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Multi-Level Process Integration of Heat Pumps in Meat Processing

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Abstract: Many countries across the globe are facing the challenge of replacing coal and natural gas-derived process heat with low-emission alternatives. In countries such as New Zealand, which have access to renewably generated electricity, industrial heat pumps offer great potential to reduce sitewide industrial carbon emissions. In this paper, a new Pinch-based Total Site Heat Integration (TSHI) method is proposed and used to explore and identify multi-level heat pump integration options at a meat processing site in New Zealand. This novel method improves upon standard methods that are currently used in industry and successfully identifies heat pump opportunities that might otherwise be missed by said standard methods. The results of the novel method application suggest that a Mechanical Vapour Recompression (MVR) system in the Rendering plant and a centralized air-source heat pump around the hot water ring main could reduce site emissions by over 50%. Future research will develop these preliminary results into a dynamic emissions reduction plan for the site, the novel methods for which will be transferrable to similar industrial sites.

Keywords: heat pump; total site analysis; energy saving; industrial heat integration; decarbonization; meat processing

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Citation: Klinac, E.; Carson, J.K.; Hoang, D.; Chen, Q.; Cleland, D.J.; Walmsley, T.G. Multi-Level Process Integration of Heat Pumps in Meat Processing. *Energies* **2023**, *16*, 3424. https://doi.org/10.3390/en16083424

Academic Editors: Antonio Zuorro, Athanasios I. Papadopoulos and Panos Seferlis

Received: 13 February 2023
Revised: 4 April 2023
Accepted: 7 April 2023
Published: 13 April 2023

1. Introduction

In response to global commitments that aim to limit climate change, such as those outlined in the recent 27th Conference of the Parties to the UNFCCC (COP27), many fossil fuel-reliant industries, including the meat industry, will have to rethink their process heat production and use [1]. In 2022, the Ministry of Business, Innovation, and Employment (MBIE) reported that 56% of all process heat in New Zealand was supplied using fossil fuels, 84% of which was used in industry [2]. This presents a substantial challenge to industry to reduce industrial emissions whilst maintaining economic viability.

There are multiple renewable energy-based technologies that could help reduce carbon emissions from industrial heating processes, including the increased use of electrode boilers, biomass boilers, or the implementation of heat pumps and Mechanical Vapour Recompression (MVR) [3,4]. This paper focuses on the latter two options: heat pumps and MVRs. An MVR is an open-cycle heat pump that uses a process stream itself as the working fluid (e.g., water vapour produced from an evaporation process may be compressed to increase its temperature before it is used to heat another stream) [5]. A common measure of energy efficiency in MVRs and heat pumps is the Coefficient of Performance (COP). This is the amount of energy delivered to a site divided by the energy consumed (in the form of electricity or combustible fuel). In boilers, the maximum COP value that can theoretically be reached is 1, whereas heat pumps and MVRs can have much higher COPs [6,7].

In New Zealand, electricity is over 80% renewably generated, giving industrial heat pumps and other electricity-fueled solutions great potential to recover waste heat and reduce industrial carbon emissions [8].

To determine which technologies will be most effective on an industrial site, some preliminary modelling of the site's utility demands and heat recovery potential is needed. Pinch analysis is a linear graphical tool used to quickly visualize potential heat recovery and energy savings for heat integration and retrofit design [9]. Process integration based on Pinch methods began in the 1970s, and the inclusion of heat pumps within the analysis was first presented by Linnhoff and Townsend in 1983 [10]. In 1993, Linhoff and Townsend brought these Pinch analysis methods together in the first iteration of the Total Site Heat Integration concept [11].

Total Site Heat Integration (TSHI) is a method of applying Pinch principles to entire industrial sites, often in combination with some mathematical programming tools. Similar to Pinch analysis, TSHI is largely a graphical tool and uses plots such as Total Site Profiles (TSP), Site Composite Curves (SCC), and Site Utility Grand Composite Curves (SUGCC) to display utility use and heat recovery options [12,13]. TSHI is generally used across multiple sites or processes, treating them as separate geographic zones within a Pinch analysis study. Physical distances between individual zones are accounted for by assuming the use of an intermediate utility fluid for any zone-to-zone heat recovery [14,15].

In addition to the assignment of zones for TSHI, a range of other TSHI and Pinch analysis methods have been developed that are progressively more accurate and applicable to real industrial processes [6,16]. For example, Liew et al. [17] modified the TSHI method to include heat transfer processes that had previously been overlooked by earlier TSHI methods, such as accounting for the sensible heating in boiler feed water in addition to the enthalpy of vaporization. Chew et al. [18] included some additional methodology to account for pressure drops. Bagajewicz et al., Becker et al., Quijera et al., Miah et al., Liew et al., Wallerand et al., and Schlosser et al. all propose improvements for heat pump integration within TSHI [6,12,19–24].

Despite being a proven aid to heat integration and retrofit design for over 50 years, literature suggests that the use of Pinch and TSHI methods is not as widespread in industry as it could be. Gorsek et al. [13] state that "intuition and experiences of engineers" aretill preferentially used over established process integration techniques, an observation that is also made by Zuberi et al. [25], who remarked on the hesitance associated with the uptake of Pinch and TSHI techniques in industry due to the perceived high risks associated with inaccurate modeling methods. Miah et al. [14] draw particular attention to non-continuous processes, such as those in the food industry, as these are processes that require a more specialized Pinch or TSHI analysis to accurately account for the process dynamics when being used to integrate and upgrade a site.

To increase the utilization of TSHI techniques and address the need for further development of Pinch-based TSHI techniques, particularly for non-continuous sites, this paper presents a novel, multi-level TSHI method. This multi-level layering of TSHI helps improve the accuracy of heat pump plans generated for a site. Previous methods focused on optimizing the application of a single TSHI analysis to find heat recovery and heat pump opportunities. A single TSHI analysis might be effective at highlighting some heat pump opportunities that exist on a site at an instantaneous level; however, there may be further heat pump opportunities available that could be missed through the lack of a multi-level TSHI application. Additionally, the method presented in this paper preferentially targets specific locations and high temperatures within the industrial site. This reduces the scheduling challenges that are common in non-continuous processing sites and frees up heat pump opportunities at the lower temperature levels where heat can typically be more easily supplied using air-source or waste heat-source heat pumps.

This paper investigates an example of this multi-level TSHI method at a meat processing site in New Zealand, building on the 'Unified Total Site Targeting' TSHI method proposed by Tarighaleslami [16,26]. The results of this multi-level TSHI method will be compared to the results of standard engineering practices previously used for the identification of heat pump opportunities on the case study site.

To summarise, the significant contributions of the research described in this paper are as follows:

- Demonstrate the use of Pinch-based TSHI methods for an industrial meat processing site.
- Demonstrate a novel multi-level TSHI method used to identify heat pump options on non-continuous industrial sites.
- Compare results from this novel method against standard pinch and general engineering knowledge and experience-based results previously conducted on the meat processing case study site.

