Joint Activity Scenarios and Modelling

Energy efficiency in industry sector

Jibran Zuberi [a,*]
Xiang Li [b,*]
Sophia Anna Wallerand [b,*]
François Maréchal [b]
Martin Patel [a]

[a] UNIGE
[b] EPFL
*First authors

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Contents

Chapter 1

Overview

The objective of this report is to highlight the main findings of the work done in SCCER-EIP for energy efficiency improvement of the Swiss industry sector relevant for the JASM scenario modelling. The document is comprised of two parts:

Part A (Chapter 2): Energy efficiency measures applicable in Swiss industrial systems and sectors.
Part B (Chapter 3): Energy efficiency improvement potential in Swiss industrial sectors based upon system optimization via pinch analysis.

Chapter 2

Energy Efficiency measures applicable in Swiss industrial systems and sectors

> Results available at https://data.sccer-jasm.ch/energy-efficiency-industry/

2.1 Introduction

After the Fukushima nuclear accident in Japan in 2011, Switzerland decided to gradually withdraw from nuclear energy. To do so, the Swiss current energy system needs to be transformed as nearly 40% of the electricity is produced from nuclear resources (SFOE, n.d.). In this context, Switzerland has developed the Energy Strategy 2050 (ES 2050) which is a strategic policy package for advancing the energy transition towards a low-carbon economy. It consists of a detailed set of new and revised laws and policy measures that are foreseen to be realized in two phases. The three pillars of the strategy are (IEA, 2014): a) withdrawal from nuclear energy, b) reduction of energy demand and GHG emissions per capita and c) promotion of renewables and energy efficiency (EE).

Since the energy and environment policies in Switzerland are gradually becoming stricter (see later in this section), the country must use energy as efficiently as possible. The industry sector, which accounts for nearly 20% of the total energy demand in Switzerland, could play a significant role in goal achievement (SFOE, n.d.). In ES 2050, the final energy demand of the industrial sector has been projected until 2050 under three different scenarios, i.e. a) business as usual (BAU), b) political measures (PM), and c) new energy policy (NEP) (Prognos AG). The first set of measures (PM), which promote renewables and energy efficiency, was approved by the Swiss parliament and entered into force on 1st of January 2018. In contrast, the key elements of the more ambitious package (NEP), a revenue-neutral energy tax[1] aiming to increase the cost of energy demand and emissions by switching from subsidies to pricing mechanisms after 2025, was rejected by the Swiss parliament in 2017. While a suitable and widely supported alternative policy measure (or a set of measures) remains to be identified and implemented, the Swiss government reiterated, in its climate policy package published in December 2017, the long-term goal of reducing until 2050 its total GHG emissions by 70% to 85%

[1] According to this concept, the tax revenue is recycled to private consumers and to companies instead of being used by the state; this principle is already to a large extent applied in the context of the Swiss CO2 taxation. The required political majorities were not achieved for the analogous application to energy use.

compared to the levels in 1990 (IEA, 2014).

Switzerland imposed a CO2 levy of 12 CHF/t CO2 on fossil fuels in 2008 which was increased to 36 CHF/t CO2 in 2010, 60 CHF/t CO2 in 2014 and 84 CHF/t CO2 in 2016. The levy was imposed to create an incentive for the end consumers (e.g. households, service sector, and parts of industry) to use fossil fuels more economically and to opt for green or more carbon-neutral energy sources. The present CO2 levy of 96 CHF/t CO2 has been charged since January 2018 (Leu, 2018). To promote EE and GHG emissions reduction in industry, the Swiss government has implemented two policy measures, i.e. reimbursement of the CO2 levy and of the electricity grid surcharge (Kostendeckende Einspeisevergütung or KEV; cost-based compensation given to the renewable energy producers by collecting it from the electricity consumers in Switzerland) (IEA, 2014). In order to get reimbursed for the CO2 levy and the grid surcharge, companies are required to enter into legally binding target agreements thus formally committing them to reduce their final energy demand and CO2 emissions to a certain level. For energy-intensive consumers, these target agreements are typically tailor-made (not forcing the implementation of standard EE measures) while for small and medium enterprises (SMEs), they are ready-made (implementation of the standard measures if applicable and economically viable) (IEA, 2014). The Swiss government mandated the 'Energy Agency of the Swiss Private Sector (EnAW)' and the 'Cleantech Agency Switzerland (act)' to help industries in the design and implementation of EE measures throughout the period of the target agreements. The agreements signed with these two third parties are called 'Universal Target Agreements' (BFE, 2014). Energy-intensive companies with more than 18 TJ (5 GWh) of heat and 1.8 TJ (500 MWh) of electricity demand per year can also opt for 'Cantonal Target Agreements'. Both the universal and the cantonal target agreements set an indicative target of 2% p.a. for EE improvement (IEA, 2014). The only difference between the two models is that under the former, reporting is done to EnAW or act while under the latter, to the canton. Not all Swiss cantons offer cantonal target agreements. The minimum requirement for energy-intensive companies not having to sign a target agreement is to have an energy demand audit (Energieverbrauchsanalyse or EVA). Companies that opt for this model are responsible to meet the required EE improvements within three years (IEA, 2014).

Large consumers (>50 participants) with an installed rated thermal input of 20 MW or more are exempt from the CO2 levy and it is mandatory for them to participate in the Swiss Emissions Trading Scheme (ETS). Under the Swiss ETS, it is foreseen to reduce the cap of CO2 emissions by 2.2% p.a. between 2021 and 2030 (FOEN, n.d.). On the other hand, companies with an electricity bill exceeding 10% of their gross value added (GVA) are fully exempt from paying the grid surcharge. Companies with electricity costs falling between 5% and <10% of their GVA can apply for partial reimbursement of the grid surcharge (Betz et al., 2015).

It should be noted that the focus of target agreements is on the implementation of cost-effective EE and CO2 saving measures (i.e. having a payback time of <4 years for process-specific measures and <8 years for measures related to infrastructure). Additionally, in order to support the implementation of electricity-saving measures that are economically challenging (i.e. having payback times >5 years) and to ensure efficient use of electricity in all sectors including industry, the Swiss Federal Office of Energy (SFOE) has been operating a competitive tenders scheme called ProKilowatt since 2009. ProKilowatt provides financial support by auctions and makes sure that projects (undertaken by and for a single entity) and programs (undertaken for several organizations) with the best cost-benefit ratio are chosen. The main performance criterion is the amount of electricity saved per unit of financial support (cost-effectiveness) (BFE, n.d.).

It is noticeable that Switzerland is making an effort to ensure EE improvement in the industry sector, however, it is not fully clear to what extent these efforts have been successful and how these policies are going to evolve in the future. The first step to analyze this domain is to estimate the EE gap currently existing in the industry sector. Furthermore, with the rapid change in technology for several unit processes, it is of utmost importance for the EE programs to update their lists of EE measures and to promote the application of these measures to achieve the ES 2050 indicative targets.

Given the research gaps identified above, this study investigates the economically viable EE improvement opportunities in the Swiss high value-added industry sector. The specific aims and objectives of this research are: a) to identify the EE potential by process groups (e.g. compressed air, pump and fan systems, etc.) for key Swiss industrial sectors, b) to evaluate the economic viability of existing and emerging EE measures, c) to identify which parameters influence the economic viability of the EE measures and to which extent, and d) to develop a bottom-up model for the industry sector and to assess techno-economic final energy saving potentials in the Swiss industry at the level of individual sectors and process groups. It should be noted that this section of the report is part of a doctoral thesis (Zuberi, 2019) and only the highlights of the detailed study are presented here.

