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Mapping Local Synergies: Spatio-Temporal Analysis of Switzerland's Waste Heat Potentials vs. Heat Demand

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Abstract: As nations transition to renewable energy, making use of waste heat becomes crucial to combat climate change. This study focused on quantifying Switzerland's waste heat potential from industrial processes and waste-to-energy facilities, using diverse methodologies tailored to facility characteristics and data availability. We assessed potential waste heat utilization by comparing local heat supply and demand, creating comprehensive heat-balance maps considering different temperature levels and seasonal fluctuations. Results revealed a substantial annual waste heat potential of 37 TWh, with almost half (17 TWh) below 45 °C, primarily from wastewater. Heat between 45 °C and 70 °C, ideal, e.g., for greenhouse heating, is mainly available from solid waste incineration plants, while industries contributed to waste heat supply exceeding 150 °C. In contrast to heat demand, seasonal variations in heat supply were small, with a 12% winter decrease. Analyzing heat demand versus supply unveiled local and seasonal disparities. Most municipalities had a net excess heat demand (totaling 89 TWh). Additionally, waste heat could not satisfy 8 TWh of industrial process heat demand exceeding 400 °C, emphasizing reliance on primary energy sources for higher-temperature heat. Targeted strategies are essential for effective waste heat utilization, especially tapping into low-temperature sources. Integrating these sources with low-carbon technologies can pave the way to a sustainable energy future.

Keywords: waste heat recovery; heat balance; GIS; energy transition; Switzerland

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1. Introduction

Geopolitically caused energy scarcity and environmental concerns drive the exploration of alternative energy sources. Waste heat emerges as an underutilized yet highly promising resource [1]. In an era defined by the pressing challenges of climate change and the need to meet CO_2 emission reduction targets, exemplified by the Paris Agreement [2], harnessing waste heat goes beyond mere opportunity; it becomes imperative for reducing reliance on primary energy sources [3]. However, despite its potential, this resource is currently not only largely untapped but also barely monitored.

Nonetheless, numerous countries have acknowledged the importance of waste heat, often referred to as excess heat, and multiple studies have sought to quantify its potential for utilization. However, assessing available waste heat is challenging due to fragmented, often incomplete, and unavailable data. For instance, Miró et al. [4] compiled industrial waste heat data from 33 countries, primarily relying on national statistics and literature sources, yet encountered substantial difficulties arising from insufficiently detailed specifications, particularly concerning the methodologies employed, thereby underscoring the imperative need for enhanced transparency in such assessments. Additionally, Brueckner et al. [5] observed that the selection of estimation methods in numerous studies hinges significantly on data availability, often leading to the use of overly generalized figures or data. Depending on the context and research objectives, studies have adopted diverse methodologies. Some have employed top-down approaches, like energy efficiency analyses applied to entire energy systems [6], while others have favored bottom-up methods, relying on data from surveys or mandatory reports. Examples of the latter include studies in the UK's industrial sector [7], the Basque Country in Spain [8], the Italian dairy sector [9], and district heating operators in Austria [10]. Each approach brings advantages: top-down methodologies offer systemic perspectives, while bottom-up methods might provide sector-specific insights and facilitate targeted interventions. Recognizing spatial distribution as a crucial factor for effective waste heat utilization, Albert et al. [11] used a hybrid approach to map the natural gas consumption of UK industries through surveys. Subsequently, they estimated the resultant waste heat availability using energy efficiency data from the literature. Similarly, Dénarié et al. [12] calculated regional waste heat from industrial processes and waste-to-energy plants in Italy. To do so, they utilized carbon dioxide emission data from the EU Emissions Trading System database to estimate primary fuel consumption and the resulting waste heat amount based on emission factors. However, it is important to note that this analysis excluded facilities with an annual production lower than 20 GWh, limiting the evaluation to larger enterprises.

In Switzerland, heat energy plays a crucial role, constituting almost 50% of the nation's total energy demand [13]. Within this energy context, researchers have also initiated investigations into waste heat, recognizing its potential to provide an attractive opportunity to substitute primary energy consumption with a low-emission alternative. For example, Arpagaus et al. evaluated the potential of industrial heat pump applications for recovering waste heat in diverse case studies [14]. Zuberi et al. [15] estimated the spatial industrial waste heat potential starting from the Swiss industry's overall energy consumption. The allocation to different industrial sectors was guided by typical relative shares among the sectors, according to European literature. Subsequently, Chambers et al. [16] conducted a study to determine the possibility of including industrial waste heat in the district heating network. These studies underscore the significant role that waste heat can play as a valuable energy resource in Switzerland, especially in a nation where heat energy makes up such a substantial portion of overall energy demand.

However, while these studies shed light on the potential of excess heat, they often fall short of fully considering critical factors, often due to data gaps. These factors include more precise sectoral allocation, variations in excess heat temperature levels, and seasonal fluctuations. Additionally, they tend to overlook the spatio-temporal distribution of waste heat potential in relation to heat demand.

This study aimed to assess the waste heat potential generated by industrial and waste-to-energy plants in Switzerland while accounting for different temperature levels and seasonal variations. In a parallel step, local heat demand was mapped using the same framework. Since heat cannot be easily transported over large distances, spatial analysis established the relationships between waste heat potential and local heat demand. The final aim was to generate comprehensive heat balance maps for Switzerland that show the heat demand that can be covered by local waste heat utilization. This innovative approach ensures a more holistic understanding of the waste heat landscape and facilitates strategic decision making in the transition to sustainable energy practices.

2. Materials and Methods

This section presents the methodology used to assess waste heat supply potential and heat demand in Switzerland, ultimately resulting in a GIS (Geographic Information System) map depicting the heat balance (i.e., the difference between supply and demand). Key components of our methodology included considering different temperature levels, ensuring spatial coherence, and evaluating temporal factors between waste heat potential and demand (see Figure 1).

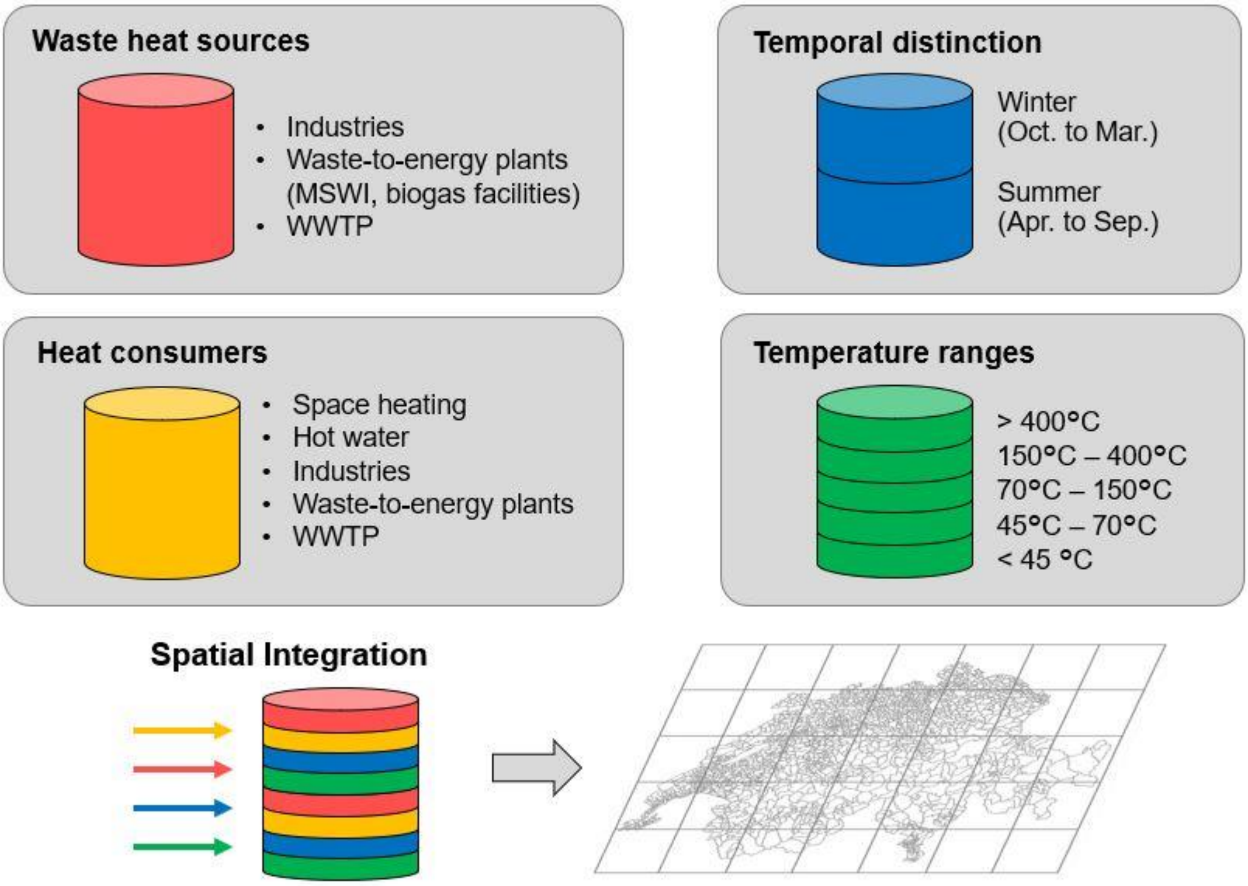

Figure 1. Schematical overview of the approach to estimating spatio-temporal waste heat potentials versus total heat demand in Switzerland.

