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ABSTRACT

The food and beverage (F&B) production is the second most energy consuming industry sector, consuming up to 14% (22 PJ) of the Swiss industry's total final energy (TFE) and emitting 14% (0.6 million tonnes) of the industry's total CO₂. In the period from 2004 to 2017, the sector's energy consumption has been increasing at a faster rate than production, which implies deterioration of energy efficiency (EE). Against the background of implicit EE improvement target of 26% between 2017 and 2050 under the assumption of constant future production, this study investigates the options of realizing the target. The process-related (e.g. excluding building envelope) technical EE improvement potential of the Swiss F&B sector is estimated at 25% whereas the currently commercially available energy-efficient technologies can potentially reduce 18% of the sector's current TFE. The cost-effective potential estimated by means of a bottom-up approach (cost curves) ranges from 14% to 16% for energy efficiency and 18% to 21% for CO₂. Results of sensitivity analysis indicate that low energy prices may act as a barrier for the adoption of cross-cutting technologies. A qualitative analysis of emerging technologies presented along with the detailed cost-effectiveness analysis of commercially available energy-efficient technologies can help to overcome the techno-economic barriers and achieve the implicit EE improvement target of the Swiss F&B sector.

1. Introduction

1.1. Background

Industry is the largest energy-consuming sector and one of the largest CO₂ emitting sectors in the world (37% and 19% respectively; International Energy Agency (IEA) 2017, European Environmental Agency (EEA) 2016)). Therefore, the improvement of energy efficiency (EE) of the industrial processes as well as the implementation of more renewables has been established as key pathways for the abatement of energy-related GHG emissions (Swiss Federal Office of Energy (SFOE) 2018, Energy Efficiency Directive 2018). Within industry, sectors producing bulk products such as basic metals, cement and pulp and paper (also referred to as homogenous industrial sectors) are generally considered more energy-intensive than intermediate or consumer products (also referred to as heterogeneous industrial sectors) (Worrell et al., 2001). As a result, myriads of studies have been published analyzing the EE potentials for homogenous industrial sectors (some notable studies being Worrell et al., 2010, Brunke and Blesl, 2014, Jibran S. Zuberi and Patel, 2017, Morrow et al., 2014). However, in some countries where high value-added products dominate the industry product portfolio (e.g. Switzerland, Denmark, Ireland), heterogeneous industrial sectors (e.g. chemicals and pharma, food and beverage, electrical and electronic device production, fabricated metal products) represent a larger share of the total final energy (TFE) consumption in industry. As a consequence of the effort to move towards higher value-added products and in line with the objective to decouple energy consumption and economic growth, the share of heterogeneous sectors is likely to grow. Heterogeneous industrial sectors were responsible for approximately 40% of the industry's global 2017 TFE consumption. The food and beverage (F&B) sector represents 21% share of the global TFE consumption of the heterogeneous industrial sectors (and 7% of the overall industry's TFE demand) (International Energy Agency (IEA) 2017). Contrary to homogenous industry sectors, the sector-wide EE potentials are rarely analyzed for heterogeneous industrial sectors. Existing literature in the domain of energy efficiency of F&B manufacturing deals with i) the energy consumption and monitoring energy efficiency trends of specific product groups, e.g. dairy (Andrea et al., 2006, Moejes and van Boxtel, 2017, Brush et al., 2011, Briam et al.,...
2015, Xu et al., 2009), meat (Ramirez et al., 2006), baking (Masanet et al., 2012), manufacturing of vegetable and fruit juice (Masanet et al., 2008) ii) potentials of EE measures in manufacturing of particular product group (Worrell et al., 2010), iii) potential of specific technologies for improving EE F&B manufacturing (Seck et al., 2013, Fluch et al., 2017, Lung et al., 2020) and iv) estimations of EE improvement and CO2 emission reduction potentials for F&B manufacturing for different geographical scopes (Meyers et al., 2016, Compton et al., 2018). The present work discusses the commercially available and emerging energy efficiency measures (EEMs) as well as their cost-effectiveness and their CO2 abatement potential for the Swiss F&B sector (The Organisation for Economic Co-operation and Development (OECD) 2020).

1.2. Current energy consumption and economic structure of Swiss F&B sector

Heterogeneous industrial sectors are responsible for approximately 65% of the industry's current (2017) TFE demand in Switzerland (Swiss Federal Office of Energy (SFOE) 2018). The F&B sector is responsible for 14% (22 PJ) of TFE demand of the Swiss industry (Swiss Federal Office of Energy (SFOE) 2018) and for 18.5% of the Swiss heterogeneous sectors (values for 2017). From 2004 to 2017, the TFE consumption and the physical output (measured in production index proxy (PIP); (Federal Statistical Office (FSO) 2018)) of the Swiss F&B sector grew on average by 1.5% and 1.3% p.a. respectively (see Fig. 1). Growth of TFE consumption outpacing the physical production implies a slight...