2.2 Methods and materials

This study investigates the potential of final energy savings for the Swiss industrial sectors and systems and its associated specific costs. The results are presented in the form of an energy efficiency cost curve. The curve shows the specific cost $C_{spec,y}$ of each measure y applicable as a function of its corresponding final energy savings potential (ES_y). For the calculation of the net present value NPV (sum of annual cashflows during the EE measure lifetime) of an EE measure y, both total investment costs and energy-relevant costs (additional costs of energy efficiency in case of early replacement of industrial equipment or economic additionally; see Zuberi and Patel (2017) for details) are used. For new installations, energy-relevant investments are considered equal to total investments. Specific costs are calculated using the following equations:

$$C_{spec,y} = \frac{ANF * NPV_y}{ES_y}$$
$$ANF = \frac{(1+r)^L * r}{(1+r)^L - 1},$$

where ANF, L, and r are the annuity factor, measure technical lifetime, and discount rate (taken as 12%) respectively. The measure lifetimes and the reason for the choice of the discount rate are explained in detail in (Zuberi, 2019). When plotting the EE cost curve, measures are arranged in ascending order by specific costs and displayed against their annual cumulative potential final energy savings. The height of each measure on the vertical axis displays the measure's specific cost while the width of each measure on the horizontal axis shows the annual final energy savings potential by that measure. Since annual benefits in the NPV calculation are considered with the negative sign convention as a consequence of energy cost savings, all measures that fall below zero on the horizontal axis are cost-effective.

Furthermore, EnAW and ProKilowatt programs made available confidential and anonymous techno-economic data on EE measures implemented by their partner companies (>3500 enterprises from all industrial sectors representing approx. 70% of the final energy demand in the Swiss manufacturing industry) from 2000 to 2012. For each of these EE measures, the two databases contain data on energy savings and investment costs. Using this information, 64 distinct EE measure categories have been classified and their respective techno-economic energy savings potentials have been estimated, refer to Zuberi (2019)) for details. Briefly, the energy-saving potential estimates for the EE measures applicable in the Swiss cement and chemical industries and motor systems are estimated based on a) the interviews with individual companies, plant manufacturers, and field experts and b) the available information in national and international literature.

2.3 Results and discussion

2.3.1 Industrial system-specific results

Since technologies for several unit processes are rapidly changing, it is of utmost importance for EE programs to update their scope of EE measures and to promote the implementation of the emerging technologies to achieve the ES 2050 indicative targets. For this purpose, the first industrial system analyzed in this study is electric motor-driven systems (EMDS). The electricity consumption by motor systems accounts for nearly 68% of the total Swiss industrial electricity demand (likewise in the EU i.e. 69% (Wuppertal Institut für Klima, n.d.). These systems can be expected to contribute significantly to achieve electricity-specific EE indicative targets. In this study, the economic potential for electricity savings in Swiss industrial motor systems is estimated at 17% of the total electricity consumption in 2015 if total investment costs are considered and 18% if energy-relevant investments are accounted for. More specifically, the economic EE improvement potential in compressed air, pump, and fan systems in the Swiss industry amount to 24%, 20%, and 22% respectively.

Table 2.1 presents the annual technical and economic potential electricity savings in industrial motor systems in different countries. The table shows that for developed countries including the US, Canada, the EU, and Switzerland, the potentials are lower than those for the developing countries (Brazil, Thailand, and Vietnam) but significant. For a developed country like Switzerland, nearly 60% (on average) of the potential electricity savings in industrial EMDS are associated with the installation of new equipment while the remainder is related to energy management and process control.

Table 2.2 presents the contribution of the measure clusters (e.g. all individual measures applicable to compressed air systems) in the Swiss industrial system-specific total final energy savings. The clusters are ranked based on their contribution. For EMDS, the sub-systems that possess the greatest potential for saving electricity are found to be pump systems (i.e. 30%) followed by fan systems. Motor systems other than the major three listed in the table also have a large potential collectively. It should be noted that the effect of interdependent measures is multiplicative while Table 2.2 illustrates full exploitation of all measures (i.e., this is a given ‘snapshot’ for which the savings may be added up). Therefore, the implementation of only one or several of these measures would result in higher electricity savings than shown in the table.

2.3.2 Industrial sector-specific results

Apart from analyzing the aforementioned process groups, the EE improvement potentials in the two most energy-intensive Swiss industrial sectors, i.e. the chemical and pharmaceutical and the cement

Table 2.1: Annual technical and economic potential electricity savings in the industrial EMDS in different countries (values for all countries except for Switzerland are taken from (McKane and Hasanbeigi, 2011)

Sector	Base year	Potential electricity savings (% f total electricity demand in the base year)							
		Compressed air systems		Pump systems		Fan systems		Total (major EMDS)	
		Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.
Switzerland	2015	-	24	-	20	-	22	-	21
United States	2008	29	21	43	29	30	25	35	25
Canada	2008	41	26	45	37	27	14	40	25
European Union	2007	38	28	44	30	29	28	39	29
Thailand	2008	55	47	45	36	46	46	49	43
Vietnam	2008	56	46	57	49	45	41	54	46
Brazil	2008	47	42	45	43	40	40	44	42

Table 2.2: Ranking and contribution of the measure clusters in the total Swiss industrial system-specific potential final energy savings

Rank	**Measure clusters**	**Final energy savings (% of total)**
1	Rest of the motor systems	40%
2	Pump systems	30%
3	Fan systems	20%
4	Compressed air systems	11%
	Total	100%

sectors (representing 23% and 12% of the total final energy demand in the Swiss industry in 2017) are also analyzed respectively.

The economic potentials for final energy savings and CO2 abatement in the chemical and pharmaceutical sector are estimated at 15% and 22% (based on energy-relevant investment costs) and at 14% and 21% (based on total investment costs) of the respective total final energy consumption and fossil fuel-related CO2 emissions in 2016. As presented in Table 2.3, process heat integration can play a key role in EE improvement in the chemical and pharmaceutical sector. The measures related to motor systems are expected to contribute most of the economically viable electricity savings. It was further realized that the size of economic EE improvement potential across the sector decreases from 15% to 11% for 50% lower final energy prices while the size increases slightly for 50% higher final energy prices.

As mentioned earlier, the EE improvement and CO2 abatement opportunities in the Swiss cement sector are estimated primarily based on the data collected via interviews with the cement and the plant manufacturers. The current economic potential for final energy savings and CO2 abatement is estimated at 14% and 13% of the sector's final energy consumption and CO2 emissions in 2014

Table 2.3: Ranking and contribution of the measure clusters in the total Swiss sectoral potential final energy savings

Rank	Measure clusters	Final energy savings (% of total)
Chemical and pharmaceutical sector		
1	process heat integration	39%
2	Motor systems	36%
3	process-specific measures	14%
4	process heat supply	10%
	Total	100%
Cement sector		
1	Cement grinding (incl. cement blending)	53%
2	Clinker production	38%
3	process control	5%
4	Raw material preparation	4%
	Total	100%

respectively. The required capital to exploit the economic potential is estimated at approximately CHF 120 million. This sectoral study also highlights that due to the relatively low current final energy and CO2 prices (for large consumers), the cost savings enabled by the economically viable measures are low. Even 50% higher fuel prices are found to lead to only a limited increase in the final energy savings potential. However, in case of no exemption to Swiss cement plants from the CO2 levy, carbon capture becomes economically viable which could drastically reduce sector-specific CO2 emissions.

2.3.3 Overall results

To put all the findings into perspective, an energy efficiency cost curve for the overall Swiss industry sector is developed, refer to Figure 2.1[2]. All the sector-wide EE measures including those related to EMDS, as well as the process-specific measures for the chemical and pharmaceutical sector and cement plants, corresponding to the total economic potential of final energy savings of 23 PJ p.a. (6 PJ p.a. of electricity and 17 PJ p.a. of thermal energy) based on total investment costs. In relative terms, the economic potential for the total of all studied industrial systems and sectors represents 19% of the final energy demand of the total Swiss industry in 2017. The total of estimated thermal energy savings and savings from measures exclusively targeting CO2 mitigation (e.g. fuel substitution) is equivalent to a CO2 emission reduction potential of 1.3 Mt CO2 p.a. (34% of the fossil-based CO2 emissions in Swiss industry in 2017). These estimates are based on today's projections of future energy and CO2 prices. It should be noted that the consideration of additionality (supplementary impact of a measure beyond standard practices and autonomous change) may strongly influence the cost-effectiveness of

[2] It should be noted that Figure 2.1 also includes measures related to heat integration based on an approach different from Part B. Hence the total potential as stated in the figure cannot be directly added to the potential in Part B. The JASM data platform provides measure-specific data (provided by (Zuberi, 2019)) from which heat recovery measures must be excluded to avoid potential overlap if the results of Parts A and B of this report are to be combined.