2.1. General Framework and System Boundaries

In addressing heat demand (Section 2.2), our analysis encompassed various key consumers. Firstly, we assessed the heat demand for building heating, a significant component that accounts for the largest share of heat demand [13]. Additionally, we assessed the heat demand for providing hot water to Switzerland's population. Furthermore, our analysis extended to include the additional heat demand from industrial processes and waste-to-energy plants, which are not covered by internal waste heat recovery.

Regarding waste heat sources, we considered several key categories, including industrial installations (with special attention given to cement plants due to their substantial heat output), municipal solid waste incinerators (MSWI), biogas plants, and wastewater treatment plants (WWTP). Waste heat, in this context, refers to the thermal energy produced as a byproduct of these facilities. Notably, we focused exclusively on the unutilized portion of waste heat within a facility, which we call "waste heat potential." Thus, we did not consider existing external uses, such as district heating systems or greenhouses, already benefiting from waste heat. Also, we did not evaluate the potential for heat extraction from surface waters, groundwater, or geothermal sources. The specific methodologies are elaborated upon in Section 2.3.

Our analysis encompasses three temporal frameworks: the entire year, the winter (October to March), and the summer (April to September) half-year periods. These temporal distinctions allow us to identify variations in heat dynamics, notably revealing potential winter heat deficits or summer surpluses. While seasonal heat storage solutions theoretically hold promise in addressing these imbalances, their practical implementation remains a challenging endeavor [17]. Therefore, this temporal distinction sheds light on the practical considerations of implementing seasonal heat storage solutions.

To address temperature-related limitations impacting the suitability of waste heat for various applications, we categorized waste heat potentials and heat demand into five temperature ranges, drawing insights from [18].

Our geographical system boundaries were established to encompass Switzerland, a country divided into 2136 municipalities, each constituting the smallest administrative unit with considerable independence [19]. Our initial calculations involved point data for waste heat production and demand sites. Subsequently, we aggregated these results at the municipal level, using spatial joins to associate data sources with their respective municipalities. This approach provides clear and intuitive representation, particularly valuable for policymakers. The effectiveness of the municipal-level representation in facilitating implementation has been confirmed in prior studies (e.g., [20,21]). Additionally, operating at the municipal level offers the advantage of semi-anonymizing industrial point data.

By comparing the waste heat supply potential with heat demand, we derived a heat balance. This involved subtracting heat demand from the waste heat supply potential across various spatial, temporal, and temperature scales. A negative heat balance indicates that the heat demand in a specific area exceeds the available waste heat generation, whereas a positive heat balance signifies the opposite scenario.

2.2. Assessment of the Heat Demand

In evaluating heat demand, our study concentrated on three fundamental categories: process heat, space heat, and hot water; these categories collectively constitute significant portions of Switzerland's total final energy consumption, accounting for 34%, 12%, and 6%, respectively [22]. The primary energy sources prominently utilized are heating oil, natural gas, and electricity (heat pumps). More than 90% of process heat demand is attributed to the industrial sector [22]. We did not consider process heat from households and the service sector in our analysis because of the scattered nature of these heat contributors, making practical recovery methods challenging to implement effectively due to their small scale and dispersion. Our analysis considered on-site waste heat utilization to meet internal heat demands. Only heat demand that could not be satisfied internally with waste heat was accounted for in the (net) heat demand maps.

2.2.1. Industries

Heat energy is required for various industrial processes, including material drying, metal melting, and chemical reactions. We utilized the reported energy consumption data from the Swiss industrial sector to estimate the heat demand of industries not covered by internal waste heat recovery mechanisms [23]. These figures are determined annually by the Swiss Federal Office of Energy in an extensive process that combines data collection and energy–economy model calculations with bottom-up methods. In 2022, the data collection process involved evaluating more than 7000 questionnaires out of 13,000 that were distributed. The collected data were then systematically extrapolated to represent the entire country while distinguishing between 19 branches. This breakdown aligns with the international energy statistics (IEA) criteria and simplifies comparing the results to the existing literature. Of these branches, 9 pertained to industries further investigated in this study (namely food production, textile/leather, paper/printing, chemical/pharma, cement/concrete, metals, machinery/other industries), while the remaining were associated with businesses or construction sectors that were not subject to further investigation.

The next step consisted of dividing the heat demand into different temperature levels based on [22]. However, this dataset primarily provides insights into allocating the overall Swiss process heat demand across various temperature ranges. Thus, we applied a uniform average temperature distribution percentage to all industrial branches. We represented these data spatially by distributing the overall branch-specific heat demand values based on geo-referenced data of the number of employees [24].

The heat demand of cement plants was assessed separately, drawing upon available reports from the industry branch [25], given the limited number of six plants in Switzerland. To establish this demand, we multiplied each plant's specific thermal energy demand by the quantity of cement they produced. The specific heat demands of these plants can be found in the Supplementary Materials (Table S1).

2.2.2. Waste-to-Energy Facilities

Even though waste-to-energy facilities primarily generate energy, we also considered their occasional external heat demand. We assessed this demand, applying a methodology akin to the one outlined in Section 2.3.2 for waste heat estimation. For MSWIs, the heat demand mainly encompasses the energy required to initiate combustion in the furnace, operating within a range of 800 °C to 1000 °C. Based on energy flow diagrams from [25], the external heat requirements of all individual MSWIs could be quantified [26].

We also examined the eventuality of occasional external heat demand in biogas plants, e.g., to heat the fermenter during the coldest days in harsh regions. However, no documented instances were found to either confirm or refute this hypothesis; thus, this aspect was not further considered in this study.

2.2.3. Wastewater Treatment Plants

For wastewater treatment plants (WWTPs), a limited external heat demand arises in winter, typically ranging from 70 °C to 150 °C, which is needed to ensure the digestion process. Indeed, during cold winter days, the waste heat generated falls short of the needed supply, leading to a small heat deficit in certain regions.

2.2.4. Space Heating

In addressing the heat demand for space heating, Buffat [27] developed a comprehensive computational tool in line with the Swiss Society of Engineers standards (SIA380). This tool incorporated a GIS-based bottom-up approach considering building-specific and climatic variables and was made openly accessible on GitHub [28]. Here, we used the monthly average heat demand simulation to consider the seasonal fluctuations. In terms of temperature level, we adhered to the standards of district heating networks, selecting an average temperature range of 60 °C to 100 °C as suggested by Nussbaumer in 2020 [29]. Thus, space heat demand was categorized within our temperature range of 70 °C–150 °C.

2.2.5. Hot Water

In older residential buildings, the demand for hot water typically constitutes a considerably smaller proportion than that for space heating, whereas in modern structures, the demand for hot water is comparable to that for space heating [29]. We calculated the hot water demand using the same methodology as Buffat [27], applying the following equation for estimation:

$$HW = P \times 833 \tag{1}$$

HW = Annual hot water demand [kWh/a]
P = Number of inhabitants [-]
833 = Typical annual hot water demand per person [kWh/a]

Data on the number of inhabitants were obtained from the Federal Office of Statistics population database, available in aggregated form per hectare [30]. Following sanitary recommendations [31], it is essential to ensure that hot water is supplied at least once a day for three minutes at 70 °C or for eleven minutes at 60 °C to mitigate the risk of Legionella proliferation. Therefore, hot water consumption was categorized within the heat demand range of 70 °C–150 °C. It was assumed that the winter and summer half-years have equivalent heat demand for hot water due to the unavailability of precise figures differentiating hot water consumption between the two seasons.