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**Nomenclature and abbreviations**

| A | Age of equipment at the time of replacement (years) |
| ANF | Annuity factor |
| \( B_y \) | Annual benefits of the measure (CHF) |
| \( C_{vl,y} \) | Levelized costs of energy saved by measure y (CHF/GJ) |
| \( C_{vl,CO2,y} \) | Levelized cost of CO2 abatement by measure y (CHF/t CO2) |
| \( C_A \) | Annual potential CO2 savings by measure y (tCO2/year) |
| CFt | Annual cash flow for the year t (CHF) |
| CHF | Swiss Franc |
| \( d_i \) | Remaining diffusion of measure (or category) y (%) |
| DR | Discount rate |
| \( E_{Ci} \) | Total final energy demand of production step i in particular establishment x (GJ/yr) |
| \( E_{c0,t} \) and \( E_{c,t} \) | Energy consumption of the sector for base year t0 and year t respectively (TJ) |
| EE | Energy efficiency |
| EECC | Energy efficiency cost curve |
| EF | Weighted Emission factor of energy carrier (tCO2/GJ) |
| EMDS | Electric motor driven system |
| ES2050 | Energy strategy 2050 |
| \( ES_y \) | Annual potential final energy savings by measure y (GJ/yr) |
| \( ESL_y \) | Energy savings for year t by entire sector (TJ) |
| \( E_{c,EnAW} \) | Energy consumption of the establishment e implementing the measure y reported in EnAW database (GJ/yr) |
| \( E_{s,EnAW} \) or \( FS_{s,EnAW} \) | Electricity or Fuel savings reported for the measure x implemented to the end-use i in the particular establishment (GJ/t of product) |
| F&B | Food and Beverage |
| GHG | Greenhouse gases |
| Iy \( \text{and} \) Iy-1 | Physical EE index for year t and t-1 |
| Iy | Initial investment (CHF) |
| Iay | Annualized initial investment cost (CHF) |
| \( I_{y,ref,CH} \) | Energy-relevant investment cost (CHF) |
| \( I_y \) | Lifetime of measure y (years) |
| NEP | New energy policy |
| NPVy | Net present value of measure y (CHF) |
| O&My | Annual operations and maintenance costs of measure y (CHF) |
| \( P_e \) | Price of electricity (CHF/GJ) |
| \( P_f \) | Price of fuel (CHF/GJ) |
| \( PCO2 \) | CO2 price in year t (CHF/t CO2) |
| Prj | Annual physical production of sub-sector i for the base year (i = Dairy, Chocolate, sugar, meat etc.) (t/a) |
| r | Real discount rate |
| RESy | Relative energy savings for the measure (or category) y implemented in production step or end-use i (i = pasteurization, evaporation, drying, EMDS, refrigeration etc.) (in %) |
| RFG | Refrigeration system |
| \( SEC_{j,CH} \) | Specific energy consumption for product group j in Switzerland (energy consumed/tonne of product or feed) |
| \( SEC_{j,REF} \) | Reference SEC based on best available technique for product group j (energy consumed /tonne of product or feed) |
| SpESy or SpFSy | Specific electricity or fuel savings for measure y (energy saved/tonne of product) |
| SP | Simple payback period |
| SS | Steam system |
| TFE | Total final energy |
| \( Tpj \) | Technical potential (%) |
| t | year |
| WHR | Waste heat recovery |

Fig. 1. (a) Trends of TFE consumption and CO2 emissions for the Swiss F&B sector (2004-2017) (b) Trends of energy efficiency, CO2 and production for the Swiss F&B sector (2004-2017) (Source TFE – SFOE, 2018 (Swiss Federal Office of Energy (SFOE) 2018); CO2 emissions- EEA, 2018 (European Environmental Agency (EEA) 2018); Production index – FSO, 2018[26]).
deterioration in the physical energy efficiency (energy consumed/physical output; index value representing the change over time according to ODEX approach) of the Swiss F&B sector (at 0.2% p.a.). However, it is evident from the analysis of the EnAW database, the companies included in the database improved their EE at an average annual rate of 1.6% during 2009 and 2016 (Jibrán S. Zuberi et al., 2019). During the same period, technology modifications related core processes (see section 2.1 for definition) and waste heat recovery were most instrumental in achieving the EE improvement, contributing 59% and 19% of overall energy savings respectively. In contrast to energy consumption, CO₂ emission grew at a lower rate than the physical production resulting in reduction of CO₂ emission intensity (t CO₂/t of production) by 0.6% per year from 2004 to 2017 (see Fig. 2(b)). Swiss F&B manufacturing is responsible for generating 12% of the total value added of the industry sector (only second to chemical and pharmaceutical manufacturing). Whereas, the economic output of Swiss F&B manufacturing, measured in value-added, rose on average by 2.1% p.a. from 2004 to 2017.

While fossil fuels are still fulfilling the majority share of sector’s energy requirements (56% of the sector’s 2017 TFE demand), electricity consumption grew over-proportionally in the Swiss F&B sector at an average annual rate of 3.5% (as opposed to 0.4% p.a. growth of fossil fuel consumption). The share of electricity in the sector’s energy mix consequently rose from 34% in 2002 to 44% in 2017 (Fig. 2(b)). Given the very low CO₂ emission factor of Swiss electricity (Swissgrid), this rise in the share of electricity along with the efficiency improvement in fuel consumption reported in the EnAW database can partially explain the aforementioned reduction of CO₂ emissions intensity despite the rise in overall TFE consumption and physical activity.

Swiss dairy products are the largest energy consuming product group (20% of Swiss F&B industrial sector’s TFE), followed by meat production and preservation (13% of Swiss F&B industrial sector’s TFE; Fig. 3(a)). In contrast, bakery products generate the largest share of value added (22%) in the Swiss F&B industrial sector, closely followed by dairy products (20%) (Eurostat 2018).