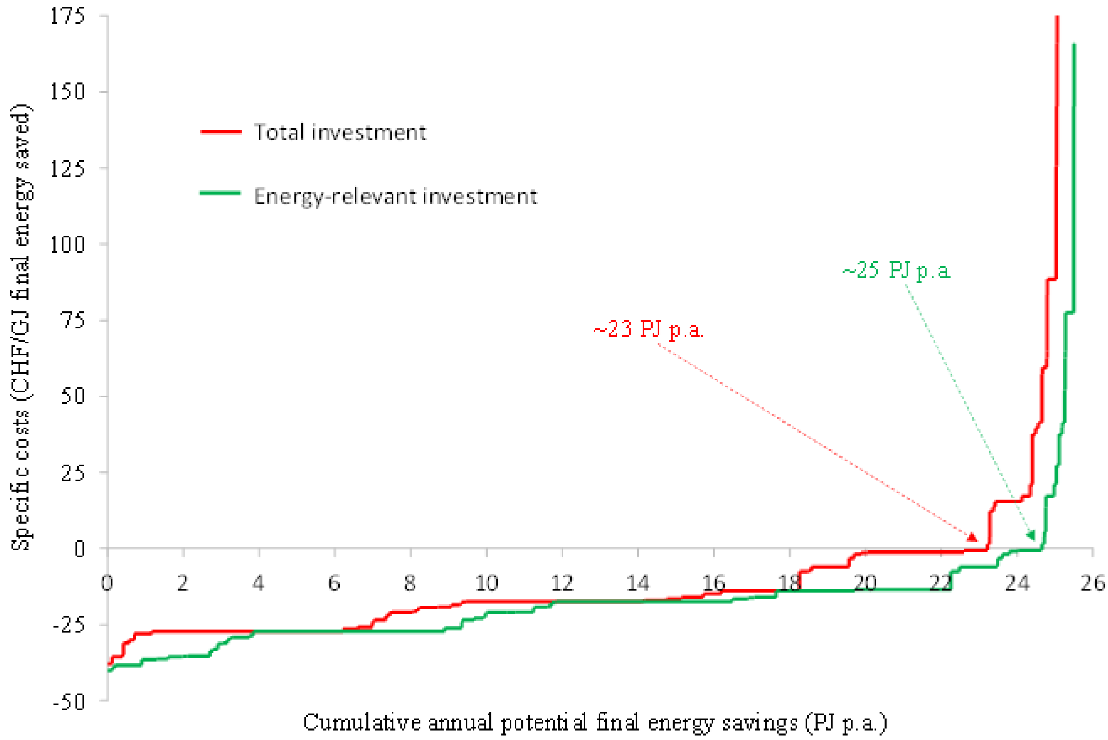


Figure 2.1: Energy efficiency cost curve for the overall Swiss industry (64 measures in total)

Data available at https://data.sccer-jasm.ch/energy-efficiency-industry/

the EE measures and consequently the decision by policymakers. If the energy-relevant investments (economic additionality) of the measures investigated in this study are accounted for, then the total economic potential increases to 25 PJ p.a. (21% of the final energy demand of the total Swiss industry in 2017).

As stated earlier in the introduction, the first package of measures of the Swiss ES 2050 (Political Measures – PM) aims to decrease final energy demand in industry by 18% and 26% in 2035 and 2050 respectively compared to the level in 2010. Depending on whether additionality is considered, the suggested economic EE measures, could contribute to 57-82% and 53-65% of the indicative targets for 2035 and 2050 respectively. Moreover, implementation of EE measures applicable to other industrial sectors (such as food, paper and metals sectors, etc.; not analyzed in this part) could contribute to achieving the overall targets.

Chapter 3

Innovative process design and integration for Swiss industry sectors

3.1 Introduction

According to the Swiss Federal Office of the Environment FOEN (2019), industrial processes account for more than one quarter of global CO2 emissions. With an increasingly imperative need for actions to reach climate goals, industry is asked to face their responsibilities. Reducing industrial emissions is most effectively achieved through energy efficiency measures, together with cleaner fuels, and a reduced demand for products by society. Assuming that the latter cannot be altered by industry alone, this study addresses the former two points. Apart from energy efficiency improvement via performance enhancement of key equipment in industry in previous sections, it is equally crucial to investigate the potential of energy saving in industry from the perspective of system design. The goal of the present study is to derive energy saving potentials in energy intensive industrial sectors by heat pumps (HP) integration; therefore, increasing the energy efficiency of the processes. Heat pumping has gained increasing attention in recent years, not only for household applications but also for improving energy efficiency of industrial processes through waste heat recovery and valorisation at elevated temperatures (IEA, Chua et al.).

With the help of the Swiss Federal Office of Energy, the IPESE group at EPFL under the leadership of Professor François Maréchal has explored new horizons for industrial heat pumping in industry and participated in IEA annex 48 regarding industrial heat pumps on behalf of Switzerland. In collaboration with the SCCER-EIP, the goal is to develop new methods to improve industrial energy efficiency and mitigate CO2 emissions by the proper integration of industrial heat pumps and investigate the role of industrial heat pumps towards the goals of the energy transition 2050. The proposed research integrates innovative concepts of industrial heat pumps considering progress in working fluids, heat exchange, multi-stage systems, compression and expansion technologies using optimization methods and process integration techniques. This section is an updated and consolidated version of the final report for WP 4 in Phase I of the SCCER - EIP project, prepared by the IPESE group, and the major improvements are summarized in the following list.

- A thorough literature review and cross-check of all provided data has been conducted. An extensive description of all sources has been added to this report (see Fig. 3.1). Alongside this report, a paper was published detailing the methodology used to generate the energy saving scenarios in Kantor et al. (2018).
- The overall industrial energy consumption data has been updated with the 2016 BFE reported values Bundesamt für Energie BFE (a) (as compared to the 2010 data published by Prognos AG Prognos AG).
- The saving potentials and specific energy consumption values are provided for both electricity and primary thermal energy instead of total energy. This offers deeper insights and thus more detailed conclusions.
- A detailed description of the underlying assumptions and the primary focus of this report and the work conducted by the IPESE group was added in Section 3.4.7.
- At the process level, an indicator based on expert opinion EO (☆☆☆) was introduced, which allows to assess the feasibility of the proposed energy saving measures.
- At the sector level, three different energy saving scenarios were developed, namely: *i*) a **conservative** scenario, *ii*) the technical potential based on a pragmatic expert assessment (**technical**), and *iii*) the *thermodynamic maximum* (**optimistic**). A description of the considered scenarios is provided in Section 3.4.7.

The report is structured in three major parts. First, an analysis of state-of-the-art on industry efficiency is conducted based upon literature review; Secondly, the methodology of this study is presented, elaborating the bottom-up approach applied in this work, together with the materials and data. Finally, the energy saving potentials of various industry sectors are reported and discussed.

