Decarbonizing Swiss industrial sectors by process integration, electrification, and traditional energy efficiency measures

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Abstract

The Paris Agreement 2015 is a historic initiative taken by the global community to fight against climate change and steer the world towards clean energy transition and deep decarbonization. Switzerland has developed the Energy Strategy 2050 which is a strategic policy package for realizing the transition towards a low-carbon economy. Energy efficiency (EE) is one of the strategy's major pillars. Although several steps to incentivize EE improvement in the industry have been taken in Switzerland, the size of the EE gap that currently exists in its high-value-added manufacturing sector is largely unknown majorly due to the complexity of the sectors and lack of data. Moreover, since industrial technologies are advancing rapidly, it is essential to evaluate the potential wide-scale application of emerging technologies and best practices in the industry. To this end, this study explores the techno-economic final energy and CO_2 saving potentials in the Swiss industry in the short-to-medium term at the level of individual sectors and for cross-cutting technologies. In total, the studied EE measures correspond to an economic final energy savings potential of 23 PJ per year (19 % of the final energy demand in the Swiss industry; potential dominated by process heat integration measures) if total investments are considered. If additionality is accounted for, then the total economic potential increases from 19 % to 21 %. The estimated thermal energy savings, in addition to the savings from measures exclusively related to CO_2 mitigation, are equivalent to a potential CO_2 abatement of 1.3 Mt CO_2 p.a. (34 % of the fossil-based CO_2 inventory in Swiss industry). This work is a contribution to the so far limited international literature on economic EE measures applicable to high value-added and heterogeneous manufacturing sectors and is meant to inform decision-makers.

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 2018): 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 2012). Table 1 presents an overview of the indicative targets of ES 2050 for the Swiss industry relative to the year 2010. The first set of meas-

Table 1. Key indicative targets of the Swiss Energy Strategy 2050 for the industry sector.

Category	Scenario	Indicative target vs. 2010 level
Final energy demand	PM	-4 % by 2020
		-18 % by 2035
		-26 % by 2050
	NEP	-7 % by 2020
		-27 % by 2035
		-39 % by 2050
Electricity demand	PM	-5 % by 2020
		-17 % by 2035
		-23 % by 2050
	NEP	-4 % by 2020
		-23 % by 2035
		-34 % by 2050

ures (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 % compared to the levels in 1990 (IEA 2018).

Switzerland imposed a CO_2 levy of CHF 12/t CO_2 on fossil fuels in 2008 which was increased to CHF 36 /t CO_2 in 2010, CHF 60/t CO_2 in 2014, and CHF 84/t CO_2 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 CO_2 levy of CHF 96/t CO_2 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 CO_2 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 2018). To get reimbursed for the CO_2 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 CO_2 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 2018). 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 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 (energy savings compared to the previous year) (IEA 2018). 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 2018).

Large consumers (>50 enterprises) with an installed rated thermal input of 20 MW or more are exempt from the CO_2 levy and they must participate in the Swiss Emissions Trading Scheme (ETS). Under the Swiss ETS, it is foreseen to reduce the cap of CO_2 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 electricity 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; IEA 2018).

It should be noted that the focus of target agreements is on the implementation of cost-effective EE and CO_2 saving measures (i.e. having a payback time of <4 years for process-specific measures and <8 years for measures related to infrastructure). Additionally, 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) (ProKilowatt n.d.).

Switzerland is an interesting study case not only due to its ambitious energy and climate policy but also because of the specific features of the industry sector. Switzerland has made the transition from traditional manufacturing (e.g. production of primary aluminum, railway locomotives, etc.) to a knowledge-based economy. The country is highly specialized in precision engineering with many applications and is currently one of the world leaders in high-value products including specialty chemicals and pharmaceuticals (SWI 2017). Supported by the legal, financial, and political context, many hi-tech and successful companies in life sciences, biotechnology, microelectronics, etc. are operating in Switzerland (Switzerland Global Enterprise n.d.-a). The Swiss chemical and pharmaceutical industries produce over 30,000 products, nearly 90 % of which are specialties. The global annual demand for some of these

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 CO_2 taxation. The required political majorities were not achieved for the analogous application to energy use.