According to the New Energy Policy (NEP) scenario (target scenario) prepared by PROGNOS AG for the Swiss Federal Office of Energy (SFOE), the TFE of the Swiss F&B sector will decrease by 60% between 2017 and 2050 and its share in the industry’s TFE demand will decrease by 5 percentage points (i.e.from 12% in 2017 to 7% in 2050) (PROGNOS 2012). The overall reduction of TFE demand will be a combination of EE improvement, change in structure and change in the activity. The NEP scenario furthermore projects the CO₂ emissions of the Swiss industry sector to decrease by 60% by 2050 and the F&B sector, currently responsible for 14% of CO₂ emissions (European Environmental Agency (EEA) 2018), is expected to play an important role in achieving the aforementioned target. More than 95% of enterprises in the Swiss F&B sector can be categorized as small and medium sized enterprises (SMEs) (based on STATENT database (FSO) 2013), i.e. companies with less than 250 employees (SME 2005). In total, 73% of all employees of this sector work in SMEs, while the remainder (27%) is employed by large companies. On average, Swiss F&B companies spend 4% of their gross value added on energy (Eurostat 2018), (Swiss Federal Office of Energy (SFOE) 2018). Diffusion of energy efficiency measures in an industrial sector with a large share of SMEs is especially challenging because of the fragmented nature of the industry, lack of available EE expertise and low financial flexibility which translates to higher hurdle rates in the context of investment decisions for implementing EE improvement projects (Meyers et al., 2016, Fleiter et al., 2011).

1.3. Aims and objective

Given this background, the main objectives of this work are:

- Establish the current levels of specific energy consumption (SEC) and levels of technical EE improvement potentials for major product groups within the Swiss F&B sector.
- Identify the EE measures which are cost-effective for the Swiss F&B sector and estimate the overall cost-effective EE improvement and associated CO₂ abatement potential.

This analysis is conducted with the aim to help SMEs in the Swiss F&B sector overcome the barriers of lack of information by providing a database of cost-effective options for EE improvement along with the techno-economic data. Estimation of current SEC levels, technical potential and its comparison with cost-effective EE improvement potential will help to put the available EE improvement potential in perspective and create more awareness about the energy efficiency gap. (Swiss Federal Office of Environment (FOEN) 2020)

The paper is structured as follows. Section 2 consists of a detailed explanation of the categorization of the techno-economic data and the methodology used in the present analysis. Section 3 presents the estimations of current SEC levels, the energy efficiency potentials and the detailed results of the cost effectiveness analysis of the base case along with the discussion of the sensitivity of the cost-effective potential for various exogenous parameters of the analysis. Section 4 concludes the paper.

2. Methodology

2.1. Data categorization

The techno-economic data used for the present analysis of industrial

![Fig. 2. (a) Trends of electricity and fuel consumption for the Swiss F&B sector (2002-2017) (b) Share of electricity and fuel in the energy mix of the Swiss F&B sector (2002-2017) (Source: SFOE, 2018 (Swiss Federal Office of Energy (SFOE) 2018)).](image)
sector-wide EE improvement potentials was provided by EnAW. The EnAW database contains techno-economic data such as annual energy savings achieved (GJ/year), annual energy consumption (GJ/year) of each participating establishment (confidential and anonymized), initial investment and energy-related investment cost (see section 2.7) for already implemented EEMs (CHF) in the Swiss industry sectors along with a brief implementation description; for the period of 2000-2016. The establishments included in the EnAW database are categorized according to the 4-digit NOGA classification, thus allowing to estimate the shares of individual product groups (e.g. dairy products) in the sector’s TFE consumption within the EnAW database. Absolute values of TFE demand of individual product groups at the national level were then estimated by multiplying these shares of individual product groups (in terms of energy use within the EnAW database) to the sector’s TFE demand according to national statistics. However, it should be noted that, establishments covered in the EnAW database represent 71% of Swiss F&B sector’s TFE demand according to the value in national statistics (estimated based on (Swiss National Office for Agriculture (ENAW) 2018, Swiss Federal Office of Agriculture (SFOE) 2018)) and given the lack of a better data source, the EnAW database was assumed to represent the TFE demand structure of the entire F&B sector. For individual product groups, for which production statistics were publicly available (e.g. tonnes of poultry, cheese, sugar etc. produced; see Table 1 in the results section), the specific energy consumption (SEC; GJ/tonne of product) was then estimated. Absolute TFE demand for each individual production steps (e.g. pasteurization in cheese production, centrifugal separation in sugar, vacuum drying in chocolate production) was then estimated with the help of generic energy profiles available from the literature for particular types of establishments (e.g. dairy producing fluid milk/cheese/powdered milk, chocolate manufacturing, sugar factory etc.) (Brush et al., 2011, European Integrated Pollution Prevention Control Bureau (IPPC) 2018, Office of Energy Consumption and Efficiency statistics (EIA) 2017). Using the aforementioned production data, SEC values of individual production steps were established which were then used for the estimation of technical EE improvement potentials and diffusion estimates (see sections 2.5 and 2.4. Fig. 4 (a) graphically represents approach explained above.