Citation	Anal.	Foc.	Sector	Siz.	Obj.	HR	PA	H+C	HP	AHP	ORC	Solar ener. Coll.	Stor.	Synthesis
This study	🔍	🔧	EIIS	M	env, eco	✔	✔	✔	✔	-	-	-	-	Technology energy saving potentials in the energy intensive industrial sectors (EIIS).
Meyers et al. [7]	🌍	🔧	none	C	env, eco	-	-	(✔)^{H}	✔	-	-	ST	✔	General comparison of heat production through heat pumps and solar thermal systems, not focusing on integration with the industrial processes.
Arpagaus et al. [8]	🌍	🔧	EIIS	C	thermo	-	-	(✔)^{H}	✔^{ME}	-	-	-	-	Rough potential estimation across industrial sectors by analysis on the temperature ranges, focus on high temperature HPs and working fluid analysis.
Wilk et al. [10]	🔍	🔧	paper mill, laundry, foams	C	env, eco	✔	-	✔	✔^{ME}	-	-	-	-	Analysis of different industrial processes and the benefits related to installation of heat pumps based on flow sheet software.
Sharma et al. [19]	🌍	🔧	dairy	C	energy	-	-	(✔)^{H}	-	-	-	PT	-	Potential analysis of solar heat for dairy industry in India, considering solar sizing (by capacity) and locations of plants.
Sharma et al. [20]	🌍	🔧	paper making	C	energy	-	-	(✔)^{H}	-	-	-	PT	-	Potential analysis of solar heat for paper industry in India, considering solar sizing (by capacity), location, and co-generation.
Brckner et al. [6]	🌍	🔧	EIIS	C	eco	-	-	(✔)^{H}	✔	✔	-	-	-	Economic potential for compression and absorption heat pumps and heat transformers in different industrial sectors (in Europe) based on estimated heat demands.
Wolf et al. [5]	🌍	🔧	LT EIIS	C	env, eco	-	-	(✔)^{H}	✔	-	-	-	-	Potential estimation in industrial sectors in the German context by analysis based on the temperature ranges.
Mller et al. [22]	🔍	🔧	liquid food industry	C	energy	-	-	(✔)^{H}	-	-	-	var.	✔	Methodology is presented on how to estimate the potential for solar heat in the liq. food industry, based on available area, and temperature levels.
Campana et al. [13]	🌍	🔧	HT EIIS	C	env, eco	-	-	(✔)^{C}	-	-	✔	-	-	Potential estimation of ORC integration in the EIIS in the EU.
Calderoni et al. [21]	🔍	🔧	textile, laundries	F	eco	-	-	(✔)^{H}	-	-	-	PT	✔	Economic feasibility study of solar-assisted process plants in Tunisia.
Beath [17]	🌍	🔧	overall industry	C	energy	-	-	(✔)^{H}	-	-	-	var.	-	Top-down analysis of industrial heat demand, temperature ranges, and location, matched with solar availability in Australia.
Lauterbach et al. [18]	🌍	🔧	LT EIIS	C	energy	-	-	(✔)^{H}	-	-	-	var.	-	Top-down analysis of industrial heat demand, temperature ranges in Germany.
Schweiger et al. [16]	🌍, 🔍	🔧	LT EIIS	B	eco	-	-	(✔)^{H}	-	-	-	var.	-	Potential anaylsis and design of SHIP in Spain and Portugal through steam production and integration with conventional utility system.
Brown et al. [14]	🌍	🔧	EIIS	C	eco	-	-	(✔)^{H}	-	-	-	PT	-	End-use matching analysis of parabolic trough collectors with industrial process heat.
Wallerand et al. [11]	🔍	🔧, ◕	dairy	M	env, eco	✔	✔	✔	✔^{ME}	-	-	-	-	Potential analysis based on optimization of detailed heat pump features for the dairy industry.
Seck et al. [9]	🔍	🔧, ◕	food & beverage sector	C	env, eco	-	-	✔	✔	-	-	-	-	"Bottom-up" technical (TIMES) model used to estimate the potential for heat pumping in the French food and beverage sector.
Murray [15]	🔍	🔧, ◕	primary alum. making	C	env	-	-	(✔)^{H}	-	-	-	CSE	-	Conceptual analysis of potentials for highly concentrating solar heat in the primary aluminum industry.
Fleiter et al. [25]	🌍	◕	pulp & paper	C	energy, eco	✔	-	-	-	-	-	-	-	Energy saving measures in the pulp and paper industry, with focus on heat recovery and processing technology upgrading.
Neelis et al. [24]	🌍	◕	petrochemical	C	energy	-	-	(✔)^{C}	-	-	-	-	-	Investigation of the petrochemical industry and energy saving potentials by analysis of the main system losses.
Worrell et al. [23]	🌍	◕	cement industry	C	env, eco, energy	✔	-	-	-	-	-	-	-	Potential for energy efficiency improvements in the cement industry based on energy conservation supply curve.
Codina Gironès et al. [26]	🌍	🏭	overall industry	C	env, eco	-	-	-	-	-	-	PV	✔	Country energy system analysis where industrial sector is treated as one entity with overall energy saving potentials based on user input.
Lu et al. [27]	🌍	🏭	EIIS	C	env, energy	✔	-	(✔)^{H}	(✔)*	-	-	-	-	Analysis of energy saving potentials in the EIIS in Taiwan by review of the best available technologiess (BATs) and best practice technologies (BPTs) compared to current consumption values.
Prognos AG [28]	🌍	🏭	overall industry	C	env, eco	-	-	-	-	-	-	-	-	Swiss energy system analysis, general estimation of energy intensity of future industrial system based on assumptions.
Bunse et al. [29]	🌍	🏭	overall industry	C	energy	-	-	-	-	-	-	-	-	Analysis of gaps in research in order to achieve energy efficiency measures in the industry.
Worrell et al. [30], Worrell et al. [31]	🌍	🏭	HT EIIS	C	env, energy	✔	-	-	-	-	-	-	-	Literature review of energy saving scenarios in the main industrial sectors based on estimations from theintergovernmental panel on climate change [32] (IPCC), BPT, and expert judgment.
Bonilla et al. [33]	🌍	🏭	overall industry	C	energy	✔	-	✔	✔	✔	✔	-	-	Estimation of waste heat recovery potential by various technologies from industry in the Basque country.

[*] Heating ventilation and air conditioning (HVAC) is considered
Analysis: 🔍- bottom up analysis, 🌍- top down analysis
Focus of the study: 🏭- Cross-sectoral studies (🏭): energy saving potentials across various industrial sectors and technologies, 🔧- Technology specific studies (🔧) : energy savings through one specific technology, ◕- Sector-specific studies (◕) : energy savings potentials in one specific industrial sector
Sizing of the technologies: M - mathematical approaches, C - conceptual approaches, F - fixed sizes, B - brute-force sizing
Objective of the study: env - environmental, eco - economic, thermo - thermodynamic objectives, energy - energetic objectives
Technologies & methods considered: **heat recovery (HR)** - in the industrial processes, **pinch analysis (PA)** - as a method in the study, **H+C** - technologies are considered as hot and cold utilities: ✔(hot and cold), (✔)^{H} (hot only), (✔)^{C} (cold only), **heat pumping (HP)**: ✔(modeled by Carnot factor), ✔^{ME} (mass and energy balances), **absorption heat pump (AHP)**, **organic rankine cycle (ORC)**, **Solar energy** - collector types: solar (non-concentrating) thermal systems (STs), Portugals (PTs), concentrated solar energys (CSEs), photovoltaic modules (PVs), various - storage considered: ✔(yes), (✔) (simplified assumptions)

Figure 3.1: Literature review of studies estimating energy saving potentials in various industrial sectors

3.2 State-of-the-art

This section depicts the state-of-the-art of the industrial energy saving potentials from three perspectives: technology specific studies, sector-specific studies and cross-sectoral studies.

3.2.1 Technology specific studies ()

Heat pumps (HPs) Most heat pump studies present top-down () approaches in which the industrial sectors are listed by the temperature levels of their thermal requirements and matched with heat pump operating temperature ranges. Heat pumps are mainly modelled based on the Carnot factor. Further, heat pump integration is often considered from the **hot side** only, meaning that the condenser of the heat pump is considered as a hot utility for the process. This has been applied by Wolf et al. (2014) who estimated the global energetic potential and resulting fuel savings for heat pumps in various German industrial sectors based on the temperature ranges of the thermal requirements. Similarly, Brückner et al. (2015) calculated the economic potential for compression and absorption heat pumps and heat transformers in different industrial sectors (in Europe) based on estimated heat demands. Meyers et al. (2018) compared the heat production through heat pumps and solar thermal systems, but without considering integration with the industrial process. Finally, Arpagaus et al. (2018) presented an approximate potential estimation across low- and medium-temperature sectors and focused their analysis mainly on high-temperature heat pumpings (HPs) and possible working fluids.

Few studies presented bottom-up () approaches considering the hot and cold sides of a heat pump, such as Seck et al. (2013) who presented a TIMES model to estimate the potential for heat pumping in the French food and beverage sector. Wilk et al. (2017) analyzed different industrial processes and the benefits related to installation of a (detailed) heat pump (model) based on flowsheeting software. Wallerand et al. (2019) derived an approach for pre-feasibility analysis of energy saving measures based on optimization of detailed heat pump features for the dairy industry.

Organic Ranking Cycles (ORC) A variety of studies concerning organic Rankine cycle (ORC) modelling and design of different architectures has been reported Lecompte et al. (2015). However, only one study was identified which addressed potential estimation of ORC integration in energy intensive industries in the EU, presented by Campana et al. (2013) using a top-down approach.