Future research on this case site will develop these preliminary results into a dynamic emissions reduction plan for the site and estimate the economic cost of said emissions reduction plan.

2. Case Study

The case study site processes 1.3 million lambs and 800,000 beef cattle per year. The site consists of separate lamb and beef slaughter and boning facilities, a casings plant, a Rendering plant, and a fellmongery. The range of products produced at the site includes meat cuts, offal, lamb skins, wool, blood meal, bone meal, and tallow. Typically, the slaughter processes are the first to start up and the first to shut down each weekday, creating a scheduling mismatch between slaughter zones and other processing zones.

The main source of process heat is two coal boilers in the boiler house, with additional heating provided by small-scale electric and electrode boilers. These boilers provide all the steam and most of the hot water needs for the site. Coal is an emissions-intensive fuel source with the highest carbon content per unit energy of all fossil fuels; hence, it is the key heat source targeted for reducing the site's CO_2 emissions [24].

Previous work has been performed to reduce the sites CO_2 emissions. This resulted in the identification of two heat pump opportunities, identified using both general engineering knowledge and experience and a standard pinch analysis. The installation of one of the heat pumps has already begun and uses waste heat from local refrigeration units to heat hot water in a ring main to the temperatures needed for sterilization on the Beef Slaughter floor. Similar plans are in place to install a heat pump for heating sterilization water on the Lamb Slaughter floor.

The flow of hot water utilities across the case study site is controlled through a collection of heat exchangers and storage tanks that make up the Hot Water Utility System. Figure 1 shows the flows to and from the Boiler and Hot Water Utility System before any heat pump installations.

The steam produced by the coal boilers is used to heat water from 10 °C to approximately 70 °C. Each of the main site processes has local boilers that are used to top up the delivered hot water to 90 °C for sterilization. A portion of this hot water is mixed with cold water to create medium-temperature hot water for blood washdown and low-temperature hot water for hand washing. The approximate split between each of these hot water streams was estimated using hand calculations based on the number and flow rate of individual sterilizing, hand washing, and washdown outlets:

- 90 °C for sterilization: 47% of the total volume of hot water;
- 60–65 °C for blood washdown: 42% of the total volume of hot water;
- 40–45 °C for hand washing: 11% of the total volume of hot water.

Steam is also used directly in rendering dryers.

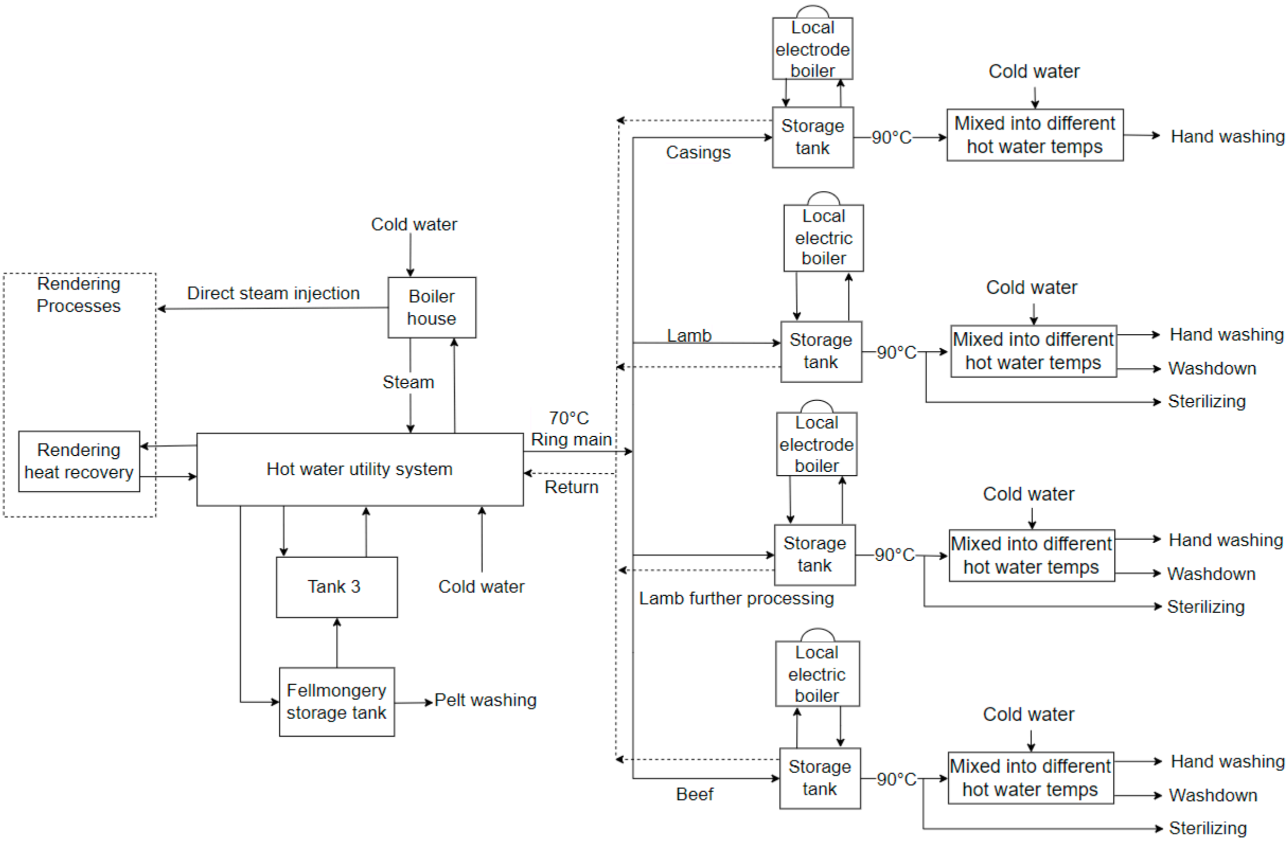

Figure 1. Simplified flow diagram of the utility system at the case study site before any heat pump installation plans are proposed.

3. Materials and Methods

3.1. Data Acquisition and General TSHI Method

Information about the case study site was gathered via correspondence with the site staff and consulting engineers. Site visits also aided in mapping out the large variety of processes and heating requirements throughout the site. It is important to note that the data taken from the site only provided a SCADA (supervisory control and data acquisition) snapshot during typical operating conditions and, hence, does not represent the dynamic changes in heat flows that are experienced over time.

The heat flows in each stream were calculated based on the SCADA-measured stream temperature and mass flow rate. The main heat streams directly incoming and outgoing from the Hot Water Utility System (Figure 1) were metered and monitored at the site. However, the exact quantities of each utility further down the processing line were estimated. For example, the total hot water being used from the ring main in each zone is measured by the SCADA system, but the end-point use in individual sterilizers, hoses, and washing stations is unmetered.