Based on the end-uses (i.e. core production processes, refrigeration (RFG), steam systems (SS), electric motor driven systems (EMDS)), the EEMs from the EnAW database are classified in two broad categories: 1) Core process-specific technologies and 2) cross-cutting technologies. The core process-specific EEMs include very specific technology modifications such as reverse osmosis instead of multiple effect evaporators for evaporation stage in the dairies; or the use of vacuum pumps instead of steam ejectors for drying of cocoa. Cross-cutting EEMs, on the other hand, consist of technical and organizational (e.g. good housekeeping, scheduling etc.) measures concerning ubiquitous technologies such as motors, pumps (EMDS), HVAC, the refrigeration system and waste heat recovery from compressors/flue gas/condensate (see Table 2). The related techno-economic data for aforementioned EEMs is estimated as an average of the techno-economic data each measure reported in the EnAW database under that particular sub-category (for example see Appendix A; Eq. 2). For the core process-specific EEMs category, however, each EEM represents the techno-economic data reported as an individual measure in the EnAW database and not averaged across the EEMs reported in EnAW database.

2.2. Specific and relative energy saving potential

For some EEMs, the specific electricity and fuel savings potential (SpESx, and SpFSy; GJ savings/t of product) can be estimated based on the physical production data provided in the descriptions accompanying the techno-economic data reported in EnAW database. However, for the majority of EEMs, we lack information on the physical production and therefore, the energy saving potential (electricity and fuel) is estimated as the percentage relative to the energy consumption of that particular production step (in case of core process-specific measures) or end-use (in case of EMDS, RFG, SS and waste heat recovery (WHR)) (see Eq. 1). Fig. 4 (b) represents this approach in a graphical manner.

\[
RES_x = \frac{(ES_{x,EnAW} + FS_{x,EnAW})}{EC_{i,e}}
\]  

(1)

Where,

- \(RES_x\) = Relative energy savings for the measure x implemented in production step or end-use i (i = pasteurization, evaporation, drying, EMDS, refrigeration etc.) (in %)
- \(ES_{x,EnAW}\) and \(FS_{x,EnAW}\) = Electricity and fuel savings of measure y reported in EnAW database for the particular establishment (GJ)
- \(EC_{i,e}\) = Final Energy consumption of production step or end-use i of the particular establishment (estimated based on EnAW database; see Appendix A for details) (GJ)

Values of \(RES_x\) are then averaged across all the individual measures (x) reported in EnAW database for end-use i in order to estimate the representative value of relative energy savings for the EEM category y (RESy) which was then used to estimate the cost-effectiveness.

\[
RES_y = \frac{\sum_{x=1}^{n} RES_x}{n}
\]

(2)

Where,
Table 1. Technical potential of selected product groups for Swiss F&B sector along with current SEC levels.

| Product group [source of production data] | Current Swiss SEC_{CH} (GJ/t) | Reference SEC_{app} (GJ/t) | Source of reference SEC (reference country) | Technical EE potential | Percentage TFE demand |
|------------------------------------------|-------------------------------|----------------------------|---------------------------------------------|------------------------|-----------------------|
| Other foods1                             | N/A                           | N/A                        | N/A                                         | 5%                     | 39%                   |
| Processing and preserving meat2          | 2.56                          | 1.8                        | (European Integrated Pollution Prevention Control Bureau (IPPC) 2018) (EU) | 30%                    | 13%                   |
| Cheese (ODYSSEE-MURE 2018)2             | 1.16                          | 0.36                       | (Brush et al., 2011, European Integrated Pollution Prevention Control Bureau (IPPC) 2018) (U.S, EU)4 | 69%                    | 10%                   |
| Fresh Dairy (milk production) (ODYSSEE-MURE 2018) | 2.01                          | 0.84³                      | (Brush et al., 2011, European Integrated Pollution Prevention Control Bureau (IPPC) 2018) (U.S, EU)4 | 58%                    | 9%                    |
| Beer and wine production (FederalCostums Administration 2019) | 1.2                           | 0.9                        | DE                                          | 23%                    | 8%                    |
| Coffee and tea                          | N/A                           | N/A                        | N/A                                         | 8%                     | 8%                    |
| Sugar production2 (Food and Agriculture Organization of United Nations 2019) | 0.23                          | 0.1                        | (European Integrated Pollution Prevention Control Bureau (IPPC) 2018) (EU) | 56%                    | 6%                    |
| Cocoa and Chocolate (Food and Agriculture Organization of United Nations 2017) | 5.70                          | 6.4                        | (United Nations Industrial Development Organization (UNIDO) 2010) (OECD) | 0%                     | 6%                    |
| Vegetable oil refining (Food and Agriculture Organization of United Nations 2019) | 7.70                          | 0.36                       | (European Integrated Pollution Prevention Control Bureau (IPPC) 2018) (EU) | 96%                    | 3%                    |
| Total                                    |                               |                            |                                             |                        | 25%                   | 100%                  |

1 Due to lack of data availability, the core process-specific technical potential could not be estimated, i.e. only the technical potential for EMDS measures is included in the table.
2 SEC based on the raw material (e.g. sugar beet, meat processed or milk) instead of the product.
3 Reference SEC is assumed to be 20% more (Riva, 1993) than the value in the literature source in order to make it comparable with the SEC of Swiss dairy which is dominated by the production ultra-high temperature (UHT) milk.
4 For Fresh dairy products and cheese, SEC of individual production steps is estimated based on the energy consumption breakdown provided for generic establishment in US (Brush et al., 2011) and the EU best SEC value for comparison is obtained from BAT/BREF document (European Integrated Pollution Prevention Control Bureau (IPPC) 2018).
n = number of individual measures reported under the category y.

It should be noted that the average values are estimated only for cross cutting technologies.