2.3. Assessment of Waste Heat Supply Potentials

In this study, we assessed the waste heat supply potential of industrial facilities, waste-to-energy facilities (comprising MSWIs and biogas plants), and WWTPs across Switzerland (see Figure 1). Our analysis prioritized on-site waste heat utilization to meet internal heat demands over off-site waste heat utilization because it minimizes heat losses through transportation and is already practiced to a large extent. Similar to demand, only the unused waste heat within the facility was considered as (net) waste heat supply potential.

2.3.1. Industries

The estimation of waste heat was derived from a comprehensive study conducted in Germany [32], which quantified the waste heat potential in various industrial sectors as a proportion of the total energy consumption within those sectors. The identified proportions were subsequently applied to the reported energy consumption data of industries and businesses in Switzerland [22]. The Swiss data provide information on total annual energy consumption, categorizing it into 10 industrial branches and offering detailed breakdowns by various energy sources (Section 2.2.1).

While the data in [32] provided insights into the distribution of industrial waste heat in the different temperature ranges, waste heat below 60 °C was neglected. To fill this gap, we consulted a Norwegian nationwide study on low-temperature industrial waste heat, specifically waste heat below 60 °C [33]. From these data, we quantified the ratio between waste heat below 60 °C and that above 60 °C. This ratio was applied to the previously calculated values to complete the assessment of all the temperature ranges.

Industrial waste heat was assumed to remain relatively constant throughout the year due to the continuous and consistent nature of many industrial operations. These operations typically run continuously, generating stable waste heat levels. While exceptions may exist with seasonal variations or maintenance shutdowns, this assumption serves as a practical starting point for the analysis. Finally, the spatial allocation of waste heat supply in each industry was based on the number of full-time jobs, as reported by the Swiss Federal Statistical Office for the different industrial sectors [24].

The waste heat calculation for cement plants was conducted individually for each of the six specific plants. To estimate potential waste heat, we relied on Holcim's report, which states that waste heat potential represents around 20% of the thermal energy demand [34]. Subsequently, we employed the following equation for waste heat calculation:

$$WH_{total} = (TED_{spec} \times m_{cement} \times 0.2)/(1000 \times 3.6) \quad (2)$$

WH_{total} = Total waste heat [MWh]
TED_{spec} = Specific thermal energy demand [MJ/t]
m_{cement} = Cement production quantity [t]

To determine the temperature of the waste heat, we first identified the different waste heat sources generated within the cement plant. Subsequently, we assessed each source's temperature and heat output [35]. The considered waste heat sources and their corresponding temperatures and heat outputs are listed in the Supplementary Materials (Table S2). Cement production is primarily driven by incoming orders, regardless of the season, resulting in no significant seasonal variations. Hence, waste heat production is considered constant over the year. The spatial locations of the six cement plants in Switzerland were well known.

2.3.2. Waste-to-Energy Facilities

MSWIs typically have three primary energy outputs: steam, heat, and electricity. A recent survey commissioned by the Swiss federal government and conducted by Rytec [26] comprehensively covered all 29 active MSWIs in Switzerland. This survey measured heat and steam exports, excluding internal usage. The resulting illustration depicting the average expected energy flows within MSWIs can be found in the Supplementary Materials (Figure S1).

MSWIs generate thermal energy by incinerating waste, producing high-temperature steam at 400 °C. A share of the high-temperature steam can be supplied directly to industries for high-temperature process heat (if such industries are located in the vicinity of the MSWI plant), while the rest is typically used in two turbine stages producing electricity. Finally, the remaining low-pressure steam is condensed to water. Although the released heat from the condenser could be used for applications like greenhouse heating, this is seldom practiced [36]. On average, nearly half of the total energy in the waste (100%) is lost, primarily due to flue gas losses over the boiler (16%) and the condenser (33%) [26]. It was assumed that the ratio of heat flows is similar across all MSWIs, only varying according to the amount of incinerated waste. Since MSWIs operate at or near capacity year-round, we assumed a consistent heat production rate throughout the year [37].

In Switzerland, 126 agricultural and 28 industrial biogas plants, fermenting manure and organic wastes, are scattered across the country [38]. The federal government recently released comprehensive data on electricity production from individual biogas plants [39]. Leveraging this dataset, we estimated the waste heat potential of these plants. In line with the insights from Utiger in 2019 [40], we assumed that, on average, a Combined Heat and Power (CHP) plant's output comprises 55% heat and 45% electricity. Our analysis also delved into the digester self-consumption rates, which vary depending on the plant's size. Indeed, larger biogas plants usually exhibit lower self-consumption percentages compared to their smaller counterparts [41]. Utiger's work [40] provided the basis for expressing heat self-consumption as a percentage of the heat generated by the CHP, as detailed in the Supplementary Materials. By subtracting this internal heat consumption, we estimated the annual waste heat potential available for external applications. From the same study, we extracted information regarding the temperature of the waste heat [40]. Approximately one-quarter of the generated waste heat was found to fall below the 45 °C threshold, while three-quarters fell within the range of 70 °C to 150 °C.

For assessing seasonal fluctuations in waste heat potential, the variable self-consumption of the digester holds particular significance, given that CHP heat production remains approximately constant throughout the year, solely contingent on the quantity of burned biogas. To capture these fluctuations, we referred to the measurement data provided by [40], depicting the seasonal self-consumption patterns of an average digester. Using these data, we calculated the percentage difference in self-consumption between the winter and summer half-years, concluding that the average self-consumption during winter is 40% higher than in summer (see Supplementary Materials). This finding allowed us to distribute the previously derived total annual consumption between the summer and winter halves of the year.

2.3.3. Wastewater Treatment Plants

In Switzerland, over 98% of the population is connected to one of the more than 750 central WWTPs [42]. To assess their waste heat potential, we utilized an empirical formula [18], which is based on the number of connected inhabitants to the individual WWTP, as provided by the data from the government [43]:

$$\mathrm{Wpot} = \mathrm{PE} \times 1.811 \tag{3}$$

Wpot = Annual waste heat potential [MWh/a]

PE = Number of connected population equivalents [-]

1.811 = Typical annual waste heat amount per number of connected population equivalents [MWh/a]

Although this formula seems straightforward, it relies on several assumptions. It assumes a continuous wastewater generation, utilizing a standard volume of 180 L per population equivalent per day. Heat extraction occurs after the wastewater treatment process to prevent disruption in purification processes. An average annual wastewater temperature of 13.5 °C is assumed, with wastewater cooled to 5 °C during heat extraction.

In addition to the waste heat in the wastewater, the largest 266 WWTPs generate sewage gas through the anaerobic digestion of sewage sludge, which is subsequently used in CHP systems to generate electricity and heat [38]. This second waste heat source of WWTPs arises from this combustion, akin to biogas plants. To quantify this heat production, we applied Hungerbühler's findings [44] for the canton of Zurich, multiplying the specific average value of 35 kWh/PE/year by the number of connected population equivalents in individual WWTPs. These calculations are based on assumptions regarding sewage gas production (9.125 Nm^3/PE/a), CHP thermal efficiency (60%), and the calorific value of sewage gas (6.4 kWh/Nm^3).

The waste heat temperature from wastewater is below 45 °C, while waste heat from the CHP is within the temperature range of 70 °C to 150 °C. While the CHP's heat production remains consistent throughout the year, the heat demand within WWTPs varies seasonally, and the winter half-year experiences heat demand 1.8 times higher than in the summer half-year [44]. The final calculation involved adding the wastewater heat potential and the waste heat potential of the CHP for both half-years and then subtracting the WWTP's own heat demand.

3. Results

3.1. Heat Demand

Figure 2 visually represents Switzerland's total heat demand across all temperature levels for an entire year at the municipal level. The calculated heat demand amounts to 89 TWh (see Table 1 for details). Notably, the most significant temperature demand range, comprising nearly 90%, falls within the 70 °C to 150 °C spectrum, primarily addressing space heating needs. This high demand is particularly evident in large cities with significant space heating requirements.

In contrast, the heat demand between 150 °C and 400 °C and temperatures exceeding 400 °C account for a mere 2% and approximately 9%, respectively. These higher temperature ranges are primarily dedicated to industrial processes.

