



High-temperature heat pumps in climate pathways for selected industry sectors in Switzerland

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ABSTRACT

To reach the goals of long-term energy and climate policy, the contribution of the industrial sector is important. Upgrading low temperature industrial waste heat using electric high-temperature heat pumps (HTHPs) can improve the overall energy-efficiency and mitigate CO₂ emissions by replacing fossil fuels. The pulp and paper and the food and beverage industries use significant quantities of heat up to 200 °C and therefore have a high potential for the application of HTHPs. In order to assess the role of HTHPs, a techno-economic bottom-up cost optimization model is developed building on the Swiss TIMES Energy system Model (STEM). We present an advanced modeling framework including energy and material flows, with a high temporal resolution and a segregation of the temperature level of the process heat. The results show that HTHPs are cost-effective up to a temperature of 150 °C. Switzerland has the economic potential to deploy of about 100 MW_{th} in the pulp and paper industry and 900 MW_{th} in the food and beverage industry by 2050. Incentivizing the exploitation of this significant potential will require very high CO₂ prices of several hundred €/tCO₂ or additional policies to overcome investment barriers by supporting investment and flexible system-serving operation of heat pumps.

1. Introduction

Switzerland has accepted its Swiss Energy Strategy 2050 (SES) in 2017 which includes the following goals until 2035 (International Energy Agency IEA, 2018):

- Reduction of the final energy consumption per capita by 43% compared to 2000
- Reduction of the electricity consumption per capita by 13% compared to 2000

Until 2018, the final energy consumption and the electricity consumption have decreased by 21% and 7% respectively. Consequently, a further reduction until 2035 is required to reach the goals stated above.

In line with the goal of the Paris Agreement that Switzerland ratified in 2017, the Swiss Federal Council has declared a target to reach net-zero emissions until 2050 within Switzerland. Nevertheless, a short-

term policy target for the period until 2030 does not exist currently after the rejection of the revision of the CO₂ law by public referendum in 2021. Therefore, this study only investigates long-term pathways to reach net-zero emissions until 2050.

Reaching policy goals on energy efficiency improvement and CO₂ emission mitigation requires the contribution of all demand sectors. In 2018, Swiss industry accounted for 18% of the total final energy consumption in Switzerland (150 PJ) (Bundesamt für Energie BFE, 2019) and 19% of the direct CO₂ emissions in Switzerland (6.8 Mt) (Federal Office for the Environment FOEN, 2021). Therefore, industry is an important demand sector in long-term energy and climate pathways. Though the Swiss industry has a relatively high share of electricity consumption for motor driven applications, fossil fuels like natural gas and fuel oil still represent a large share of the energy consumption (Fig. 1).

Process heat represents 56% of the final energy consumption in industry and is mainly produced from natural gas and fuel oil (Fig. 1). Therefore, it is vital to assess possibilities to replace these fossil fuels by

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Nomenclature

BAU	Business As Usual
CH	Switzerland
CHP	Combined Heat and Power plant
CLI	Net-zero CO ₂ emissions scenario
CO ₂	Carbon Dioxide
COP	Coefficient Of Performance
DH	District heat
E-POL	Energy policy scenario
ETS	Emissions Trading Scheme
ETSAP	Energy Technology System Analysis Program
EU	European Union
FC	Fuel Cell
HP	Heat Pump
HTHP	High-Temperature Heat Pump

IEA	International Energy Agency
MARKAL-EFOM	Market Allocation Energy Flow Optimization Model
PEMFC	Proton-Exchange Membrane Fuel Cell
PH	Process Heat
PPP	Purchasing Power Parity
PSI	Paul Scherrer Institute
SCCER JA-S&M	Swiss Competence Center for Energy Research – Joint Activity Scenarios & Modeling
SES	Swiss Energy Strategy 2050
SOFC	Solid Oxide Fuel Cell
STEM	Swiss TIMES Energy system Model
SWH	Space and Water Heating
TES	Thermal Energy Storage
TIMES	The Integrated MARKAL-EFOM System
WHR	Waste Heat Recovery

zero-carbon bio-fuels and electrification options. Based on the International Energy Agency's (IEA) roadmap, in a net-zero emissions scenario, the share of the electricity will take up 76% of the of the final energy consumption in light industry by 2050 (International Energy Agency IEA, 2021). One technology option to electrify and decarbonize the heat supply up to 200 °C with simultaneous improvement of the energy efficiency is the deployment of high-temperature heat pumps (HTHP's). This study investigates the role of HTHP's in climate and energy efficiency pathways in selected Swiss industrial sectors.

Based on the literature review in section 2, the following research gaps are identified and addressed in this paper. Techno-economic bottom up optimization models are applied to analyze energy-efficiency and CO₂ emission mitigation pathways of the energy system. However, in order to analyze high-temperature heat pumps in industrial processes, the conventional modeling approach focusing on energy flows only is not adequate. A new modeling technique is developed and presented in this paper that has the following novelties:

- including material flows in addition to energy flows,
- a high temporal resolution to account for volatile electricity prices and
- a disaggregation into different temperature levels.

To achieve this, the Swiss TIMES Energy System Model (STEM) (Panos et al., 2021) has been coupled with a new detailed industry

model incorporating a novel modeling methodology. This finally allows a detailed analysis of high-temperature heat pumps in the Swiss industrial sector to reach energy and climate policy goals, which is presented in this study.

The paper is structured as follows: Section 2 with the background and literature review gives an overview of the current research on high-temperature heat-pumps and their implementation in energy system models. The methodology of this study is explained in section 3. The results are presented in section 4 and discussed in section 5. Finally, the conclusion and policy implications are summarized in chapter 6.

2. Background and literature review

2.1. High-temperature heat pumps and heat sources

High-temperature heat pumps (HTHPs) are usually used in industrial applications to supply process heat. Compared to heat pumps in the residential sector that deliver heat up to 80 °C using geothermal heat or ambient air as a heat source, emerging state of the art HTHPs deliver heat up to 160 °C (Arpagaus et al., 2018) and typically use industrial waste heat as a heat source. Ongoing research is focused on refrigerants, cycle configurations and components to expand the temperature range (Arpagaus et al., 2019b); (Arpagaus et al., 2019a); (Mateu-Royo et al., 2021); (Zou et al., 2020); (Gao et al., 2021); (Wang et al., 2020); (Wu et al., 2020). The highest potential for high-temperature heat pump

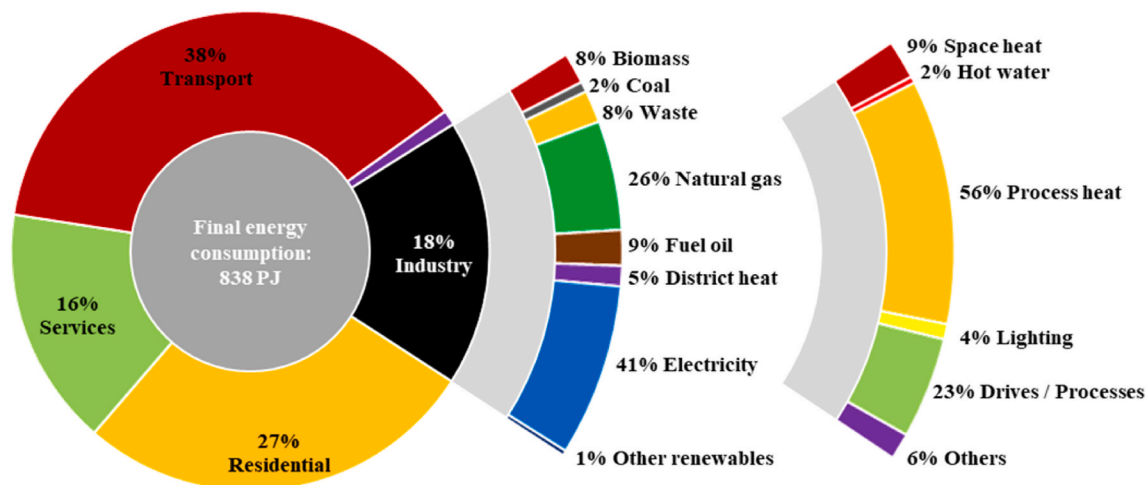


Fig. 1. Final energy consumption in Swiss industry in 2019 by energy carrier and application (Bundesamt für Energie BFE, 2019); (Bundesamt für Energie (BFE), 2020).

installations is expected in the pulp and paper and the food and beverage industry because of their high demand for heat up to 200 °C (Arpagaus et al., 2018); (International Energy Agency IEA, 2014); (De Boer et al., 2020). Typical processes within this temperature range are drying, boiling, pasteurization, sterilization, bleaching and de-inking processes.

In Switzerland, the project HTHP-CH is focusing on the integration of HTHPs in Swiss industrial processes. The energy savings potential from a switch from fossil fuels to HTHPs in the Swiss industrial sector addressing process heat and steam below 150 °C was roughly estimated at 2'893 GW per year, which is approximately 6.7% of the total process heat demand (Arpagaus et al., 2022).

Industrial high-temperature heat pumps can upgrade heat from a low temperature level to a higher temperature level (Fig. 2). Possible low temperature heat sources include waste heat from internal production processes, as well as external heat sources, such as district heat:

Process-internal sources.

- Waste heat from production processes
- Refrigeration processes

External sources.

- Environment (air, underground, lakes or rivers)
- Waste heat from other industries, power plants or waste incineration plants via local or district heating network

The maximum theoretical coefficient of performance (COP) of a heat pump is defined by the Carnot efficiency (Equation (1)). The sink temperature is usually defined by the production process, which means that a high temperature of the heat source improves the performance of a heat pump.

$$COP_{heating} = \frac{T_H}{T_H - T_C} \quad (1)$$

where: COP = Coefficient of performance.

T_H = Sink temperature.

T_C = Source temperature.

2.2. Literature review

For a detailed representation of the industrial sector, it is important

to consider production processes along with material and energy flows to account for specific process improvements and material efficiency enhancements – especially in energy-intensive sectors where material substitution can strongly impact the process specific energy consumption. But it is also important to consider the industrial sector in the wider context of other energy transformation and demand sectors, because of linkages through energy carriers and differing abatement costs to reach overarching targets (see section 1).

However, most existing national energy system models focus on energy and emission flows only: For example, the FORECAST model for the EU industry (Fleiter et al., 2018) focuses on energy saving options and their sectoral diffusion, other models have implemented detailed sector specific measures in their model for the UK (Fais et al., 2016) or have applied a TIMES model to the French food and beverage industry (Seck et al., 2015). Studies focusing on Switzerland have used a model with energy flows only and little detail on industrial production processes for their Swiss energy perspectives (Prognos, 2012); (Prognos, INFRAS, TEP Energy, 2020) or have carried out a scenario analysis of the energy saving potentials for the industry (Zuberi et al., 2020). STEM (Panos et al., 2021), used as a starting point for this study, has a rather generic structure with an aggregated industry sector and also considers energy and emission flows only.

In addition to this, an assessment of high-temperature heat pumps requires to differentiate the process heat demand and the waste heat by temperature levels. However, most of the existing long-term energy system models treat process heat without temperature levels or with a very coarse subdivision into low-, medium- and high-temperature heat, meaning the existing approaches are limited in analyzing HTHPs. Besides temperature levels, a high temporal resolution (preferably an hourly resolution) is also required to analyze the operational flexibility of HTHPs (with volatile electricity prices) and the need for heat storage. Furthermore, a time- and temperature-dependent approach to calculate the COP of a heat pump is needed. On the example of the residential heating sector in Munich, different approaches to integrate heat pumps into an energy system optimization model concluded that assuming a time-constant COP leads to misleading results (Halilovic et al., 2022). An implementation of heat pumps with a temperature dependent COP in a TIMES model has been done (Petrović and Karlsson, 2016), but is limited to the residential sector only.

