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Table of contents

sweet swiss energy research for the energy transition

Summary

Electrification of process heat and integration of renewables are some of the essential pathways for industrial heat decarbonization. However, in order to achieve optimum integration of process heat electrification and renewable technologies, it is important to have a comprehensive knowledge of process heating and cooling demands in the industrial processes. In this deliverable report, the concept of exemplar grand composite curves (GCCs) is presented. The application of exemplar GCCs is demonstrated to assess the potential of HP integration using the Swiss chocolate industry as a case study. The GCCs representative of typical company sizes in the Swiss chocolate industry are constructed based on the typical thermal requirements by process step. The exemplar GCCs are used for the identification of appropriate HP sizes and operating conditions. Based on the results of exemplar GCCs, the HP integration between the excess heat available from refrigeration and hot water production for tracing circuits is the most technically feasible option for the chocolate manufacturing process. The overall sector-wide potential for CO_2 abatement and total final energy reduction of the HP integration opportunities identified using exemplar profiles can be estimated using aggregated bottom-up sectorial profiles (as reported in Deliverable 4.3.2). The HP integration offers a cost-effective sector-wide potential in the range of 45% to 56% for CO_2 abatement and 23% to 28% for total final energy reduction in today's Swiss chocolate manufacturing. Moreover, the economic feasibility analysis suggests that HPs with coefficients of performance (COPs) above 2.6 for the identified operating conditions are cost-effective for average energy prices, current CO_2 levy, and even for the most risk-averse companies in the Swiss chocolate sector except for very small companies. Thus, the exemplar GCCs will facilitate the development and assessment of solutions for the optimal integration of energy efficiency measures (EEMs; closely linked with WP05), renewables, as well as negative emission technologies (NETs, WP12). Moreover, the results of exemplar GCCs and sectorial profiles also suggest there is substantial excess heat available from chocolate production in Switzerland. This heat can be used for more ambitious CO_2 emission reduction in the sector studied for space heating (direct use or via district heating). These solutions can be assessed in more detail in the context of WP01.

1 Introduction

1.1 Background

In order to achieve the climate targets defined in the framework of the Paris Climate Agreement, 192 countries, including the majority of European countries have set net-zero emissions targets for the middle of this century [1]. Industrial process heat, domestic hot water production and space heating together contribute to about 40% of global GHG emissions. Industrial process heating accounts for more than 50% of global heat demand [2], making the decarbonization of process heat generation a crucial step towards achieving the said net-zero targets. Industrial decarbonization can be achieved by improving the efficiency of fuel consumption, by replacing fossil fuels with low-carbon fuels or renewables, by electrification of industrial processes, and by implementing negative emission technologies. While improvement in the fuel consumption efficiency and negative emissions technologies are more suitable for energy-intensive industry sectors with relatively high-temperature process heat requirements (such as iron and steel, cement, chemicals), process heat electrification is more suitable for non-energy intensive sectors with relatively low process temperatures (such as food and beverage).

In line with many other countries, Switzerland has set a net-zero target for 2050 [3]. With industrial processes being responsible for 20% [4] of total fuel demand and 15% of CO2 emissions [5], they will play an important role in the Swiss energy system's transition towards net-zero emissions. Due to the very low CO2 emission intensity of electricity generated in Switzerland (i.e., 0.12 kg CO2/kWh [6]) compared to other European countries, electrification of the industrial processes can be a very effective way of industrial decarbonization. Process heat electrification can be achieved by replacing fossil fuels either by direct conversion of electricity to heat (e.g., electric arc furnaces in steel industry or convection drying with infrared dryers in food industry) or by excess heat utilization primarily through the integration of technologies like heat pumps (HP) [7].

Utilization of excess heat from industrial processes is technically one of the most impactful ways of improving the efficiency of industrial processes and for reducing their CO2 emissions (Bhadbhade and Patel, 2022; under review). HPs are a potentially very convenient and cost-effective electrification options that can be implemented without any major modifications to the core processes [8].

The existing literature pertinent to the present work can be broadly categorized into three topics; development of total site profiles and net heat sink and source profiles using the concepts of Pinch Analysis, the use of grand composite curves (GCCs) and total site profiles to identify various heat integration opportunities (e.g., HPs, thermal storage) and techno-economic analysis of these opportunities. Wallin et al. [9] introduced an approach to identify the potential for HP integration using the composite curves (CC) and further extended the methodology to the use of GCCs for identifying HP integration opportunities. Agner et al. [10] presented a graphical method for the combined integration of HP and indirect heat recovery. Schlosser et al. [11] presented a review of sector and process-specific integration concepts for HPs based on the evaluation of GCCs. Stampfli et al. [12] built on the previous approach and presented a practical method for HP integration in a non-continuous process. In order to estimate the sector-wide theoretical and practical heat integration potentials, by Kantor et al. [13] developed a methodology to construct sector-wide bottom-up GCCs. Ong et al. [33] developed an approach to construct a bottom-up sector wide net heat sink and source profiles based on the Pinch Analysis of individual industrial sites.

Due to the relatively high share of heat demand at rather low temperatures [14], the food industry subsector is one of the most suitable industry subsectors for HP integration, which has been analyzed in several studies. For example, Zuberi et al. [8] analyzed HP integration potential in U.S. food industry and concluded that the U.S. food industry represents about 20% total final energy (TFE) reduction potential through process heat electrification. A similar study on the integration potential of high temperature heat pumps (HTHP) in the French food industry was published by Seck et al. [15], which led to a conclusion that HP integration can potentially reduce up to 13.6 % of TFE demand from the French food industry compared to the energy demand in the year 2010. Both Zuberi et al. [8] and Seck et al. [15] made assumptions about the availability of excess heat, a drawback which was avoided by Becker [16] who presented a practical case study of the application of Pinch Analysis and HP integration in a Swiss dairy. Likewise based on Pinch analysis, Wallerand et al. [17] presented an optimization framework for HP integration along with integration of renewables for a Swiss cheese factory. Given their outstanding role in industrial decarbonization, there has been a growing interest in the techno-economic analysis of commercially available HPs for various industry sectors. Arpagaus et al. [18] presented a comprehensive review of commercially available industrial HPs in Switzerland. Schlosser et al. [19], presented the application, performance and economic feasibility of large-scale industrial HPs for Germany. Using sectorial profiles and exemplar GCCs for various company categories, the current work analyzes the potential of cost-effective HP integration in Swiss chocolate manufacturing industry, a sector for which no publications so far exist on deep decarbonization.

1.2 Structure of the chocolate manufacturing industry in Switzerland and process description

In 2021, the overall production in the Swiss chocolate industry reached about 200,000 tonnes. Accounting for about 6% TFE demand of the Swiss food and beverage industry [20], the Swiss chocolate manufacturing employs about 4,000 workers and generates about CHF 1.7 billion in annual sales [21].

1.2.1 Industry structure

Shares of energy carriers in the TFE consumption of chocolate manufacturing in Switzerland are estimated based on the information provided in EnAW database and presented in Figure 1. The majority of processes involved in chocolate production utilize electricity (i.e., conching, grinding, winnowing, refrigeration, etc.; see below, Figure 3). As a result, approximately 59% of the TFE demand in the Swiss chocolate industry is covered by electricity. Roasting and debacterization are large heat consumers at high temperatures. Roasting technologies employed in Swiss chocolate manufacturing typically utilize steam or direct natural gas. Thus, the majority of heat generated for use in chocolate manufacturing is produced using natural gas (31% of TFE). District heating (8%) and biogas (1%) are responsible for relatively small shares of TFE demand.