2.3. Sector-wide energy savings potential

Annual energy saving potential by an individual measure or an EEM category is scaled up to the level of the entire F&B sector based on the estimates of remaining diffusion. Eq. 3 is used to estimate the sector-wide potentials for EEMs where the production data is available (i.e., specific saving potential in GJ/t). In contrast, Eq. 4 is used for the estimation of sector-wide energy saving potential in the case of lack of production data (i.e. relative saving potential in %) (See Appendix A for sample calculations).

\[ E_{Sy} = (SpES_y + SpFS_y) \times Pr_j \times D_y \]  

(3)

Where,

- \( E_{Sy} \) = Industrial sector-wide energy saving potential of EEM y (TJ)
- \( SpES_y \) & \( SpFS_y \) = specific electricity and fuel saving potential for measure y (GJ/t)
- \( Pr_j \) = Production related to product group j (j = Dairy, Chocolate, Sugar, Meat etc.) (tonne)
- \( D_y \) = Remaining estimated diffusion of that particular technology (in %; See section 2.4 for details)

Or

\[ ES_y = RES_y \times EC_i \times (D_y) \]  

(4)

Where,

- \( RES_y \) = Relative energy savings for EEM (or category) y (in % see Eq. 2)
- \( EC_i \) = sector-wide energy consumption by the production step (or end-use) i (TJ)

2.4. Remaining diffusion estimates

Sector-wide EE improvement potential of an EEM depends on the remaining diffusion potential of that particular technology. The remaining diffusion potential \( D_y \) is established based on: i) estimates of the remaining technical EE potential (core process-specific EEMs in meat, dairy and chocolate; see Eq. 5), ii) the data from sectoral EE reports available from the literature (EMDS and WHR related EEMs of all product groups; (Werle et al., 2013), (Industrial Process and Energy Systems Engineering (IPSE) 2019)) and iii) the share of particular fuel in total energy mix of the sector (fuel switch-related EEMs; for example, the diffusion potential for switching oil to natural gas is < 10% of process heat since the share of oil as an energy carrier represents 10% of the process heat demand).

\[ D_y = (EC_{ij} - \sum_{e=1}^{n} EC_{ie}) \times TP_j \times EC_{ij} \]  

(5)

Where,

- \( EC_{ij} \) = energy consumption of production step (or end-use) i for the product group j (TJ)
- \( TP_j \) = Technical EE potential of the product group j (in %; see Eq. 6)
- \( EC_{ie} \) = Energy consumption of the end-use i in the establishment e which has already implemented the measure y (TJ)

2.5. Technical EE potential

Technical EE potentials for selected product groups is estimated by comparing the current SEC (GJ/t) values for the product groups in Swiss F&B manufacturing industries to the reference SEC values with least possible energy consumption for that product available from the literature, e.g. Best Available Technology (BAT) values (Brush et al., 2011, European Integrated Pollution Prevention Control Bureau (IPPC) 2018, United Nations Industrial Development Organization (UNIDO) 2010). The estimated technical EE potential \( TP_j \) allows to account for the diffusion of EEMs also in non-EnAW establishments albeit a conservative value.

\[ TP_j = \frac{SEC_{j,CH} - SEC_{j,REF}}{SEC_{j,CH}} \]  

(6)

Where,

- \( SEC_{j,CH} \) = Specific energy consumption of product group j for Switzerland (GJ/t of product)
- \( SEC_{j,REF} \) = Reference SEC of the best available technique (GJ/t of product)

This approach is only applicable to product groups for which BAT values are available and physical production is known.

2.6. Carbon dioxide emission reduction potential

The only source of GHG emissions from the Swiss F&B sector is...
Table 2.
Techno-economic data for energy efficiency measures for Swiss F&B sector.