3.2.2 Sector-specific studies ()

Studies considered in this section focus on energy savings in one specific sector. Worrell et al. (2000) estimated the potential for energy efficiency improvements in the cement industry through heat recovery and equipment upgrading with aid of an energy conservation supply curve, while Neelis et al. (2007) focused on the petrochemical industry and energy saving potentials by analysis of the main system losses. Fleiter et al. (2012) presented energy saving measures in the pulp and paper industry, with additional focus on heat recovery and equipment upgrading.

3.2.3 Cross-sectoral studies ()

Studies in this section focus on the energy savings across various industrial sectors and technologies. Bonilla et al. (1997) presented an extensive analysis of the industrial waste heat recovery potential separated by material flows in the Basque country considering a variety of technologies and options for adjacent utilization of the recovered waste heat. The applied method to identify overall potentials and the data sources are not consistently reported, but the study provides a comprehensive starting point. Worrell et al. (2008) and Worrell et al. (2003) performed a literature review of energy saving scenarios in the main industrial sectors based on estimations from the IPCC, BPT, and expert judgement, not focusing particularly on any of the technologies discussed above. Similarly, Lu et al. (2013) analyzed energy saving potentials in the energy intensive sectors in Taiwan by reviewing the BAT and BPT compared to current consumption values. Bunse et al. (2011) approached the topic differently, by identifying the gaps in research that need to be overcome to achieve wider acceptance and implementation of energy efficiency measures in the industry. A more global approach was presented by Prognos AG who analyzed the entire Swiss energy system and estimated the potential energy savings across the entire industry but without transparently explaining the methodology or assumptions. Codina Gironès et al. (2015) presented a similar approach with more consistent data reporting where the industrial sector is treated as one entity with energy saving potentials based on user input.

3.3 Contribution

The main findings from the literature review are reported below in four points.

1. Most articles focus on saving potentials either in one specific industrial sector or one specific technology, neglecting potential interactions between technologies.

2. Most studies present top-down approaches, state-of-the-art methods such as process integration and pinch analysis (PA) are almost neglected, which can have the effect of energetically non-beneficial technology placement.

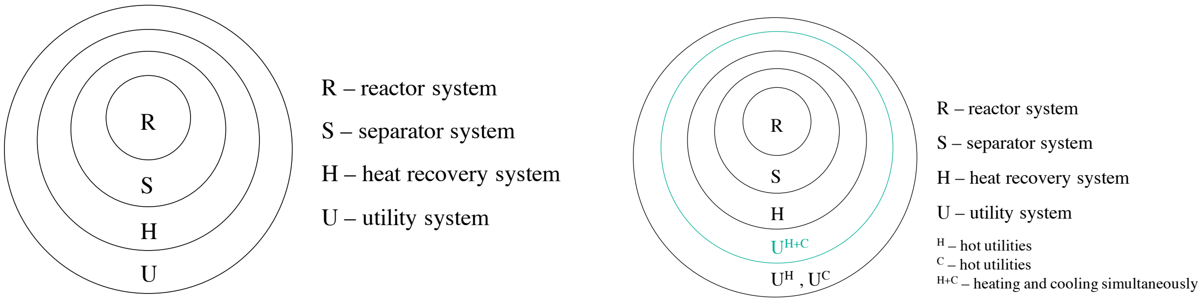
3. Comprehensive methodologies for consistent analysis with state-of-the-art methods of energy saving potentials by various technologies across the main industrial sectors are lacking.

This study foremost addresses points (2) by presenting a method which provides consistent analysis of the energy saving potentials from HP integration across the industrial sectors. The method relies on pinch analysis and sector representative process thermal profiles to assure adequate technology integration, respecting the double impact of heat pumps.

3.4 Methodology

3.4.1 Process synthesis approach

From a chemical engineering perspective, improving or designing an industrial processes should follow a hierarchical order as shown in the onion diagram in Fig. 3.2A. Since chemical reactions (R) are at the core of most industrial processes, they form the basis of the process and its energy requirements.



(A) Traditional process synthesis approach

(B) Proposed process synthesis approach

Figure 3.2: Onion diagram of process synthesis approach, adapted from Kemp (2011)

The next step is the separation system (S) which also generates energy requirements to ensure proper separation of feed and product flows. Once these sub-processes have been investigated or designed, the standard approach addresses internal heat recovery (H) and the utility system (U). The best utility integration is generally achieved by investigating all potential utility technologies simultaneously to incorporate possible interactions. This is typically a complex task which can be treated using optimization algorithms such as mathematical programming as first described in the context of industrial processes by Papoulias and Grossmann (1983).

Since expertise in mathematical programming is not wide-spread, an alternative process synthesis approach is proposed in this work to reach 'good' utility integration solutions without the need for optimization algorithms. As shown in Fig.3.2B, this approach differentiates between thermal utilities which provide only heating (boiler, co-generation engine) or cooling (cooling water) and utilities which provide heating and cooling to the process simultaneously. Those are treated in an advanced step and include compression and absorption heat pumps and heat transformers[1]. There are two reasons why those utilities are treated in a particular manner: (1) having both a cooling and heating functions means that they interact with the entire hot and cold utility system, which is simplified by treating them in an advanced step; (2) providing heating and cooling to the process provides a way to convert excess process heat into useful heat, which is why their application results in improved system energy efficiency and therefore making them a priority for process improvement measures.

3.4.2 Thermal profiles: heat recovery and utility integration

The heat recovery and utility integration steps from the process synthesis approach can be treated by pinch analysis and the resulting **thermal profiles**. Pinch analysis is a powerful method developed by Linnhoff and Flower (1978) and Linnhoff et al. (1979) and thoroughly described by Kemp (2011) that allows identification of the true thermodynamic requirements of an industrial process. This is achieved by mapping all process heating and cooling requirements and deriving the maximum internal heat recovery potential. The results are a set of (hot and cold) thermal profiles which can be represented graphically by hot and cold Composite Curve (CC) and the Grand Composite Curve(GCC). The

[1] ORC, steam networks and other type of co-generation systems are not considered as utilities with a heating and a cooling capacity (even though strictly speaking this is untrue) since their primary function is either heating (co-generation) or cooling (ORC)

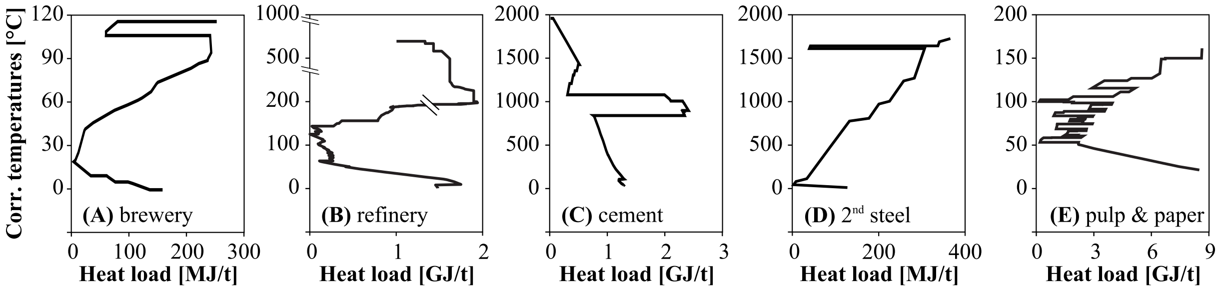


Figure 3.3: **GCC** of various industrial processes. **(A)** brewery reproduced from (r.f.) Klemeš (2013), Fig. 27.12, **(B)** refinery r.f. Bungener (2016), Fig. 5.15, **(C)** cement production r.f. Bendig, Fig. 2.17, **(D)** secondary steel making r.f. Stadler (2014), Fig. 8.4, **(E)** sulphite pulping r.f. Périn-Levasseur (2009), Fig. 3.5.

GCC represents the net thermodynamic requirements of the process (maximizing heat recovery) and their temperature levels. The GCC of several industrial processes across various sectors are shown in the Fig.3.3, highlighting the diversity of industrial thermal energy requirements. Since the thermal profiles and GCC reveal the true thermodynamic needs of the process, they also indicate how the thermal utilities should be integrated to achieve maximum benefits[2]. One important indicator which needs to be identified in pinch analysis is the so-called **pinch point**, which is located at the intersection between the GCC and the temperature axis. It separates the process into a section above the pinch, which exhibits a net heating requirement, and below it, which represents a net cooling requirement.