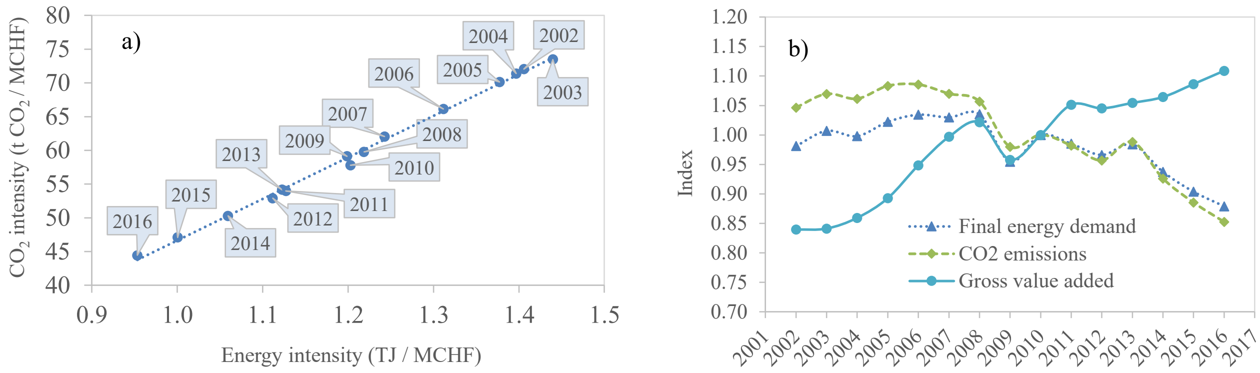

Figure 1. Development of a) CO_2 and energy intensities and b) final energy demand, CO_2 emissions and gross value added in the Swiss industry sector from 2002 to 2016 (2010 = 1) (BFE 2017; FSO 2017; FOEN 2018).

specialty chemicals is even below a few metric tonnes. In 2011, 98 % of the Swiss chemical and pharmaceutical sector's total sales, i.e. CHF 149 billion, were outside Switzerland (Scienceindustries 2012). Swiss watch-making industry is another example of high value-added manufacturing. Switzerland is the third-largest exporter of wristwatches (exported over 20 million timepieces of worth CHF 18.8 billion in 2017) after China and Hong Kong. The average price of a Swiss exported watch is over CHF 800 (luxury watches) which is 200 and 30 times more than the average price of a Chinese and a Hong Kong watch respectively (Federation of the Swiss Watch Industry 2018). Furthermore, almost 80 % of the products manufactured by the Swiss mechanical, electrical, and metal (MEM) industry are exported, of which the EU has a share of 60 %. Switzerland is also among the top ten largest exporters of machinery in the world (Deloitte 2014; Switzerland Global Enterprise n.d.-b). Although Switzerland, as a manufacturer of high-value products, has strengthened its economy in recent years, many of its traditional manufacturers like cement and paper industries face difficulties due to global competition. In addition to the increasing regulations, sales fluctuations due to globalized markets and high labor costs are some of the key challenges which the industries are facing today (Deloitte 2014).

Figure 1a presents the CO_2 intensities[2] and energy intensities of the Swiss industry sector from 2002 to 2016. Across the entire period, the figure shows an almost linear relationship between the two indicators, displaying a decreasing trend. While both intensities have decreased over time, CO_2 intensity has decreased at a faster rate (3.4 % p.a.) than energy intensity (2.7 % p.a.) probably due to fossil fuel substitution as one of the reasons. Figure 1b displays indices for final energy demand, CO_2 emissions, and GVA for the Swiss industry for the same period. The figure shows that the GVA in the Swiss industry increased by almost 2 % p.a. during the period from 2002 to 2016. In the same period, final energy demand and CO_2 emissions decreased by 0.8 % p.a. and 1.5 % p.a. respectively. The reduction in energy demand and the emissions could be the consequence of a decrease in production volume or due to an increase in energy efficiency or both. The rate of increase in GVA is found to be higher than the rate of decrease in the other two variables, which may be explained by the increasing share of high-value-added products in the overall product portfolio of Swiss industry. However, it is difficult to pinpoint the exact reasons, especially when there are no statistics on production volume available at the federal level.

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 its ambitious energy and CO_2 laws and its hi-tech industry sector, Switzerland can serve as an ideal candidate for analyzing policy and research-driven EE improvement opportunities in a high value-added manufacturing sector.

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. electric motor systems, excess heat recovery, 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 article is part of a doctoral thesis (Zuberi 2019) and only the highlights of the detailed study are presented here.