Several studies have also estimated the future application potential of HTHPs in the European industry and concluded that HTHPs could

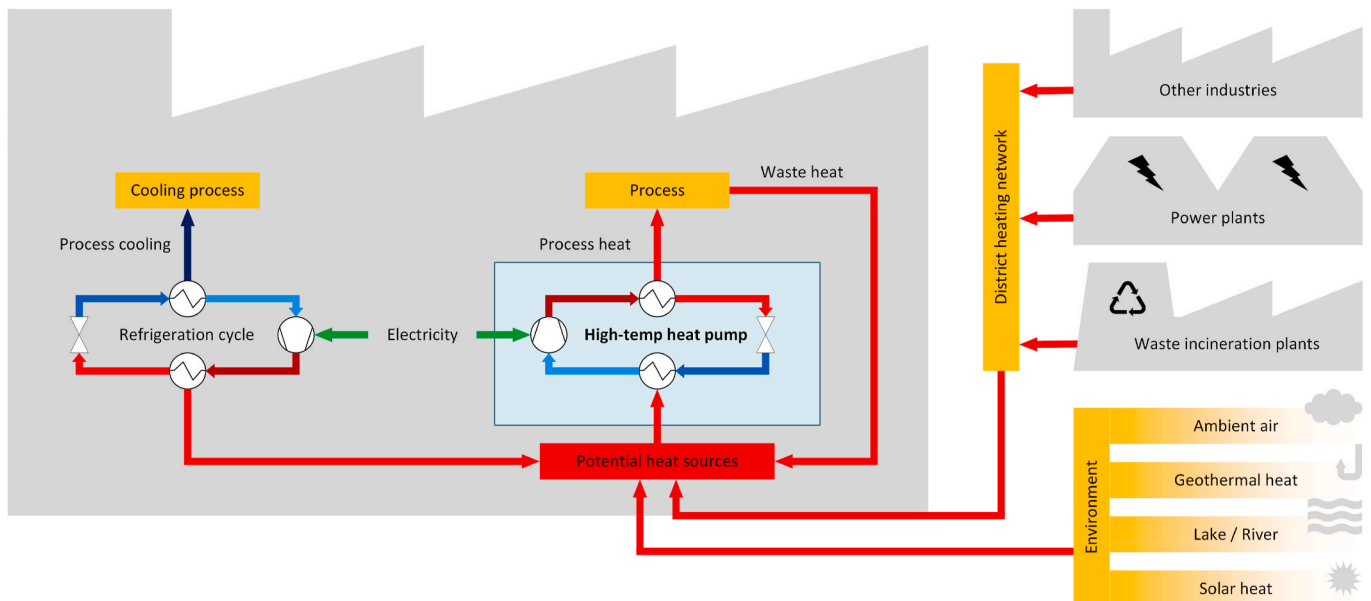


Fig. 2. Potential heat sources for high-temperature heat pumps in industry.

cover 37% of the total process heat demand (De Boer et al., 2020) and 73% of the process heat up to 150 °C (Marina et al., 2021). The most promising process for heat pump integration have been identified as sterilization and drying processes (Zühlsdorf et al., 2019b) and potential applications have been demonstrated with case studies in Switzerland (Arpagaus and Bertsch, 2020) and Germany (Schlosser et al., 2020). An analysis of the potential for HTHP's above 150 °C in selected European countries (Zühlsdorf et al., 2019a), and their integration into industrial processes like spray dryers in the food industry (Wang et al., 2018) or pasteurization in the dairy industry (Cox et al., 2022) have been carried out. Estimating the current potential of HTHPs for waste heat recovery only in EU industries by comparing the process heat demand and waste heat potential for different industry sectors led to the conclusion that 15% of the heat demand from 100 °C up to 200 °C can be covered by HTHPs using the available waste heat (Kosmadakis, 2019).

Hence based on the above literature review, we conclude that no studies have quantified the role of HTHPs in specific (Swiss) industry sectors to meet energy and climate policy goals, in the context of a national energy system model, with a detailed approach to energy and material flow modelling that differentiates between temperature levels.

3. Methodology

This section explains the general modeling methodology, followed by a more detailed description of the novel improvements to the conventional modeling approach. Finally, the general assumptions and the analyzed scenarios are presented.

The pulp and paper and the food and beverage industry have been identified as the most promising sectors for high-temperature heat pump application (section 2.1). Therefore, an integrated techno-economic model has been developed based on the model from our previous work (Obrist et al., 2022) for these two sectors. The model was developed in the integrated MARKAL-EFOM System (TIMES) modeling framework developed in the International Energy Agency (IEA)'s Energy Technology System Analysis Program (ETSAP) (Loulou et al., 2016). The model has a one-way coupling regarding scenarios and fuel prices to the Swiss TIMES Energy system Model (STEM) (Kannan and Turton, 2014); (Panos et al., 2021) which was developed at the Paul Scherrer Institute (PSI) (Fig. 3). Besides the expansion of the scope of the established model (Obrist et al., 2022) with the food and beverage sector, the new methodology improvements are described in sections 3.1 to 3.3:

- Expanding the material flow and production process modeling technique to an industry sector with diverse products and production processes.
- Further disaggregation of the heating and cooling demands into different temperature levels that allows the accurate analysis of HTHPs.
- Expansion of intra annual time resolutions and representation of variability in solar irradiation profiles, heat pump COP profiles, production profiles and electricity prices.

3.1. Modeling of process steps with material flows

Modeling product and material flows in addition to conventional energy flows has already been introduced in reference (Obrist et al., 2021). This modeling technique, which refers to the cement sector, has subsequently been applied and expanded for the pulp and paper sector (Obrist et al., 2022). Conversely to the cement industry, the pulp and paper industry is characterized by different products, while the main process steps still remain the same. This study is built upon the authors' previous modeling technique by developing the food and beverage industry with very diverse products that have multiple production processes (see section 3.1.2).

3.1.1. Modeling of the pulp and paper industry

A modeling approach of the pulp and paper industry with product and material flows has been introduced previously (Obrist et al., 2022). This modeling structure is also applied in this study (Fig. 4). Important for the modeling of HTHPs is to note that potentials and usage of waste heat is explicitly taken into account. The available waste heat that is an input for the heat pumps in this study is connected to each production step and its heat input and temperature level.

3.1.2. Modeling of the food and beverage industry

The food and beverage industry model includes production processes for multiple products which have been identified to represent the food industry sector. Their specific energy consumption per ton of product is then multiplied by their production values from references (European Commission, 2022); (Schweizer Bauernverband, 2017); (Federal Statistical Office, 2018); (Food and Agriculture Organization of the United Nations, 2022). This leads to a representation of 56% of the Swiss food and beverage industry in terms of energy consumption which is then scaled up to cover the whole sector. Because of the diversity of the products and the similarities to the production of the products that are not included, this representation of the food and beverage sector can be justified. For a more detailed representation, a much higher number of different products, their respective production processes and the corresponding data would be needed. Due to similarities in the process steps that appear in the whole sector, the material and product flow modeling from our previous work (Obrist et al., 2021); (Obrist et al., 2022) is expanded to a matrix structure (Fig. 5). The specific processes and their waste heat recovery (WHR) potential is thereby connected with the corresponding production steps. This allows to maintain the advantages of a modeling technique for single production processes, for example the estimation of the WHR potential within the process. On the other hand, it provides an aggregation which keeps the number of individual process steps with their respective improvement potentials at a reasonable number. The advantage is that technology improvement options for single process steps can be modeled in the same way for the whole food and beverage sector. For example, improvement of refrigeration systems can be modeled once for all processes that require cooling.

3.2. Temperature levels

The COP of high-temperature heat pumps highly depends on the temperature lift and the source and sink temperature (Equation (1)). Therefore, the heat demand of the production steps and the potential heat sources is divided into different temperature levels based on previous studies (Arpagaus et al., 2018); (International Energy Agency IEA, 2014) and shown in Fig. 6. Furthermore, on each temperature level, a thermal storage option is modeled. The temperature-dependent efficiencies and thermal losses of the storage are shown in Appendix A1. The potential interconnections with HTHPs is shown in Fig. 6. The distinctions of temperature levels is very important to correctly assess the potential of HTHPs in combination with heat storage and waste heat recovery. It should be noted, that the availability of waste heat is limited and depends on the production process.

The high temperature heat pump COP is then calculated depending on the temperature lift using our previous methodology (Obrist et al., 2022) which results in the values presented in Table 1.

3.3. Extension of intra-annual time resolutions

The model developed for this study has a time horizon from 2015¹ to 2050 with eight five-year time steps. At the intra-annual level, it has

¹ 2015 is used as a base year in the model structure. However, because more recent data on the energy consumption is available, the model is also recalibrated for 2020.

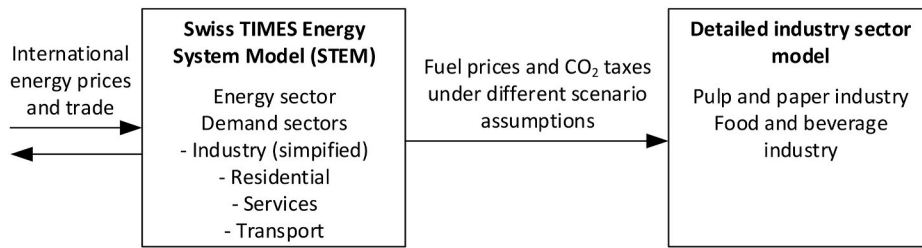


Fig. 3. Soft-link to the swiss times energy system model (STEM).

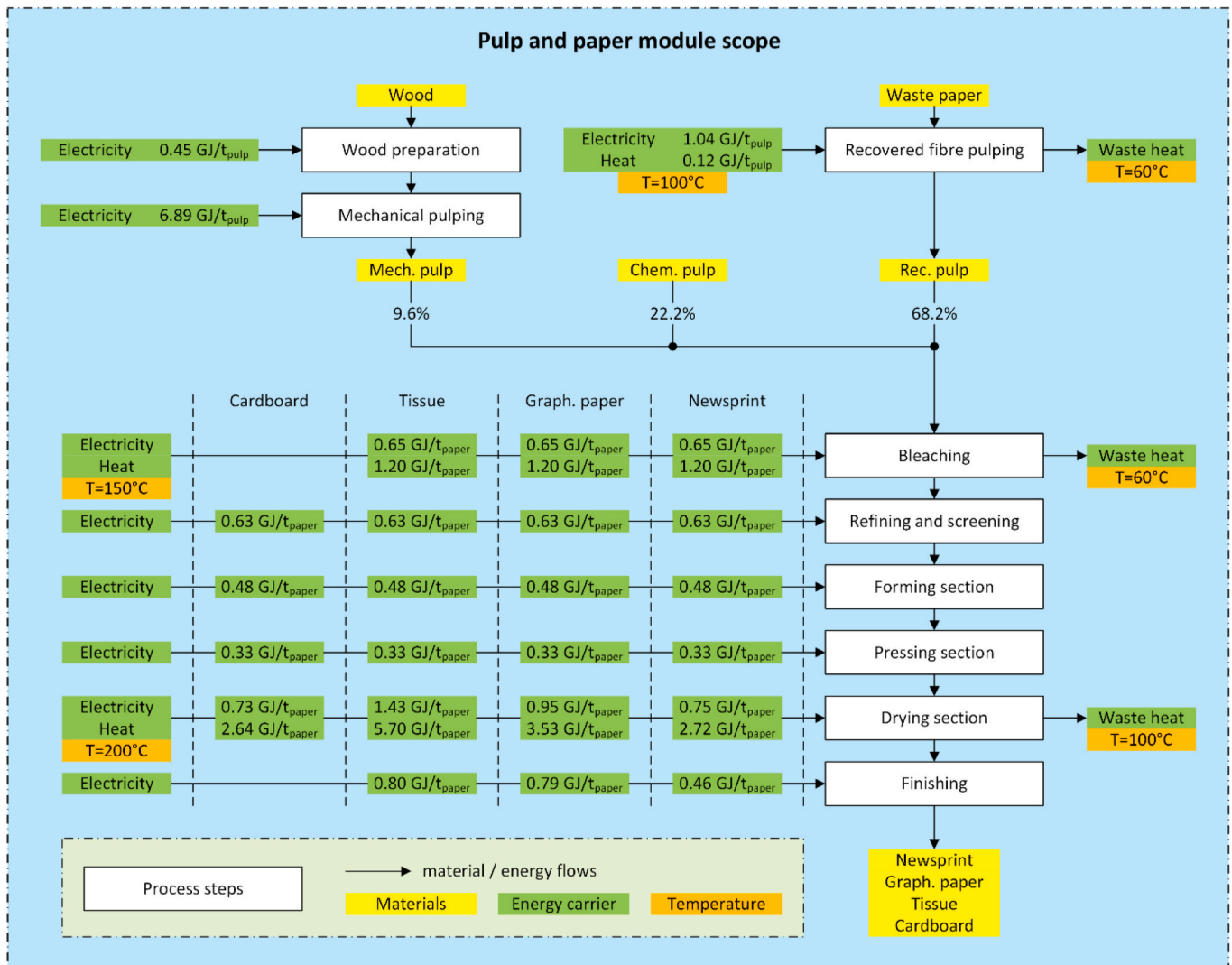


Fig. 4. Extended modeling approach of the pulp and paper sector with material and energy flows (Obrist et al., 2022).

four seasons, two representative days (weekday and weekend) and 24 h which results in 1'536 timeslices (see Fig. 7).