Abiding by the principles of pinch analysis, a set of **pinch rules** can be defined according to Kemp (2011) (1-3) for the placement of hot and cold utilities, and according to Townsend and Linnhoff (1983a,b) (4,5) for the placement of HP and ORC:

1. Hot utilities should be placed above the pinch point (temperature)
2. Cold utilities should be placed below the pinch point
3. No heat exchange should occur across the pinch point
4. Heat pumps should be placed across the pinch point
5. Heat engines should be placed either entirely above or entirely below the pinch point

In this study, the thermal profiles of the most relevant industrial sectors and processes were considered and utility integration was conducted consistently according to the defined process synthesis approach and the pinch rules. The thermal profiles were generated based on published studies and literature data, references for which can be found in the results section of each process and in the supplementary materials. In general, each sector was represented by the main energy consuming processes within that sector.

[2] The thermal profiles can be seen as the idealized version of the real requirements of the process. The reason for considering these and not the current requirements to study the integration of new thermal utilities aims at future potential heat recovery measures: Following the thermal profiles will ensure that if future actions increase internal heat recovery in the process, the utility temperature levels and sizes will still be beneficial to the process.

3.4.3 Utility integration

The utility integration is suggested to be conducted according to the indications found in the previous two sections. Therefore, the thermal profiles are individually inspected before quantitatively determining the integration potential. As discussed in section 3.4.1, several approaches can be applied for consistent utility integration which agrees with the principles of process integration and pinch analysis. Those can be generally distinguished into two groups: conceptual approaches are based on a graphical analysis of the process composite curves for identifying the best utility composition and sizing; and mathematical approaches perform this task relying (computer aided) mathematical algorithms. Following the process synthesis approach, the first measure to be considered is heat pump integration. To be more specific, a flowchart for heuristic utility integration based on a composite curve is presented in Wallerand et al. (2020). This work focuses on steps 0.) and 1.) considering pinch analysis and heat pump integration.

3.4.4 Heat pumps

A concise mathematical approach for optimal heat pump integration has been presented by Wallerand et al. and in deliverables D1, D2, and D3 of SCCER EIP. This approach is applied in this study to identify temperature levels, fluids, heat pump features and compressor types. For this task, the grand composite curve is used as a reference for identifying the temperature levels of interest.

3.4.5 Solution generation

Initial screening, using the MILP (mixed integer linear programming) subprocess from Wallerand et al. and not the full approach, was applied to the heat pumps integration method. For each process thermal profile, 1,000 samples were created with various combinations of two compressor types (12 different as presented in D3) and two fluid types (14 fluids). In each run of the MILP, the total annualized cost are minimized. Subsequently, the best solutions in terms of CO2-equivalent emissions and the total annualized cost for each compressor type combination were identified and further treated.

3.4.6 Extrapolation to the sector

As the processes modelled in this study do not cover the entirety of their respective industrial sectors in terms of energy consumption and CO2 equivalent emissions, two saving scenarios were developed at the sector level:

- **Optimistic**: Assumption that the modelled process thermal profiles are representative of the entire sector and thus the weighted average of CO2 emission saving potentials of the investigated processes can be extrapolated to the entire sector.
- **Conservative**: Assuming that within each sector, the savings potentials can be realised only for the processes investigated in this report. All other processes in the sector are assumed to have zero reduction potential.

This work focuses on thermodynamic and technical potentials for energy saving measures. The integration of HPs was studied to demonstrate the savings potential offered by this technology. Upgrading existing equipment (e.g. to higher efficiency, or modern technology) was not considered. The calculated energy requirements are therefore linked to current process operation with current equipment (pumps, mills, compressors, etc.). Analysis of electrical (and thermal) saving potentials linked to upgrading of equipment as performed by Zuberi and Patel, for example, was not considered.

3.4.7 Key assumptions

The list of key assumptions is stated below.

- BAU: The business as usual (BAU) energy consumption is based either on data from industrial plants, or on current consumption values documented e.g. in the BREFs, which is indicated for each investigated process.
- Two energy saving potentials were investigated for each of the considered processes and the sum of these improvements is thus reported as the total potential.
  - ΔMER: The maximum energy recovery in the process (MER) considers heat recovery (HR) in the process and, thereby, allows derivation of the minimum thermodynamic energy requirements.
  - Δdirect: In addition to the MER, two direct efficiency improvement measures are investigated: organic Rankine cycles (ORCs) and heat pumping (HP). HP can reduce the hot utility consumption at the cost of increasing the electricity requirements while ORCs can decrease the net electricity requirement without changing the hot utility requirements by producing electricity from waste heat.
  - Δtotal: the total reduction potential of each process is derived by adding the ΔMER to the Δdirect: Δtotal = ΔMER + Δdirect
- Expert opinion (EO): For each investigated processes an indicator for the feasibility of the realization of the calculated potentials was introduced. This qualitative indicator relies on an expert opinion to judge safety constraints, heat transfer restrictions and the maturity of required equipment.
  - ★☆☆: Technically very challenging realization (due to safety, technical maturity)
  - ★★☆: Technically feasible, but with challenges to face
  - ★★★: Technically possible, even economically feasible
- Additionally, as the processes modeled in this study do not cover the entirety of their respective industrial sectors in terms of energy consumption, three saving scenarios were developed at the sector level:
  - **Optimistic**: Assumption that the weighted average of saving potentials of the modeled processes can be extrapolated to the entire sector.
  - **Technical**: Based on the *optimistic* potential, though reduced accounting for the *expert opinion (EO)*.
  - **Conservative**: Assuming that within the sector the **Technical** savings potentials can be realized only for the processes investigated in this report. All other processes in the sector are assumed to have zero saving potential.

- This work focuses on thermodynamic and technical potentials for energy saving measures. As an example, the integration of HPs and ORCs was studied to demonstrate the savings potential offered by these technologies. However, the upgrading existing equipment (e.g. to higher efficiency, or modern technology) was not accounted for. The calculated energy requirements are therefore linked to the current process operation with current equipment (pumps, mills, compressors, etc.). Analysis of electrical (and thermal) saving potentials linked to upgrading of equipment as performed, for example, by Zuberi and Patel was, hence, not considered.

3.5 Results and discussion

Table 3.1 summarizes the results of the combined research activity between SCCER EIP and JASM by IPESE. The table is sorted by the main energy intensive sectors and shows the current specific electricity (EL) and fuel primary energy (used for heating) (FUEL) consumption of various processes (BAU), the CH annual production rates, and by calculation, the total annual energy consumption (CH). It further shows the estimated saving potentials and their feasibility in form of the expert opinion (EO). Each sector also has several specificities which are briefly introduced here to aid the comprehension of the performed work and the results.

3.5.1 Food and beverage

The food and beverage sector covers 14% of the Swiss electricity and primary thermal energy consumption. The food and beverage sector is diverse and thus difficult to represent completely. Several representative processes were identified which consume approximately 35% and 10% of the thermal and electrical energy of the sector, respectively. The ΔMER saving potentials range between 30-70% (thermal), and the direct efficiency measures can reach between 20-30% additional (thermal) reductions, mainly with effective integration of heat pumping for heating and cooling of the process. The expert judgment of the potential of these energy reduction measures is generally favorable. The processes are mainly based on water-based fluids below 100 °C. The main obstacles for such integration in the food and beverage sector are safety, contamination regulations, and batch operations (such as in breweries) which require storage between batches.

3.5.2 Pulp & paper

In Switzerland, there are two main processes for making pulp, the sulphite process and mechanical processes European Commission. The production volumes reveal, however, that the most dominant part in the CH pulp and paper industry is paper-making, since most producers use old paper as raw material Verband der Schweizerischen Zellstoff-, Papier- und Kartonindustrie. This is also in agreement with the energy consumption data, which are dominated by the paper-making process covering about 96% and 68% of the thermal and electrical energy of the sector, respectively.