For ease of modelling, the Rendering streams that require direct steam injection are lumped together in this analysis; however, in reality, blood products and meat are processed in separate streams. Likewise, the refrigeration loads on site were based on previous calculations by consultant engineers (separate from this study) into values of net heat rejection from condensers.

Data was analysed using the Unified Total Site Targeting (UTST) TSHI method, as described by Tarighaleslami et al. [26]. This method calculates a unified total site target at the individual zone Grand Composite Curve level, rather than at the final total site plot, and helps ensure that heat recovery is not overestimated, as it often is using conventional TSHI methods. The steps used in this UTST method are summarised as follows:

1. Data specification:
2. Extract stream data from the site.
3. Select a minimum approach temperature (gases, and liquids prone to fouling will have higher minimum approach temperatures).
4. Process level targeting:
5. Shift stream temperatures to intermediate temperatures T*.
6. Construct a problem table, Composite Curve, and Grand Composite Curve for each zone.
7. Target intra-zonal heat recovery, including overall minimum hot and cold utility targets for each zone.
8. Select utilities and their respective minimum approach temperatures.
9. Remove 'pockets' for intra-zonal Heat Recovery from the Grand Composite Curves to focus on net utility demands.
10. Calculate individual zone utility generation and consumption.
11. Total site Level Targeting
12. Shift intermediate temperatures (T*) to the utility temperature scale (T**).
13. Construct the Total Site Profile (TSP).
14. Match utility generation and consumption to calculate Total Site utility targets (plotted alongside the TSP).
15. Construct the Site Utility Grand Composite Curve to find the Total site Pinch temperature region and utility needs.

Process level targeting requires the utilization of Pinch techniques to create Composite Curves and Grand Composite curves. This involves the classification of process streams as either those that have excess heat or those that have a heat deficit, so that they can be coupled together in heat exchange networks. The various streams are presented graphically in Composite Curves which display temperature with respect to heat flows.

A Grand Composite Curve allows the identification of a Pinch temperature where the hot and cold streams converge on the Y axis (Figure 2) and heat recovery is most constrained by temperature difference.

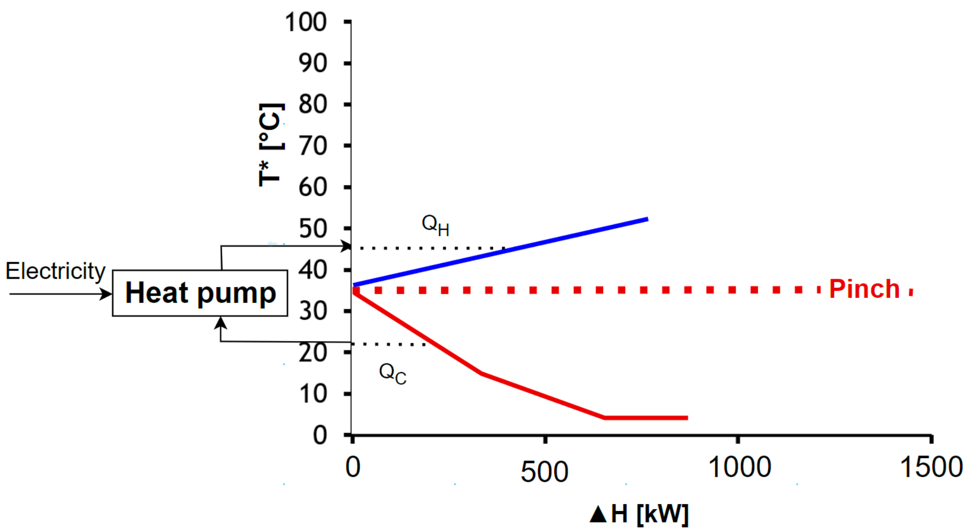

Figure 2. Example of a Grand Composite Curve with an across Pinch placement of a heat pump upgrading excess heat below the Pinch for use above the Pinch [9]. Blue curves indicate process streams that require heating, and red curves indicate process streams that require cooling. T* referring to the shifted temperature.

Heat pumps are traditionally implemented to upgrade excess heat from streams below the Pinch temperature for use in streams above the Pinch temperature (Figure 2) [12].

The following section describes the application of this existing method and how it is adjusted to best analyze the case study site and produce insights into multi-level heat pump opportunities.

3.2. Case Study Method Application

The case study site was broken down into Beef, Lamb, Lamb-further-processing, Casings, Fellmongery, Rendering, and Wastewater zones. The boundary of each zone was determined firstly by geographic location; for instance, Casings processing occurs in a building separate from the rest of the processing areas; likewise for Rendering and Fellmongery. Local scheduling was also considered in determining the boundaries of each zone. For example, although the Beef and Lamb further processing zones are in the same building, each of these zones processes meat independently of the other, resulting in potentially different operating hours and loads.

As it is preferable that any streams involved in heat recovery are close to each other and operating at the same time, these selected zones ensure the UTST method (Step 2c of the General Method) will calculate the intra-zonal heat recovery first, following which any zone-to-zone heat recovery available is calculated assuming the use of an intermediate utility fluid. The ΔT_{min} selected was 5 °C to account for the age and fouling of the plate heat exchangers on site [27]. The utilities included in this analysis are steam at 130 °C, hot water at 90 °C, ring main hot water at 70 °C, and cooling water at 10 °C.

Previous work has been conducted on this site to try to identify heat pump opportunities using standard Pinch TSHI analyses. For the purposes of this research, data has been used from before any heat pump installation so that any differences between the results from standard Pinch TSHI and the novel method proposed are clear.

3.3. Novel TSHI Method Application

To integrate the case study site most efficiently for heating and to find optimal heat pump placements, the results for the UTST were first evaluated for any MVR or heat pump integration that could reduce fossil fuel use in the high load, high temperature regions. Addressing these higher temperatures first helps free up additional heat pump opportunities at lower temperatures that can typically be more easily supplied using air-source or waste heat source heat pumps. This creates a multilevel design where TSHI is applied multiple times to identify new integration options that are only available after other integration techniques or heat pump installations are implemented.

For the first application of the UTST method, the Total Site Plot (TSP) and Site Utility Grand Composite Curves (SUGCC) were generated to provide a graphic identification of the utilities that have the highest demand. Once high temperature and high demand utilities were identified from the TSP and SUGCC, details of these high temperature and high demand areas were then extracted from the individual Grand Composite Curves (GCCs). The GCCs for each zone were evaluated by looking at streams either side of Pinch temperatures to see if any zones have clear high-temperature across-pinch heat pump or MVR options.