For each season, hourly solar irradiation and heat pump COP profiles are implemented for heat pumps that use ambient air as a heat source (appendix A3.1 and A3.2). The latter is based on average ambient temperature profiles as explained in section 3.2. However, for the production of the pulp and paper and the food and beverage industry, no seasonal differences are implemented. The production in the pulp and paper industry is assumed constant during the day, and the food and beverage industry is assumed to produce only during typical Swiss work hours (from 6 a.m. to 6 p.m.) with a reduced production in the weekend (Appendix A3.3).

Hourly electricity prices are implemented for each season based on the output from the STEM model (Panos et al., 2021). Unlike all the other profiles, the electricity prices change over time and are implemented separately for each period.

3.4. General assumptions and scenario definition

Three scenarios in line with the Swiss energy and climate policy targets (see section 1) which reflect different transition pathways have been quantified (Table 1). The model is fully calibrated to the Swiss energy balance of 2015 (Bundesamt für Energie BFE, 2016), which represents the base year in the model. An intermediate calibration was

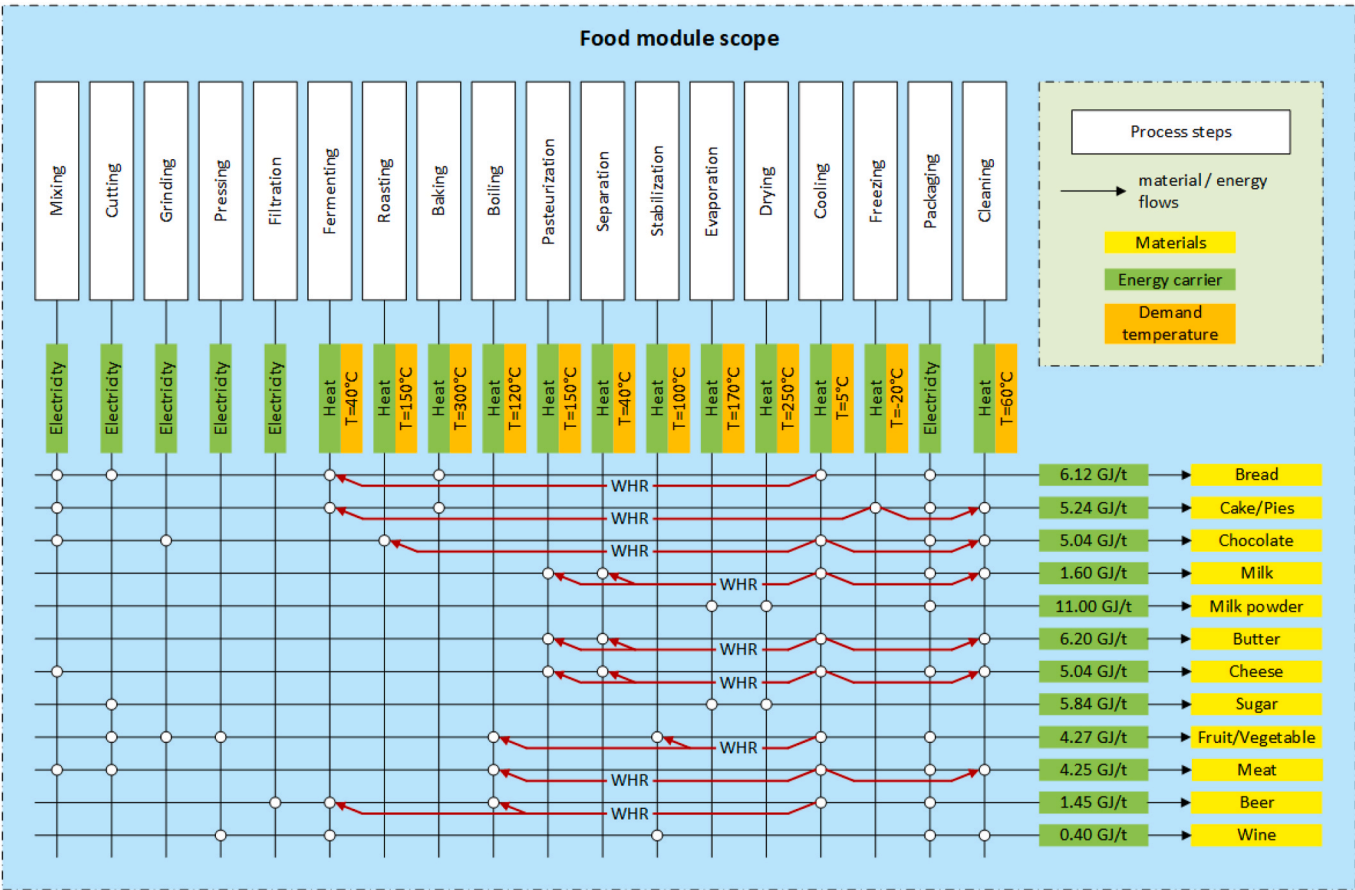


Fig. 5. Extended modeling approach of the food sector with material and energy flows.

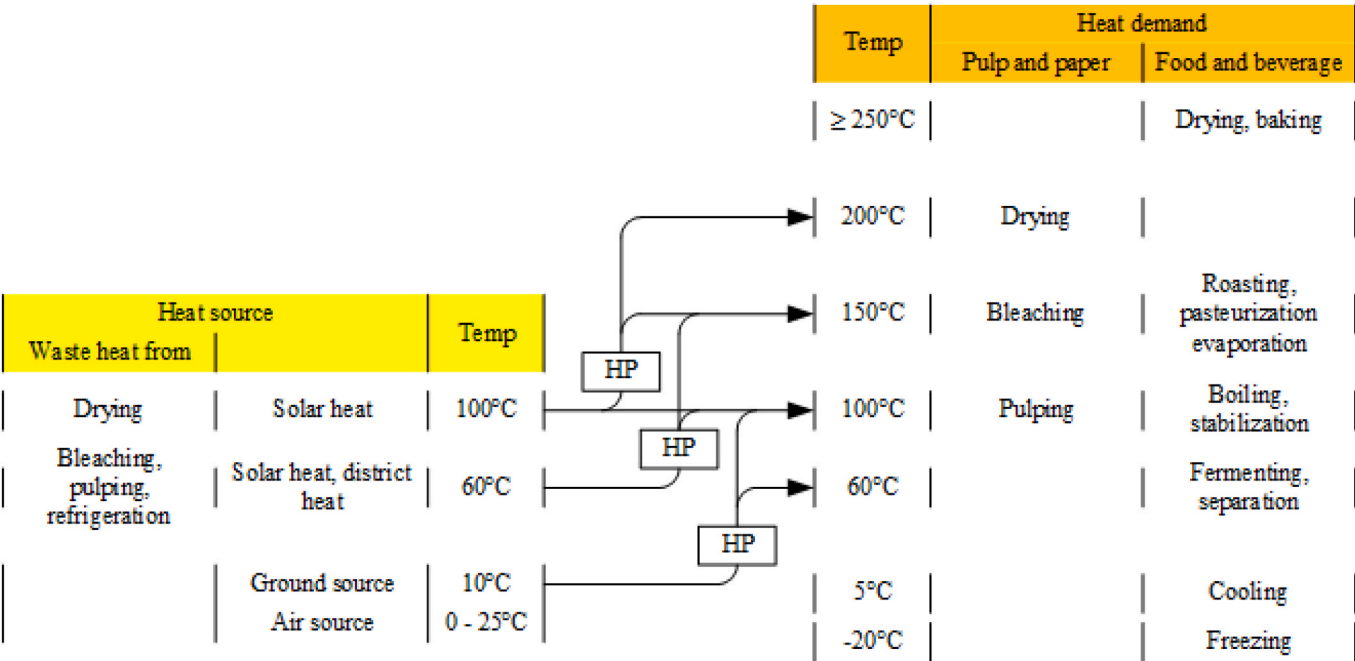


Fig. 6. Temperature levels and heat pump interconnections (based on (Arpagaus et al., 2018)).

Table 1
COP for selected heat pump configurations (Obrist et al., 2022).

Source type	Temperature lift [°C]	COP ₂₀₂₀	COP ₂₀₃₀	COP ₂₀₄₀
Air source ^a	... to 60 °C	2.88	3.03	3.17
Air source ^a	... to 100 °C	1.90	2.00	2.09
Ground source ^a	... to 60 °C	2.98	3.13	3.28
Ground source ^a	... to 100 °C	1.94	2.04	2.13
Waste heat	60–100 °C	2.19	2.30	2.53
Waste heat	60–150 °C	1.18	1.23	1.29
Waste heat	100 to 15 °C	2.12	2.22	2.33
Waste heat	100–200 °C	1.19	1.24	1.30

^a The source temperature of air source and ground source heat pumps depends on the season. Therefore, averaged COP values over the entire year are shown.

Table 2
Scenario overview (Panos et al., 2021).

Scenario	Energy efficiency	CO ₂ reduction	EU ETS CO ₂ price
BAU	–	–	27 EUR/ t _{CO2} in 2030 41 EUR/ t _{CO2} in 2040 55 EUR/ t _{CO2} in 2050
E-POL	Reduction target for specific final energy consumption (GJ per ton of product) relative to 2000: –43% in 2035 –54% in 2050 Specific electricity consumption (GJ per ton of product): –13% in 2035 –18% in 2050	–	36 EUR/ t _{CO2} in 2030 73 EUR/ t _{CO2} in 2040 109 EUR/ t _{CO2} in 2050
CLI	–	Net-zero in 2050 from fuel combustion and industrial processes	76 EUR/ t _{CO2} in 2030 114 EUR/ t _{CO2} in 2040 363 EUR/ t _{CO2} in 2050

done for the milestone year 2020 based on the data of 2018.

• BAU - Business As Usual

The Business As Usual (BAU) scenario assumes an unchanged market environment without further policy measures to reach climate or policy goals. Existing trends in technology development, energy consumption and fuel prices are expected to continue. However, existing technologies will be decommissioned at the end of their lifetime and replaced by new, more efficient technologies.

• E-POL – Energy policy

The Energy Policy (E-POL) scenario aims to meet the energy and electricity reduction targets of the SES which are implemented in the model as constraints. We assume an equity-based approach in which each demand sector contributes to the reduction targets proportionately. The energy and electricity reduction per capita translate into specific energy and electricity reduction per ton of production for the pulp and

paper and the food and beverage sector. The model takes the energy and electricity reduction achieved until 2018 into account and therefore only considers further reductions from 2018 until 2050. Although no explicit climate goals are defined in the E-POL scenario, EU ETS prices are included based on a 2.2% linear emission reduction factor (announced by the European Commission).

• CLI – Net-zero

The indicative goal to achieve net-zero emissions in 2050 announced by the Swiss Federal Council provides the baseline for the CLI scenario. No compensation from the industry sectors to other sectors is considered (negative emissions from industry could compensate for emissions in other sectors or the other way around). Therefore, industry has to reach zero emissions until 2050. In the CLI scenario, more stringent EU ETS prices compared to the E-POL and the BAU scenarios are implemented.

The three scenarios are consistent with the scenario analysis from STEM (Panos et al., 2021) and our sectoral model (Obrist et al., 2022) and therefore we adopt corresponding scenario specific inputs from the STEM. The fuel prices for the scenarios are shown in Appendix A2.

In all of the scenarios, the model has to meet the energy demand of an exogenously defined product demand at least energy-related costs (investment, operation and fuel costs, taxes etc.). In addition to the scenario-specific assumptions and boundary conditions, the following general assumptions are made in all scenarios:

- The domestic production of products from the pulp and paper and the food and beverage industry is assumed to remain stable until 2050. However, the domestic demand can also be satisfied with imports and is not necessarily reflected in domestic production.
- Besides the social discount rate of 2.5% a technology-specific discount rate² of 8% is defined for new process technologies to account for risk and uncertainty associated with new technologies.
- The availability of industrial waste for energy recovery is limited at 2018 levels³.

4. Results

To assess the role of high-temperature heat pumps, we first quantify the reference scenario for the food and beverage industry in this section. The reference scenario results of the pulp and paper industry have been published already (Obrist et al., 2022). The section then highlights the role of HTHPs by analyzing the process heat supply for both industry sectors. The capacity addition and the corresponding investment in HTHPs for the three scenarios is finally presented in section 4.3.

