.; Favrat, D. Indirect and Mixed Direct-Indirect Heat Integration of Batch Processes Based on Pinch Analysis. *Int. J. Thermodyn.* **2001**, *4*, 135–143.
28. Olsen, D.; Liem, P.; Abdelouadoud, Y.; Wellig, B. Thermal Energy Storage Integration Based on Pinch Analysis—Methodology and Application. *Chem. Ing. Tech.* **2017**, *89*, 598–606. [CrossRef]