2. Process related CO_2 emissions are not included. Indirect CO_2 emissions due to electricity consumption are included. All GHG emissions as the result of fossil fuel combustion are expressed in terms of CO_2-equivalent.

Key energy efficiency measures for industry

This section presents an overview of the technical EE measures that are analyzed in this study and/or applicable in the Swiss industrial sectors and systems.

PROCESS HEAT INTEGRATION

Process heating contributes significantly to the total production costs in the manufacturing industry (Iowa State University 2005). Two major components of process heating systems are a heat generator (e.g. boiler) that produces and supplies heat and a heat exchanger that transfers heat from the source to the product. A significant amount of heat leaves the system via exhausts, product and waste streams, and through the walls of heat generation and transfer devices (Iowa State University 2005). This heat, also called excess heat, leaving the system is a potential resource that can be studied by applying different techniques such as pinch analysis to maximize heat recovery through intra-plant integration (Bendig et al. 2013; ICF 2015). In this study, EE measures related to heat integration are classified into different categories. While classifying measures, a clear distinction was made between low/medium/high-temperature heat from multiple sources including utility systems and unit processes.

Excess heat sources at different temperatures imply different theoretical efficiency limits depending on end-use applications (US DOE 2008). For example, excess heat at medium-to-high temperatures (>150 °C) can be utilized for steam generation, which can either be used for process heating directly or for driving a heat engine (gas or steam turbine) to generate electricity. Another example, during the operation of compressors, approx. 80–93 % of the electricity used is transformed into the heat of which 50–90 % can be recovered by a properly designed heat recovery unit (LBNL 2006). This recovered heat can be used in multiple applications depending on the required temperature levels. The temperature is often too low (30–90 °C) to allow heat utilization in the core industrial processes. Low-temperature excess heat from motor systems and other potential sources is typically used for space heating of industrial buildings as well as heating of process fluids, boiler water, and/or air pre-heating.

Pinch analysis is a well-established tool for identifying opportunities for heat integration in continuous processes. However, the potential for application to semi-continuous and batch processes is often overlooked. Since batch processes exhibit time-dependent behavior including inherent variability in the process heating and cooling requirements, heat integration has not been a priority in such processes due to the indispensable flexibility, low volume, and high-quality demands (Kemp 2011). However, research on process heat integration of the batch process has progressed in recent times by optimizing not only direct heat recovery using a heat exchanger network but also for indirect heat recovery using thermal energy storage (Becker 2012; Krummenacher 2002; Olsen et al. 2017). This study analyzes both direct and indirect heat recovery measures.

PROCESS ELECTRIFICATION BY HEAT PUMP INTEGRATION

Electrification of the process industry is one of the key possible transition pathways to contribute to sustainable energy supply assuming that carbon-neutral electricity will be widely accessible to the industry in the future (ISPT 2017). Electrification is very promising for industrial heat applications, as it enables process heat to be supplied efficiently and enables the utilization of renewable electricity as well as renewable heat sources like low-temperature excess heat, geothermal or ambient heat via heat pumps (Schüwer and Schneider 2018). Electrically driven high-temperature heat pumps (HTHP) can be used in several industrial processes to upgrade low-temperature heat to process heat (Arpagaus et al. 2018).

Some of the examples of heat pump integration are its application in the dairy industry. For pasteurization, a dairy product needs to be heated above 70 °C and is later cooled down. The product temperature thus varies from the cold before pasteurization to hot during pasteurization and returns to cold again after pasteurization. In most pasteurization processes heat exchange between the cold and hot product flows is rather common. The hot product after pasteurization is used to pre-heat the cold product before pasteurization. For additional heating and cooling, steam injection and chilled water are typically used. In such a case, a heat pump could be an ideal solution to extract heat from the product that needs to be cooled and supply this heat at a higher temperature to the product that needs to reach pasteurization temperature (Industrial Heat Pumps n.d.).