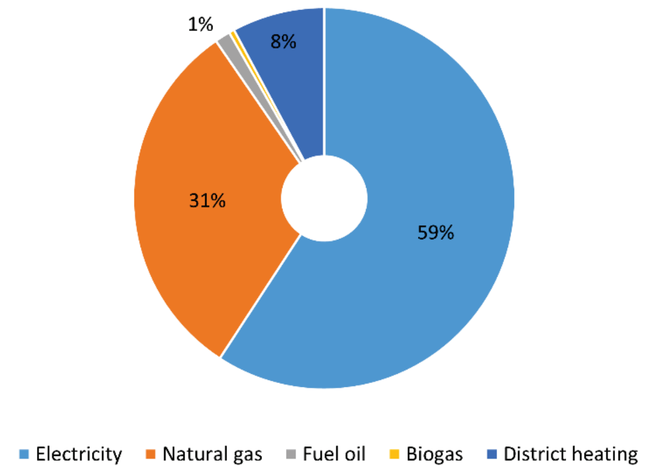


Figure 1. Energy mix for Swiss chocolate production (EnAW)

In order to take the differences in electricity prices paid by Swiss chocolate manufacturers into account, companies in Swiss chocolate manufacturing are categorized into small, medium and large enterprises based on the definitions provided by Elcom [22]. Figure 2 presents the estimated shares of annual production by companies of various sizes and corresponding Elcom categories.

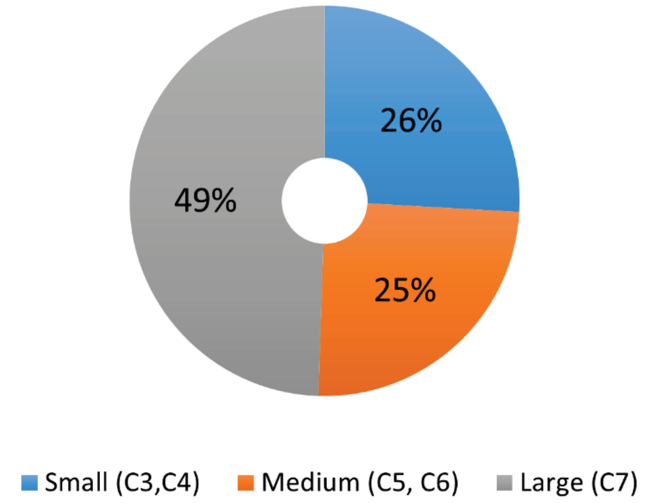


Figure 2. Share of chocolate production by company size ([22], STATENT)

1.2.2 Process description

A schematic of the generic process for chocolate manufacturing in Switzerland is presented in Figure 3. The process begins with the cleaning and debacterization of raw materials such as cocoa beans. Depending on the intended product, cocoa beans are either fed to the breaking and winnowing process (cocoa powder) or directly to the roaster (cocoa liquor). In order to bring out the aroma of the cocoa and remove the moisture, cocoa beans or cocoa nibs (cocoa beans after removal of shells) are roasted at 100°C to 120°C. Depending on the intended product, roasting occurs either using the hot air produced by the heat exchange with steam (for whole bean roasting) or in a natural gas-heated roaster (for nibs roasting e.g., tornado roaster). Whole roasted beans are lightly crushed to remove the shell from the nibs using toothed rollers or impact rollers. The shells and nibs are then separated using the winnowing process. The nibs are fed to the rollers, where they are ground to a fine cocoa paste. The heat from grinding melts the cocoa butter, which is removed using large hydraulic presses. The remainder is cocoa cake which is ground and sifted to produce cocoa powder. The cocoa powder is mixed with cocoa butter, sugar as well as either condensed milk or milk powder in a kneader to prepare a homogenous, paste-like mixture or fed directly to rolling mills. This paste is then further refined to the particle size of 15 to 20 microns in rolling mills. The desired aroma, texture and flavor are imparted to chocolate through surface scraping and agitation in the process step called conching. The temperature of chocolate paste rises to about 80°C during the conching process and is then typically maintained at about 55°C using cooling water. Chocolate mass formed in the conching process is transferred to the tempering and molding process which takes place at about 45°C. Molded chocolate is cooled down to between 5°C and 7°C using a refrigeration system. It should be noted that chocolate facilities producing specialty products have dedicated production lines that exhibit some variation in process steps and process conditions described above and depicted in Figure 3. However, due to data confidentiality and heterogeneity in process conditions, they are not included in the analysis. The sectorial profiles presented below and the subsequent HP integration analysis are based on the description and generic schematic presented in this section.

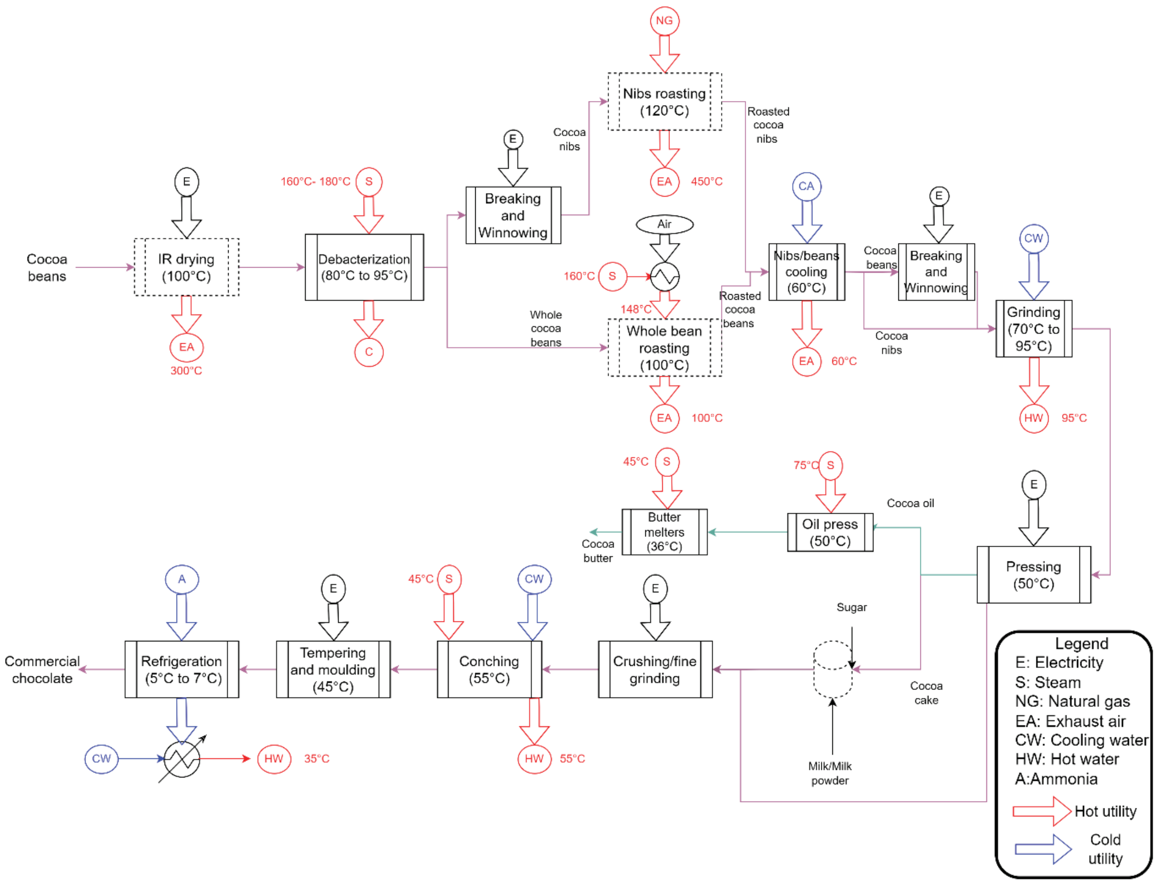


Figure 3. Schematic of chocolate production process in Switzerland

Based on the data gathered through various Pinch studies of Swiss chocolate manufacturing companies [23] [24], approximately 63% of the total heat in chocolate production is required below 55°C. The process steps of conching, blending, tempering and molding require heat below 55°C. Cleaning in place (CIP) and heating, ventilation and air conditioning (HVAC) represent approx. 15% of the total heat demand at temperatures between 55°C and 100°C. Processes of roasting, beans/cocoa paste drying and debacterization require heat above 100°C and together represent up to about 23% of total heat demand (see Figure 4).