Promising MVR opportunities are those that have the heat sink stream above the Pinch temperature and the heat source stream below the Pinch temperature (referred to as 'placement across the Pinch') with a small temperature lift between vapour streams. Vapour streams are visible on TSP, SUGCC, and GCC's as near horizontal lines since they release heat nearly isothermally (enthalpy of vaporisation). By contrast, liquid streams are typically diagonal as heat is transferred over a temperature range. Promising heat pump opportunities are also located across Pinch temperatures but apply to liquid rather than vapour streams and require a working fluid as an intermediate to the heat transfer between the heat source and heat sink.

The smaller the temperature lift, the higher the COP for MVRs and heat pumps. Hence, if adjustments to utility temperatures and flexible process stream temperatures can be made without adversely affecting the processes involved there is opportunity for increasing the COPs of the identified MVRs and heat pumps.

Once heat pump placement was identified from the TSP, SUGCC, and GCC's, the UTST data input was adjusted accordingly, and the results were recalculated. The results of this second UTST analysis show the site as if the heat pump opportunities from the first UTST were implemented. The TSP and SUGCC show the new utility profile for the site and how this profile fits with the process streams. It was expected that in the new SUGCC, there would be a lower demand in the high temperature region previously targeted for heat pump integration and a potential shift in demand in the lower temperature regions, which are generally easier to satisfy with air-source or waste heat source heat pumps. The TSP, SUGCC, and GCC graphs generated from this second UTST were evaluated for more heat pump opportunities by looking at the new utility demands. Similar utility temperature adjustments can be made where possible to improve the COP of any identified heat pump opportunities.

A third UTST iteration was used to display the final results of the two layers of heat pump integration previously identified in order to summarise remaining utility demands and emissions.

3.4. Assumptions and Limitations

This research only considered a single set of data taken during regular day operations on site. It is likely that throughout the day, week, and year, there will be substantial variations in heating loads and utility demand. Hence, future research will look at data noise, dynamics, and the site's need for storage to buffer fluctuations in heating demands.

Economic costs have not been calculated within this research; however, future research is intended to incorporate this into the novel TSHI method.

The only emissions considered in this analysis are those produced during the operation of the plant components; emissions associated with the manufacture and maintenance of new and existing components are not accounted for.

4. Results

Emissions calculations were based on the New Zealand Government's 2020 summary of emissions factors for purchased electricity and coal [28]. Electricity in New Zealand has an emissions factor of approximately 30 g CO_2-e/MJ or 108 g CO_2-e/kWh, including transmission and distribution losses. The coal used on the case study site is sub-bituminous, with a calorific value of 21.5 MJ/kg and an emissions factor of 2.01 kg CO_2-e per kg coal, or 92 g CO_2-e/MJ.

The ratio of electricity to coal emissions factors reflects the lowest allowable COP for CO_2 emissions reduction [29]. Assuming a coal boiler efficiency of 80%, this gives a minimum COP target of 0.26:

$$\text{COP} > 30/92 * 0.8 = 0.26$$

Figure 3 shows a simplified Sankey diagram of the case study site's process heat sources and uses. The corresponding CO_2 emission associated with this process heat demand is approximately 9300 t CO_2-e per year, assuming a coal boiler efficiency of 80%.

Total Site Heat Integration (TSHI) was used to determine heat recovery and utility targets. Based on the results and process Pinch analysis, heat pump implementation, and utility optimization were recommended. Table 1 summarises the results of the case study site's TSHI analysis.

Each individual zone can only undergo interzonal heat recovery if the local Pinch temperatures are different. Hence, heat recovery between Casings and the Fellmongery is not an option because they have the same Pinch temperature of 12.5 °C (Table 1). Similarly, heat recovery between beef and lamb is not an option. If all possible heat recovery opportunities are used on-site, a maximum of 4233 kW can be recovered. Much of this heat recovery is also limited by fouling issues since any water that has been used to wash slaughter floors will likely be heavily contaminated with blood and fat. Additionally, slaughter zones operate at slightly earlier hours than other zones, which reduces zone-to-zone heat recovery options. Realistically, with heat recovery between rendering and slaughter zones removed, the Unified Total Site Target for heat recovery achievable on-site may be closer to 2097 kW. This is equivalent to a carbon emissions reduction of around 2159 t CO_2-e per year. The corresponding Grand Composite Curves (GCC) are shown in Figure 4, and the total site plot and Site Utility Grand Composite Curve (SUGCC) plots are shown in Figure 5.

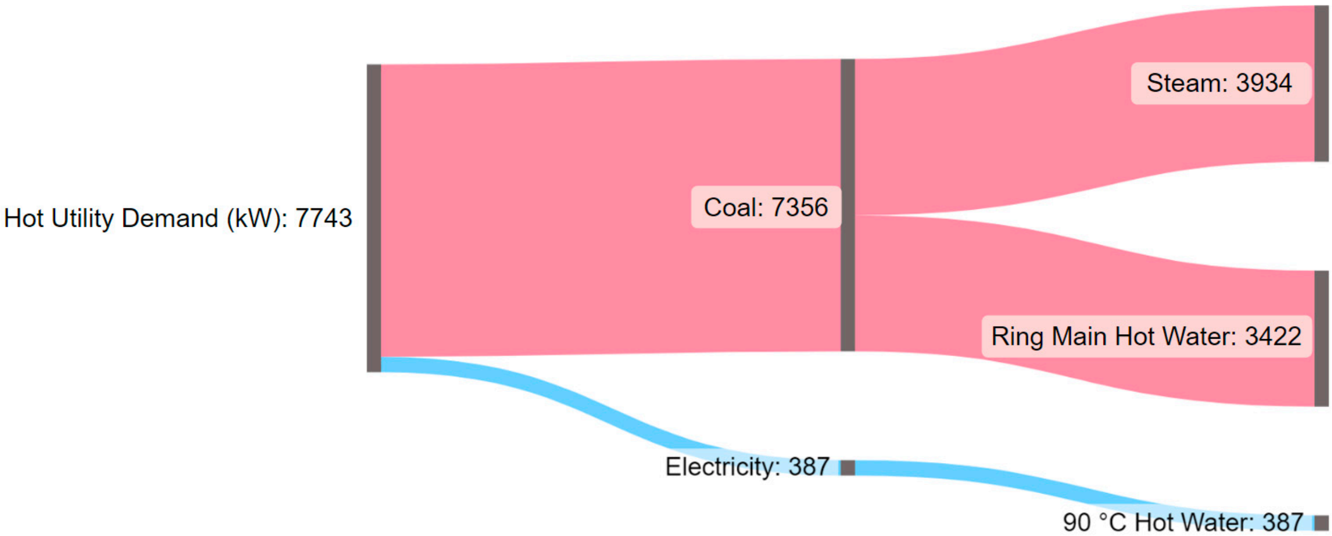

Figure 3. Sankey diagram of case study process heat sources and uses in MW.