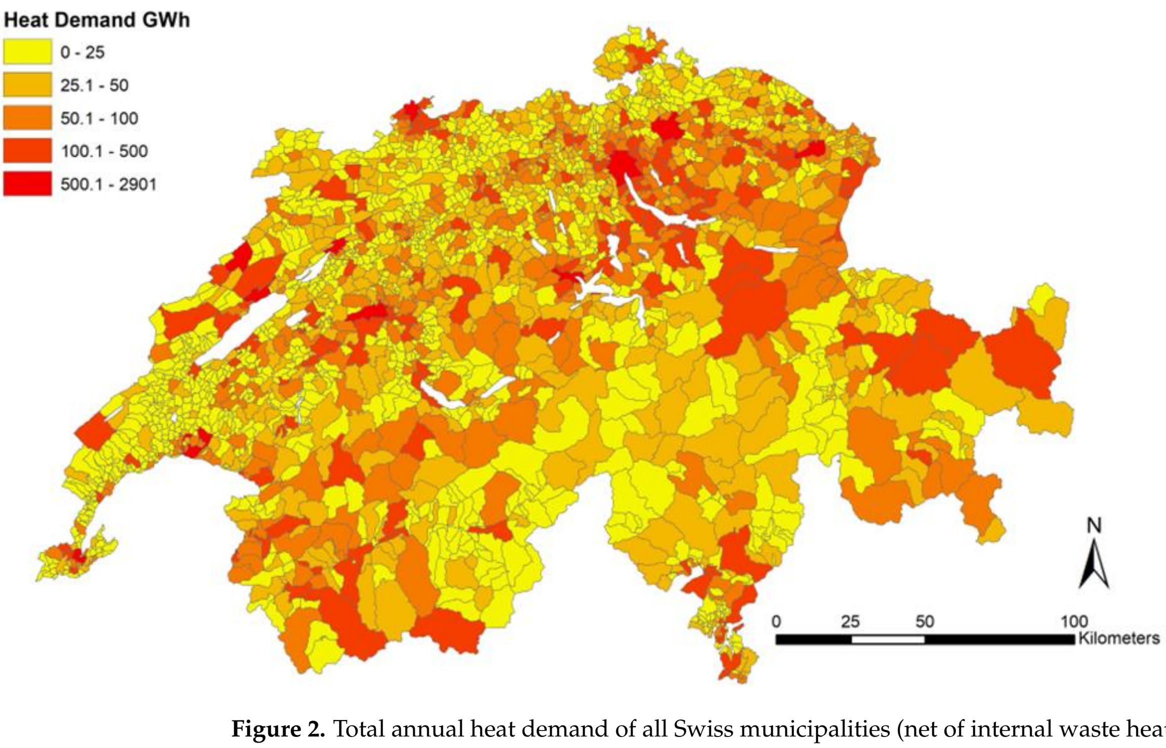

Figure 2. Total annual heat demand of all Swiss municipalities (net of internal waste heat use).

Table 1. Breakdown of Switzerland's calculated heat demand across different sources and temperature categories (net of internal waste heat use); Color scale ranging from yellow (indicating lower values) to red (indicating higher values).

		<70 °C [TWh]	70–150 °C [TWh]	150–400 °C [TWh]	>400 °C [TWh]	Total [TWh]
Space heating	Total	0	69.34	0	0	69.34
	Share		87%	0%	0%	78%
Water heating	Total	0	7.34	0	0	7.34
	Share		9%	0%	0%	8%
Industries	Total	0	2.92	1.57	7.69	12.18
	Share		4%	100%	100%	14%
Waste-To-Energy Plants (MSWIs)	Total	0	0	0	0.02	0.02
	Share		0	0	0	0
WWTPs	Total	0	0.06	0	0	0.06
	Share		0%	0%	0%	0%
Total	Total	0	79.67	1.57	7.71	88.95
	Share		100%	100%	100%	100%

3.2. *Waste Heat Supply Potentials*

Switzerland's annual waste heat supply potential amounts to 36.5 TWh (as detailed in Table 2). WWTPs emerge as the primary contributors within this total, accounting for a remarkable 15 TWh or 41%. This substantial contribution can be attributed to wastewater's considerable waste heat potential, albeit predominantly generated at temperatures below 45 °C. Alongside WWTPs, MSWIs contribute significantly, with an estimated 10.7 TWh annually, particularly within the 45 °C to 70 °C temperature range. Switzerland's industrial sector adds 9.9 TWh to the waste heat supply potential, with both high temperatures (150 °C to 400 °C) and lower temperatures. In contrast, waste heat from biogas plants (1%) and cement plants (2%) constitutes a relatively modest portion on the national scale. Nevertheless, these plants remain important contributors at a local level. Figure 3 illustrates the spatial distribution of Switzerland's waste heat potential, highlighting municipalities with MSWI plants, cement plants, and big cities with large WWTPs or numerous industrial activities as significant centers of waste heat availability.

Table 2. Breakdown of Switzerland's calculated waste heat supply potential across different sources and temperature categories (net of internal waste heat use); Color scale ranging from white (indicating lower values) to dark green (indicating higher values).

		<45 °C [TWh]	45–70 °C [TWh]	70–150 °C [TWh]	150–400 °C [TWh]	Total [TWh]
Industries	Other industries	1.78	3.13	1.67	3.35	9.94
	Cement plants	0	0.05	0.28	0.32	0.64
	Total	1.78	3.18	1.95	3.67	10.58
	Share	11%	28%	49%	81%	29%
Waste-to-energy plants	MSWIs	0	7.87	1.97	0.87	10.7
	Biogas facilities	0	0.16	0.05	0	0.21
	Total	0	8.03	2.02	0.87	10.92
	Share	0%	72%	51%	19%	30%
WWTPs	Total	15	0	0.03	0	15.03
	Share	89%	0%	1%	0%	41%
Total	Total	16.78	11.21	4	4.53	36.52
	Share	100%	100%	100%	100%	100%

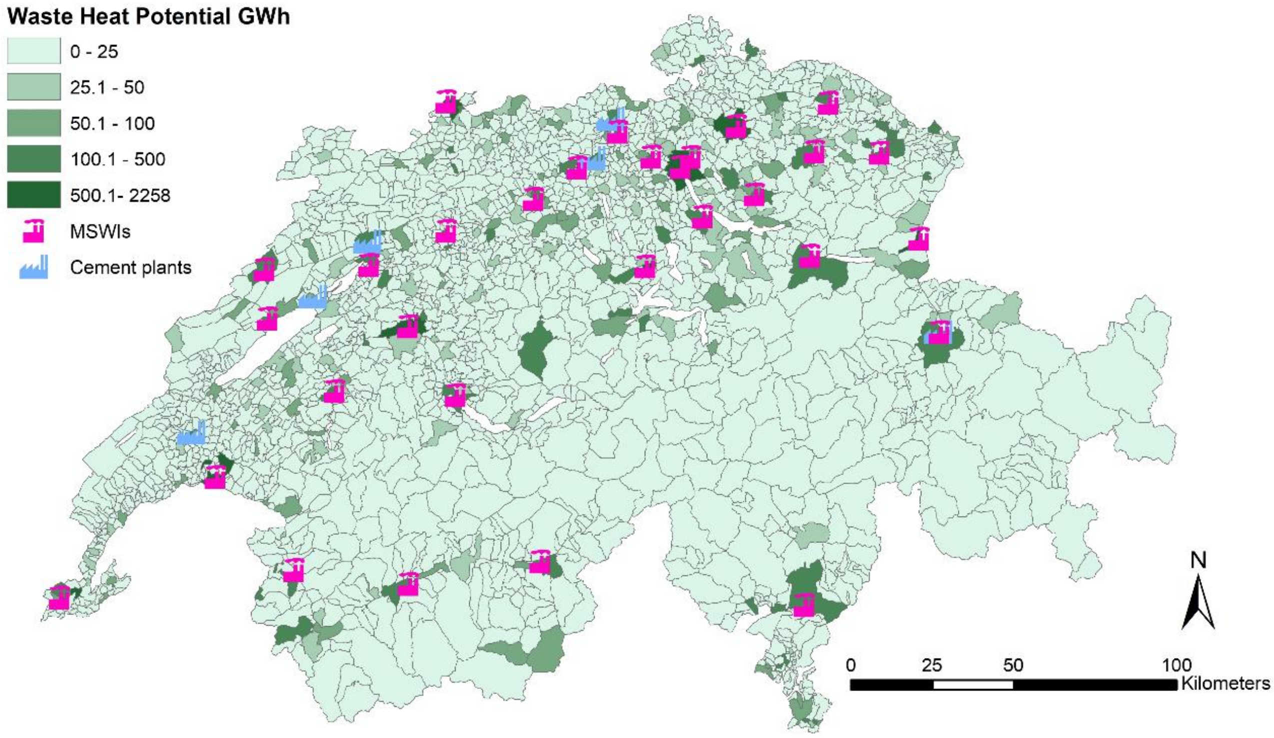

Figure 3. Total annual waste heat supply potential across all Swiss municipalities, along with municipal solid waste incinerators (MSWIs) and cement plants (net of internal waste heat use).