As shown by Wallerand et al. (2018a), concentrated milk production is another dairy process that lends itself to heat pumping due to repeated heating and cooling with a small temperature lift. In such a case of a "sharp pinch point", single-stage heat pumps are typically a suitable choice whereas multi-stage heat pumps or other heat pump types (e.g., Zeotropic mixture cycles based on latent heat release of refrigerant mixtures or Inverse Brayton cycle heat pumps based on sensible heat release of refrigerants) may be chosen in the case of a larger temperature lift and a "smooth" temperature/heat load profile (Wallerand et al. 2018b; Wallerand et al. 2018c). Optimal heat pump integration is a complex problem because of the large number of optimization parameters including the type of refrigerants, the number of stages, evaporator and condenser design, etc., hence calling for a superstructure-based computational approach. It was shown that its application for combined heat integration with heat pumping in a dairy allowed to identify a saving potential of around 60 % of natural gas, notably at lower total annual costs (Wallerand et al. 2018a). Apart from the food sector, combined heat integration with heat pumping can also offer very attractive opportunities in the chemical industry, e.g. in distillation, where energy savings in the order of 40 % for bioethanol (Hokkaido Bioethanol Co. Ltd. 2015) to 60 % for methanol (Meito Sangyo Co., Ltd. 2017) have been reported in Japan, in the latter case with a payback time of only 2.5 years.

Heat pumps also have applications in refrigeration systems. Food and pharmaceutical industries produce products that are needed to be cooled or frozen before transport and/or consumption. On the other hand, hot water is needed for the process and cleaning purposes. Excess heat from a refrigeration system has a temperature of approx. 25–30 °C. With the help of a heat pump, excess heat from the condensing side of the refrigeration system can be used to heat water to temperatures up to 80 °C. The heat pump could further increase the pressure of the refrigerant from the refrigeration system to achieve high condensation temperatures (Industrial Heat Pumps n.d.). In more complex systems of the chemical industry, optimized refrigerant choice, multistage compression, and improved design have been demonstrated to offer very significant energy savings (e.g. 30 % less electricity) at clearly lower capital expenditure and lower annual cost (e.g. ethylene separation train according to (Wallerand 2018a)).

Low-pressure steam generation by evaporating water under low pressure at temperatures below 100 °C provided by heat pumps (or excess heat directly) is another example of process electrification. The vapor compressors are then used to reach the required steam pressure at a later stage. For example, at about 0.1 bar, water evaporates at 50 °C and the steam can be compressed in three stages to increase its pressure to about 3 bar. Bless et al. (2017) assessed this technique in detail and concluded that such a system is far more energy-efficient than conventional fossil fuel boilers for steam generation. The additional energy used for vapor recompression is substantially lower than the avoided heat of evaporation. Figure 2 demonstrates the schematics of steam generation by low-pressure evaporation and vapor recompression (LPE&VC) using two different types of intercooling for multi-stage compression, i.e. a) by water injection (WI) cooling and b) by heat exchanger (HX) cooling. In the WI cooling case, cold water is injected into the superheated steam to obtain a fluid at the desired conditions (see Figure 2a). In the HX cooling case, heat exchangers are used in series that transfer heat from the superheated steam to the fresh inlet water (see Figure 2b). For heating, two types of configurations are used, i.e. a) the low-temperature excess heat (30–80 °C) is either used directly for water evaporation or b) excess heat (30–50 °C) is first upgraded with a heat pump. The latter option may be convenient in the case of excess heat availability at varying temperature levels. As a third option (not shown in Figure 2) is a high-temperature heat pump (HTHP), which directly converts the low-temperature excess heat (30–80 °C) to steam (Arpagaus 2017; Arpagaus et al. 2017). If the low-temperature excess heat is directly used for steam generation, then the industry would only pay for the electricity demand by the vapor compressors (and the pump in the case of WI cooling). In case the temperature of the excess heat is upgraded by a heat pump (HP), electricity consumed by the HP would also be added in the total electricity consumption resulting in higher expenditure.

In this study, the short-to-medium term (10–15 years) potential of process electrification via heat pumps has also been investigated for industrial applications however, the manner of heat pump integration differs depending on the concrete case. The actual implementation in processes also needs to consider the technology readiness level of heat pumps as a function of the temperature level. Moreover, the EE gains of heat pump integration depend on the temperature lift, and the benefits of decarbonization are directly related to the carbon intensity of grid electricity.