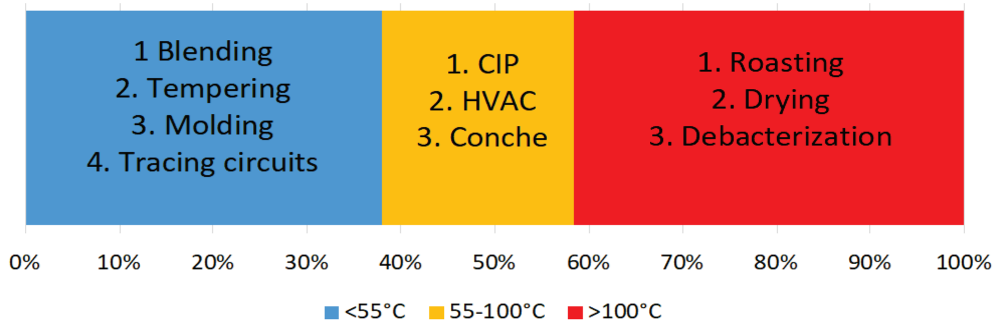


Figure 4. Share of heat consumption by temperature levels in chocolate production

1.3 Heat pumps

HPs are reverse heat engines that are used to transfer the available heat from lower temperatures (Tsource) to higher temperature (Tsink). HPs typically consist of an evaporator to absorb heat, a compressor to raise the pressure and temperature of the working fluid and a condenser to reject the heat. External energy or work needed by the HP to transfer heat from a lower temperature to a higher temperature is typically provided by electricity (more specifically for closed-system compression HPs).

Table 1 presents the typical classification of HPs based on the maximum Tsink that can be achieved by the HP. Moreover, HPs can also be classified as open system and closed system. Open system HPs are further classified as thermal vapor recompression and mechanical vapor recompression based on the technology. Closed system HPs are further classified as sorption and compression HPs based on the technology. Both open circuit and closed loop HPs are implemented in the industry. However, open circuit HPs are confined to niche applications, and they often compete with direct heat integration opportunities using heat exchangers. Due to their flexibility and high supply temperatures, closed loop HPs on the other hand, are most suitable options for industrial applications [25]. Thus, current work focuses on the analysis of single stage, closed loop HPs, which are commercially available and for which the implementation data is publicly available.

Table 1. General categories of heat pumps based on the maximum achievable Tsink [18]

Heat pump category	**Maximum T_{sink} (°C)**
Standard heat pump (SHP)	80
High temperature heat pump (HTHP)	80 - 100
Very high temperature heat pump (VHTHP)	100 - 160

1.4 Aims and objective

Despite being one of the promising electrification technologies and a steady increase in the range of available HP models in the market in recent years [18], the wider spread of industrial HPs in the industry has been facing barriers such as a lack of awareness about the possible economic opportunities for HP integration, lack of knowledge about commercially available options among potential users, high initial capital costs and low expected payback periods [18][25]. The tailor-made designs for the HP systems often have higher initial investment costs than the commercially available, off-the-shelf HP options leading to higher payback times [19]. Thus, the aim of this deliverable is to demonstrate the use of exemplar GCCs and sectorial profiles (D4.3.2) to identify the optimum placements for HP integration, the most cost-effective commercially available HPs and the potential for their integration in the chocolate industry to reduce TFE consumption and energy-related CO_2 emissions. This report is presented with the objective to help industrial decision-makers identify the cost-effective off-the-shelf HP options for the given temperature levels and sizes of heat sinks and sources.

2 Data and methods

2.1 Chocolate process data

Process stream data for chocolate production such as temperature levels, specific heat and mass flow rates are obtained from publicly available Pinch Analysis studies for chocolate and cocoa manufacturers in Switzerland [23][24]. Average specific final energy consumption (SEC; kWh/tonne) for chocolate manufacturing process steps in Switzerland are estimated based on typical temperature levels, mass flow rates, and annual production of the companies for which the pinch studies are available.

Table 1. Average specific final energy consumption for process steps in the Swiss chocolate sector

Process	Specific final energy consumption (kWh/tonne)	Modeling approach for pinch analysis
Roasting (beans)	110	Grey box model
Roasting (nibs)	133	Grey box model
Drying	50	Grey box model
IR drying	85	Grey box model
Debacterization	88	Grey box model
CIP	30	Grey box model
Tracing circuits	240	Grey box model
Conching	60	Grey box model
Blending	11	-
Tempering	110	Grey box model
Molding	37	Grey box model

Companies in the Swiss chocolate industry are segmented into four categories based on the estimates of annual production. Typical company sizes are selected based on the most commonly occurring annual production estimates within a certain category (see Table 3). For example, the majority of companies belonging to “very small” company category have annual production of approximately 1,000 tonnes. The annual production for each company is estimated using the average annual production per employee obtained from the statistics published by ChocoSuisse for 2021 [21] and the number of employees per company obtained from the STATENT database. Based on the estimates of total electricity and fuel consumption, the electricity and natural gas prices paid by each company are identified using the categories defined by the Elcom [22] and the survey of natural gas prices [26]. Cost-effectiveness of various commercially available HPs in the European market is analyzed for these typical company sizes and for energy prices paid by the company categories.

Table 2. Categories of chocolate manufacturing companies in Switzerland

Company category	Size (annual production in tonnes)	Energy price category
Category 1 (Very small)	1,000	C3
Category 2 (Small)	10,000	C4
Category 3 (Medium)	20,000	C5, C6
Category 4 (Large)	30,000	C7

2.2 Techno-economic data for heat pumps

The technical data (such as typical temperature ranges, heating/cooling capacities, working fluids and compressor types) and corresponding cost data (such as HP cost, installation cost and annual operation and maintenance costs for commercially available SHPs and HTHPs) for selected HP models are obtained from various literature sources and reports ([27], [18], [19], [28]). In total, 30 HPs installed between 2008 and 2019 across Switzerland, Germany, Austria, France and Denmark were identified from the aforementioned sources for which the technical and economic data along with operating conditions were reported (summarized in Table 4). The cost data from countries other than Switzerland are converted to Swiss Francs (CHF) using the purchasing power parity (PPP) exchange rates. Despite the growth in the market, HP costs reported in the literature have remained relatively constant for the past couple of decades [19]. As a result, the HP costs are converted to 2021 CHF by only correcting for inflation using producer price indices (FSO). The required heating capacities of HPs for various sizes of companies in the Swiss chocolate sector are estimated using the exemplar GCCs for chocolate production (see 3.1 below).

Table 3. Select commercially available heat pumps in European market ([18], [27], [28])

Heat pump model	Working fluid	Compressor	Heating capacity (kW)	Maximum T_{sink} (°C)	Investment cost (2022 CHF)	Installation cost (2022 CHF)	Cost type[1]
SHP1	R134a	NA	20	80	44,709	58,121	HP
SHP2	R407c	Piston	61	90	162,255	243,383	Total
SHP3	R404A	Piston	64	100	106,297	138,187	HP
SHP4	R134a	Screw	77	80	47,690	61,997	HP
SHP6	R134A	NA	194	80	407,745	611,617	Total
SHP7	Ammonia	Gas driven	194	150	93,520	140,280	Total
SHP8	R134A	Piston	194	80	156,430	203,359	HP
HTHP1	R134A	Piston	200	80	293,388	381,404	HP
SHP9	R134A	Screw	220	80	118,677	154,280	HP
SHP10	R404A	Piston	240	100	159,217	238,826	Total
SHP11	R134A	Screw	260	80	155,781	202,515	HP
SHP12	R134A	Piston	274	80	417,859	626,788	Total
SHP13	R1234ze	Piston	276	120	139,582	181,457	HP
SHP14	Ammonia	Piston	370	150	261,100	391,649	Total
SHP15	R134A	Piston	382	80	195,703	254,414	HP
SHP16	Ammonia	Screw	410	150	157,613	236,420	Total
SHP17	R134A	Screw	410	80	146,777	190,811	HP
SHP18	R134A	Piston	420	80	359,897	539,846	Total
SHP19	R1234ze	Screw	471	120	161,288	350,000	HP
SHP20	Ammonia	Piston	507	90	247,983	322,378	HP
HTHP2	R1234ze	Screw	520	120	258,162	335,610	HP
SHP21	R134A	Screw	550	80	249,006	323,708	HP
SHP22	R134A	Screw	692	80	316,160	474,239	Total
HTHP3	R744	Screw	800	90	391,024	508,332	HP
SHP23	R134A	Screw	800	80	686,041	1,029,062	Total
SHP24	Ammonia	Piston	1000	150	347,562	451,831	HP
HTHP4	Ammonia	Piston	1050	150	205,488	267,135	HP
HTHP5	Ammonia	Piston	3000	150	3,605,996	5,408,994	Total
SHP25	Ammonia	Screw	3250	150	1,276,958	1,915,438	Total

[1] The costs are reported either only for "HP" or "Total" cost (i.e., HP cost + installation). Cases where only "Total" costs are reported, the HP costs are estimated assuming HP costs contribute to about 40% of total costs [29].