4.1. Industry sectors

In the food and beverage industry (Fig. 8), the existing heat supply from natural gas and fuel oil is ultimately replaced by biomass in the BAU scenario. This leads to very low annual CO₂ emissions in 2050 (37 kt, –74% compared to 2020) in the BAU while the remaining emissions are caused by natural gas ovens. Similar to the pulp and paper industry, the existing equipment is replaced by the end of its lifetime by more energy efficient technologies which improves the energy efficiency in 2050 by 21% from 2020 (compared to 23% in the pulp and paper industry (Obrist et al., 2022)). This value is well within the range from other sources (Zuberi et al., 2020), who have found a potential of 16% (conservative) up to 59% (optimistic technical potential) for the primary

² The technology specific discount rate is used to calculate the annual payments resulting from a lump-sum investment in some year.

³ Future work include the implementation of the pulp and paper sector module into STEM. Waste allocation in the energy system is then endogenous to the model.

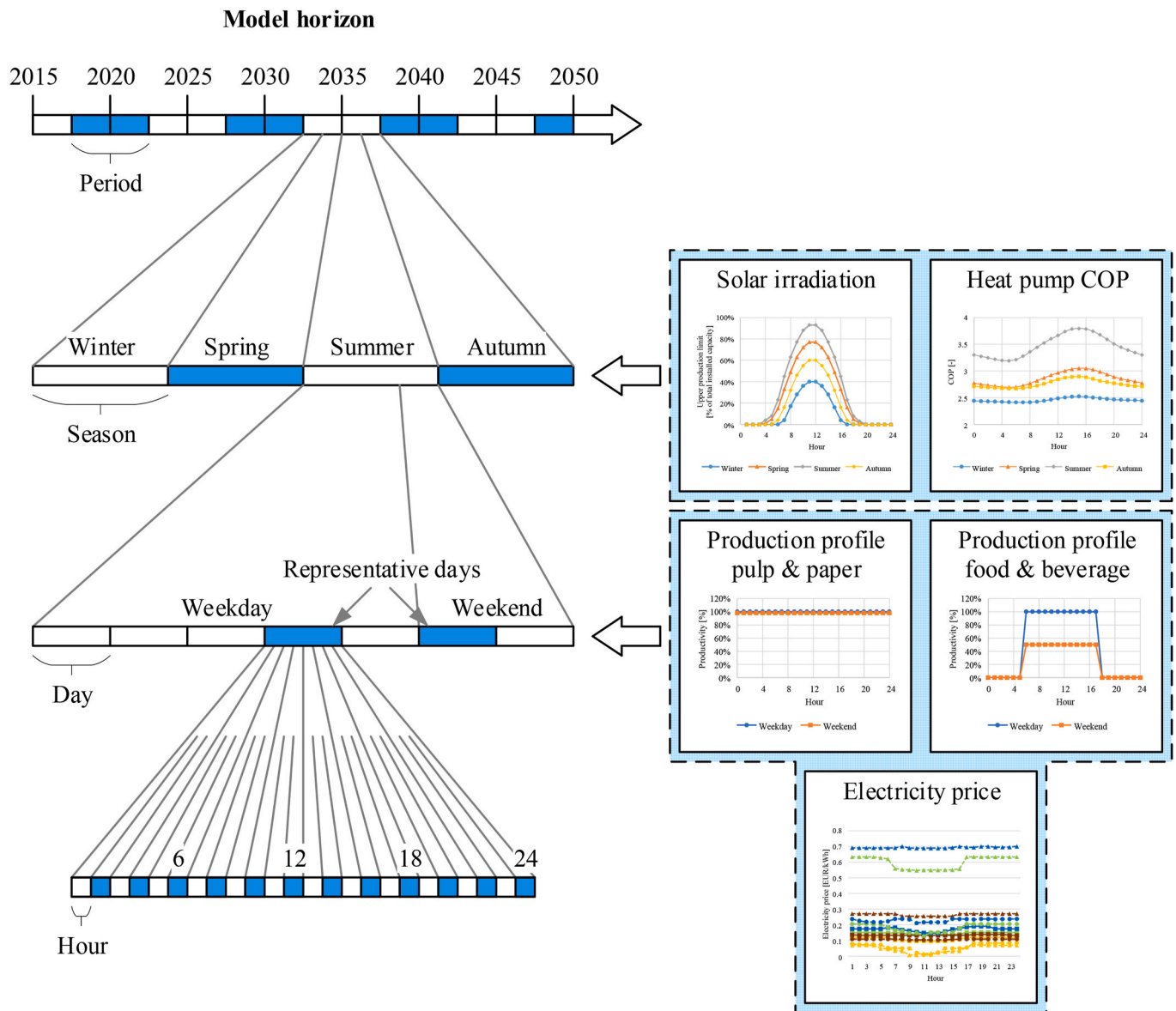


Fig. 7. Subdivision of the model horizon into timeslices with the corresponding implementation of seasonal solar irradiation profiles and heat pump COP profiles, and daily production profiles and electricity prices.

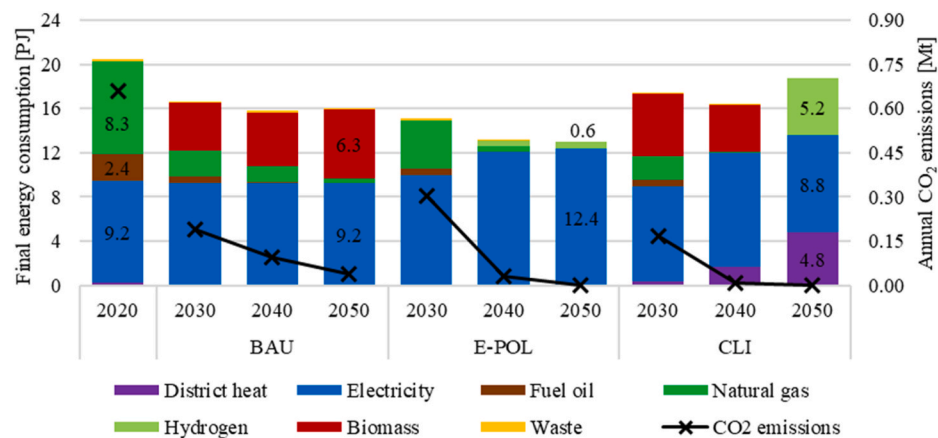


Fig. 8. Final energy consumption (left axis) and annual CO₂ emissions (right axis) in the food and beverage industry in the BAU, E-POL and CLI scenarios.

thermal energy consumption in the Swiss food and beverage industry.

In the E-POL scenario, the energy consumption is significantly reduced compared to the BAU scenario. An energy efficiency improvement of 36% compared to 2020 is possible in the food and beverage industry, but the electricity reduction target is not met (similar to the pulp and paper industry). A high share of the heat supply is electrified by HTHPs (79%) with the remaining share above 150 °C supplied through hydrogen and electric ovens. These technology deployment trajectories lead to a full decarbonization by 2045 in the food and beverage industry, although this is not a target of the scenario.

In the CLI scenario, the heat supply switches to biomass technologies in the short term, before they are replaced by district heat, HTHPs and hydrogen CHPs in the long-term. This leads to a full decarbonization of the sector by 2040 and beyond.

The annual CO₂ emissions are reduced in all scenarios due to energy efficiency improvements, fuel switching and electrification of the heat supply. The cumulative CO₂ emissions from 2020 until 2050 (Fig. 9) in the E-POL and BAU scenarios are at the same levels. Even though the annual CO₂ emissions reach net-zero in the food and beverage industry by 2045 in the E-POL scenario, the cumulative emissions from 2020 until 2050 are slightly higher because of the continued usage of natural gas usage in the short term. Only in the CLI scenario, the cumulative CO₂ emissions are reduced by 43% in the pulp and paper industry and by 25% in the food and beverage industry compared to the BAU case.

4.2. Process heat supply

In order to analyze the role of HTHPs, understanding the interaction with competing and complementary technologies is very important. Therefore, the total heat supply in the pulp and paper industry in 2050 shown for the four seasons in Fig. 10. In the BAU scenario the role of HTHPs is insignificant, because biomass and waste-fueled CHPs can produce at lower cost. HTHPs are more cost-efficient in summer and fall because of the lower electricity prices (Appendix A2) and the high COP of heat pumps (due to high ambient air temperature, Appendix A3.1). On the other hand, CHPs are more cost-efficient in winter because of the higher grid electricity price that can be avoided by self-production (see Fig. 11).

The same trend with a higher magnitude can be observed in the E-POL scenario. HTHPs replace heat from waste CHPs in summer and fall. However, more heat supply is electrified throughout the whole year and HTHPs are deployed to upgrade waste heat to a higher temperature level (instead of direct waste heat recovery and waste heat usage for space heating and hot water in BAU).

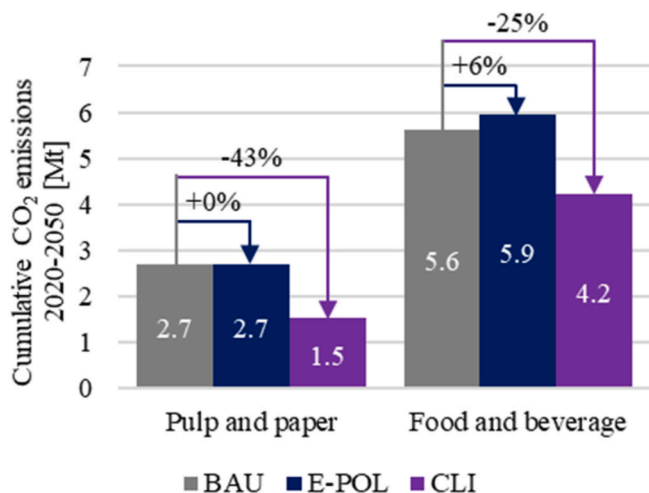


Fig. 9. Cumulative CO₂ emissions from 2020 until 2050 in the pulp and paper industry (left) and the food and beverage industry (right).

In the CLI scenario, the heat supply from HTHPs is comparable to the E-POL scenario. However, heat pumps replace the heat from district heating networks compared to waste CHPs in the E-POL scenario. Furthermore, because of the low electricity price in summer and fall, electrification of the drying processes becomes cost-efficient, which reduces the district heat usage even more.

In general, HTHPs are only used to a temperature up to 150 °C in the pulp and paper industry, although heat pumps up to 200 °C are available. This is because of the low efficiency of HTHPs, the operation cost is high. Because most of the heat in the pulp and paper industry is used for drying at 200 °C, the role of HTHPs is limited but not insignificant in the pulp and paper industry.

In the food and beverage industry, a lower seasonality of the heat production from the HTHPs is observed in the BAU and E-POL scenarios. Only in the BAU scenario, the heat supply from HTHPs in winter is reduced and replaced by biomass and natural gas. In the E-POL scenario, the whole heat demand up to 150 °C is covered by HTHPs. The heat demand for baking processes up to 250 °C is covered by electric ovens in summer and fall while hydrogen-fired baking ovens are used in winter and spring.

The heat supply in the CLI scenario has the highest seasonal variability of all analyzed scenarios. The variability mainly results from the different electricity prices. Because of the low grid electricity prices in summer and fall, operation of the CHP is not cost competitive. On the other hand, CHP operation is cost efficient in winter and spring because of the high electricity prices. In summer and fall electric ovens are used to substitute the heat supply from hydrogen. Though HTHPs are operated in all seasons, their production is high in summer and fall due to relatively cheap grid electricity. Heat from the district heating network and thermal energy storages serves as buffer to cope with shortfall from heat pumps or CHPs. Fig. 12 shows the thermal energy storage and use on a daily level for an optimal plant management with the existing capacities.

Compared to the results presented in this section, report higher values for the EU28 industrial heat pump market potential have been reported (69% coverage of the process heat up to 200 °C in the pulp and paper industry and 51% in the food and beverage industry (Marina et al., 2021)). However, they do not take CHPs and district heat as substitution options for HTHPs into account. Furthermore, when focusing only on the process internal waste heat recovery potential with HTHPs (Kosmadakis, 2019), the fraction of the total heat consumption covered by HTHPs is lower (10.8% in the pulp and paper industry and 6.5% in the food and beverage industry).