TRADITIONAL EE MEASURES

The traditional EE measures that are analyzed in this study include efficient electric motor systems (sub-measure categories include replacement of inefficient motors, leak repairs and pressure adjustments for compressed air systems, installation of variable frequency drives for pumps and fans, etc.), replacement of inefficient process equipment (such as boilers, burners, column trays, and packings), improved reactor designs (for the chemical industry), improved operation of cement rotary kilns, process control and monitoring, insulation, and energy management and optimization, etc. The exhaustive list of EE measures analyzed in this study and their detailed descriptions can be found in (Zuberi 2019).

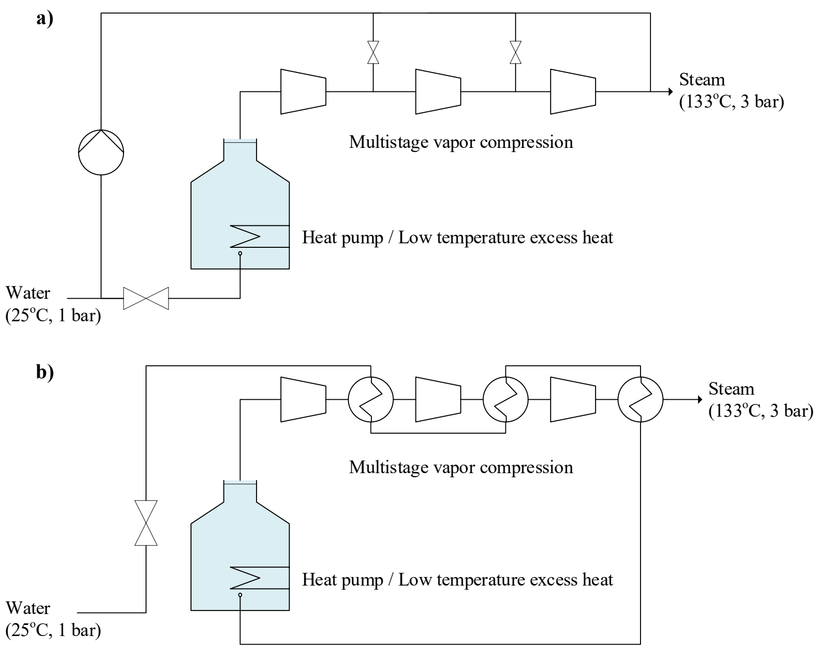

Figure 2. Schematics of steam generation by low-pressure evaporation and vapor recompression (LPE&VC) using a) water injection cooling or b) heat exchanger cooling; adopted from (Zuberi et al. 2018).

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 (as shown in Figure 3). The curve shows the specific cost $C_{spec,y}$ of each measure 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 additionality; 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:

$$C_{spec,y} = \frac{ANF \times NPV_y}{ES_y} \quad (1)$$

$$ANF = \frac{(1+r)^L \times r}{(1+r)^L - 1} \quad (2)$$

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 (>3,500 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. The techno-economic potential for excess heat recovery in Swiss industrial process heating systems is estimated through exergy and energy analysis.

Results and discussion

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 % (Eichhammer et al. 2009)). 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 23 % respectively. Table 2 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.

The next end-use application is process heat which is responsible for more than half of the Swiss industry sector's total final

Table 2. Annual technical and economic potential electricity savings in the industrial EMDS in different countries (values for all countries except for Switzerland are taken from (UNIDO 2010)).

Country	Base year	Potential electricity savings (% of 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

energy demand. A considerable share of this energy could theoretically be delivered by excess heat recovery. The mean exergy and energy efficiencies of the Swiss overall industry sector are estimated at 27 % and 61 % respectively. The specific costs and payback periods of excess heat recovery by conventional and emerging technologies are further investigated in this study, as well as the overall costs of sector-wide excess heat recovery. The total economic potential of recoverable excess heat is estimated at 14 PJ per year, which corresponds to about 12 % and 24 % of the total final energy and process heat demand of the Swiss industry in 2016 respectively. The economic potential corresponds to about 750 kt CO_2 per year or 20 % of the total CO_2 emissions due to fossil fuels used for process heat in 2016. In contrast, the economic potential amounts to only 5 % to 10 % if payback times of 3–4 years are assumed. Table 3 compares the excess heat recovery potential in Switzerland with the results estimated for other countries. According to this comparison, the heat recovery potential in the Swiss industry is less than for other developed countries. The reason may be the relatively high energy efficiency in the Swiss industry (61 %) because the Swiss industrial processes are more based on low-to-medium temperature process heat as Switzerland has a limited manufacturing of bulk chemicals and no primary production such as steel and aluminum. It was also found that the long payback times of heat recovery measures and a high share of low-quality and low-volume heat streams are the most important barriers to increased excess heat recovery in the Swiss industry. Besides, independent of EnAW data analysis, 30 % to 40 % of the Swiss industrial steam demand could be cost-effectively provided from excess heat recovery, if all excess heat available at temperatures <80 °C is utilized for steam production using LPE&VC and/or high-temperature heat pumps.