Based on the cost data adopted for the Swiss market, a cost function is derived to estimate the specific investment cost of HP (CHF/ kW heating capacity) as a function of the heating capacity for the HP (see Figure 5). The specific costs for the HPs decrease exponentially and then levels off with the increase in the heating capacity. Specific investments for the HPs shortlisted in this study range between 2600

CHF/kW heating and 200 CHF/kW heating of heating capacity based on the adjusted costs. The cost function estimated based on these values is later used to assess the cost-effectiveness of HP integration for various size categories.

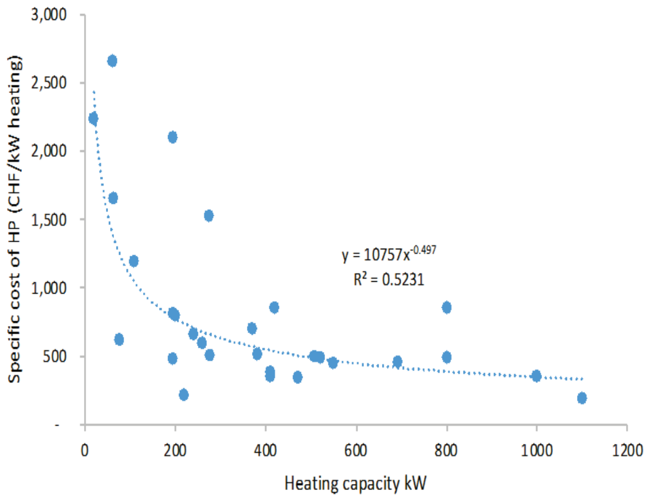


Figure 5. Specific investment costs (without installation costs) for heat pumps as a function of heating capacity

2.3 Energy prices and CO_2 levy

The annual energy efficiency (EE) improvement-related benefits generated by HP integration are estimated as the annual energy costs saved due to achieved net TFE savings, thereby using the energy prices for the year 2021. The average prices paid for natural gas within Switzerland are monitored for nine standardized consumer categories including three categories for industrial companies and are obtained from the survey of natural gas prices [26] . By analogy, the prices paid for electricity by the Swiss industry are also reported for four industrial consumer categories and obtained from Elcom [22]. The cost-effectiveness of HP options is assessed for three different ratios of electricity to natural gas prices typically paid by the companies in Switzerland (henceforth referred to as energy price ratio); (1) minimum energy price ratio (i.e., lower electricity price compared to natural gas), (2) average energy price ratio (i.e., the ratio of average electricity and natural gas price across cantons) and (3) maximum energy price ratio (i.e., higher electricity prices compared to natural gas prices). The annual benefits from fuel-saving measures also depend on the cost savings generated by CO2 abatement. Annual CO2 abatement-related cost savings are estimated using the CO2 abatement generated through HP integration and the CO2 levy. The CO2 emission factors for natural gas (0.2 kg CO2/kWh) is obtained from the Swiss national inventory report [30] and the CO2 emission factor for electricity generation is assumed to be 0.12 kg CO2/kWh [6]. The current CO2 levy of 120 CHF/tonne CO2 is used for the cost-benefit analysis in this study [31].

2.4 Discount rates and lifetime

Discount rates (DR) are used in the cash flow analysis to amortize the initial capital investment cost over the lifetime of the investment. DR used by the industrial decision makers to analyze the cost-effectiveness of EE-related investment vary based on the various techno-economic characteristics of the industrial companies. The DR used in the cash flow analysis by industry decision-makers typically reflect both the time value of money and the perceived risk for the investment decisions. In order to reflect the company-level investment decision criterion for the Swiss industry, a DR of 21% is assumed in the present analysis for cost-effectiveness analysis of HP integration based on the authors' previous work (Bhadbhade and Patel; under review). A technological lifetime of the HP is assumed to be 20 years based on the typical technological lifetime of its components ([8]).

2.5 Representative grand composite curves for company sizes and sectorial profile

Assessment of HP applicability requires identification of available excess heat (i.e., source) and demand for process heat (i.e., sink) as well as their temperature profiles. Exemplar GCCs for each company size help to identify the operating temperatures and size of the HP, while bottom-up sectorial profiles allow to estimate sector-wide HP integration potentials for the identified T_{sink} and $T_{sources}$. The exemplar GCCs and sectorial profile for the Swiss chocolate industry presented in this study are based on the methodology developed by Ong et al. [33]. The average thermal power requirement (kW) for each process step is estimated for each production route and company size using publicly available data. A GCC representative of the company size and production route is created using average thermal power requirements. The exemplar GCCs thus obtained are multiplied with operating hours for each process step and each company size to obtain representative profiles with heat quantities (kWh) for each temperature interval. A representative net heat sink and source profile is then created for each category (size and production route) of the company by scaling up the net heat sources and sinks to the annual production represented by all companies of the given category (equation 1). For example, a exemplar GCC for a company with an annual production of 1,000 t p.a. (i.e., "very small" companies) is created and scaled up to total annual production represented by all companies in this category. A representative profile for the entire chocolate manufacturing sector (i.e., sectorial profile) is created by aggregating the net heating and cooling demand in each temperature interval for all company categories obtained in the previous step.

$$SF = \frac{TAP_{Sector}}{TAP_{Analysed\ Plant}} \qquad \text{Eq. 1}$$

Where,

SF = Scaling factor

TAP=Total annual production

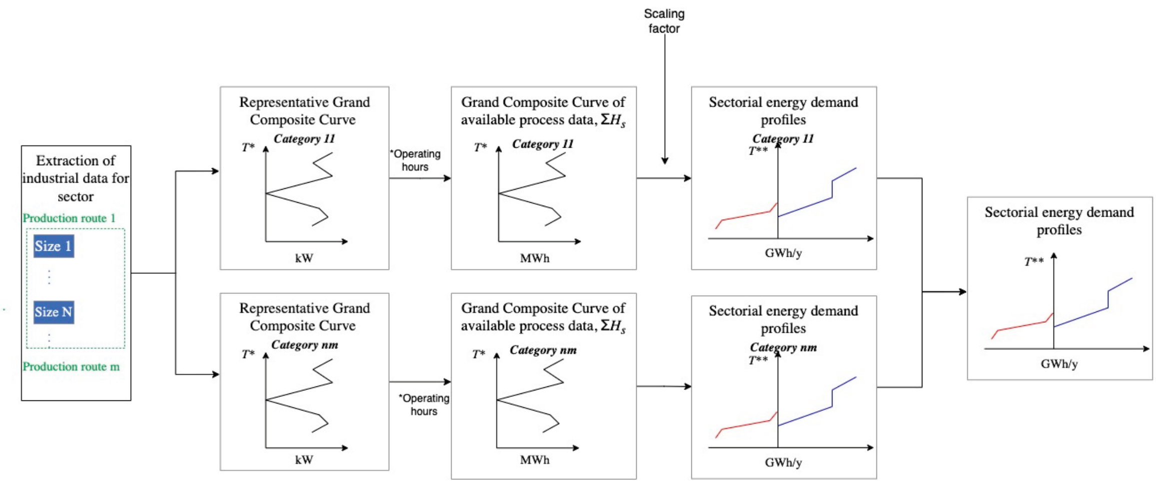


Figure 1. Methodology for sectorial profile generation from representative grand composite curves

Based on the type of commonly employed technologies in chocolate production, two representative profiles are identified for two production routes in the Swiss chocolate manufacturing: 1) chocolate production via whole beans roasting and 2) chocolate production via infrared (IR) drying and cocoa nibs roasting. Configuration of process steps and process conditions for the process steps other than roasting and drying remain unchanged for both production routes. However, since the HP integration for nibs roasting was found to be economically unattractive (section 3), and since all other process steps are similar for both production routes, only production route 1 is analyzed in detail in the present work. The companies are further classified based on the typical sizes of the companies in the Swiss chocolate sector.