Upon analyzing different temperature levels, it becomes evident that most waste heat, totaling 16.8 TWh, is generated at temperatures below 45 °C (primarily WWTPs). The temperature range between 45 °C and 70 °C represents the second-largest waste heat potential, amounting to 11.2 TWh. MSWIs stand out as the primary source within this range, contributing over 70% of the waste heat in this band. Collectively, waste heat below 70 °C constitutes 77% of the total waste heat potential. In contrast, waste heat is less available within the temperature band from 70 °C to 150 °C, totaling 4 TWh from various sources, with contributions primarily from MSWIs and industrial processes. The industrial sector emerges as the predominant source of waste heat generated between 150 °C and 400 °C, contributing over 80% of the total waste heat of 4.5 TWh in this temperature range.

3.3. Heat Balance

3.3.1. Overall Heat Balance

Figure 4 presents Switzerland's heat balance normalized by the area of each municipality, allowing for comparisons between municipalities of varying sizes. The total heat balance values for individual municipalities can be found in the Supplementary Materials. The visualization highlights a widespread heat deficit across municipalities, shown in yellow–red negative balances. This indicates a substantial mismatch between current heat demand and available waste heat supply. On the national scale, the municipal heat balance lies at almost 53 TWh. In other words, if we could close the loop between all waste heat to cover heat demand, we would still need to provide this amount of heat with primary energy sources. However, due to the inherent challenges in transporting heat, aggregating all deficits without accounting for municipalities with surpluses results in an even larger deficit, reaching up to 64 TWh. In contrast, around 200 municipalities, marked in green, have higher waste heat availability than demand, especially near MSWIs or large industries. Since in Figure 4 no differentiation between temperature levels was carried out, WWTPs, despite their substantial waste heat potential, often blend into the balance map due to their alignment with local space heating needs within the same area.

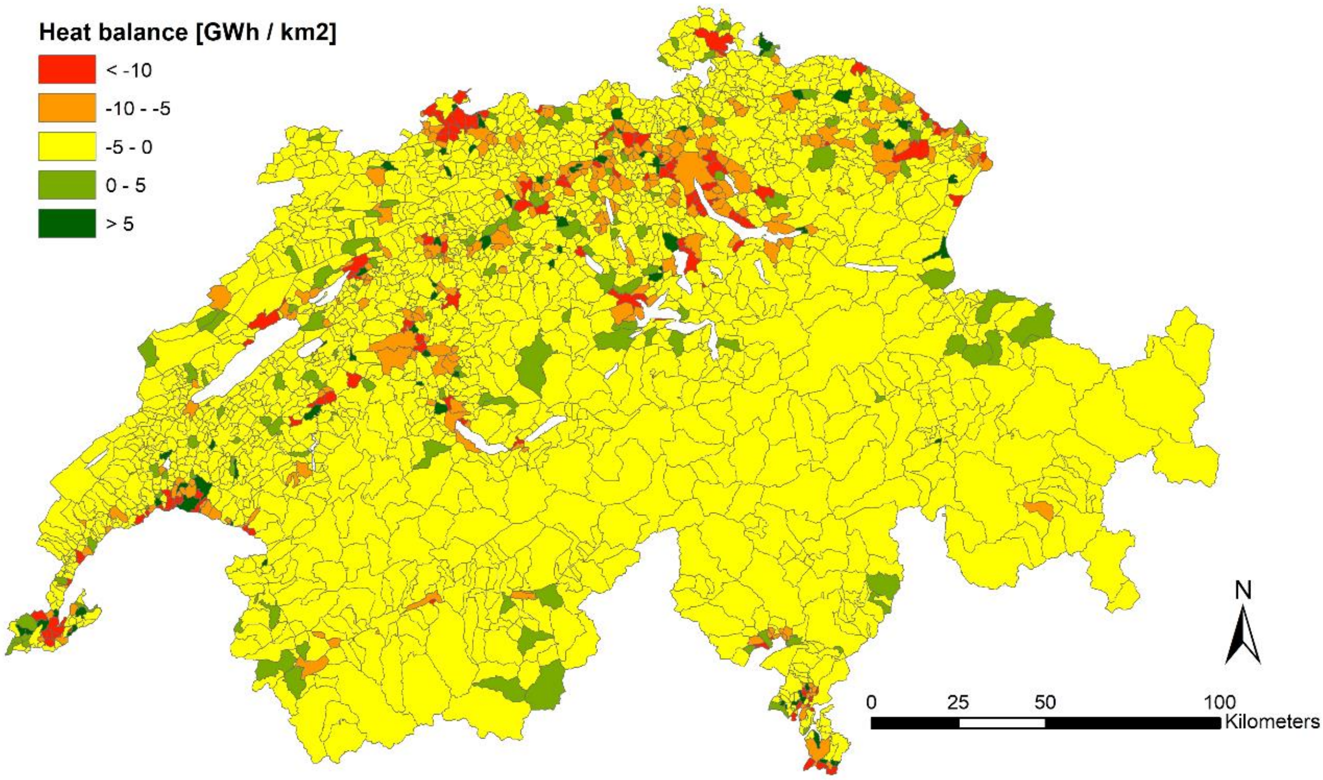

Figure 4. Total annual heat balance per km^2 across all Swiss municipalities, without consideration of the temperature level constraint.

3.3.2. Seasonal Heat Balance

Significant shifts become apparent when considering seasonal variations in the total heat balance. During the summer months (April to September), the demand for space heating notably decreases, leading to a surplus of waste heat in over 300 municipalities. This discrepancy is most pronounced in urban areas, where a substantial heat surplus becomes apparent during the summer, as illustrated in Figure 5. At the national level, heat demand and waste heat supply potential are well balanced, resulting in a mere 1 TWh remaining in heat demand. However, when summing all heat deficits without considering the surpluses, the remaining demand rises to 11 TWh, primarily in rural and mountainous regions.

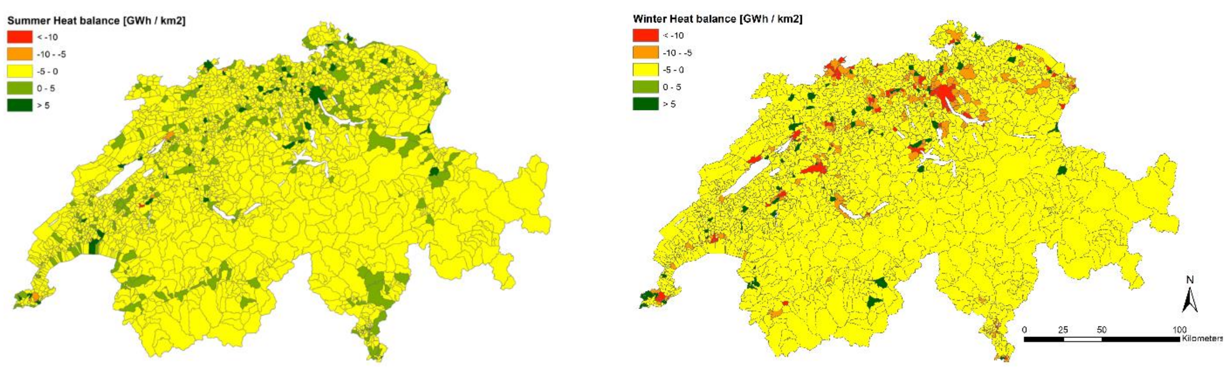

Figure 5. Annual heat balance per km^2 across all Swiss municipalities for the summer half-year (**left**) and winter half-year (**right**).

In general, the findings for the winter half-year align with those for the entire year, further accentuating the scarcity of heat supply. The winter imbalance reaches −51.7 TWh (−54.9 TWh when summing up all deficits only), indicating a significant increase in demand during this period, surpassing the available waste supply heat potential. Nevertheless, Figure 5 reveals that in 67 specific municipalities, a surplus of waste heat persists.