Table 4 presents the contribution of the measure clusters (e.g. all individual measures applicable to compared 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 4 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. For process heat, the results show that high-temperature heat recovery for steam generation is among the most effective. In other words, although the high-temperature excess heat is not available in large quantities in the Swiss industry sector, exploiting this rather small untapped potential could lead to high impact and large energy and cost savings. Process heat integration between product streams from different unit processes within an individual plant also has great potential (i.e. 33 %) however, its implementation is rather demanding due to technical challenges of diverse nature and risks. Load preheating (heat exchange between input and output streams of the same process) and heat recovery from utility systems are rather easy to implement.

Heat pumps for process electrification are still in an early stage of diffusion mainly because of the high investment cost

Table 3. Excess heat recovery potentials in the industry sector estimated for different countries.

Study	Country	Heat recovery potential (% of final energy)
US DOE (2008)	US	20–50
Enova (2009)	Norway	25
Pehnt et al. (2010)	Germany	18
Berthou and Bory (2012)	France	29
This study	Switzerland	12

Table 4. 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)
Electric motor-driven systems		
1	Rest of the motor systems	40 %
2	Pump systems	30 %
3	Fan systems	20 %
4	Compressed air systems	11 %
	Total	100 %
Excess heat recovery (HR)		
1	HR for steam generation	36 %
2	Process heat integration	33 %
3	Load preheating (15%), HR from motor systems (7%), Condensate recovery (2%)	24 %
4	Heat pumps	4 %
5	HR for district heating	4 %
	Total	100 %

and electricity prices. In general, the industry sector also lacks operational experience, but this challenge could be overcome quickly if heat pumps become economically attractive. Despite several potential low-temperature heat applications in the Swiss industry, the actual implementation of heat pumps to date has been low and the short-to-medium term potential estimated on this basis is very limited. However, the approach in this study may lead to a significant underestimation of the real potential of heat pumps, as the examples from the dairy sector and the chemical industry indicate. HTHP technology is gradually becoming available on the global market as well, as shown in a review by Arpagaus et al. (2018). More than 26 electric HTHPs from 15 manufacturers with supply temperatures above 90 °C, in some cases even above 120 °C and up to 165 °C have been identified.

Heat integration in batch processes, especially in multi-product and multi-path batch processes, is a very complex problem given their time-dependent behavior and need for thermal energy storage. In continuation of the macro-level analysis as discussed above, a micro-level case study on heat integration of complex batch processes in a medium-sized European textile plant using pinch analysis was also conducted. The approach followed in the case study is to first optimize for direct heat recovery and to subsequently optimize the residual process requirements through indirect heat recovery using thermal energy storage, see Zuberi (2019) – Chap. 6 for detailed descriptions of the process and the methodology. The maximum direct heat recovery potential in the plant during different time slices of a day is estimated at 21 % to 43 %. The recommended heat exchanger network from a practical standpoint ensures a maximum direct heat recovery potential of almost 85 GJ per day (25 % of the daily heat energy consumption of the process). Moreover, a closed intermediate loop and heat storage system with four temperature levels is recommended with a maximum indirect heat recovery potential of almost 17 GJ per day (5 % of the daily heat energy consumption of the process). In total, the direct and indirect heat recovery potentials correspond to a total CO_2 abatement of 5.75 tonnes per day (29 % of total CO_2 emissions per day). The proposed heat exchanger and storage designs are found to be economically viable, with payback times ranging from 1–5 years. The approach applied for this case study demonstrates an effective way of identifying practical solutions for heat integration in complex batch processes. Furthermore, the total energy saving potential (i.e. 25 % (direct) + 5 % (indirect) = 30 %) at the micro-level (or plant-level) somewhat indicates that the potential estimated at the macro-level (i.e. 24 % of the process heat demand) for the overall Swiss industry is realistic and plausible.