Energy consumption reduction was analyzed mainly considering HR, indicating fuel savings up to 30%. These ΔMER results are reasonable compared to BAU ranges, since the energy carriers are mostly water and steam which are good heat recovery media according to expert opinion.

Table 3.1: Swiss industrial energy saving potentials toward the ES2050 goal. Synthesis of research activity carried out by the IPESE group.

Sector / process specifications				Swiss (CH) annual consumption					Spec. consumpt.		Saving potential				
									BAU[00]		ΔMER[01]		Δdirect[02]		EO[03]
Sector	SFOE No.	Process	NOGA	Electricity (EL)		FUEL		Flow rate	EL	FUEL	EL	FUEL	EL	FUEL	
				TJ/y (% Total SFOE)		TJ/y (% Total SFOE)		t/y	MJ/t	MJ/t	$\%_{red}$	$\%_{red}$	$\Delta\%_{red}$	$\Delta\%_{red}$	☆☆☆
	1	Dairy	10.1501,3,.52	303[05]	(4%[04])	524[05]	(6%[04])	2,021,983[10]	150[11]	259[12]	3%[12]	29%[12]	-8[13]	30%[13]	★★⯪[14]
	1	Cheese	10.1502	132[05]	(2%[04])	869[05]	(10%[04])	188,806[10]	698[15]	4600[16]	20%[17]	30%[17]	-42%[18]	22%[18]	★★⯪[14]
Food & beverage	1	Brewery	11.05	90[05]	(1%[04])	310[05]	(3%[04])	346,364[19]	260[1a]	894[1b]	15%[1c]	72%[1c]	-3%[1d]	18%[1d]	★★⯪[1e]
	1	Sugar	10.81	235[05]	(3%[04])	1,436[05]	(16%[04])	233,600[1f]	1,008[1g]	6,145[1g]	N/A[1h]	N/A[1h]	45%[1i]	42%[1i]	★★★[1k]
	1	Total (calc.)[06]	10, 11	761	(10%[04])	3138	(35%[04])				9% (8%)[0a]	37 (30%)[0a]	3% (5%)[0a]	32% (30%)[0a]	
	1	**Total (SFOE)**[07]	10, 11, 12	7,381	(14%[08])	9,108	(14%[08])				1%[0b]	6%[0b]	1%[0b]	10%[0b]	
	3	Pulping (sulphite)	17.11	(*) 142[05]	(3%[04])	(*) 647[05]	(11%[04])	53,942[30]	2,640[31]	12,000[31]	N/A	28%[32]	N/A		★★⯪[33]
Pulp & paper	3	Pulping (thermo-mechanical)	17.11	(*) 481[05]	(9%[04])	(*) 449[05]	(8%[04])	80,914[34]	5,950[31]	5,550[31]	N/A	62%[32]	N/A		★★⯪[33]
	3	Paper-making	17.12	3,471[05]	(68%[04])	5,606[05]	(96%[04])	1,042,355[30]	3,330[35]	5,378[35]	N/A	28%[32]	N/A		★★⯪[33]
	3	Total (calc.)[06]	17.1	(*) 3,471[05]	(68%[04])	(*) 5,606[05]	(96%[04])				-	28% (22%)[0c]	-	-	
	3	**Total (SFOE)**[07]	17, 18	5,097	(10%[08])	5,857	(9%[08])				-	21%[0b]	-	-	
	4	Refining	19.2, 20	555[05]	(6%[04])	11,605[05]	(62%[04])	3,626,640[40]	153[41]	3,200[41]	0%[42]	69%[42]	N/A		★★☆[43]
Chemicals	4	Total (calc.)[06]	19.2, 20	555[05]	(6%[04])	11,605[05]	(62%[04])				0% (0%)[0a]	62% (41%)[0a]	-		
	4	**Total(SFOE)**[07]	19, 20, 21	8,668	(17%[08])	18,799	(30%[08])				0%[0b]	25%[0b]	-		
	5	Dry process	23.51	1390[05]	(83%[04])	13,514[05]	(114%[04])	3,860,000[50]	360[51]	3,500[51]	0%[52]	0%[52]	50%[53]	0%[53]	★☆☆[54]
Cement	5	Total (calc.)[06]	23.51	1390[05]	(83%[04])	13,514[05]	(114%[04])				0% (0%)[0a]	0% (0%)[0a]	50% (15%)[0a]	0% (0%)[0a]	
	5	**Total (SFOE)**[07]	23.32, 23.51, 23.52	1,684	(3%[08])	11,896	(19%[08])				0%[0b]	0%[0b]	12%[0b]	0%[0b]	
	7	EAF	24.10	3,691[05]	(71%[04])	3,093[05]	(85%[04])	1,400,000[70]	2,637[71]	2,209[71]	0%[72]	87%[72]	23%[73]	0%[73]	⯪☆☆[74]
Steel	7	Total (calc.)[06]	24.10	3,691[05]	(71%[04])	3,093[05]	(85%[04])				0% (0%)[0a]	87% (9%)[0a]	23% (2%)[0a]	0% (0%)[0a]	
	7	**Total (SFOE)**[07]	24.10,.20,.31-34,.51-52	4,049	(8%[08])	3,589	(6%[08])				0%[0b]	8%[0b]	2%[0b]	0%[0b]	
	8	Aluminum (2nd)	24.42	63[05]	(5%[04])	532[05]	(35%[04])	140,000[80]	450[81]	3,800[81]	0%[82]	52%[82]	N/A		⯪☆☆[83]
Non-ferrous metals	8	Total (calc.)[06]	24.42	63[05]	(5%[04])	532[05]	(35%[04])				0% (0%)[0a]	52% (5%)[0a]	-		
	8	**Total (SFOE)**[07]	24.41-.46	1,300	(3%[08])	1,533	(2%[08])				0%	2%[0b]	-		
	1,3-5,7,8	Total (calc.)[0c]	10,11,17,19, 20,23,24	10,491	(37%)	38,051	(75%)				1% (1%)[0f]	36% (19%)[0f]	27% (6%)[0f]	5% (5%)[0f]	
Sector total	1,3-5,7,8	Total (SFOE)[0d]	10-12,17-23,24	28,179	(55%)	50,782	(81%)								
	1-12	**Total (SFOE)**[0e]	10-33	**51,535**	(100%)	**62,795**	(100%)				0%[0g]	11%[0g]	1%[0g]	1%[0g]	

(*) Theoretical thermal and electrical requirements for pulp production are not considered in the main energy requirements. Since pulping is self-sufficient due to black liquor boiler, in reality, there is mainly an electricity output. In the calculated total, these values are neglected.
00 Public Business as usual (BAU): [MJ/ton product] Based public data from current consumption e.g. in the European reference documents for best available techniquess (BREFs), which is indicated in each case.
01 *Calculated value* from the flow rate and business as usual (BAU).
02 *Calculated* percentage of *SFOE sector total*[04].
03 *Calculated sector total* from investigated processes.
04 *SFOE sector total* 2018 energy consumption data from Swiss Federal Office of Energy (SFOE) Bundesamt für Energie BFE (b).
05 *Calculated* percentage of *SFOE industry total*.
06 *Calculated* values and percentage of the processes covered in this table.
07 *Calculated* values and percentage of the sector totals (SFOE) covered in this table.
08 *SFOE industry total* energy consumption data from SFOE Bundesamt für Energie BFE (b).

3.5.3 Chemicals

Though an extremely diverse sector, the chemical industry can be classified into refining and production of fine chemicals. The *refinery* category comprises products derived from crude oil such as gasoline, diesel, LPG, etc. Organic fine chemicals include pharmaceuticals and vitamins, crop protection, colors etc. Due to the diversity of the production and limited public data of organic fine chemicals and the market dominance in terms of thermal requirements (62%) of the refineries, the latter were the only process considered in this sector. Energy consumption reduction was analyzed mainly considering HR, indicating fuel saving up to 62%. These ΔMER results reveal some challenges compared to the BAU ranges, due to safety, quality limits, and lack of process interruptions in which retrofits can occur. Distillation processes drive the temperature requirements of the process and require temperatures which are too high for currently-available heat pumping technologies and do not provide sufficient exergy for significant ORC exploitation. Potential for improvements in Swiss refining could be realised by integration with other processes such as biomass-derived fuel synthesis; however, these potentials are not explored in the context of this report.