Table 1. Summary of results from TSHI of case study site zones.

Zone	T_{Pinch} (°C)	Hot Utility Required (kW)	Cold Utility Required (kW)	Possible Heat Recovery (kW)
Beef	29	884	193	472
Casings	12.5	579	0	0
Fellmongery	12.5	183	0	0
Lamb	29	1264	288	552
Lamb Further Processing	88	4	938	94
Rendering	88	2732	2077	980
Wastewater	33	0	2977	0
Total of Zone Targets		5646	6473	2097
Unified Total Site Target	85	3511	4338	4233

The SUGCC indicates that the highest hot utility demand is in the steam region, hence high temperature MVR and heat pump opportunities were considered a priority to both reduce emissions and free up lower temperature heat pump opportunities. Grand Composite Curves were examined for each zone to find appropriate MVR or heat pump placement options. From these graphs, there appears to be an opportunity for the placement of an MVR system in the Rendering plant (Figure 6).

This Rendering MVR system would recompress waste vapour from the bone meal dryers and bloodmeal dryers for reuse in the dryer feed streams. Such an MVR would have a COP of approximately 31, assuming an isentropic efficiency of 86%, upgrading 81 °C waste steam to 110°C [3,30]. This installation could displace over 2 MW of heat from the coal boiler, resulting in a reduction in the site's carbon emissions by 2170 t CO_2-e per year. This arrangement would not suffer from scheduling issues as the heat recovered from recompression would be used within the same zone. Table 2 summarizes the results of the case study site's TSHI analysis adjusted for the inclusion of the Rendering MVR.

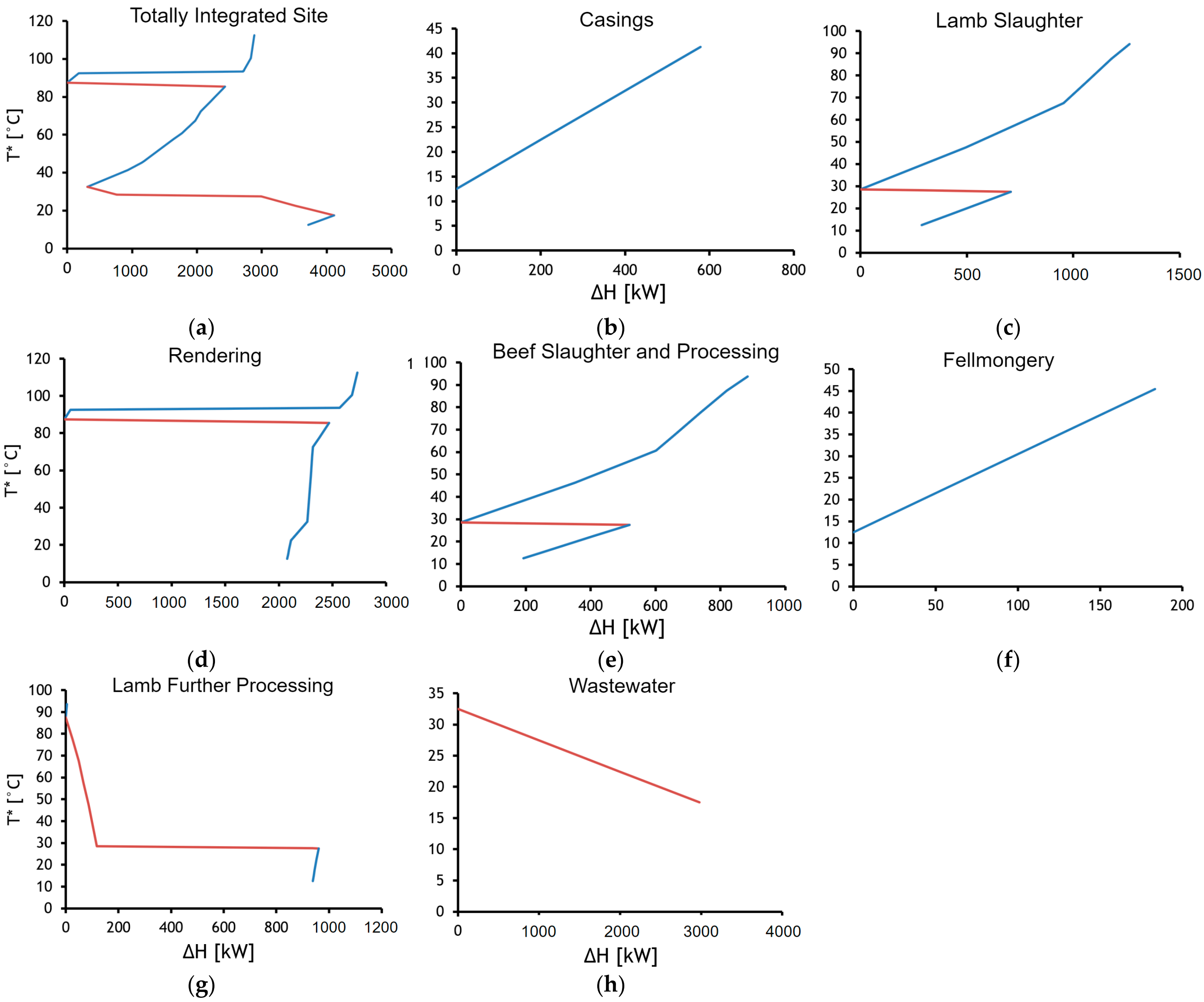

Figure 4. (**a**) Grand Composite Curve for the entire site; (**b**) Grand Composite Curve for the Casings zone; (**c**) Grand Composite Curve for the Lamb slaughter zone; (**d**) Grand Composite Curve for the Rendering zone; (**e**) Grand Composite Curve for the Beef processing zone; (**f**) Grand Composite Curve for the Fellmongery zone; (**g**) Grand Composite Curve for the Lamb Further Processing zone; and (**h**) Grand Composite Curve for the Wastewater zone. Red colored lines represent streams that require cooling, and blue colored lines represent streams that need heating. T* referring to the shifted temperature.

In comparison to the original TSHI analysis results (Table 1), there is a large decrease in hot utility demand within Rendering, with a reduction in hot utility demand from 2732 kW to 621 kW. Ultimately, this helps shift the case study site's hot utility demand to lower temperatures, opening new opportunities for heat pump use on site.

Figure 7 gives the Total Site Profile and SUGCC once the Rendering MVR is installed, showing that the main heat demand from the site has been shifted down into the lower temperature regions in the SUGCC (c.f. Figure 5). This temperature region is easier to satisfy using more traditional air- or water-source heat pumps.