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 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 CO_2 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 CO_2 emissions in 2016. As presented in Table 5, 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 CO_2 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 CO_2 abatement is estimated at 14 % and 13 % of the sector's final energy consumption and CO_2 emissions in 2014 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 CO_2 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 CO_2 levy, carbon capture becomes economically viable which could drastically reduce sector-specific CO_2 emissions.

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 3. All the sector-wide EE measures including those related to EMDS and heat integration, 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 CO_2 mitigation (e.g. fuel substitution) is equivalent to a CO_2 emission reduction potential of 1.3 Mt CO_2 p.a. (34 % of the fossil-based CO_2 emissions in Swiss industry in 2017). These estimates are based on today's projections of future energy and CO_2 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 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, refer to Table 6. Moreover, implementation of EE measures applicable to other industrial sectors (such as food, paper and metals sectors, etc.; not analyzed in this study) could contribute to achieving the overall targets.

Conclusions and recommendations

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). The sector-specific EE measures and the cross-cutting technologies assessed in this study correspond to total economic potential final energy savings and CO_2 abatement of 21 % and 34 % of the Swiss industrial final energy demand and the fossil-based CO_2 inventory in Swiss industry in 2017 respectively. To exploit this potential, all the stakeholders must engage further in developing a concrete strategy that allows clean energy transition and CO_2 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 CO_2 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

Table 5. 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 (heat)	38 %
3	Process control	5 %
4	Raw material preparation	4 %
	Total	100 %

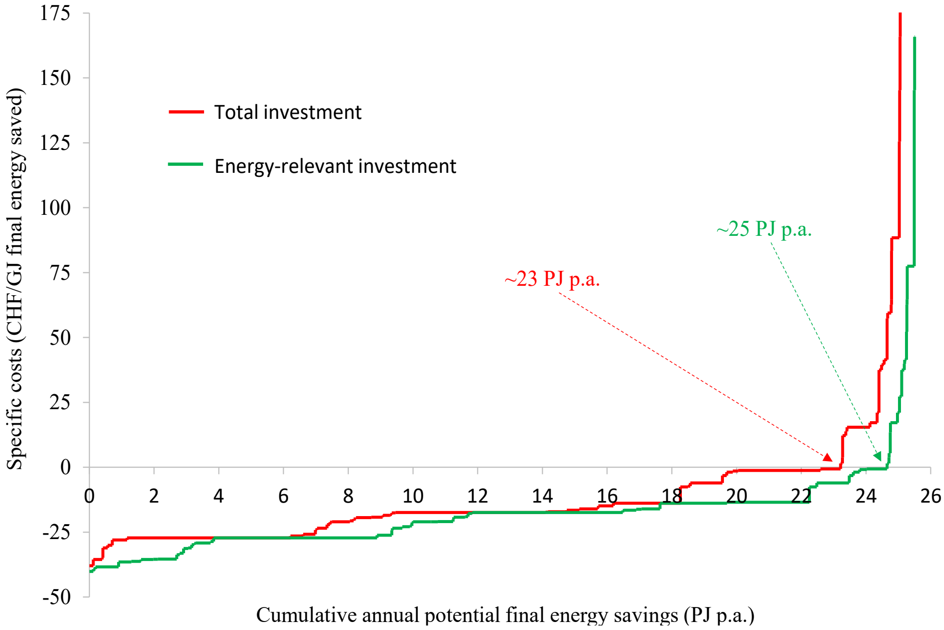

Figure 3. Energy efficiency cost curve for the overall Swiss industry (64 measures in total).

Table 6. Contribution of the assessed EE measures to ES 2050 indicative targets.

	Indicative target		Overall potential	Economic potential	Contribution to indicative targets	
	2035	2050			2035	2050
Final energy savings						
Total investment	18 %	26 %	22 %	19 %	57 %	39 %
Energy relevant investment				21 %	82 %	56 %
Electricity savings						
Total investment	17 %	23 %	17 %	13 %	53 %	41 %
Energy relevant investment				15 %	65 %	50 %

Note: This table does not report fuel savings because the Swiss ES 2050 formulated policy targets only for final energy and electricity. For the same reason, the table does not include results for individual industrial sectors.

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 CO_2 pricing mechanism and to provide better incentives for EE improvement in the industry. For example, the CO_2 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 CO_2 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 and 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 CO_2 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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