3.5.4 Cement

In Europe, the dry process is the most common for cement making; in Switzerland in particular, it is the only used process. The specific energy consumption, together with the estimated CH production volume, amounts to a value which even slightly above the sector total energy consumption estimation provided by SFOE (114%); this is attributed to the generalized input data (clinker blending, specific energy consumption) used to represent the process in Switzerland. Additionally, modernized and more efficient equipment may be used within Switzerland, thus contributing to the discrepancy between the consumption extrapolated from benchmark processes and the values reported by the SFOE. The highly integrated nature of clinker production, where the hot utility cannot be extricated from the process, led to the conclusion that the ΔMER case does not provide thermodynamic improvements (under the key assumptions taken in Section 3.4.7). One study reported the possibility of reducing the thermodynamic requirement of cement production by 29% Bendig but was based on a complete re-design of the process and therefore was not included in the context of this study. The second case (Δdirect) assumes the use of waste heat for electricity production with an ORC generating up to 50% potential reductions of the electricity consumption. Though not considered in the analysis, it should be noted that cement production provides waste incineration services with valuable products and that the fuel mixture heavily influences the cost and emissions profile from the process. Up to 90% of the fuel can be derived from waste and therefore should be considered within the larger context of the energy and material system in future work.

3.5.5 Steel, non-ferrous metals

The metals sector is categorized by the SFOE in two groups: ferrous metals and non-ferrous metals. The total calculated energy consumption based on the assumed specific energy consumption and production volumes covers up to 85% (thermal) of the steel sector reported by the SFOE, which is sufficiently precise using generalized data. In Switzerland, steel production from scrap is the only process in operation and thus analysis and improvements which can be realized in the blast furnace/basic oxygen furnace route were not considered. This limited the analysis compared to other publications in the field of steel sector energy consumption.

For the non-ferrous sector, secondary aluminum production was used as the sector representative, being the biggest consumer. It covers approximately 35% (thermal) of the sector SFOE total, missing noble metal, lead, zinc, tin, and copper production.

For both ferrous and non-ferrous metals, heat recovery (ΔMER) options were analyzed, generating potentially drastic reductions in the thermal energy consumption up to 87% and 52% for steel and aluminum, respectively. For steel, integration of an ORC was also considered, reducing the electricity requirement by 23%. The expert judgment, however, indicates great challenges in the technical realization of such energy reduction measures, since heat recovery and transfer from hot metals to cold metals or to an ORC are at early research stages and there are also strong motivational barriers.

3.5.6 Summary

A summary of the total sector reduction potentials toward the goals of ES2050 presented in the previous section is provided in Table 3.2 by resuming the research conducted by IPESE group. Two energy saving cases (ΔMER and Δdirect) were analyzed, which are further described in Section 3.4.7, and the total savings were derived (Δtotal).

In Table 3.2, it can be observed that electricity saving potentials were mainly identified in the food and beverage sector. These potentials stem from a reduction in the refrigeration needs due to heat recovery (HR). In sectors with high process temperatures (e.g. steel and cement), electricity saving potentials can additionally be identified through ORC installations.

Three scenarios (optimistic, technical, conservative) were defined to account for the technical feasibility of the realization of the derived potentials and extrapolation to processes which have not been studied. These are further described in Section 3.4.7. Disregarding expert judgment and assuming that the analyzed processes are representatives of their sectors (*optimistic*), overall fuel thermal energy savings of up to 42% could potentially be reached. However, this number is reduced to 24% considering expert judgment (*technical*), and to 12% considering only the known processes and their savings including the factor for expert opinion (*conservative*). Values in Table 3.2 which are marked as being not applicable (N/A) reflect that the analysis has not been completed for the context of this report. The processes may be evaluated for further improvement in the future.

The range of saving potential compares well to the previous study in SCCER-EIP by Industrial Process and Energy Systems Engineering (IPESE). However, in this analysis, the focus was placed on a more distinctive analysis, highlighting the trade-off between electricity and thermal energy savings between different measures and the influence of expert judgment on the results.

Table 3.2: Total sector energy reduction potentials.

Sector	ΔMER						Δdirect						**Δtotal**					
	Electricity			Primary thermal			Electricity			Primary thermal			Electricity			Primary thermal		
	Opt.	Techn.	Cons.	Opt.	Techn.	Cons.	Opt.	Techn.	Cons.	Opt.	Techn.	Cons.	Opt.	Techn.	Cons.	Opt.	Techn.	Cons.
Food & beverage (1)	9%	8%	1%	37%	30%	10%	3%	5%	1%	32%	30%	10%	12%	13%	1%	69%	59%	16%
Pulp & paper (3)		N/A		28%	22%	21%		N/A			N/A			N/A		28%	22%	21%
Chemicals (4)		0%		69%	41%	25%		N/A			N/A			0%		69%	41%	25%
Cement (5)		0%			0%		50%	15%	12%		0%		50%	15%	12%		0%	
Steel (7)		0%		87%	9%	8%	23%	2%	2%		0%		23%	2%	2%	87%	9%	8%
Non-ferrous metals (8)		0%		52%	5%	2%		N/A			N/A			N/A		52%	5%	2%
Total industry (weighted)	1%	1%	0%	36%	19%	11%	27%	6%	1%	5%	5%	1%	28%	7%	1%	42%	24%	12%

Data available at https://data.sccer-jasm.ch/swiss-ind-improvement/

In summary, the five industries consuming the most energy in Switzerland had previously been identified and energy profiles were generated from publicly available data to allow the potential of the methods to be explored and disseminated. These data were updated, verified, consolidated and re-processed for the updated report which also uses recent data on sectoral energy consumption as published by the SFOE.

The potentials for reducing industrial energy consumption in Switzerland were calculated under optimistic, moderate and conservative assumptions to yield total thermal fuel savings of 42%, 24% and 12%, respectively. Total electricity savings were found to be 28%, 7% and 1%, respectively.

Further reduction potentials could be realized by integrating other technologies and exploring symbiosis opportunities between various processes and production plants. Applying the energy efficiency methods developed and measures identified for the industries considered in this report, and extended to the recommendations of further process integration and symbioses, would transform Swiss industry and undoubtedly create some of the most novel, efficient and innovative production processes.

Chapter 4

Conclusions

The Swiss energy and climate policies as described earlier clearly show that some efforts have already been made to accelerate EE improvement in the Swiss industry, however, further measures will need to be taken to achieve the ES 2050 targets, as has been shown also by top-down analysis using the Odyssee methodology (Bhadbhade et al., 2020). To exploit the estimated sector- and system-specific potentials, all the stakeholders must engage further in developing a concrete strategy that allows clean energy transition and CO2 mitigation without compromising the competitiveness of the industrial sectors. The strategy requires an integrated approach to optimize industrial energy systems and to reduce final energy demand and CO2 emissions where it is most efficient and cost-effective. We also recommend the Swiss industry to work in close collaboration with government policymakers to ensure that the future policies are more effective, and the targets are achievable, yet sufficiently ambitious. Industrial energy consumers must prioritize the implementation of best available technologies, heat integration, process optimization, and energy management systems (as these possess the highest economic potential) with the support of the government through policy measures such as target agreements, an energy levy, and development of energy performance standards for different types of equipment.

From the policy perspective, it is concluded that the Swiss government needs to improve the CO2 pricing mechanism and to provide better incentives for EE improvement in the industry. For example, the CO2 price for large energy consumers (e.g. cement industries) in the Swiss ETS is very low and is unlikely to serve as a meaningful incentive for energy efficiency in energy-intensive industries. While the future linkage to the EU ETS may lead to some increase in CO2 price levels, it remains to be seen how this market will develop in the future and whether it will trigger, contrary to the past, significant additional investment. There is presumably a need for more policies and financial mechanisms, covering both tailor-made measures for discrete industrial sectors or further promoting energy-efficient cross-cutting technologies across all industrial sectors. The results further show that there are substantial amounts of excess heat available which require planning and strategies to facilitate regional heat integration and reduction in thermal energy demand and the corresponding CO2 impact. Although carbon capture has not been studied for all industrial sectors, its consideration for the cement sector shows that the measure has a very large potential, calling for dedicated efforts from all stakeholders.

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