In Fig. 12 the daily heat supply for a typical weekday in winter in 2050 in the CLI scenario is shown to showcase challenging heat balancing under the highest variability of technologies of all analyzed results. During the night, cooling is provided for refrigeration and freezing, which means that waste heat is available. This waste heat at 60 °C is stored in a thermal storage. Furthermore, hydrogen CHPs supply the electricity needed for refrigeration and freezing. The heat from the CHPs at 150 °C is also stored in a thermal storage. In the morning hours, the waste heat from refrigeration and freezing is directly upgraded to 100 °C with the help of HTHPs and stored in a thermal storage. Because of the higher storage losses at higher temperatures, the model minimizes storage of high temperature heat. When production starts at 6:00, heat is supplied by the district heating network, hydrogen CHPs and the storages which were charged throughout the night. Fig. 12 highlights that optimizing heat production throughout the day can be beneficial in 2050 in the CLI scenario and should be considered by the food and beverage industry.

4.3. High-temperature heat pumps

As already seen in the scenario analysis (section 4.1) and the heat supply analysis (section 4.2), high-temperature heat pumps supply a considerable share of the heat in both the pulp and paper industry and

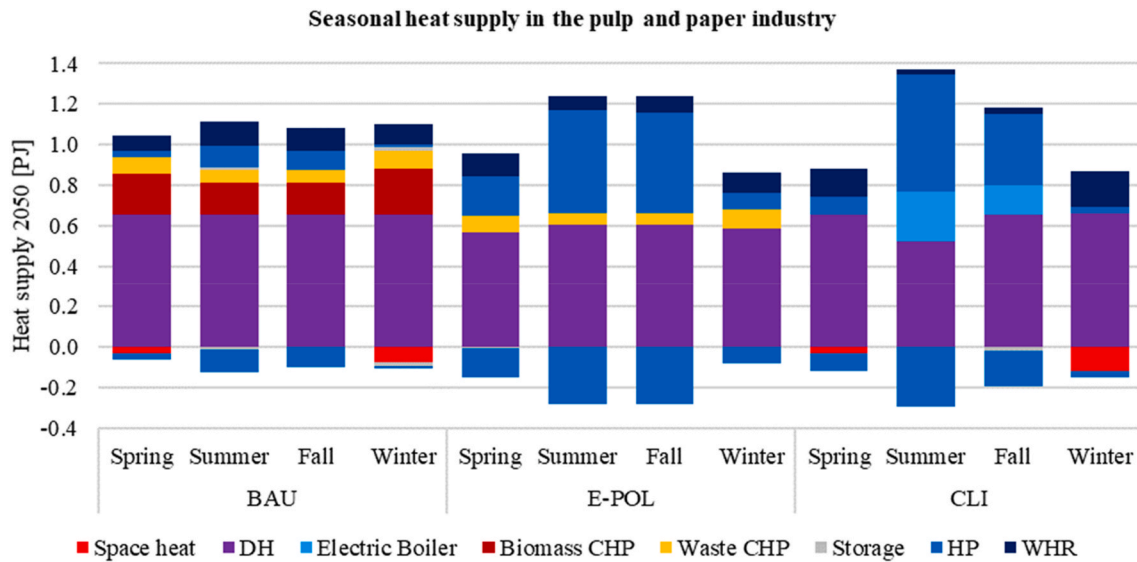


Fig. 10. Seasonal heat supply in 2050 in the pulp and paper industry in the BAU, E-POL and CLI scenarios.

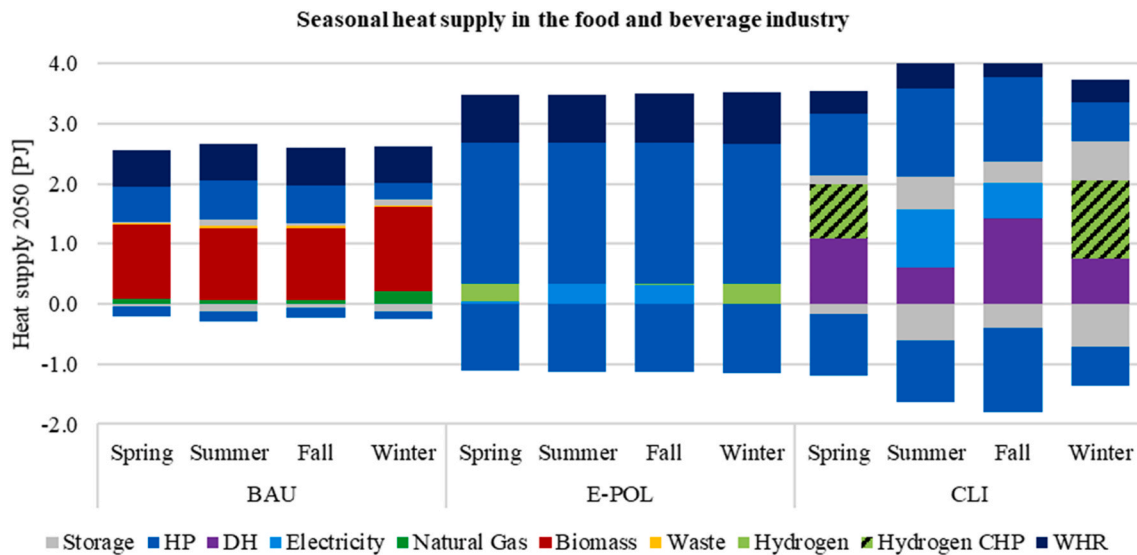


Fig. 11. Seasonal heat supply in 2050 in the food and beverage industry in the BAU, E-POL and CLI scenario.

the food and beverage industry by 2050. In addition to this, analyzing the installed capacity in Fig. 13 and the corresponding investments in Fig. 14 reveals that, even in the BAU scenario, the installed heat pump capacity in 2050 increases to about 50 MW_{th} (a factor of 2.4 from 2020 levels) in the pulp and paper industry and 300 MW_{th} (a factor of 6.6) in the food and beverage industry from 2020 to 2050. Compared to the BAU scenario, waste heat upgrade by HTHPs becomes more important in the CLI scenario which is the main reason why the installed capacity increases even more to about 90 MW_{th} (a factor of 4) in the pulp and paper industry and 470 MW_{th} (a factor of 10.1) in the food and beverage industry from 2020 to 2050. Investments in heat pumps peak towards the end of the end of the model horizon (Fig. 14). HTHPs help to improve the energy efficiency and therefore become very important in the E-POL scenario with a capacity increase to about 100 MW_{th} (a factor of 4.6) in the pulp and paper industry and 900 MW_{th} (a factor of 19.5) in the food and beverage industry from 2020 to 2050. Compared to the CLI scenario, large investments in new heat pump capacity is needed earlier (already in the period from 2035 to 2040) and more air- and ground-source heat pumps are installed because of the imposed energy

efficiency target and the lower electricity prices in the E-POL scenario (see Fig. 15).

Fig. 12 has shown that with the help of thermal storage, the operation of HTHPs and the whole heat supply can be optimized. In addition to this, Fig. 16 shows the storage capacity needed depending on the industry, the scenario and the temperature level. It should be noticed that also thermal storage for cooling is needed in the food and beverage industry. In general, due to the storage losses, thermal storage compromises the energy efficiency, therefore, the application in the E-POL scenario is even lower than in the BAU scenario. On the other hand, thermal storage is economically beneficial in the CLI scenario with sector wide capacity installations of 10 MW_{th} in the pulp and paper industry and 6.6 GW_{th} in the food and beverage industry. Storage is more beneficial in the food and beverage industry because of the more volatile production profile (Appendix A3.3), whereas the production from the pulp and paper industry is assumed constant.

Finally, the electricity prices from STEM (Appendix A2) show only low daily volatility, which leads to negligible demand response from the industry sectors to the grid. However, because of the high volatility of

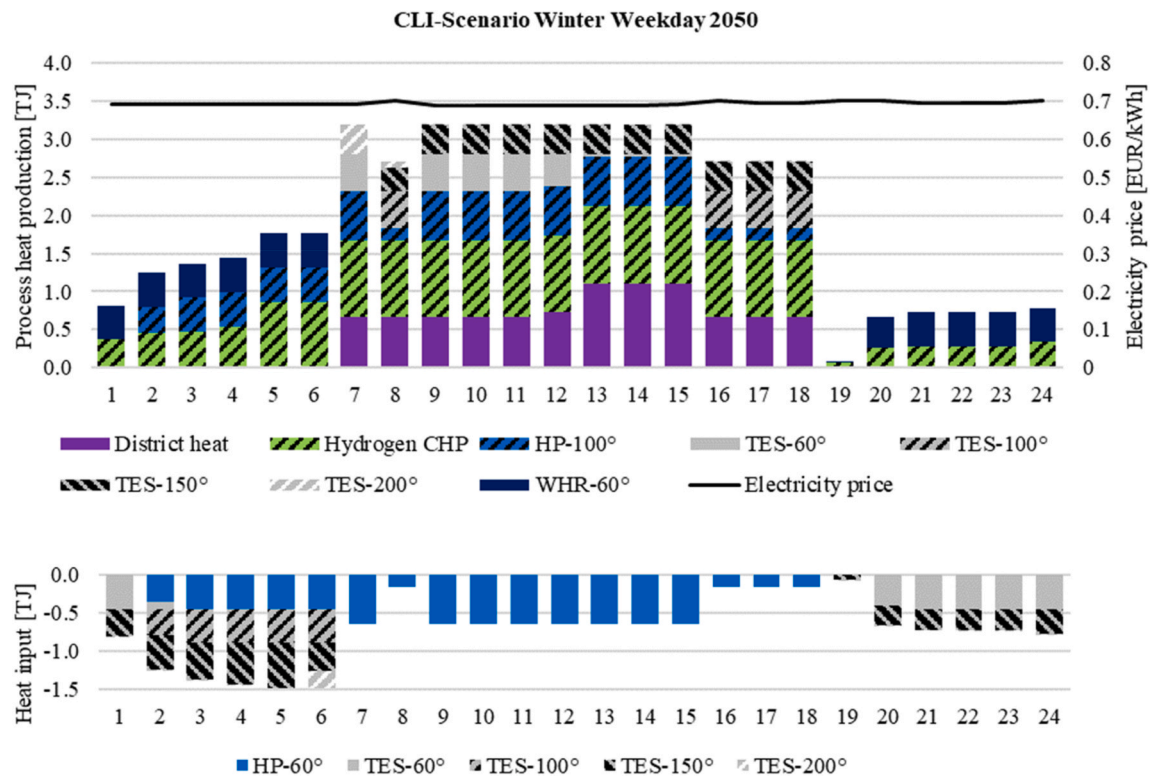


Fig. 12. Heat supply in the food and beverage industry in the CLI scenario on a weekday in winter.⁴¹

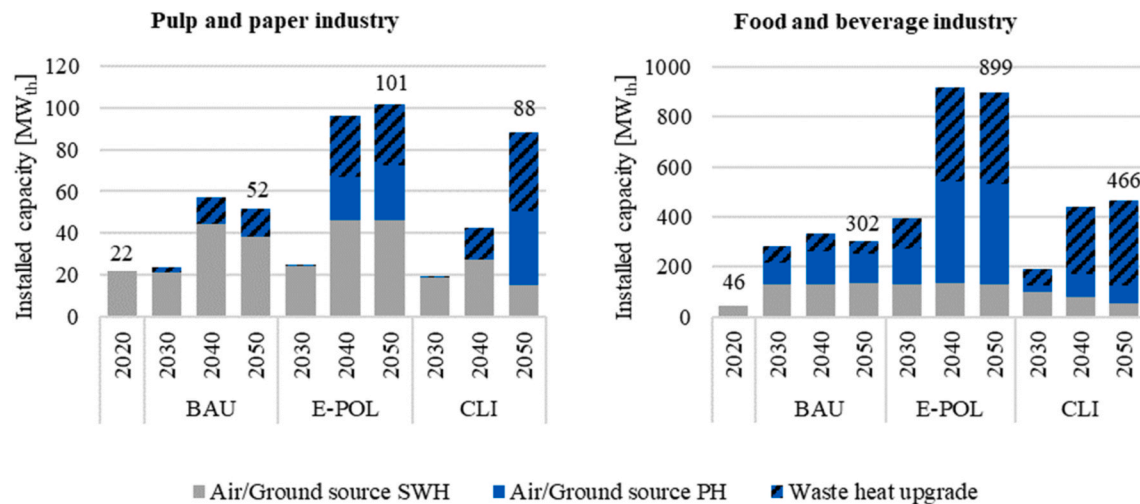


Fig. 13. Cumulative installed heat pump capacity in the pulp and paper and in the food and beverage industries for the three analyzed scenarios, the installed capacity includes heat pumps used for space and hot water heating (SWH).

the electricity prices especially in the CLI scenario at the seasonal level (which is a direct result from the analysis with the STEM model (Panos et al., 2021) where these values refer to marginal costs to provide the corresponding energy carrier), seasonal demand response can be observed from both industry sectors (Fig. 17). The demand response results from the increased electrification of the heat supply in summer and fall on the one hand and from the self-production of electricity with CHPs in winter and spring on the other hand. This requires additional investments in more equipment which is compensated by lower operational costs.