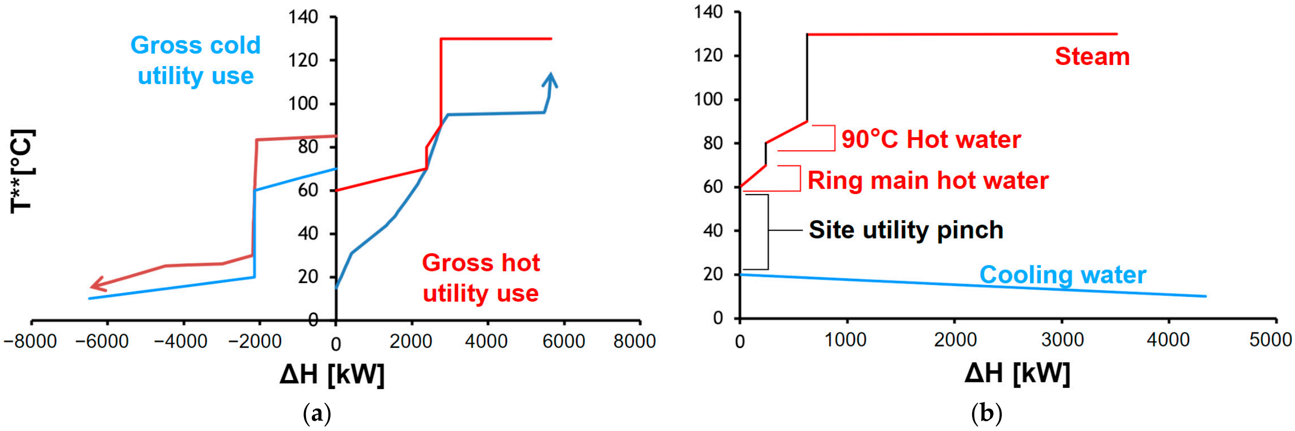

Figure 5. (**a**) Total Site Plot, the red coloured lines on the Gross cold utility use side of the plot, represent process streams that require cooling, and the blue colored lines represent the cold utility streams that would be required to carry out this cooling. The blue colored lines on the Gross hot utility use side of the plot represent process streams that require heating, and the red colored lines represent the hot utility streams that would be required to carry out this heating; (**b**) SUGCC of current site utilities. Red colored lines represent hot utilities, and blue colored lines represent cold utilities. T** referring to twice shifted temperature.

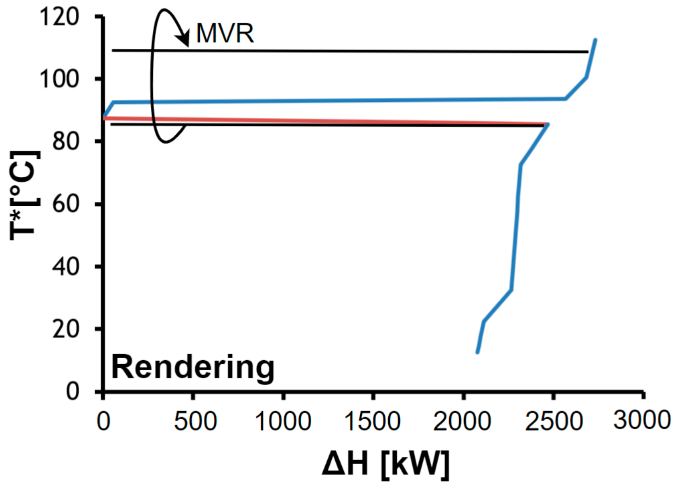

Figure 6. System Composite Curve of the Rendering processing zone with potential Mechanical Vapour Recompression (MVR) placement. Red lines represent streams that require cooling, and blue lines represent streams that need heating. T* referring to the shifted temperature.

Table 2. Summary of results from TSHI for case study site zones adjusted for MVR incorporation.

Zones	Hot Utility Required (kW)	Cold Utility Required (kW)	Possible Heat Recovery (kW)
Beef	884	193	472
Casings	579	0	0
Fellmongery	183	0	0
Lamb	1264	288	552
Lamb Further Processing	4	938	94
Rendering	621	0	565
Wastewater	0	2977	0
Total of Zone Targets	3535	4396	1682
Unified Total Site Target	3459	4320	1759

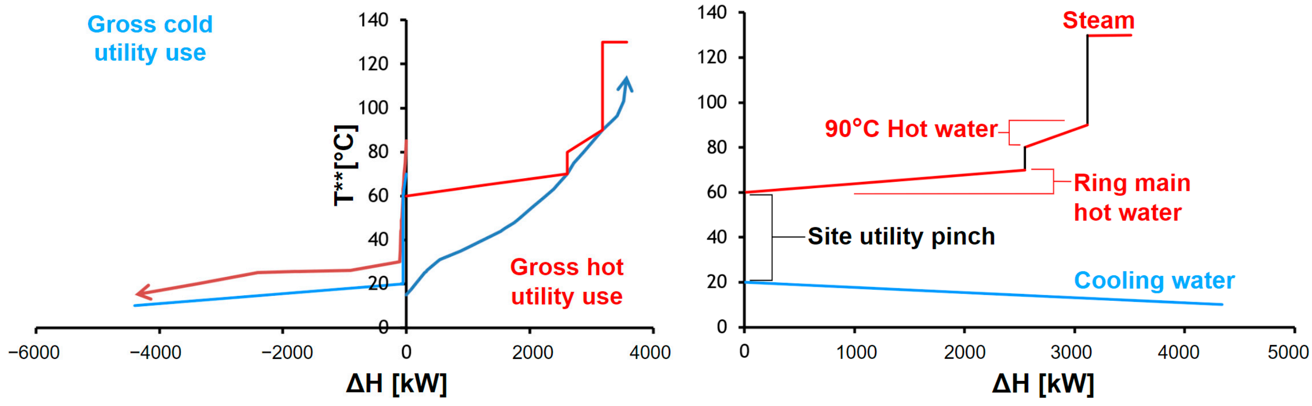

Figure 7. (**a**) Total Site Plot with MVR implemented. The red lines on the Gross cold utility use side of the plot represent process streams that require cooling, and the blue lines represent the cold utility streams that would be required to carry out this cooling. The blue lines on the Gross hot utility use side of the plot represent process streams that require heating, and the red lines represent the hot utility streams that would be required to carry out this heating; (**b**) Site Utility Grand Composite Curve with MVR implemented. Red lines represent hot utilities, and blue lines represent cold utilities. T** referring to twice shifted temperature.

A centralised air-source or ground-source heat pump in the Hot Water Utility System could be utilised to heat cold utility water from between 10 and 20 °C up to the ring main temperature of 60 to 70 °C (Figure 8). Such a heat pump could replace the coal boiler in providing ring main hot water. With the current ring main temperature of 70 °C, a heat pump operating between the cold utility and the ring main could have a COP of 3 (assuming 50% of Carnot COP) [31].