| Sr. no. | Measure ID | End use/Production step | Type of energy carrier saved | Description | Initial investment (CHF) | Relative energy saving potential (% of energy demand of the end use) | Sector-wide EE improvement potential (TJ/year) | Sector-wide CO₂ abatement potential (t CO₂/year) | Current diffusion estimates (% of energy) | Measure lifetime (years) | Levelized cost (for 23% DR) (CHF/GJ) | Simple payback period (years) |
|---------|------------|--------------------------|-------------------------------|-------------|--------------------------|---------------------------------------------------------------|-----------------------------------------------|---------------------------------------------|------------------------------------------|-------------------------------|-----------------------------------|----------------------------------|
| 1       | SPR1       | Production F             | Installing new effluent process equipment: sugar mfg. | 644 889     | 1%                       | 31                                                             | 1 774                                         | 30%                                         | 10                                        | -5                            | 3                                 |
| 2       | SPR2       | Pulp drying F            | Use of plaster pressing aid during pulp drying | 50 000      | 1%                       | 4                                                              | 231                                           | 56%                                         | 10                                        | -13                           | 1                                 |
| 3       | SPR3       | Pulp drying E            | Use of dry pulp pelletizing | 1 000       | 1%                       | 1                                                              | -                                             | 56%                                         | 10                                        | -35                           | 0.5                               |
| 4       | DPR1       | Production F             | Installation of new effluent process equipment: dairy mfg. | 144 564     | 9%                       | 121                                                            | 6 951                                         | 44%                                         | 10                                        | 40                            | 12                                |
| 5       | DPR2       | Evaporation F            | Replacing evaporation by reverse osmosis | 3 000 000   | 21%                      | 108                                                            | 10 276                                        | 57%                                         | 30                                        | 12                            | 7                                 |
| 6       | DPR3       | Evaporation F            | Replacing evaporation with vapor recompression | 2 250 000   | 14%                      | 88                                                             | 7 458                                         | 53%                                         | 30                                        | -3                            | 3                                 |
| 7       | DPR4       | F                        | Preheating using micro-gas turbine | 6 400       | 2%                       | 21                                                             | 1 214                                         | 47%                                         | 10                                        | -16                           | 0.1                               |
| 8       | DPR5       | CIP                       | Buffer tanks for CIP | 10 000      | 10%                      | 10                                                             | 571                                           | 37%                                         | 20                                        | -5                            | 3                                 |
| 9       | DPR6       | Pasteurization F         | Replacing batch autoclave with continuous pasteurization | 660 000     | 2%                       | 5                                                              | 297                                           | 47%                                         | 10                                        | 146                           | 37                                |
| 10      | CPR1       | Production F             | Installation of new effluent process equipment: chocolate and cocoa mfg. | 8 731       | 1%                       | 0.8                                                            | 1 119                                         | 99%                                         | 10                                        | -16                           | 1                                 |
| 11      | CPR2       | Drying F                 | Replacing steam ejectors by vacuum pumps | 10 000      | 40%                      | 0.5                                                            | 1 792                                         | 99%                                         | 15                                        | -16                           | 0.2                               |
| 12      | CPR3       | Conching F               | Modifying conching temperature | 200         | 30%                      | 0.04                                                           | 1 202                                         | 99%                                         | 10                                        | -17                           | 0                                 |
| 13      | CPR4       | Other E                  | Replacing vibrators with pneumatic knockers | 35 000      | 9%                       | 0.01                                                           | -                                             | 99%                                         | 10                                        | -30                           | 1                                 |
| 14      | CPR5       | Conching F               | Process control for conching water circulation | 12 000      | 2%                       | 0.01                                                           | 48                                            | 99%                                         | 10                                        | -11                           | 1                                 |
| 15      | MPR        | n/a                      | Replacing steam humidifier with air humidifier | 45 000      | 1%                       | 2                                                              | 109                                           | 31%                                         | 10                                        | -29                           | 1                                 |

Vegetables and fruits processing and preservation (VPR) (continued on next page)
| Sr. no. | Measure ID | End use/ Production step | Type of energy carrier saved | Description | Initial investment\(^1\) \((\text{CHF})\) | Relative energy saving potential (\% of energy demand of the end use) | Sector-wide EE improvement potential (TJ/year) | Sector-wide CO\(_2\) abatement potential (t CO\(_2\)/year) | Current diffusion estimates (\% of energy) | Measure lifetime \((\text{years})\) | Levelized cost (for 23% DR) \((\text{CHF/GJ})\) | Simple payback period \((\text{years})\) |
|---------|------------|--------------------------|-----------------------------|-------------|---------------------------------|---------------------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 16      | VPR1       | Process heat             | F                           | Aroma concentration for vegetable juice | 800 000         | 11%                           | 9                              | 534                             | 38%                             | 10              | 80                              | 22              |
| 17      | VPR2       | Drying                   | F                           | Frequent replacing silica gel packets in dryer | 205 000         | 1%                            | 1                              | 75                              | 31%                             | 10              | 4                               | 5               |
| 18      | BPR        | Distillation             | F                           | Energy saving through high specific gravity of wort | 10 000          | 1.3%                          | 8                              | 449                             | 78%                             | 20              | -15                             | 0               |
| 19      | OFPR1      | Concentration            | F                           | Reverse osmosis for concentration | 59 000          | 10%                           | 63                             | 8 177                            | 37%                             | 10              | -8                              | 2               |
| 20      | OFPR2\(^1\)|                                            | F                           | Preheating for pasta oven | 106 200        | 6%                            | 38                             | 4 914                            | 34%                             | 10              | -9                              | 2               |
| 21      | PR1        | -                        | E/F                         | Optimization of process scheduling | 8 263           | 4%                            | 193                            | 9574                            | 33%                             | 10              | -31                             | 0.5             |
| 22      | PR2        | -                        | F/E                         | Process equipment modification (size, geometry) | 61 519          | 2%                            | 100                            | 4986                            | 30%                             | 10              | 6                               | 5               |
| 23      | PR3        | -                        | F/E                         | Process equipment insulation (furnaces, ovens, evaporators etc.) | 11 340          | 2%                            | 98                             | 4 887                            | 31%                             | 15              | -6                              | 3               |
| 24      | PR4        | -                        | F/E                         | Process parameter modification (pressure, temperature) | 11 627          | 2%                            | 98                             | 4 887                            | 31%                             | 20              | -15                             | 1               |
| 25      | PR5        | -                        | E/F                         | Process equipment Maintenance and repair | 27 557          | 1%                            | 50                             | 2 439                            | 30%                             | 20              | -25                             | 1               |