5. Discussion

5.1. Limitations and scope

The model employed for this study only has a one-way coupling to the national energy system model (STEM), whereby the scenario results from STEM are taken as an input for the sectoral model. However, there is a feedback from the sectoral model to the energy system, for example relating to the achieved emissions savings due to relative abatement costs within the sector. The energy consumption of the pulp and paper and the food and beverage industry is rather small compared to the final energy consumption of Switzerland, which is the justification for neglecting the influence on the whole energy system with this one-way

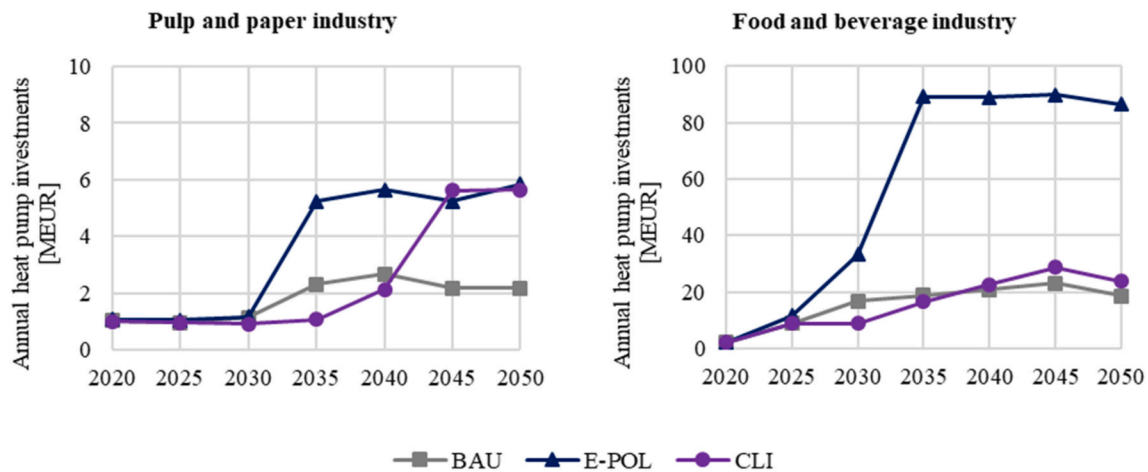


Fig. 14. Heat pump investments in the pulp and paper and in the food and beverage industry.

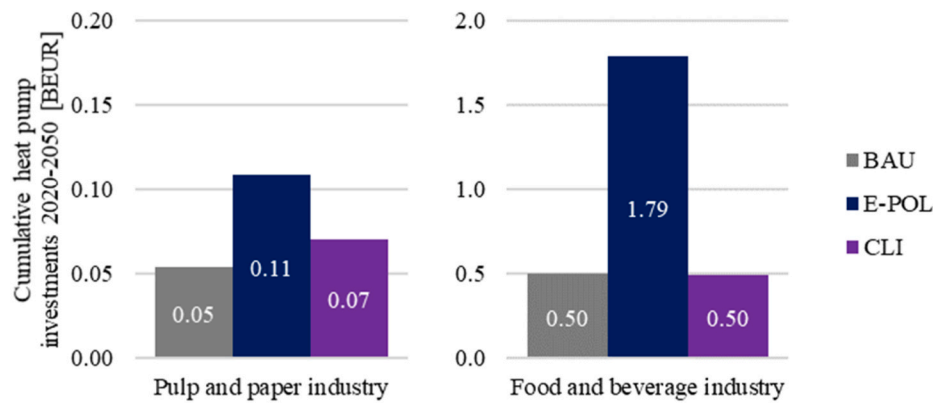


Fig. 15. Cumulative heat pump investments (without thermal storage) in the pulp and paper and in the food and beverage industry.

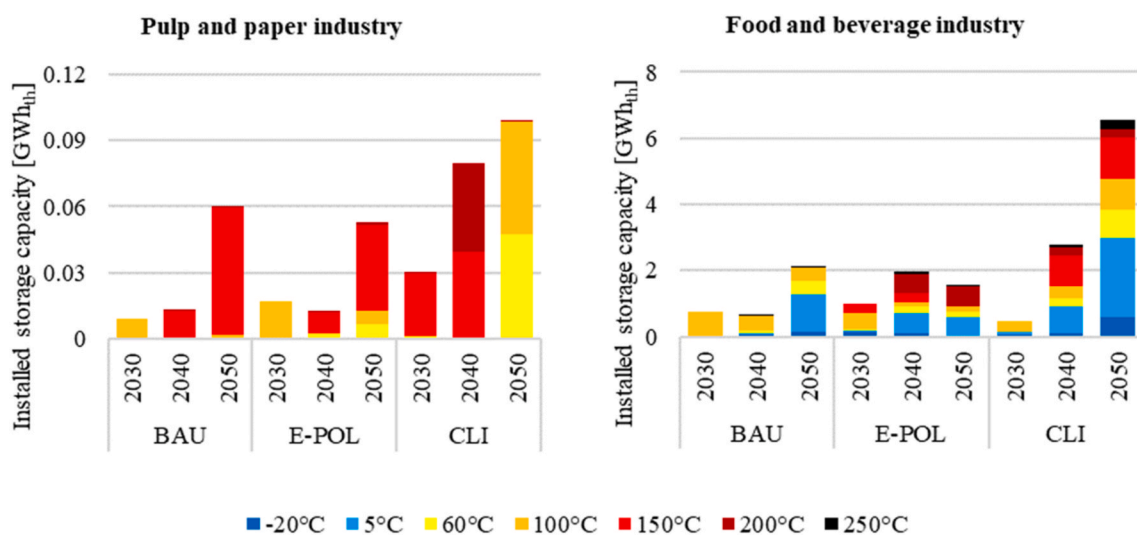


Fig. 16. Additionally installed thermal storage capacity from 2020 in the pulp and paper and in the food and beverage industry.

coupling. Nevertheless, electricity demand profiles can influence the electricity price and the allocation of limited resources (for example

⁴ The negative scale represents the heat input to the storage and the heat used in heat pumps as a source.

biomass or waste) is not fully represented in the sectoral model. A comprehensive analysis of all interactions to the energy system would require a fully integrated model.

As a single region aggregated model, the spatial dimension is also not accounted for in this model, which is critical for district heating networks to connect the heat source to the consumer. Both the pulp and

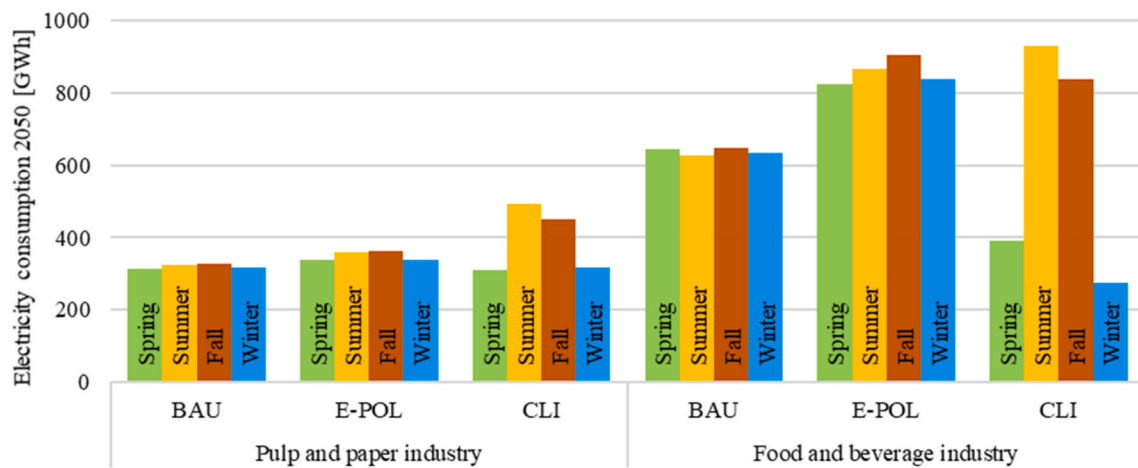


Fig. 17. Seasonal demand response to the electricity grid from the food and beverage and the pulp and paper industry.

paper and the food and beverage industry have a considerable amount of district heat consumption depending on the scenario. Furthermore, also the potential of rivers and lakes as a heat source for heat pumps depends on the location. So a full analysis of the district heating potential would also require a spatial differentiation of the model below the national level. In addition, data for hourly production profiles for the different industry sectors is generally lacking, therefore simplified assumptions (Appendix A3.3) have been made to represent the basic daily production patterns of the industry. Furthermore, the approach to modelling HTHPs might overlook long-term implications for the process, for example by hindering additional/alternative process integration measures which might achieve higher economic/energetic savings from a system perspective. Hence why more detailed data on the production profiles could help improve the model in the future. Finally, it should be noted that the segregation into discrete temperature level bands is a simplification, which on one hand might overestimate the potential of HTHP application by disregarding thermodynamic constraints within the process. On the other hand, it might underestimate the HTHP application using smaller temperature lifts. From a specific application point of view, detailed knowledge about the process' temperature levels is essential and pinch analysis on a plant level can support the integration of the HTHP within the entire process chain.

5.2. Discussion of results

Despite the stable production processes and thereby the process heat demands, high-temperature heat pumps can provide demand flexibility, especially on a seasonal level, if combined with other back-up systems. Nevertheless, on a diurnal level the electricity prices (Appendix A2) are not very volatile, probably because of short term electricity storage in the electricity sector, which helps to balance the grid. Therefore, daily flexibility is not needed, although HTHPs in combination with thermal energy storage could provide this demand response on a daily level.

Our analysis has shown that it can be cost-efficient to upgrade waste heat from the production process or refrigeration using high-temperature heat pumps. In cases where the environmental heat is used as a heat source, using ground sources would be more efficient in winter and using the ambient air as a heat source would be more efficient in summer. Unlike the residential sector where most of the heat demand is in winter, the process heat demand in industry is constant throughout the whole year which makes air source heat pumps more cost-efficient than ground source heat pumps because of the additional costs of ground source heat pumps. Furthermore, ground source heat pumps cannot be installed everywhere and especially for energy intensive industry with a high heat demand, space requirements for the ground source need to be considered.

Both industry sectors reach net-zero emissions in the CLI scenario by 2050. In these scenarios, high-temperature heat pumps help to decarbonize the sectors by efficiently electrify the heat supply up to 150 °C. However, it should be noted that net-zero emissions can also be reached without HTHPs. Alternative technologies that can substitute HTHPs include biomass boilers/ovens and hydrogen boilers/ovens, which means that such a scenario would require high amounts of biomass and/or hydrogen. However, the availability for biomass and hydrogen in these sectors is uncertain and would need to be assessed with a fully integrated model including all competing sectors. Nevertheless, the consumption of biomass and hydrogen in our results for the pulp and paper and the food and beverage industry are within the bounds from the previous analysis with the STEM model (Panos et al., 2021) for the whole industry sector. In addition to this, such a solution would compromise the energy efficiency due to less efficient conversion paths. As a result of this, and because of the higher fuel prices for bioenergy and hydrogen in the future, this pathway would also not be competitive (see Table 2).

The results of the E-POL scenario in the food and beverage industry (Fig. 8) show that electricity consumption increased by 34% from 2020 to 2050 because of the electrification of the heat demand. This means that also an expansion of the grid must be considered, especially when looking at the peak electricity demand in Table 3. However, a detailed analysis of the electricity network exceeds the scope of this study.

Because of the one way coupling of the model to the energy system, hydrogen supply is not further analyzed because it is not within the scope of the model. However, in scenarios where the food and beverage industry has a high hydrogen consumption (5.2 PJ in 2050 in CLI), renewable hydrogen supply and the corresponding electricity demand should be considered in an integrated model. Similarly, the district heating network expansion in the food and beverage industry in the CLI scenario is not further resolved in this sectoral model, but should be considered in an integrated model.

The scenario results for the food and beverage industry reveal the need for seasonal fuel flexibility in the long-term and the corresponding infrastructure. This means that technical solutions (dual fuel ovens) need to be developed that allow ovens to switch between different fuels according to their seasonal availability and pricing. Furthermore, it is questionable whether it is possible to operate a CHP with hydrogen and

Table 3
Electricity peak demand (compared to 2020).