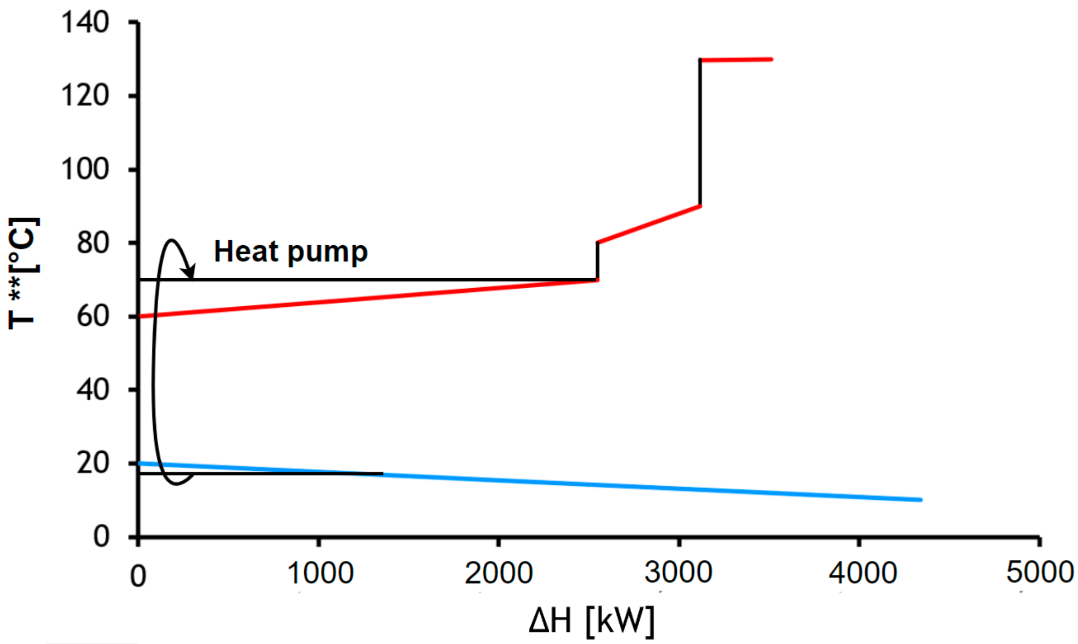

Figure 8. Site Utility Grand Composite Curve of the case study site with position of centralized heat pump shown heating to a lowered ring main temperature of 60°C. Red colored lines represent hot utility, and blue colored lines represent cold utility. T** referring to twice shifted temperature.

However, by reducing the ring main temperature to 60 °C, it is probable that a more favourable COP of almost 4 could be achieved, although this puts a greater load on the localised electric and electrode boilers in each processing zone. Similarly, the impact of ambient temperature fluctuations on the heat pump COP may be mitigated by connecting the Hot Water Utility System directly to one of the existing electric boilers, so that it can be used to top up temperatures on an as-needed basis. Positioning a heat pump as indicated in Figure 8 could reduce the site's emissions by 2060 t CO_2-e per year, in addition to the energy savings from implementing the Rendering MVR. Further analysis would be needed to establish the economic trade-off between lowering the ring main temperature to increase heat pump COP and increasing the load on the electric boilers.

Table 3 summarizes the results of the case study site's TSHI analysis adjusted for the incorporation of the Rendering MVR and centralized heat pump.

Table 3. Summary of results from TSHI of case study site zones adjusted for MVR and centralized heat pump incorporation.

Zones	Hot Utility Required (kW)	Cold Utility Required (kW)	Possible Heat Recovery (kW)
Beef	348	613	52
Casings	0	0	0
Fellmongery	0	0	0
Lamb	1015	795	45
Lamb Further Processing	10	980	40
Rendering	437	0	565
Wastewater	0	2977	0
Total of Zone Targets	1810	5376	702
Unified Total Site Target	1789	5355	724

In comparison to the original TSHI analysis (Table 1), the total hot utility requirement has decreased from 5646 kW to 1810 kW. The remaining 702 kW of heat recovery within site zones after the installation of both the Rendering MVR and centralised heat pump would reduce the site's emissions by another 723 t CO_2-e per year. Figure 9 shows a simplified summary of the case study site's process heat sources and uses after installation of the proposed MVR and Heat Pump.

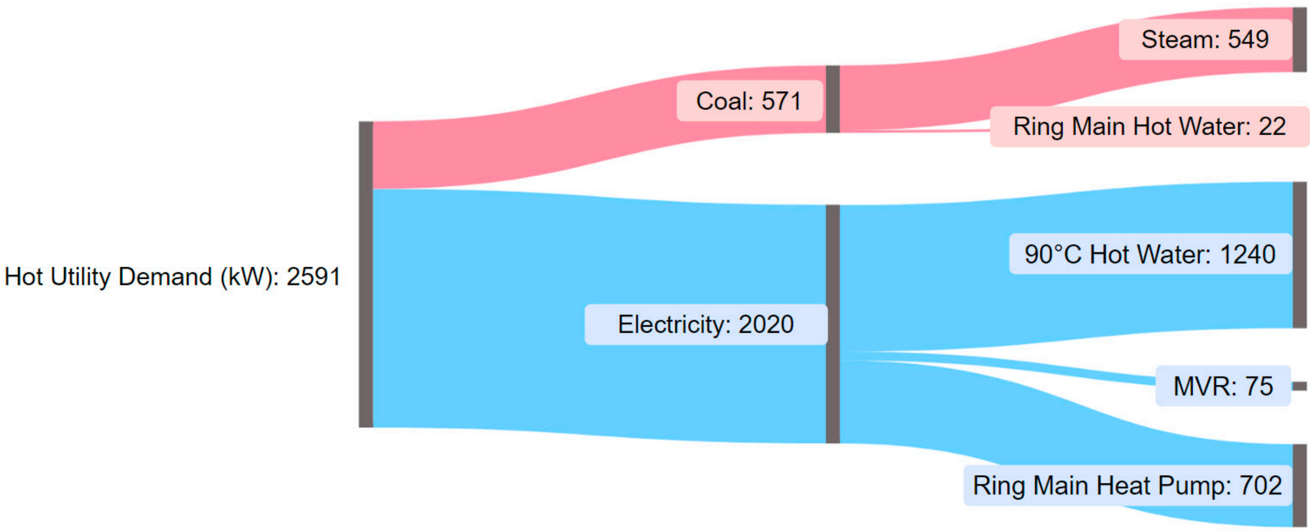

Figure 9. Sankey diagram of case study process heat sources and uses in the MW after MVR and Heat Pump installation.

5. Discussion

The initial TSHI analysis reveals heat recovery opportunities of 4233 kW without considering heat pumps or MVRs. However, due to the fat- and blood-based fouling and contamination issues from the water used around slaughter floors, as well as scheduling differences between the rendering plant and the other slaughter and processing areas, much of the inter-zonal (zone-to-zone) heat recovery will be unachievable. This would likely result in heat recovery opportunities closer to just 2097 kW (Table 1). This is equivalent to an emissions savings of approximately 2159 t CO_2-e per year.