**CROSS CUTTING TECHNOLOGIES**

Electric motor driven system (EMDS)\(^2\)

| Sr. no. | Measure ID | End use/ Production step | Type of energy carrier saved | Description | Initial investment\(^1\) \((\text{CHF})\) | Relative energy saving potential (\% of energy demand of the end use) | Sector-wide EE improvement potential (TJ/year) | Sector-wide CO\(_2\) abatement potential (t CO\(_2\)/year) | Current diffusion estimates (\% of energy) | Measure lifetime \((\text{years})\) | Levelized cost (for 23% DR) \((\text{CHF/GJ})\) | Simple payback period \((\text{years})\) |
|---------|------------|--------------------------|-----------------------------|-------------|---------------------------------|---------------------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 26      | EMDS1      | EMDS                     | E                           | Installing frequency converters | 39 970          | 4%                            | 120                            | 44                              | 30%                             | 15              | -9                              | 0               |
| 27      | EMDS2      | EMDS                     | E                           | Installing more efficient motors | 22 799          | 3%                            | 79                             | -                               | 30%                             | 25              | -12                             | 3               |
| 28      | EMDS3      | EMDS                     | E                           | Pump schedule optimization | 8 885           | 3%                            | 79                             | 1 912                            | 30%                             | 10              | -33                             | 0               |
| 29      | EMDS4      | EMDS                     | E                           | Installing more efficient compressor | 9 000           | 3%                            | 79                             | 592                             | 30%                             | 15              | -16                             | 0               |
| 30      | EMDS5      | EMDS                     | E                           | Installing more efficient pumps | 20 989          | 1%                            | 26                             | -                               | 30%                             | 20              | -8                              | 3               |

Steam system (SS)

| Sr. no. | Measure ID | End use/ Production step | Type of energy carrier saved | Description | Initial investment\(^1\) \((\text{CHF})\) | Relative energy saving potential (\% of energy demand of the end use) | Sector-wide EE improvement potential (TJ/year) | Sector-wide CO\(_2\) abatement potential (t CO\(_2\)/year) | Current diffusion estimates (\% of energy) | Measure lifetime \((\text{years})\) | Levelized cost (for 23% DR) \((\text{CHF/GJ})\) | Simple payback period \((\text{years})\) |
|---------|------------|--------------------------|-----------------------------|-------------|---------------------------------|---------------------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|
| 31      | SS1        | Steam system             | F                           | Substitution of fuel oil by natural gas boiler | 118 432         | 21%                           | 240                            | 27 634                           | 90%                             | 15              | -35                             | 1               |
| 32      | SS2        | Steam system             | F                           | Substitution of fossil fuels by industrial waste | 249 375         | 10%                           | 190                            | 5                               | 66%                             | 15              | -113                            | 3               |
| 33      | SS3        | Steam system             | F                           | Solar thermal integration | 80 667           | 5%                            | 122                            | 6 056                            | 66%                             | 30              | 63                              | 23              |

(continued on next page)
Table 2. (continued)

| Sr. no. | Measure ID | End use/Production step | Type of energy carrier saved | Description$^3$ | Initial investment$^2$ (CHF) | Relative energy saving potential (% of energy demand of the end use) | Sector-wide EE improvement potential (TJ/year) | Sector-wide CO$_2$ abatement potential (t CO$_2$/year) | Current diffusion estimates (% of energy) | Measure lifetime (years) | Levelized cost (for 23% DR) (CHF/GJ) | Simple payback period (years) |
|---------|------------|--------------------------|-------------------------------|-----------------|--------------------------------|------------------------------------------------|------------------------------------------|-------------------------------------------|---------------------------------|--------------------------|--------------------------------------|--------------------------|
| 34      | SS4        | Steam system F           | Boiler modification (pressure, control system) | 11 000          | 3%                              | 98                                           | 1 690                                     | 32%                                      | 15                             | -13                      | 1                                    |
| Refrigeration (RFG)                    | RFG1       | Refrigeration E          | Optimization of refrigeration system (pressure, temperature) | 35 667         | 15%                             | 408                                          | -                                        | 50%                                      | 20                             | -30                     | 1                                    |
| 36      | RFG2       | Refrigeration E          | Installing new more efficient equipment | 113 750        | 11%                             | 351                                          | -                                        | 50%                                      | 20                             | -7                      | 4                                    |
| 37      | RFG3       | Refrigeration E          | Improving/installing insulation in refrigeration network | 2 487          | 11%                             | 351                                          | -                                        | 50%                                      | 20                             | -3                      | 4                                    |
| Waste heat recovery (WHR)$^5$ | WHR1 | Process heat F           | WHR from process equipment (Process heat integration) | 162 315        | 7%                              | 357                                          | 16 233                                   | 39%                                      | 15                             | -4                      | 3                                    |
| 39      | WHR2       | Process heat F           | WHR from flue gas Low temperature heat pump integration | 66 800         | 4%                              | 193                                          | 9 575                                    | 33%                                      | 15                             | -8                      | 2                                    |
| 40      | WHR3       | Process heat F           | WHR from compressor | 333 000        | 18%                             | 165                                          | 8 100                                    | 37%                                      | 15                             | -0                      | 4                                    |
| 41      | WHR4       | Process heat F           | WHR from condensate | 147 750        | 2%                              | 98                                           | 4 887                                    | 31%                                      | 15                             | 7                       | 6                                    |
| 42      | WHR5       | Process heat F           | WHR from condensate | 117 546        | 2%                              | 98                                           | 4 887                                    | 31%                                      | 15                             | 1                       | 4                                    |
| 43      | WHR6       | Process heat F           | Optimization of existing WHR system | 25 000         | 1%                              | 50                                           | 2 469                                    | 31%                                      | 15                             | -8                      | 2                                    |
| EMERGING TECHNOLOGIES$^6$ | All Product groups | | | | | | | | | | | |
| 44      | EMR1       | Process heat F           | High temperature heat pump | N/A            | 10%                             | 435                                          | 24 935                                   | 0%                                       | N/A                            | N/A                     | N/A                                  | N/A                                    |
| 45      | EMR2       | Process heat F           | Steam generation from excess heat$^7$ | N/A            | 10%                             | 255                                          | 14 635                                   | 0%                                       | N/A                            | N/A                     | N/A                                  | N/A                                    |
| 46      | EMR3       | Process heat F/E         | Radio frequency drying | N/A            | 5%                              | 130                                          | 7 466                                    | 0%                                       | N/A                            | N/A                     | N/A                                  | N/A                                    |
| 47      | EMR4       | Process Heat F           | Energy efficient blanching | N/A            | 10%                             | 17                                           | 979                                      | 0%                                       | N/A                            | N/A                     | N/A                                  | N/A                                    |
| 48      | EMR5       | Process heat F           | Pulse electric pasteurization | N/A            | 10%                             | 502                                          | 28 780                                   | 0%                                       | N/A                            | N/A                     | N/A                                  | N/A                                    |