	BAU	E-POL	CLI
Pulp and paper industry	−15%	−6%	+23%
Food and beverage industry	+7%	+45%	+44%

use the waste heat for baking processes. Nevertheless, the model shows that technical solutions outside of today's technology portfolio are needed in the future.

Besides the analyzed pulp and paper industry and food and beverage sector, this study anticipates that high-temperature heat pumps can be used in other industry sectors as well. In general, the following conditions favor the application of HTHPs:

- Heat demand up to 150 °C
- Potential heat sources (especially waste heat from production processes or refrigeration processes)
- High energy efficiency targets
- Low electricity prices

On the other hand, the present study also reveals that HTHPs are not cost-efficient for a temperature range above 150 °C in the analyzed sectors, although heat pumps up to 200 °C would be available as an option to the model. Nevertheless, high-temperature heat pumps with a sink temperature above 150 °C could be favored in other industry sectors if the temperature lift is 100 K or lower.

6. Conclusion and policy implications

For this study, a TIMES-based techno-economic energy system optimization model has been developed for the Swiss food and beverage sector with its diverse product range incorporating detailed production processes with energy and material flows. Most importantly, the scope has been expanded with a high level of process heat temperature granularity and an hourly time resolution. This extension allows for an advanced analysis of the potential for high-temperature heat pumps using multiple scenarios. The novel methodology has been applied for an analysis of the pulp and paper industry and the food and beverage industry which have been identified as the most promising sectors for HTHP application.

The results show that high temperature heat pumps are cost-efficient in both industry sectors and help reaching policy goals regarding energy efficiency (E-POL scenario) and CO₂ emission mitigation (CLI scenario). The highest application potential has been identified in the E-POL scenario with a total sector wide capacity of 100 MW_{th} in the pulp and paper industry and 900 MW_{th} in the food and beverage industry in 2050. Nevertheless, despite the higher electricity price (especially in winter and spring), electrification of the heat supply with HTHPs is also cost-efficient to reach net-zero emissions in the CLI scenario with a total sector wide capacity of 90 MW_{th} in the pulp and paper industry and 470 MW_{th} in the food and beverage industry in 2050.

An efficient use of HTHPs refers to the upgrade of waste heat from production processes and refrigeration processes, but also environment can be used as a heat source. The results show that HTHPs are cost-effective for temperatures up to 150 °C. Application above 150 °C is not cost-optimal due to the low efficiency at high temperature lifts. The comparably low electricity prices in summer and fall in the CLI scenario favors the application of HTHPs. On the other hand, the high electricity price in winter and spring compromises the competitiveness of HTHPs. Therefore seasonal flexibility of the heat generation should be considered in the future which translates into additional investment needs to install complementary systems. Furthermore, the results also revealed that it can be economically beneficial to optimize the heat supply on a daily level using thermal storages at different temperature levels.

The primary policy implication of this study relates to the need to provide adequate incentives for industrial companies to invest in HTHPs. This incentive should be given by high carbon prices in the EU ETS in the range of 100–400 €/tCO₂ as considered in the two normative scenarios of this study. Indeed, this external factor is the main driver for the roughly 1 GW_{th} of identified potential for HTHPs in 2050 in the food and beverage and pulp and paper sectors. There is a large degree of uncertainty whether such high CO₂ prices will indeed be encountered by

2050; the recent strong developments in the carbon price to almost 90 €/tCO₂ have mainly been due to price hikes in fossil fuel markets, which may be relieved in the short-to-medium term. Hand in hand with the economic motivation is the environmental one, which is based on the assumption that the electricity used to drive the heat pumps is partly or wholly low-carbon. If this is not the case, for example due to large imports of electricity to Switzerland in the future, then the environmental case is (also) not necessarily given.

Apart from the EU ETS as the main incentive mechanism for industrial investors, and especially in the case where carbon prices do not approach 400 €/tCO₂ by 2050, there may be a need for policy intervention to support capital-intensive investments in HTHPs for industry. Compared to the alternatives, emerging HTHP technologies are relatively expensive so policy might need to incentivize and support investments until scale effects and technology learning result in cost reductions. Whether or not such support is provided on a temporary (loans) or permanent (grants, payments) will depend on the prevailing energy strategy and policy and the priorities that policymakers place on specific technologies. Nevertheless, there is evidence that policy uncertainty itself is one reason for a lack of uptake of heat pumps to date (Gaur et al., 2021).

In addition, there is also a need to overcome well-known barriers to investment in low-carbon and/or energy efficient technologies, especially heat pumps in this context (Jesper et al., 2021). The modelling approach in this paper rests on assumptions of perfect foresight, competition and information, none of which wholly apply in the real world. The latter (information) is an important case where policy measures need to ensure that adequate and high-quality information is provided to decision makers, especially as lacking or imperfect information are some of the main barriers to investment in energy efficient technologies, alongside long payback periods and customer concerns (Wolf et al., 2012). Even if the information is adequate, there is extensive evidence that organization and behavioral issues may hinder an otherwise apparently attractive business case – for example issues of split incentives within organizations, adverse selection and/or principal/agent problems (Cagno et al., 2013). Other barriers relate to the hosting capacity of the electrical distribution infrastructure to incorporate heat pumps, but also differ strongly by country (Gaur et al., 2021).

An additional area that policy needs to address is to support and emphasize the advantages of heat pumps as a source of flexibility within a highly-renewable energy system (Møller Sneum et al., 2018). Both from the perspective of the production facility, as shown in this paper, and that of the whole energy system/grid operator, heat pumps can facilitate the integration of renewable energy sources in a cost-effective and efficient way. But here also there are numerous barriers in place that hinder the exploitation of heat pump flexibility, for example due to lacking price signals or incentives from the marketplace (Møller Sneum, 2021). Currently, industrial consumers in Switzerland with an annual electricity consumption over 100 MWh can participate in the unregulated electricity market. However, most of the individual units of the food and beverage sector are well below this level and therefore policies should address a market re-design with appropriate market instruments for smaller installations to tap grid and market flexibility mechanisms from these sectors. Since HTHP enables meeting the policy goals on efficiency standards (E-POL scenario), HTHP could be promoted via voluntary or mandatory standards in new installations and overhauling of existing industrial facilities. In view of stringent carbon tax policies aiming at a zero carbon energy system (CLI scenario), particular emphasis should be dedicated to further mitigation measures, such as district heat and hydrogen technology (partly with onsite electricity generation) as HTHP might be affected by high electricity price resulting from higher electricity demand in the entire energy system.

CRedit authorship contribution statement

Michel D. Obrist: Conceptualization, Methodology, Validation,

Investigation, Writing – original draft, Visualization, Project administration. **Ramachandran Kannan:** Conceptualization, Resources, Writing – review & editing, Supervision. **Russell McKenna:** Writing – review & editing. **Thomas J. Schmidt:** Supervision, Writing – review & editing. **Tom Kober:** Conceptualization, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

A1. Technology data

All costs shown in this section consider retrofit costs to replace the existing equipment. Based on the methodology introduced by (Zuberi and Patel, 2017), a cost conversion is applied to account for higher labor costs in Switzerland compared to other countries.

$$TC_{y,CH} = (S_{EC,y} \bullet CF_{EC} + S_{LC,y} \bullet CF_{LC,z}) \bullet TC_{y,z}$$

where: $TC_{y,CH}$ = Total cost for technology y in Switzerland

$TC_{y,z}$ = Total cost for technology y in region z

$S_{EC,y}$ = Share of equipment cost on total costs of technology y

$S_{LC,y}$ = Share of labor costs on total costs of technology y

$CF_{LC,z}$ = Cost factor for labor costs from region z to Switzerland (appendix A4)

CF_{EC} = Cost factor for equipment costs (= 1)

A1.1. Energy technologies

Table A1

Technology data for energy technologies

Technology	Efficiency [%]	Lifetime [years]	Investment [EUR/kW]	Fixed O&M costs [EUR/kW]	Variable O&M costs [EUR/GJ]
Natural gas boiler	90%	20	75	5	0.15
Light fuel oil boiler	90%	20	75	5	0.15
Biomass boiler	75%	20	150	10	0.15
Waste boiler	75%	20	150	10	0.15
Electric steam boiler	90%	20	170	11.3	0.15
Hydrogen boiler	90%	20	120	4	0.15
Evacuated tube collector at 60 °C	67%	15	1253 ⁶	0.40	–
Evacuated tube collector at 100 °C	58%	15	1447 ⁶	0.46	–
Evacuated tube collector at 150 °C	46%	15	1825 ⁶	0.58	–
Evacuated tube collector at 200 °C	35%	15	2399 ⁶	0.76	–
Parabolic through collector	76%	15	2050 ⁶	0.65	–
DH network expansion			120	40	14
Refrigeration compression cycle	455%	15	125	5	–
Freezing compression cycle	253%	15	125	5	–
Refrigeration absorption cycle	60%	15	600	5	–
Freezing absorption cycle	50%	15	600	5	–

⁶ a cost reduction of 1% per year is implemented to account for technology learning (from base year 2015).

Table A2 Technology data for heat pump technologies (reference size 500 kW)

Source type	Temperature lift [°C]	Lifetime [years]	Investment [EUR/kW]	Fixed O&M costs [EUR/kW]
Air source ¹	... to 60 °C	25	776 ⁷	29
Air source ¹	... to 100 °C	25	1397 ⁷	52
Ground source ¹	... to 60 °C	25	1326 ⁷	29
Ground source ¹	... to 100 °C	25	1947 ⁷	52
Waste heat	60–100 °C	25	487 ⁷	18
Waste heat	60–150 °C	25	1237 ⁷	46
Waste heat	100–150 °C	25	629 ⁷	26
Waste heat	100–200 °C	25	1397 ⁷	52

⁷ see section 2.2.

Data availability

Data will be made available on request.

Acknowledgements

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Table A3 Technology data for thermal energy storage (based on (Sarbu and Sebarchievici, 2018))

Temperature	Roundtrip efficiency [%]	Storage losses [% per day]	Lifetime [years]	Investment [EUR/kWh]	Fixed O&M costs [EUR/kWh]
60 °C	90%	5%	15	10	0.1
100 °C	90%	10%	15	10	0.1
150 °C	90%	15%	15	10	0.1
200 °C	90%	20%	15	10	0.1
250 °C	90%	25%	15	10	0.1
−5 °C	90%	5%	15	10	0.1
−20 °C	90%	10%	15	10	0.1

Table A4
Technology data for CHPs

Technology	Size [MWe]	Electrical efficiency [%]	Thermal efficiency [%]	Lifetime [years]	Investment ⁸ [EUR/kW]	Variable O&M costs [EUR/GJ]
Waste CHP	50	26%	88%	20	1516	4.22
	25	26%	88%	20	2000	4.22
	10	26%	88%	20	2885	4.22
	5	26%	88%	20	3807	4.22
Natural gas CHP combined cycle ⁹	50	45%	80%	25	1583	2.53
	25	45%	80%	25	2089	2.53
Natural gas CHP ⁹	50	34%	80%	25	758	2.11
	25	34%	80%	25	1000	2.11
	10	34%	80%	25	1443	2.11
	5	34%	80%	25	1904	2.11
	2.5	34%	80%	25	2512	2.11
	1	34%	80%	25	3624	2.11
	0.5	34%	80%	25	4782	2.11
Internal combustion engine with natural gas ⁹	2.5	36%	84%	20	797	9.72
	1	36%	84%	20	1150	9.72
	0.5	36%	84%	20	1517	9.72
	0.25	36%	84%	20	2002	9.72
	0.1	36%	84%	20	2889	9.72
	0.05	36%	84%	20	3812	9.72
Biomass CHP	50	26%	88%	20	1516	4.22
	25	26%	88%	20	2000	4.22
	10	26%	88%	20	2885	4.22
	5	26%	88%	20	3807	4.22
PEM fuel cell with natural gas supply		27%	72%	10	2206	19.89
SOFC fuel cell with natural gas supply		36%	81%	10	3525	14.71
PEM fuel cell with hydrogen supply		30%	80%	10	1944	19.89
SOFC fuel cell with hydrogen supply		40%	90%	10	3389	14.71

⁸ a cost reduction is implemented to account for technology learning (from base year 2015): 0.5% for conventional CHPs and 2% for fuel cells.

⁹ Natural gas CHPs can also use biogas or hydrogen as an input fuel.

A1.2. Pinch analysis and motor efficiency improvement

Based on (Zuberi et al., 2018) and (Zuberi et al., 2017) the following cost curves for pinch analysis and motor efficiency improvement are created.