3.3.3. Heat Balance Patterns across Different Temperature Ranges

Within the temperature range below 70 °C, the heat balance aligns well with the waste heat generated within this temperature bracket, as there is currently almost no demand for heat in this temperature range (see Figure 6). Regarding temperatures below 45 °C, WWTPs emerge as the predominant contributors, accounting for approximately 89% of this category, with the remaining 11% attributed to the industrial sector (as detailed in Section 3.1). Waste heat sources are diverse in the 45 °C to 70 °C range, encompassing industries and waste-to-energy facilities. MSWIs emerge as the dominant source, responsible for around 70% of the waste heat in this temperature interval. Figure 5 illustrates the heat balance below 70 °C at the municipal level. Noteworthy locations with substantial low-temperature waste heat potential include major cities such as Zurich, Basel, Lausanne, and Geneva. These cities host significant WWTPs and MSWIs. For a more detailed breakdown of waste heat distribution within the distinct temperature ranges (below 45 °C and 45–70 °C), please refer to Supplementary Material B, which includes dedicated maps for each category.

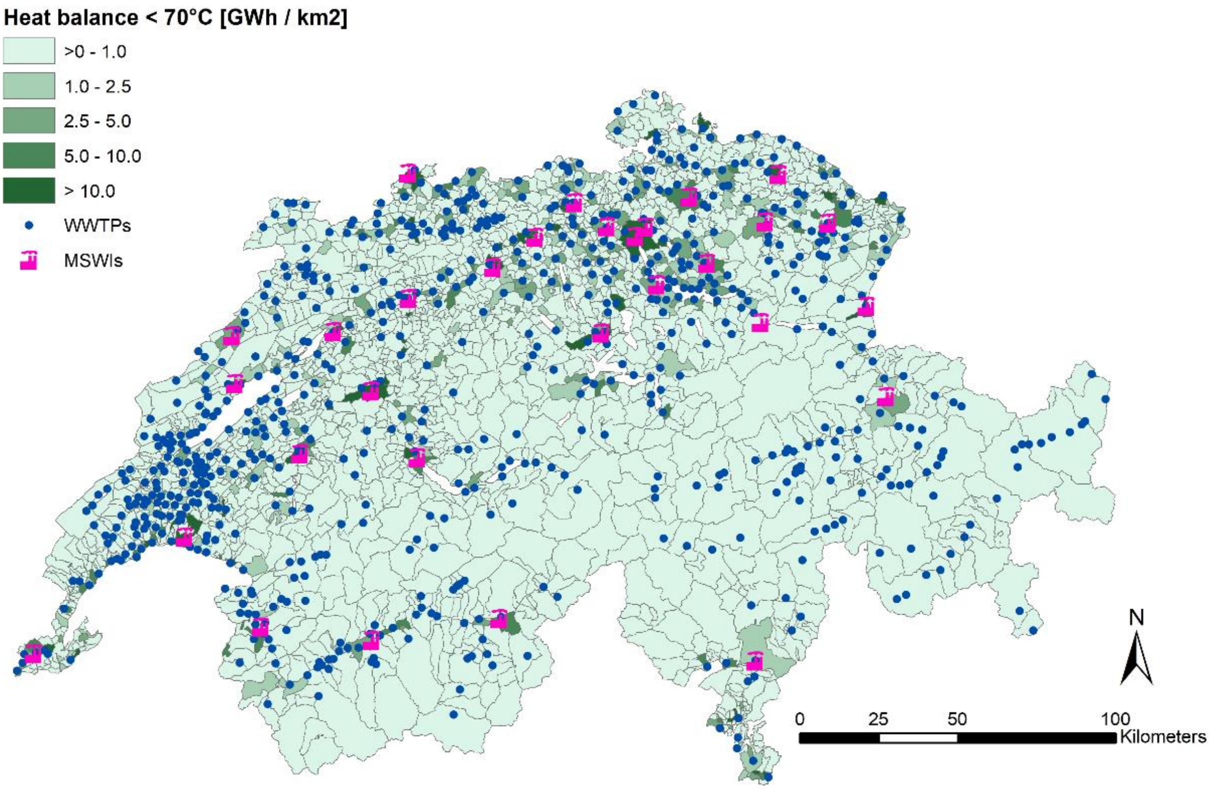

Figure 6. Total annual heat balance with temperatures below 70 °C, in GWh per km^2 (=waste heat supply surplus potential within this range, given the absence of quantifiable heat demand within this bracket), along with wastewater treatment plants (WWTPs) and municipal solid waste incinerators (MSWIs).

In the temperature range between 70 °C and 150 °C, the industrial sector and MSWIs emerge as primary contributors, with each accounting for approximately 49%. Cement production sites account for a significant portion of the industrial sector, contributing 7% of the total waste heat generated within this temperature range. Despite their limited number, each cement plant generates a substantial amount of waste heat, comparable to an MSWI. Concerning heat demand, various consumers require heat at this temperature level. However, space heating dominates significantly, constituting 87% of the demand, followed by hot water at 9%. Space heating shows substantial seasonal fluctuations, with approximately 10 TWh (15%) needed in the summer and around 59 TWh (85%) in the winter. The industrial sector accounts for around 4% of the heat demand with this temperature range and shows no significant seasonal variations. Wastewater treatment plants (WWTPs) represent a minimal share, amounting to 0.1%, with their heat demand confined to the winter season. The cumulative heat demand in this temperature range reaches approximately 80 TWh, nearly 20 times the corresponding waste heat generation. Figure 7 visually illustrates Switzerland's heat balance within the 70 °C to 150 °C temperature range throughout the year. In most municipalities, the heat demand significantly exceeds the available waste heat, particularly in larger cities with high-density residential areas, where the prevalence of space heating exacerbates the deficit. Only 10 municipalities were identified with some waste heat surpluses.

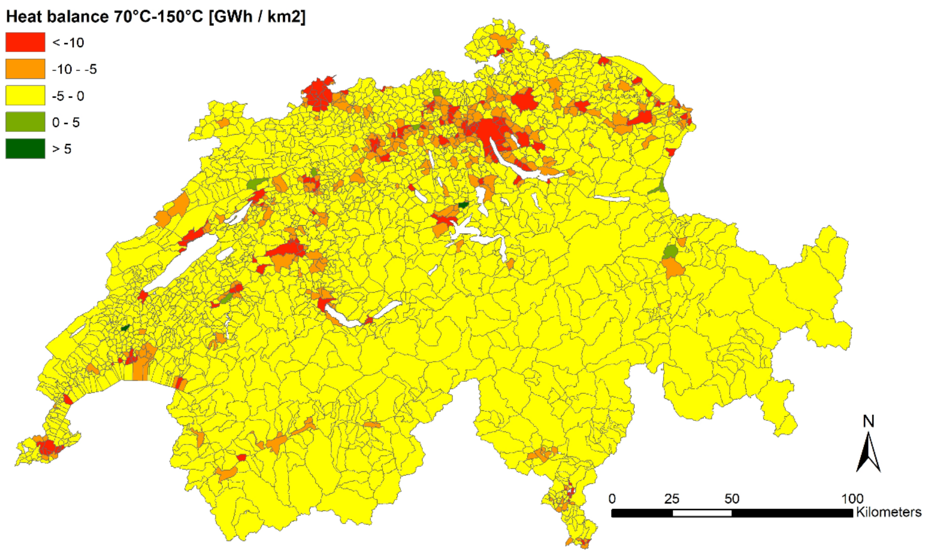

Figure 7. Total annual heat balance with temperatures between 70 °C and 150 °C in GWh per km^2.

In temperatures ranging from 150 °C to 400 °C, a total of 4.5 TWh of waste heat is generated, with the industrial sector contributing 81% (of which cement plants make up 7%). Around 19% of the waste heat supply can be attributed to MSWIs. Importantly, this waste heat generation remains relatively consistent throughout the year, displaying no significant seasonal variations. On the heat demand side, approximately 1.6 TWh is required for industrial process heat within this temperature range, showing no seasonal fluctuations. Overall, a small surplus of 2.9 TWh arises. The spatial distribution reveals that almost 700 municipalities have a small surplus of waste heat, particularly in larger cities with a significant industrial presence (Figure 7 and Supplementary Materials).

In the temperature range exceeding 400 °C, no quantifiable waste heat was identified. However, a heat demand of approximately 7.7 TWh was calculated, with over 99% of this demand attributed to industrial processes, mostly in the larger cities (Figure 8). These industries operate year-round, and the temperature differential from ambient conditions is not significant enough to induce noteworthy seasonal heat demand fluctuations. Since no waste heat is generated in this temperature range, primary energy sources are needed to meet this heat demand.