2.6 Selection of heat pumps

Commercially available HPs are shortlisted for the current study based on their application (i.e., for excess heat recovery) and exemplar GCCs are used to identify the appropriate HP capacities for the given company size. The operating conditions, such as the temperature levels over which the HP is operated, and the temperature lift also affects the HP selection. The achievable temperature levels and temperature difference depend on the selection of working fluids, compressors, and the number of stages [32]. HPs that operate across operating conditions as identified for the Swiss chocolate industry are selected for this study. The required thermal power determined from the exemplar GCCs are also taken into account while identifying HPs for each company size.

2.6.1 Coefficient of performance for the heat pump

The performance of HP is categorized using the COP. The theoretical maximum achievable COP_{carnot} for the HP is calculated by equation 2. The COPs achieved in a practical setting are, however, lower than the COP_{carnot} and represented as the ratio of the amount of useful heat (Q_{cond}) at T_{sink} to the electric power consumed by the compressor (W_{in}). The ratio of practical COP_{real} with theoretical COP_{carnot} provides the second law efficiency (η_{2nd}) of the HP system. Operating conditions and reported COPs provided for already implemented HPs are used to estimate η2nd the HPs in the given operating temperature ranges (using equation 4). The values of η2nd thus estimated are then used to estimate the COP_{real} values for all HPs included in this work over the operating conditions identified from the exemplar GCCs for chocolate production in Switzerland.

$$COP_{carnot} = \frac{T_{cond,HP}}{\Delta T_{lift}} \qquad \text{Eq. 2}$$

$$COP_{real} = \frac{Q_{cond}}{W_{in}} \qquad \text{Eq. 3}$$

$$\eta_{2nd} = \frac{COP_{real}}{COP_{carnot}} \qquad \text{Eq.4}$$

COP_{real} for HPs are then compared with the threshold COPs for the companies of all categories and different ratios of electricity to natural gas prices to identify HPs with COPs in an economically feasible range.

2.6.2 Optimal heat pump integration

The exemplar GCCs explained in the previous section allow to identify various possible T_{sink} and Tsource temperatures, the required heat load above the pinch and available excess heat below the pinch for all types of companies. The HP should be integrated to operate across the pinch point. The COP curves in combination with GCC help to estimate the optimum condenser and evaporator duties along with the evaporator integration point. Corresponding condensation and evaporation temperatures for HP are obtained based on the minimum temperature difference for heat exchangers . If the amount of excess heat available at Tsource is more than the amount of required process heat at T_{sink}, a COP curve (evaporator duty as a function of evaporation temperature is plotted by estimating the evaporation capacities for various evaporation temperatures in the range from pinch point to coldest Tsource. Evaporator duty as a function of evaporation temperature is estimated using equation 5. If the amount of excess heat available is smaller than the required heat load, the thermodynamically optimum condenser load is estimated by rearranging equation 5. The point of intersection of COP curve with the GCC provides the optimum integration point and evaporator duty of the HP for the given T_{sink} ([12]and [10]).

$$Q_{evap,HP} = Q_{cond,HP} \times (1 - \frac{1}{COP_{real}}) \qquad \text{Eq. 5}$$

2.7 Net energy savings

HP integration results in the reduction of fossil fuel consumption and an increase in electricity consumption. The thermal power required by the HP on the evaporator side depends on its COPreal (see eq. 3). COPreal for commercially available HPs identified for the given operating conditions are estimated as explained in section 2.6.1. Annual electricity consumption is then estimated using the thermal power of the HP and annual operating hours. Full load operating hours for the HP are assumed based on the typical annual operating hours of the processes identified as sinks and sources. Annual net TFE savings are estimated as the difference between fuel saved, and electricity consumed.

2.8 Cost-effectiveness analysis

The Levelized Cost of Saved total final Energy (LCSE) and the Levelized Cost of CO_2 abatement ($LCCO_2$) are estimated to assess the economic attractiveness of HPs in the Swiss chocolate sector (see eq. 6) for the given source and sink temperatures. The levelized cost for each investment in HP is reported such that negative values indicate profitability, while positive values imply higher costs. Levelized costs are used to identify the threshold COPs for HP integration and to estimate the overall cost-effective EE improvement potential for the entire chocolate sector.

$$LCSE = \frac{I \times ANF + O\&M - B}{ES} \quad , LCCO2 = \frac{I \times ANF + O\&M - B}{CA} \qquad \text{Eq. 6}$$

Where,

I= Initial investment cost for HP

ANF = Annuity factor for the given discount rate and technology lifetime

O&M = Operation and maintenance cost

B = Annual benefits, i.e., cost of saved total final energy and of avoided CO_2 tax payments

ES = Total final energy savings

CA= CO_2 abatement potential

3 Results and discussion

Following the methodology explained in section 2, this section presents the identified temperature levels and sizes of heat sinks and sources for the Swiss chocolate sector, economic feasibility analysis for generic HP integration and cost-effectiveness analysis for integration of commercialized HPs.

3.1 Heat source and sink identification and heat pump dimensioning

Typical thermal power requirements for various process steps are estimated based on SECs, pinch reports and manufacturer catalogs for various equipment. Table 5 presents typical power requirements of the selected process steps for the company of categories 1 to 4 in the Swiss chocolate sector. The required power is highest for refrigeration, followed by hot water generation, roasting, conching and CIP. The excess heat available from refrigeration re-cooling is estimated using the energy efficiency ratio for the ammonia chiller obtained from [15], and available excess heat from conches is estimated based on the energy balance over the conches.

Table 4. Typical power requirements for selected process steps in chocolate manufacturing

Process	Required power (kW) for size category 1 (1,000 tonne/year)	Required power (kW) for size category 2 (10,000 tonne/year)	Required power (kW) for size category 3 (20,000 tonne/year)	Required power (kW) for size category 4(30,000 tonne/year)
Roasting	30	230	500	1000
Hot water generation	50	400	800	1,200
CIP	6	60	120	240
Conching[1]	16	150	300	500
Refrigeration	110	2,200	2,500	4,600
[1] *Power requirement for conching varies over a wide range for each size category depending on the type of chocolate produced.*				

Figure 7 presents the exemplar GCCs for the Swiss chocolate industry. Two sources of excess heat (green line in Figure 7) and three heat sinks (red lines in Figure 7) separated by the pinch point at 38°C are identified from the exemplar GCCs. The condenser of a refrigeration unit using ammonia as working fluid is cooled using cooling water. Cooling water recovers the heat rejected from the condenser at 35°C and typically leaves the plant at ambient temperature (25°C assumed). Thus, the excess heat from the re-cooling of the refrigeration unit condenser can be recovered in the temperature range between 35°C and 25°C. Similarly, the excess heat available from conching cooling water can be recovered in the temperature range between 55°C and 25°C. A significant amount of heat is required for warm water production at 55°C, which is used in the tracing circuits to keep the chocolate in molten form. Convection roasting of whole cocoa beans is carried out with hot air. Excess heat from refrigeration re-cooling or conching cooling can be utilized as a heat source for a high temperature heat pump enabling preheating the roasting air up to 90°C. Heating required for CIP at 50°C can also be provided by recovering excess heat with a heat pump from the aforementioned excess heat sources in a typical chocolate manufacturing company. The HP integration for roasting air preheating competes with the internal direct heat recovery from roaster exhaust air (without HP).