Instead, heat pumps can be used within zones to increase the amount of recoverable heat and to upgrade the temperature of steams using low-fouling heat sources such as air or waste heat from existing refrigeration systems.

Standard Pinch analysis and general engineering knowledge and experience previously applied for heat pump identification at the site only identified heat pump opportunities in the Beef and Lamb Slaughter areas, resulting in the installation of a 1 MW heat pump using waste refrigeration heat to heat ring main water to 90 °C for sterilization. Although these heat pumps still contribute to the reduction of emissions, the novel multi-level TSHI analysis proposed in this paper revealed larger heat pump opportunities that were not identified by these standard methods.

The first level of TSHI analysis highlighted an MVR opportunity in the rendering plant that could utilize over 2 MW of waste heat for reuse. By adjusting the initial TSHI application to mimic the installation of a rendering MVR, the site can be reanalyzed in a second level of TSHI for any new heat pump opportunities. Over 2 MW of ring main hot water could be provided by an air- or ground-source heat pump. Other studies have identified that local bodies of water, such as local quarry lakes, also have potential as heat sources for similar industrial heat pumps [32].

The proposed centralized heat pump placement was not identifiable from the first TSHI analysis, which showed a total ring main utility demand of less than 500 kW (Figure 5b). However, by applying the multi-level TSHI methodology described above, a TSHI that is adjusted for the incorporation of both the Rendering MVR and centralized ring main Heat Pump, the demands for steam and hot water sources other than the heat pump and MVR are greatly reduced. This remaining heating demand could easily be supplied by the electric and electrode boilers already on site without the use of the coal boilers the site is currently dependent on, resulting in the opportunity to completely electrify process heating.

Additionally, 2170 t CO_2-e per year can be eliminated through the addition of an MVR evaporator in Rendering, and 2060 t CO_2-e per year can be eliminated through the addition of the centralized heat pump around the hot water ring main (Table 4). If the remaining intra-zonal (within zone) heat recovery available after both MVR and ring main heat pump installations is also included, an additional 723 t CO_2-e per year can be eliminated (Table 4). This ultimately reduces the site's overall process heating emissions from 9233 t CO_2-e per year to 4280 t CO_2-e per year, a decrease of over fifty percent. Figure 10 shows the suggested changes to the case study's Total Site Plots.

Ultimately, a combination of both Pinch-based TSHI and more dynamic modelling methods will be needed to accurately construct a detailed emissions reduction plan for the case study site. Hence this research presents a preliminary emissions reduction plan, with further detail on site dynamics and economics being investigated in future research.

Table 4. Summary of potential emissions reduction from suggested heat pump implementation.

Emissions Reduction Method	Emissions Reduction Quantity (t CO_2-e per Year)
MVR installation	2170
Central Heat Pump	2060
Remaining UTST heat recovery	723
Total	4953

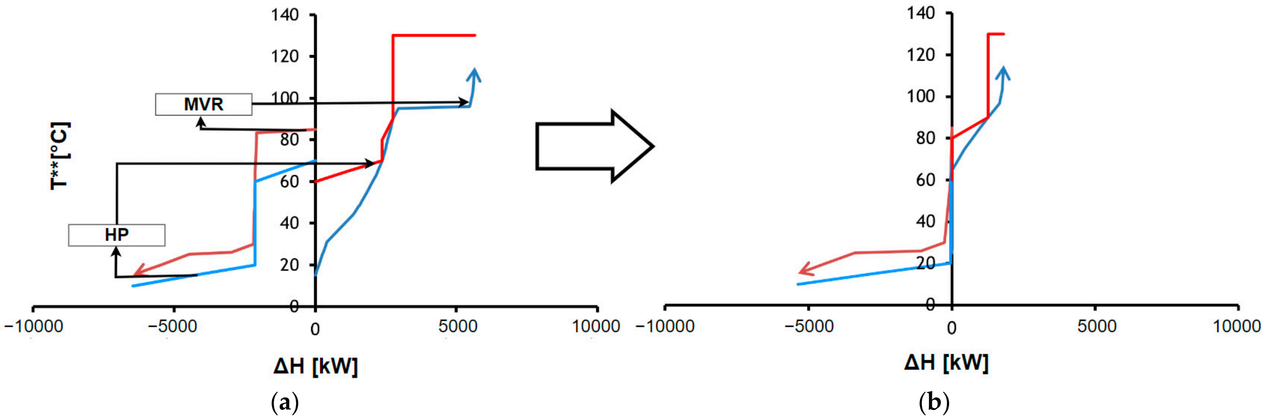

Figure 10. Total site integration plots showing potential heat pump installations (**a**), leading to final expected total site plot (**b**). The red colored lines on the Gross cold utility use side of the plot represent process streams that require cooling, and the blue colored lines represent the cold utility streams that would be required to carry out this cooling. The blue colored lines on the Gross hot utility use side of the plot represent process streams that require heating, and the red colored lines represent the hot utility streams that would be required to carry out this heating.

6. Conclusions

From the initial TSHI analysis, without consideration for heat pump and MVR integration, the maximum heat recovery that can be found on the case study site is 4233 kW. However, due to fouling and scheduling issues on site, a more realistic heat recovery target is likely to be closer to 2097 kW. This is equivalent to a carbon emissions reduction of around 2159 t CO_2-e per year. Instead, heat pumps can be used to upgrade waste heat within localised areas or from low fouling heat sources. Previous heat pump analyses using standard pinch and general engineering knowledge-based methods found two small heat pump opportunities within the Beef and Lamb zones that could help reduce the site's emissions. However, by using the novel multi-level TSHI method proposed in this paper, an additional MVR opportunity in the Rendering plant and a centralised air-source heat pump were identified. These newly identified installations could result in a total reduction in carbon emissions of approximately 4953 t CO_2-e per year (greater than 50% of current emissions). If this emissions-reduction plan is implemented at the case study site, it will contribute to the growing portfolio of successful industrial heat recovery and emissions reduction studies. Ultimately, this should help dispel industrial hesitance around investing in renewable, emissions-reducing technology.

Author Contributions: Conceptualization, J.K.C., T.G.W. and D.J.C.; methodology, T.G.W. and E.K.; formal analysis, E.K.; writing—original draft preparation, E.K.; writing—review and editing, J.K.C., T.G.W., D.H., Q.C. and D.J.C.; supervision, J.K.C., T.G.W., D.H., Q.C. and D.J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by the programme "Ahuora: Delivering sustainable industry through smart process heat decarbonisation", an Advanced Energy Technology Platform funded by the New Zealand Ministry of Business, Innovation, and Employment.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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