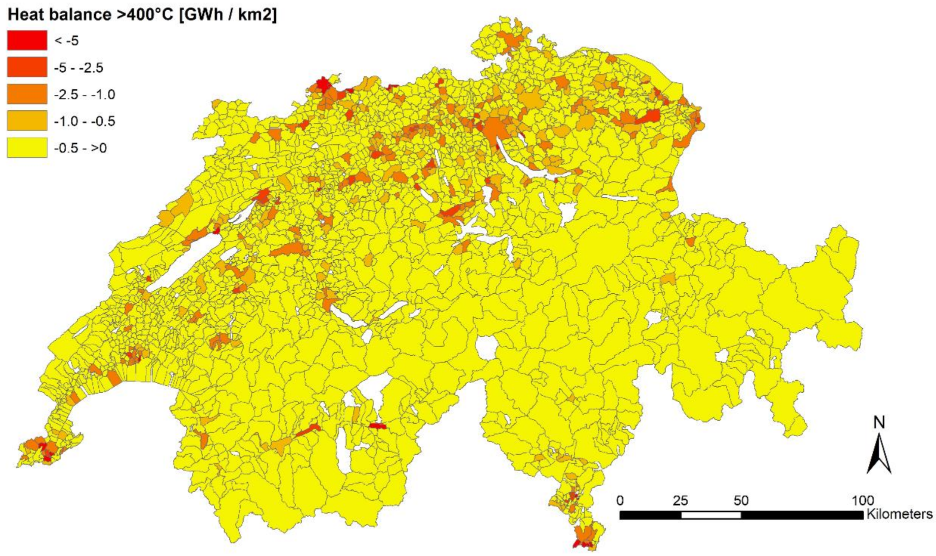

Figure 8. Total annual heat balance with temperatures above 400 °C per km^2 across all Swiss municipalities (=heat demand within this range, given the absence of quantifiable waste heat potential within this bracket).

4. Discussion

4.1. Exploring Waste Heat Potentials and Heat Demand Dynamics

Our study identified a substantial waste heat potential of approximately 37 TWh, representing 17% of Switzerland's total final energy consumption of 213 TWh in 2022 [13]. Notably, in the ideal case where all waste heat could be utilized, our findings indicated that 41% of the current heat demand, totaling 89 TWh, could be covered.

However, discrepancies between the quality of the available and required heat (represented here by temperature level) and practical challenges, such as the dependency and hence required trust between the heat-providing and heat-consuming entity, may hinder full use of this potential. Furthermore, it is crucial to acknowledge the inevitable losses occurring during the heat recovery process and subsequent heat supply and consider transport losses [29]. For example, a commonly assumed heat loss of 10% (for a 1 km pipeline length) from pipelines is generally acknowledged [29]. Additionally, it should be noted that heat transport from waste heat suppliers to heat demand points entails capital expenses for constructing pipelines and electricity costs for transporting a heat carrier (e.g., hot water) through the pipeline. The cost of heat transport can be expressed as a function of various factors, including pipeline length, heat supply temperature, pipeline diameter, connected heat load, and operating hours of heat demand. The specifics of cost estimation for waste heat transport are addressed in the work of Rezaei et al. [45].

Total energy consumption includes diverse needs beyond heat, making allocating consumed energy resources to different sectors and uses a complex challenge. We quantified a total annual heat demand of 89 TWh, which is lower than the estimate provided in the SFOE's overall energy statistics report of 109 TWh [22]. Specifically, our estimated heat demand for space heating stood at 69 TWh, constituting most of the heat needs, closely aligning with the SFOE report's estimation of approximately 70 TWh [22]. In our analysis, we assessed the heat needs of industries, drawing on a sector-specific evaluation conducted by the SFOE [23]. Based on extensive questionnaires, their meticulous approach led to an estimated heat demand of just over 12 TWh for industrial processes, a value notably different from the 20 TWh estimated by [22]. One potential explanation is that while the latter study [22] offers a comprehensive overview, it relied on more generalized data sources, including external trade statistics and overall model results, lacking detailed sector-specific insights. In a study conducted in 2016, Zuberi et al. [15] assessed the energy flow for process heat in Swiss industrial sectors and found a demand of 16.7 TWh, expected to be more than 10% lower than today's demand according to the SFOE report [23]. This estimation aligns well with our calculated industrial heat demand, highlighting the consistency of our findings with previous research. However, methodological disparities between studies and the complexities in assessing the intricate heat dynamics within industrial sectors remain challenging. This challenge is particularly pronounced in heterogeneous sectors such as pharmaceuticals and chemicals, constituting about one-third of Switzerland's total process heat demand. Additionally, allocating electricity consumption between heat and general processes adds further complexity to the analysis. Note that in our study we assumed that waste heat supply potential is directly proportional to the sector's heat demand. Thus, lower demand leads to reduced waste heat supply potentials, evening out the differences in the overall heat balance. Furthermore, our study did not consider specific heat needs (and respective waste heat potential) in the service sector, despite the possibility of certain specific needs, such as those in commercial kitchens and indoor swimming pools. Notably, data centers, an area receiving increasing attention, potentially also hold substantial waste heat potential, estimated to be around 2 TWh and rising [46].

According to our calculations, a significant source of waste heat potential were WWTPs, generating an estimated 15 TWh annually, constituting about 41% of Switzerland's total calculated waste heat potential. Unfortunately, today, this potential is largely dissipated into the environment due to its low temperature, predominantly below 45 °C. Despite active initiatives exploring the feasibility of using such low-quality heat [47,48], widespread implementation has not been achieved. Notably, the city of Berlin has strategically committed to integrating this heat source into its future energy supply plans [49], indicating a positive step forward. A promising approach involves using heat pumps to elevate the temperature for practical applications. Additionally, some studies propose localized energy recovery, such as harnessing warmth from still-warm shower water on-site [50].

The temperature range from 45 °C to 70 °C presented another underutilized annual waste heat potential of 11 TWh, concentrated near major urban centers and primarily originating from MSWIs and industrial activities. This potential holds promise for diverse localized applications. It can support water heating in specific settings such as swimming pools, power absorption chillers for air conditioning in commercial spaces during warm seasons, and is especially interesting for greenhouse heating. For example, about half of the vegetables consumed in Switzerland are imported, especially during winter when growing vegetables in greenhouses needs a significant amount of heat [51]. Each hectare of greenhouse in Switzerland needs an average of 1.8 GWh of heat annually to grow vegetables, with most of this heat currently being supplied by fossil fuels [52]. Utilizing surplus waste heat could address the heat demand of agricultural greenhouses and substitute fossil energy carriers. However, for economic viability, these greenhouses need to be located in proximity to waste heat suppliers. This necessitates a comprehensive location search procedure to identify suitable locations for greenhouse construction. The Hinwil MSWI is a prime example, providing 32.8 GWh of waste heat for greenhouse heating [21], underscoring its viability.

Most heat demand, totaling approximately 80 TWh, fell within a temperature range of 70 °C to 150 °C, primarily attributed to space heating needs. In contrast, waste heat potential within this range was limited to around 4 TWh. Therefore, additional efforts are needed to lower this demand by measures like improving insulation and meeting remaining heating needs with sustainable sources like heat pumps. Notably, space heat and hot water demand have been attributed to this temperature range. However, it is worth acknowledging that systems operating at lower temperatures are emerging and are particularly useful for heating well-insulated buildings. A significant surplus of waste heat, 19% of which comes from MSWIs, lied within the 150 °C to 400 °C range. Supplying local industrial heat demand and redistributing excess heat to nearby buildings for space heating holds promise. After all, using this surplus to fulfill demands in the 70 °C to 150 °C range, despite losses, remains a more sustainable choice than leaving it unused. Moreover, where applicable, exploring Organic Rankine Cycle (ORC) technology could further optimize heat recovery efficiency within this temperature range. In temperatures above 400 °C, where quantifiable waste heat is absent, the existing heat demand of 7.7 TWh allocated to industrial processes must rely on alternative energy sources for coverage. Prioritizing sustainable energy sources and optimizing operational efficiency is crucial in minimizing the environmental footprint of these processes.

In analyzing the heat balance, geographic location emerges as a crucial factor, as a local match between waste heat availability and heat demand is necessary for effective utilization. In most municipalities, total heat demand exceeds available waste heat potential, except in regions hosting MSWIs or cement factories, where concentrated point sources release substantial waste heat. Municipalities with surplus waste heat offer promising grounds for innovative heat recovery initiatives and targeted incentives to attract (or relocate) potential heat users.