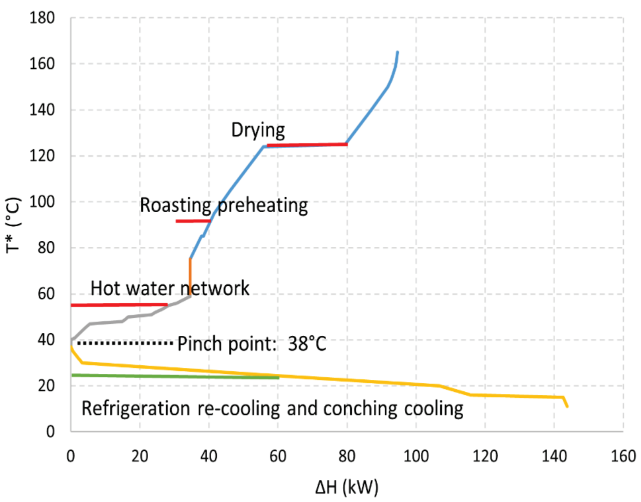


Figure 7. Representative grand composite curves for chocolate production in Switzerland

Table 5. Theoretical heat pump integration opportunities identified for Swiss chocolate manufacturing.

HP arrangement	Source	Sink	T_{source} (°C)	T_{sink} (°C)	Temperature lift ΔT_{lift} (°C)	HP type
AR1	Refrigeration re-cooling	Warm water network (tracing circuits), CIP	25	55	30	SHP
AR2	Refrigeration re-cooling	Roasting pre-heating	25	90	65	HTHP
AR3	Conching cooling water	Warm water network (tracing circuits), CIP	23	55	27	SHP
AR4	Conching cooling water	Roasting pre-heating	23	90	67	HTHP

Table 7 below presents the required heating demands (condenser duty) and the evaporator duty for the various HP integration opportunities identified above based on the exemplar GCCs for the Swiss chocolate manufacturing companies belonging to the categories 1 to 4. The evaporator load required for the identified condenser duty is estimated using the COP curves (refer to appendix 3 for GCC-spcific COP curves). The COP curves are estimated based on the COPreal of the most widely used working fluids. The COPreal for each working fluid is obtained based on the average second law efficiencies for HPs with a particular working fluid, as explained in section 2.6. According to the exemplar GCC for the chocolate factory, the sink temperature can be identified at 55°C. The required condenser duty for the HP (i.e., heating capacity) integration varies between 40kW for the company of the size category 1 to 1200 kW for the company of the size category 4. Based on the COP curves for HPs with various working fluids, the optimum temperature for evaporator placement for the ammonia HP is 23°C, for R1234 ze is 25°C and R134a HPs is 27°C. The HP evaporator size varies from 20 kW for category 1 company to for to 800kW for the company of category 4.

Table 6. Estimated condenser capacities and evaporator capacities for various heat pump arrangements and company sizes

	Size category 1		Size category 2		Size category 3		Size category 4	
HP arrangement	Condenser duty (kW)	Evaporator duty (kW)	Condenser duty (kW)	Evaporator duty (kW)	Condenser duty (kW)	Evaporator duty (kW)	Condenser duty (kW)	Evaporator duty (kW)
AR1	40	31	400	280	800	645	1,200	850
AR2	20	12	200	114	400	228	700	400
AR3	40	31	400	280	800	645	1,200	850
AR4	20	12	200	114	400	228	700	400

3.2 Bottom-up sector wide heat pump integration potential

Following the methodology presented in section 2.5, the sectorial profile for the Swiss chocolate manufacturing is presented in Figure 8. Based on the sectorial profile for the Swiss chocolate industry, there is a total requirement of 68,807 MWh of heat at 55°C to produce hot water (AR1/AR3) and 15,000 MWh at 90°C for preheating the roasting air (AR2/AR4) across all companies in the Swiss chocolate industry. Together these two opportunities represent 23% TFE reduction potential and 45% CO_2 emissions reduction potential from the Swiss chocolate industry (see Table 8). Drying process in the chocolate industry typically consumes direct steam at 120°C. Replacing the direct steam supply with steam generating HP represents an additional sector-wide potential of about 12,000 MWh. This steam demand can be further replaced using the steam generating HP increasing the total identified potential to 28% for TFE reduction and 56% for the CO_2 abatement (see Table 8). However, due to the lack of cost data related to steam generating HPs, their cost-effectiveness is not assessed in this work. The excess heat available from the refrigeration re-cooling for the entire sector is estimated at 95,000 MWh across companies of all sizes and production routes. However, based on the estimates of the evaporator duties, only 54,000MWh of excess heat is required to realize the available HP integration potential in the Swiss chocolate industry. This implies the remaining 41,000 MWh excess heat available from the Swiss chocolate manufacturing companies can be used for other purposes such as space heating or supply to district heating networks. As a caveat, it should also be noted that the estimates of sector-wide potential are based on publicly available information about HP implementation in the Swiss chocolate industry, possibly resulting in double counting for some companies which have already implemented HPs. This may lead to some overestimation of the remaining sector-wide HP integration potential for the Swiss chocolate industry.

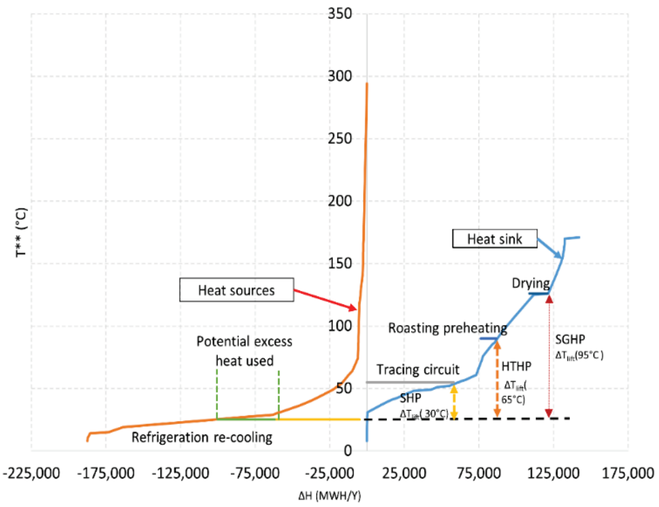


Figure 8. Sectorial profile for Swiss chocolate sector with theoretical heat pump integration potential (Potential excess heat utilized: Excess heat that can potentially be utilized for HP integration opportunities)

Table 7. Sector-wide technical TFE reduction and CO_2 abatement potentials for various heat pump arrangements

HP arrangement	**HP type**	**Sector-wide potentials**	
		TFE reduction	**CO_2 abatement**
AR1/AR3	SHP	18%	34%
AR2/AR4	HTHP	5%	11%
Steam for drying process	Steam generating heat pump	5%	11%
Total		**28%**	**56%**