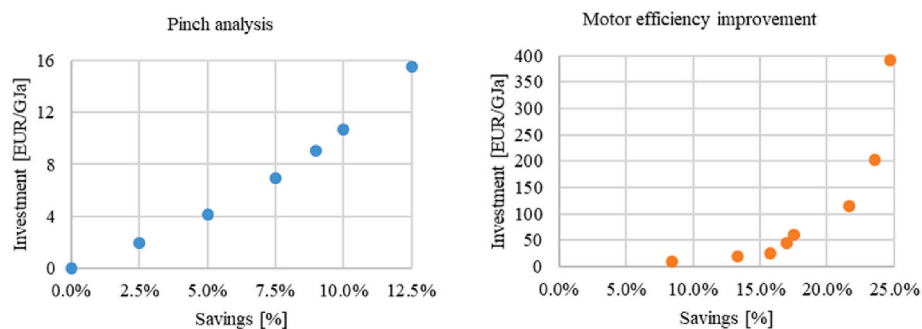


Fig. A1. Pinch analysis and motor efficiency savings cost curve

A2. Fuel prices

The fuel price assumptions (Table A5) used in the model are taken from STEM (Panos et al., 2021) and (Kober et al., 2019) and interpolated linearly.

Table A5

Fuel price assumptions including CO₂ taxes in EUR/GJ

			BAU			E-POL			CLI		
	2015	2019	2030	2040	2050	2030	2040	2050	2030	2040	2050
Natural gas	16.8	18.7	23.5	25.6	26.3	25.4	33.8	44.1	38.4	58.0	103.6
PtM	68.9	69.7	70.0	79.8	84.0	82.1	89.7	69.7	84.2	98.5	164.5
Biogas	45.0	41.1	56.3	71.2	58.8	56.5	71.7	86.1	58.5	75.7	423.6
Light fuel oil	21.5	22.6	31.2	35.3	37.2	35.4	49.3	52.2	47.4	72.1	124.0
Electricity ¹⁰	29.8	30.2	30.3	34.5	36.4	35.5	38.8	30.2	36.5	42.6	71.2
Wood	14.5	13.3	18.2	23.0	19.0	18.3	23.2	27.8	18.9	24.5	136.9
District heat	14.0	14.3	15.1	15.2	16.1	17.8	19.4	15.1	18.2	21.3	35.6
Ren. Hydrogen	36.4	36.8	36.9	42.1	44.3	43.3	47.3	36.8	44.5	52.0	86.8
SMR Hydrogen	25.2	28.1	34.6	37.4	38.1	37.1	48.8	63.2	48.1	74.7	111.5

¹⁰ Note that the shown electricity prices are averaged over the year, electricity prices are implemented hourly.

Compared to the other fuel prices, electricity prices are implemented on an hourly level for the defined timeslices in chapter 3.3. Figure A2 and Figure A3 show the implemented electricity price profiles for the weekdays in 2030 and 2050 respectively.

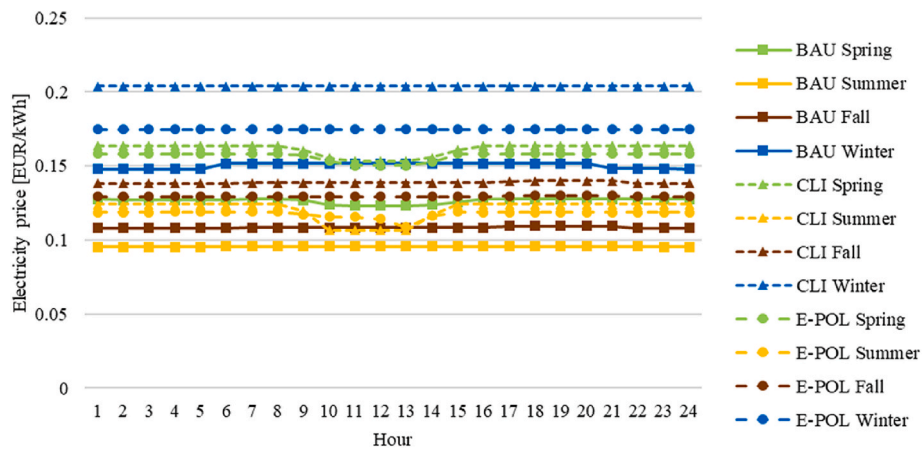


Fig. A2. Hourly electricity prices on weekdays in 2030 (Panos et al., 2021)

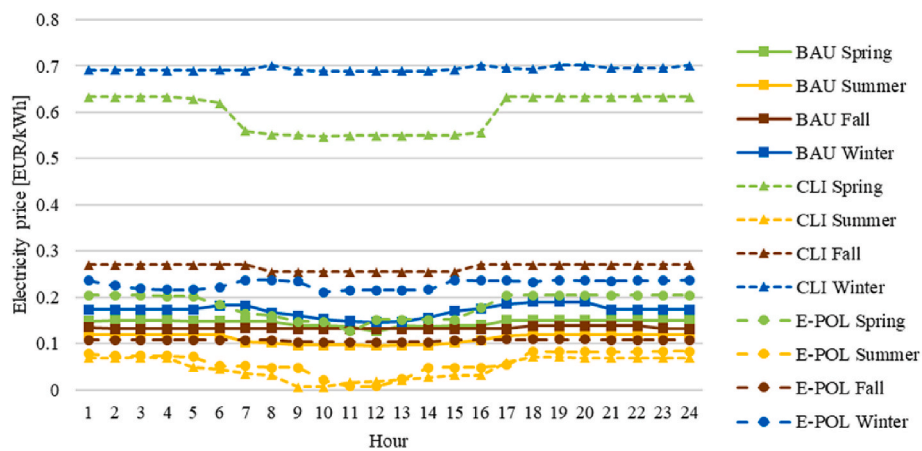


Fig. A3. Hourly electricity prices on weekdays in 2050 (Panos et al., 2021)

A3. Other model input data

A3.1. Temperature and heat pump COP profile

The average daily temperature profile in [aappsec1](#) from (Stadt Zürich, n.d.) is used to calculate the heat pump COP according to the methodology introduced in section 3.3. Note that a temperature difference on the source side of 10 °C is assumed.

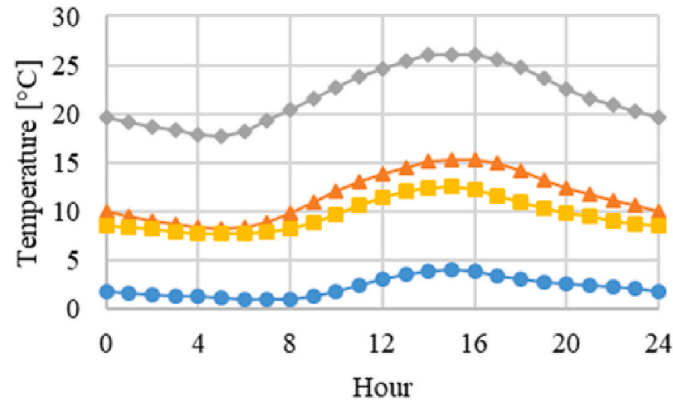


Fig. A4. Average daily temperature profile for each season in Zurich in 2015 (Stadt Zürich, n.d.)

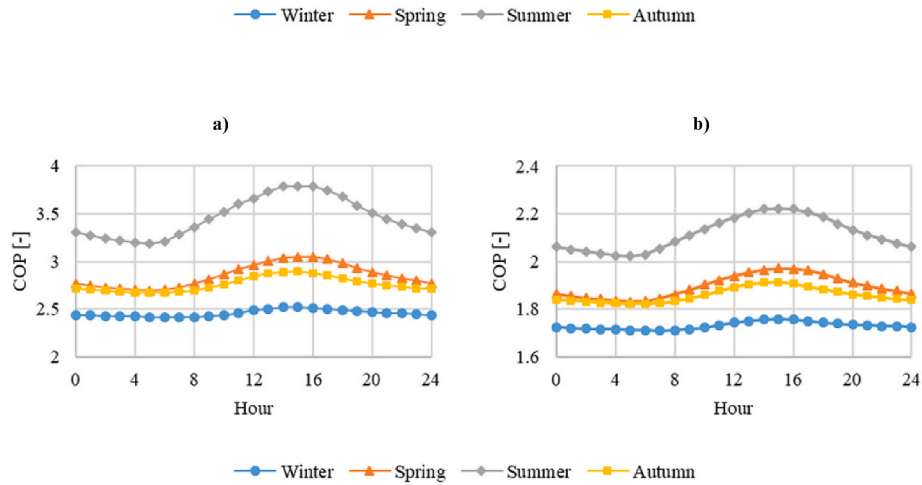


Fig. A5. Heat pump COP profiles for a) sink temperature = 60 °C and b) sink temperature = 100 °C

A3.2. Solar irradiation profile

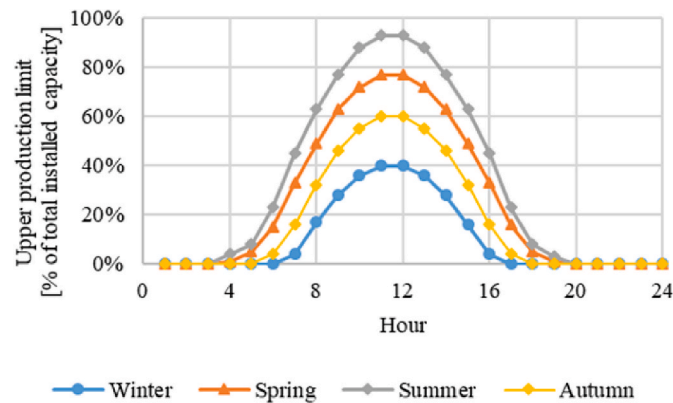


Fig. A6. Implementation of the solar irradiation profile through upper production limits

A3.3. Production profile

The production profiles for the pulp and paper industry and the food and beverage industry are based on own assumptions.

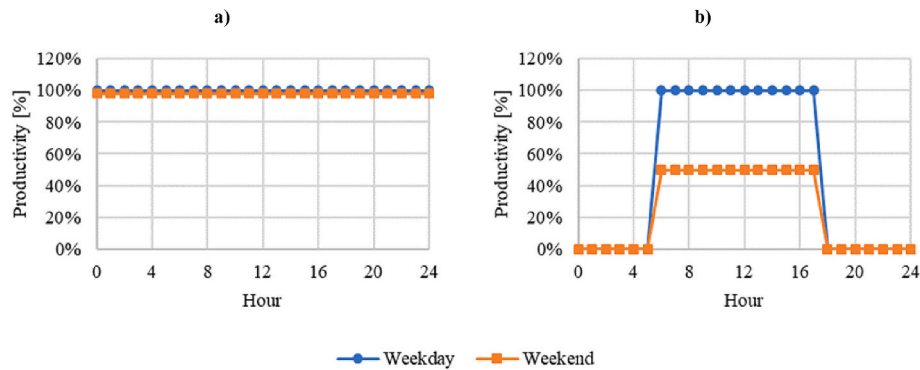


Fig. A7. Production profiles for a) the pulp and paper industry and b) the food and beverage industry

A4. Labor cost conversion factors

The labor cost conversion factors (Table A6) are used according to the methodology in chapter A1 to convert construction costs from international sources to Switzerland.

Table A6

Labor cost conversion factors compared to Switzerland

Country	Labor costs in USD PPP (2011)(International Labour Organization (ILOSTAT), 2020)	Factor to CH
Argentina	1.00	43.08
Australia	20.12	2.14
Austria	39.17	1.10
Belgium	45.62	0.94
Bulgaria	13.06	3.30
Canada	26.27	1.64
Chile	11.13	3.87
Croatia	19.37	2.22
Czechia	21.59	2.00
Denmark	39.85	1.08
Finland	35.06	1.23
France	41.34	1.04
Germany	42.00	1.03
Greece	23.30	1.85
Hungary	17.79	2.42
Iceland	33.09	1.30
Ireland	31.72	1.36
Israel	20.58	2.09
Italy	35.62	1.21
Latvia	14.57	2.96
Lithuania	16.22	2.66
Luxembourg	40.98	1.05
Netherlands	40.37	1.07
New Zealand	19.15	2.25
Norway	43.32	0.99
Poland	21.60	1.99
Portugal	21.05	2.05
Russian Federation	15.93	2.70
Slovakia	20.19	2.13
Slovenia	27.16	1.59
Spain	29.64	1.45
Sweden	39.21	1.10
Switzerland	43.08	1.00
Turkey	14.13	3.05
Ukraine	10.15	4.24
United Kingdom	29.78	1.45
EU-27	27.99	1.54

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