The heat balance performed better in summer due to reduced heat demand, contrasting sharply with the winter months, marked by a significant rise in building heating needs. Remarkably, the waste heat supply potential exhibited small seasonal fluctuations, with only a 12% decrease in winter, attributed to increased digester self-use and reduced heat extraction from cooler wastewater. This rather stable waste heat potential, especially during winter, provides an advantage over other fluctuating renewable sources like solar energy. However, addressing winter heat demands remains paramount, given Switzerland's planned shift from nuclear to renewable energy sources [53].

4.2. Practical Implications of Our Methodology and Results

By providing comprehensive insights into the waste heat potentials, our research can help identify municipalities or regions well suited for waste heat recovery initiatives. By integrating localized heat demand data, these projects can effectively be tailored to meet societal needs. For example, developing targeted district heating systems in urban areas with high waste heat availability from industrial processes strategically aligns with the significant demand for space heating, ensuring an effective deployment strategy. Similarly, focusing on waste heat recovery initiatives near MSWIs can strategically supply energy-intensive processes in nearby industries. This approach not only enhances the energy sector's renewable initiatives but also significantly benefits local communities and society, e.g., by creating targeted businesses that require heat. Furthermore, our results facilitate the identification of municipalities or entire regions sharing similar waste heat potentials and balances. This enables the discovery and utilization of synergies between areas, allowing for coordinated research and the application of knowledge across analogous initiatives [54].

Access to comprehensive data on waste heat is currently restricted, often lacking detailed measurements, presenting a significant challenge in accurately assessing waste heat potentials. In 2012, a questionnaire-based survey attempted to address this issue in the canton of Valais [55]. However, this Valais-specific dataset could not be generalized to represent the entire nation. Indeed, within the canton itself, numerous industries lacked data, and crucial nationwide metrics, such as the number of employees, were omitted from the questionnaire, hindering meaningful extrapolation efforts. Taking these limitations into account, our study employed an alternative methodology. For waste heat exceeding 60 °C, we drew upon methods from Germany [32], and for waste heat specifically below 60 °C, we referenced a study from Norway [33]. It is important to note that utilizing foreign data necessitated the assumption that their industrial processes within each sector are representative of Switzerland's. This may not be the case for some rather heterogeneous sectors, such as the chemical industry. For example, the Valais study approximated an annual waste heat potential of 1.7 TWh, whereas our calculations for the canton of Valais yielded a substantially lower figure of 0.5 TWh. This variance can be attributed, in part, to the closure of major refineries in Valais during the study period, notably Tamoil [56], and potentially to a major local chemical plant producing mainly specialty chemicals. Switzerland is a leading country for producing special chemicals, which demand more energy than bulk chemicals due to batch (versus optimized continuous) processes. Still, the discrepancy between Valais's estimated and reported data underscores the pressing need for a comprehensive nationwide survey of industrial waste heat availability. Such a survey is essential to obtain more accurate, representative, and up-to-date data on waste heat supply potential, vital for informed decision making in energy planning and policy formulation. In the case of employing a questionnaire-based survey, it is essential to consider the questions posed to stakeholders carefully, double check their understanding, and implement post-processing of the data to ensure its accuracy and reliability.

The spatial distribution of industries in our study was primarily determined by the number of employees, a metric commonly used due to its correlation with industrial scale and energy needs [57]. However, relying solely on employee count introduces uncertainty, as it may not fully capture the diverse energy usage patterns within similar-sized companies. Industrial processes, influenced by production techniques and machinery efficiency, can vary widely even among comparable enterprises. Therefore, waste heat generation relationships may not always be linear across different sectors.

The specific locations and capacities of WWTPs, MSWIs, and biogas plants were known. However, the resulting waste heat from these facilities might also depend on other characteristics not currently accounted for, such as specific operational efficiency, process specifics, or technological variations. While the distribution according to capacities might be valid for some sectors, notable differences might exist in others. Similarly, building heat demand was evaluated using averaged per-hectare consumer values, emphasizing the need for business-scale assessments to accurately size real-world waste heat recovery projects and ensure awareness of the potential existence of outliers or deviations. While our study offers a valuable overview of waste heat potential, localized detailed evaluations remain imperative for successfully implementing waste heat recovery initiatives.

It also should be noted that mutual trust between waste heat suppliers and consumers is a prerequisite for any successful waste heat cooperation initiative. A survey conducted among industrial waste heat suppliers and district heating operators in Austria revealed that trust, transparency, and clarity play a central role in the success of waste heat utilization projects [10]. The study also concluded that good understanding, regular exchange, and a certain level of trust will promote such relationships. Additionally, there are conceptual frameworks designed to cultivate trust in the context of industrial symbiosis. For example, Ramsheva et al. [58] proposed strategies that firms can employ to establish trust before investing in industrial symbiosis projects.

In summary, emphasizing a hierarchical approach, we advocate reducing heat losses as a first step. If this is not possible, our research introduces innovative waste heat opportunity maps. These maps facilitate aligning waste heat suppliers and consumers, and identifying new suitable locations for heat-demanding sectors like greenhouses or suitable locations for future heat generators, such as biogas plants. This strategic framework enables an effective and sustainable use of waste heat, marking a decisive move toward energy efficiency and environmental protection.

4.3. Limitations and Future Research Needs

Our analysis's primary focus was exploring waste heat availability and heat demand. The goal was to identify opportunities for sustainable waste heat use. In doing so, we acknowledge that our study has specific limitations, and several critical aspects essential to the broader transition to renewable energy falls beyond its scope. One such consideration is exploring additional renewable (heat) energy resources within municipalities. Additionally, gaining insights into existing energy recovery systems could provide a valuable understanding of the connections between heat balance and realized projects. Furthermore, investigating the initiation processes of waste heat recovery projects, as suggested in previous research [59], could help promote future deployment.

To mitigate distortions stemming from variations in municipal areas, we expressed the heat balance figures by area. While we considered the possibility of dividing waste heat potentials by the population of municipalities, this approach proved less relevant to our specific objectives. However, waste heat per capita could serve as a valuable indicator in diverse contexts, revealing localized energy consumption. For example, considering waste heat per capita could help identify regions with high heat demand per capita, facilitating targeted energy efficiency initiatives. Considering the multifaceted nature of waste heat, a comprehensive evaluation may also involve additional parameters such as the specific characteristics of industrial processes, the economic feasibility of implementing recovery technologies, and the environmental impact of waste heat utilization. Our analysis only offers an initial overview of the spatial distribution of heat balance within Swiss municipalities. We propose conducting detailed case studies in specific regions to gather comprehensive data on industrial waste heat availability. These efforts are crucial for shaping targeted waste heat recovery strategies contributing to the transition to renewable energy.

5. Conclusions

This study delved into the waste heat supply potentials and heat demand across all 2136 Swiss municipalities, utilizing spatially explicit data from industries, waste-to-energy facilities, and buildings. Our approach provided valuable insights into waste heat balance's spatial and seasonal distribution, differentiated by temperature profiles. The results revealed a substantial annual waste heat potential of 37 TWh, with almost half sourced from WWTPs below 45 °C. Heat between 45 °C and 70 °C, suitable for applications like greenhouse heating, primarily originated from MSWIs. Industries predominantly contributed to waste heat supply exceeding 150 °C. Most municipalities exhibited a net excess heat demand totaling 89 TWh. Additionally, waste heat fell short by 8 TWh to meet the industrial process heat demand exceeding 400 °C, emphasizing the ongoing reliance on primary energy sources for higher-temperature heat. These findings are relevant for strategic planning as well as an initial preparatory step for the effective implementation of initiatives aimed at maximizing waste heat utilization.

Our research significantly contributes to the energy transition efforts, offering essential national, regional, and municipal data. While our method cannot replace localized business-scale investigations, it is a valuable resource that guides strategic decisions in waste heat recovery. Moreover, the information generated in this study may facilitate networking and knowledge exchange among similar municipalities, fostering collaborative efforts in the renewable energy sector. Furthermore, our methodological approach could be adapted to other regions beyond Swiss borders, leveraging available data types and allowing flexibility for adjustments based on regional contexts. The approach could also be extended to explore various renewable energy sources and identify locally optimal combinations, paving the way for a more sustainable energy system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17010106/s1. References [26,35,60–68] are cited in the supplementary materials.

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