3.3 Economic feasibility of heat pump configuration for Swiss chocolate industry

The cost-effectiveness of the HP integration is estimated using the LCSE, which depends on the cost of HP, the COP of the HP, and energy prices paid by the company. The COP of the HP, in turn, depends on the temperature lift, operating hours, and the second law efficiency of the HP. The economic feasibility of various possible HP arrangements identified in section 3.1 is assessed using a threshold COP. The LCSE for various possible HP configurations is estimated for different COP values. A COP value at which the HP investment becomes cost-effective is termed threshold COP. Any HP that can operate with a COP above the threshold COP will result in a profitable investment for the given HP arrangements and the associated assumptions about HP cost, operating hours and average energy prices. The HP costs are estimated for the given size of the heat sink using the cost function presented in Figure 5. The typical operating hours for the processes considered for the heat sinks and sources are estimated based on the information available from the pinch studies. Swiss industry average electricity and natural gas prices are assumed for the economic feasibility assessment by company size. A typical refrigeration plant in a chocolate manufacturing facility runs year-round at approximately constant power. The heat is required continuously throughout the year for hot water production used in the tracing circuits. As a result, the HP arrangement AR1 (i.e., HP integration between refrigeration re-cooling and tracing circuits) has the lowest threshold COPs among the identified HP configurations, ranging from 2.8 (very small company) to 1 (large company). In other words, any HP that can operate with the COPreal of 2.8 and above can be integrated cost-effectively for HP configuration AR1 in a company of any size category in the Swiss chocolate industry. Since the HPs with smaller heating capacities have relatively higher specific costs and smaller companies pay relatively higher energy prices, the threshold COPs for size category 1 are considerably higher compared to the larger size categories. Conching process, on the other hand, is typically operated in batches, making it an intermittent heat source for HP configuration AR3 and technically less viable (i.e., HP integration between conching cooling and tracing circuits). As a result, the threshold COPs for AR3 range between 6 for small companies to 1.4 for large companies. A threshold COP value of at least 6 makes many of the currently commercially available HP options economically unviable for AR3 in a company of size category 1. Threshold COPs for HP arrangement AR3 in other company sizes are also higher compared to AR1 for the same size category. Similarly, for AR2 and AR4, with the operating hours being limited by the availability of the heat sink (i.e., roasting preheating), any HP with a COP_{real} value below 6.4 cannot be integrated cost-effectively (see Figure 9) for the average energy prices in Swiss industry and estimated HP cost. Since the COPcarnot for the ΔTl_{lift} required for AR2 and AR4 is 6, the HP integration for both of these configurations in the Swiss chocolate industry is non-cost-effective. Moreover, based on the literature reviewed, most cocoa roasters employed in chocolate manufacturing already make use of direct internal heat recovery and direct internal heat recovery is often more cost-effective than heat pump integration for heat requirements at high temperatures (Bhadbhade and Patel, submitted). It should, however, be noted that the Levelized costs of saved final energy are estimated assuming the more conservative discount rate of 21% to reflect the company-level decision-making criteria in Swiss industry, whereas typical private discount rates used for discounted cash flow analyses in the literature range between 8% to 10%.

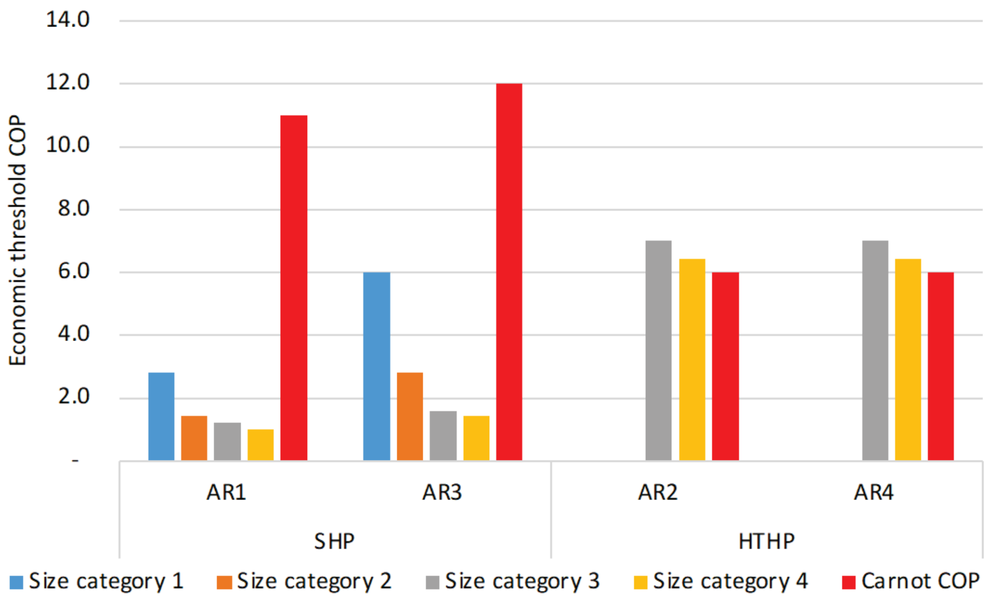
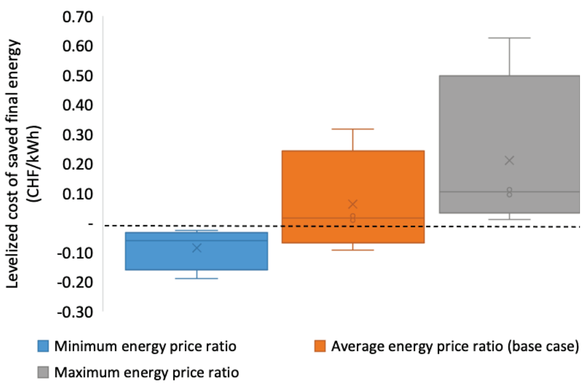


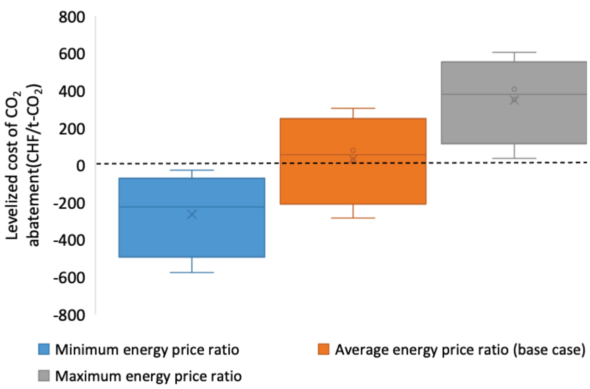
Figure 9 Threshold COPs for different heat pump integration configurations in the Swiss chocolate industry

3.4 Cost-effectiveness analysis for commercially available heat pumps in the Swiss chocolate industry.

The following section presents the range of levelized costs of saved final energy and the CO_2 abatement for commercially available HP options from the European market for the operating conditions identified in the Swiss chocolate industry. The cost-effectiveness is assessed for three different ratios of electricity to natural gas prices for the Swiss chocolate industry (see section 2.3). Based on the selection criteria explained in section 2.6, four commercially available SHPs on the European market can be potentially integrated in the company of size category 1. Relatively higher specific investment costs for HPs with smaller heating capacities in combination with a relatively higher energy price ratio on average for the company of size category 1 results in the majority of commercially available SHPs appearing non-cost-effective for the companies of category 1 for the average energy price ratio and none of the commercially available HPs appear cost-effective for maximum energy price ratio. Integration of HPs for companies paying average or high energy prices can cost in the range of 300 to 600 CHF/t-CO_2 abatement (or 0.3 to 0.6 CHF/kWh of saved final energy). However, for the companies paying the minimum energy prices, all commercially available HPs for size category 1 can be integrated cost-effectively (see Figure 10).



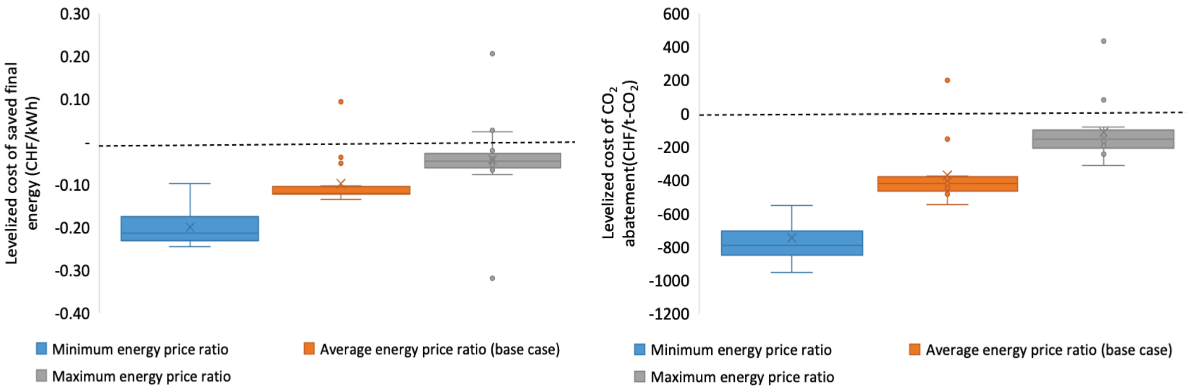
(a)



(b)

Figure 10. (a) Levelized costs of saved final energy for commercial HP options for size category 1 (b) Levelized cost of CO_2 abatement for commercial HP options for size category 1

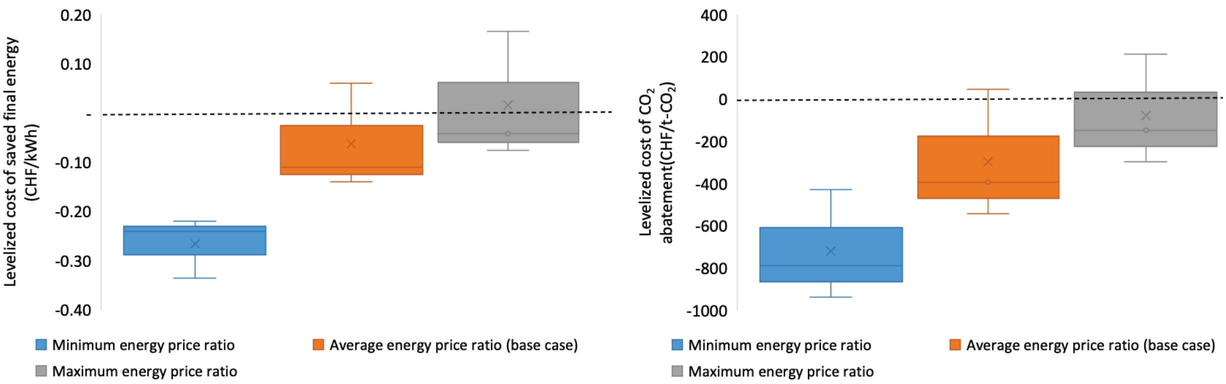
The exemplar GCC for the company of the size category 2 indicates an HP heating capacity of 400 kW for the arrangements AR1 or AR3 and HTHP of the capacity 200 kW for the HP arrangements AR2 or AR4 (see Table 7 and appendix 3). Based on the selection criteria (see section 2.6), there are 17 commercially available SHP options, which can be used to valorize the excess heat available from the refrigeration re-cooler and use it for hot water production for tracing circuits and 3 HTHP options for supplying heat for the roasting preheating. Due to the lower energy price ratio for the company of size category 2 compared to the size category 1 and relatively lower specific costs for HPs required for the identified heating capacities, the majority of the SHP options appear cost-effective and more profitable than size category 1. However, for the average and maximum price ratios, some of the commercially available HTHP options can cost as much as 200 to 400 CHF/t-CO_2 abated (or 0.1 to 0.2 CHF/kWh of saved final energy). All commercially available HP options appear economically viable for companies falling into category 2 and paying minimum energy prices (see Figure 11).



(a) (b)

Figure 11. (a) Levelized costs of saved final energy for commercial HP options for size category 2 (b) Levelized cost of CO_2 abatement for commercial HP options for size category 2

The exemplar GCC of the company category 3 indicates the required condenser duty for the HP to be 800 kW for the HP arrangements AR1 or AR3 and 400 kW for the arrangements AR2 or AR4. Based on HP selection criteria, there are two commercially available SHP options and one HTHP option for the company of size category 3. Since the reported COPs for the given operating conditions are higher than 1.2 and due to the relatively low average energy price ratio, all SHP options are economically attractive for the company of category 3 for the minimum and average price ratio. The HTHP options become economically viable only for the companies paying minimum energy prices (see Figure 12). For the companies paying average and maximum prices, the HTHP integration opportunities can cost 50 to 200 CHF/t-CO_2 abatement.



(a) (b)

Figure 12. (a) Levelized costs of saved final energy for commercial HP options for size category 3 (b) Levelized cost of CO_2 abatement for commercial HP options for size category 3

Finally, the company of size category 4 requires SHP of the size 1200 kW to valorize the heat from the refrigeration re-cooler and use it for hot water production and 600 kW HTHP for the heat sink of roasting preheating. Two SHP options and one HTHP are identified for the company of size category 4 and their levelized costs and potentials are presented in Figure 13. Similar to companies from size categories 2 and 3, both commercially available options of SHPs appear economically attractive for the companies paying average and minimum energy prices in size category 4. The HTHP option becomes economically viable only for companies paying minimum energy prices. For companies paying average or higher energy prices, the HTHP integration can cost in the range of 40 to 140 CHF/t-CO2 abatement.

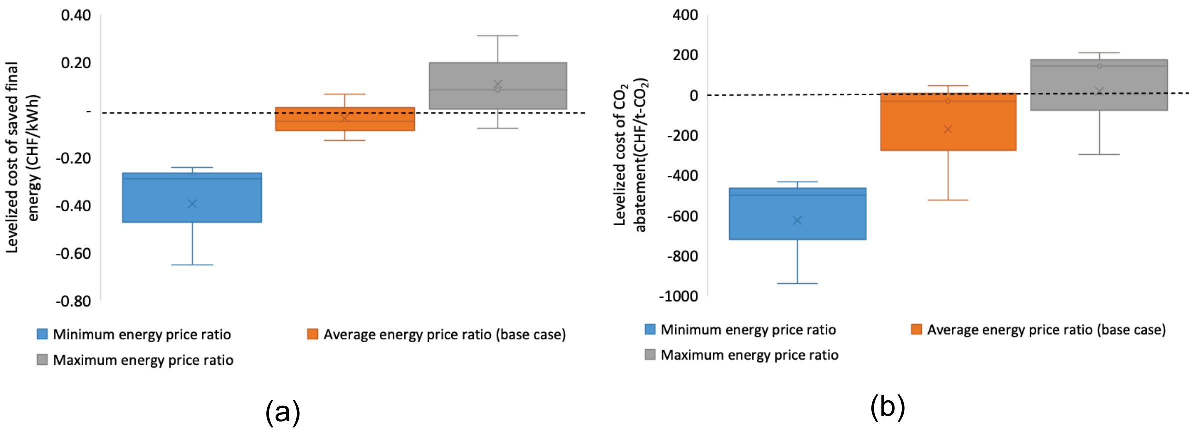


Figure 13. (a) Levelized costs of saved final energy for commercial HP options for size category 4 (b) Levelized cost of CO_2 abatement for commercial HP options for size category 4

4 Conclusions

The report for the deliverable 4.3.1 introduces the concept of exemplar grand composite curves (GCCs). This framework can allow practitioners to scale the exemplar GCCs according to their production size and explore the potential for the energy efficiency measures and renewables integration opportunities. The application of exemplar GCC and the bottom-up sectorial profiles (presented in the report for Deliverable 4.3.2) is demonstrated by estimating the heat pump (HP) integration potential in the Swiss chocolate industry leading to the estimation of the costs required for the decarbonization of the Swiss chocolate sector. Based on the data collected from Pinch Analysis performed for the companies in the Swiss chocolate sector, GCCs are created for representative company sizes and production routes. Based on the methodology presented in the report for Deliverable 4.3.2, the data for individual companies are aggregated and scaled up using the annual production to create a sectorial profile for the Swiss chocolate sector. The exemplar GCCs and the sectorial profile help to identify the sizes of heat sinks and sources along with their temperature levels for all company sizes and production routes.

Overall, five potential opportunities are identified for the integration of HPs using the exemplar GCCs of chocolate production in Switzerland. Excess heat is available below the pinch (38°C) from the refrigeration re-cooling and conching cooling at 25°C, which can be valorized using the HPs and used for hot water production (55°C), preheating of roasting air (90°C) or steam generation for direct use in drying at 120°C above the pinch. The techno-economic analysis indicates the majority of commercially available HPs can be integrated cost-effectively for the identified HP integration opportunities except for very small companies in the Swiss chocolate industry. Based on the aggregated bottom-up sectorial profile, the HP integration opportunities identified for the Swiss chocolate industry represent the potential of 28% TFE reduction and 56% CO_2 abatement. Depending on the company size categories, HPs with heating capacities of 40 kW to 1200 kW are required to make full use of the potential for excess heat recovery. For an average chocolate manufacturing company, the quantity of excess heat available is considerably higher than the process heat demand. This heat can be used for more ambitious CO_2 emission reduction in the sector studied for space heating (direct use or via district heating). The techno-economic analysis of these solutions could be assessed in the context of WP01.

Thus, the exemplar GCCs will facilitate the development and assessment of solutions for the optimal integration of energy efficiency measures (EEMs; closely linked with WP05), renewables, as well as negative emission technologies (NETs, WP12).

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