1. EEMs allowing to save both fuel and electricity are denoted as F/E or E/F depending on which energy carrier represents the larger share of saving potential.
2. Detailed descriptions of EEMs can be found in appendix B. Number of EEMs analyzed under each category can be found in appendix C.
3. Energy-relevant cost in case of core process-specific EEMs. Total investment cost for cross-cutting EEMs. A special care should be taken while interpreting the techno-economic data for core process specific measures since the data is based on only one instance of implementation.
4. Some WHR technologies are included in core process-specific category since they have applications for a specific production step.
5. Diffusion potential for EMDS adopted from (Werle et al., 2013) and estimated for WHR based on the minimum energy required presented in the sector-wide composite curves published in (Industrial Process and Energy Systems Engineering (IPESE) 2019).
6. Sector-wide EE improvement potentials and corresponding CO$_2$ abatement potentials for emerging technologies are rough and generic estimates based on relative energy savings as compared to process heat demand of the respective industrial sector.
stationary fuel consumption (emissions measured under the IPCC source category 2, i.e. there are no indirect process-related CO2 emissions (Swiss Federal Office of Environment (FOEN) 2018)). CO2 represents approximately 99% of total GHG emissions originating from the Swiss F&B sector (European Environmental Agency (EEA) 2018). CO2 emission factors are applied to estimate CO2 abatement potential associated with EEMs saving fuel (see Eq. 7). The CO2 emission reduction potential of measures whose main purpose it is to abate CO2 (i.e. fuel substitution, integration of renewables) is estimated using Eq. 8.

\[ CA_x = FS_{x,EnAW} \times EF_{f,b} \]  

Where,
- \( CA_x \) = carbon dioxide emission reduction potential (t CO2 / year)  
- \( FS_{x,EnAW} \) = Fuel savings for EEM x reported in EnAW database (GJ)  
- \( EF_{f,b} \) = weighted CO2 emission factor for Swiss F&B sector (t CO2/GJ; see footnote 10)

Or

\[ CA_x = (FC_a \times EF_a - FC_b \times EF_b) \]  

Where,
- \( EF_a \) = CO2 emission factor for fuel a (a = fuel oil, natural gas, coal) (t CO2/GJ)  
- \( EF_b \) = CO2 emission factor for fuel b (b = natural gas, industrial waste, district heating) (t CO2/GJ)  
- \( FC_a \) = Consumption of fuel a (GJ/year)  
- \( FC_b \) = Consumption of fuel b (GJ/year)

CO2 emission reduction potential is averaged across all individual measures x implemented under the sub-category y (\( CA_y \)).

\[ CA_y = \left( \sum_{x=1}^{n} CA_x \right) / n \]  

Where,
- \( n \) = number of individual measures reported under category y

2.7. Investment costs

Initial investment costs (\( I_0 \)) and energy-related investment costs (\( I_{0,er} \)) for the present analysis are adopted from the EnAW database. The costs are converted from the year in which the EEM is implemented to Swiss Francs (CHF) in 2017 using the price level index (Organisation for Economic Co-operation and Development (OECD) 2018) in order to avoid any bias when comparing initial costs with the benefits (see Eq. 16) which are calculated with the energy prices for 2017. Since the cross-cutting EEMs (i.e., EEMs for EMDS, RFG, SS and WHR) typically have no other purpose than EE improvement, the energy-relevant costs and total investment costs are equal for these EEMs. On the other hand, for the core process-specific EEMs, more often the investment is made with an intention of improving the productivity or other features (e.g. product quality or process operability) and the EE improvement is an additional benefit (based on the description from EnAW database). In such cases, it is important to use the energy relevant investment cost for the cost benefit analysis in order to only consider the part of the investment cost that is related to energy efficiency improvement (usage of total costs, in this case, would result in under-estimation of the EEM's cost-effectiveness). Energy relevant costs reported in the EnAW database are either i) estimated based on the expert judgement in case of replacement of larger sub-systems (e.g. packaging plant) or ii) the share of the EEM's total investment cost in the case of early replacement (calculated by Eq. 10).
\[ I_{x,er} = I_x \times (1 - \frac{A}{T}) \]  \hspace{1cm} (10)

Where,
- \( I_{x,er} \) = Energy-related investment costs (CHF)
- \( I_x \) = Total initial investment (CHF)
- \( A \) = Age of the equipment (years)
- \( T \) = Technical lifetime of the equipment (years)

Initial investment cost is averaged across all individual measures \( x \) reported in EnAW database under the sub-category y (only for cross cutting EEMs see footnote 8).

\[ I_y = (\sum_{x=1}^{\infty} I_x)n \]  \hspace{1cm} (11)

2.8. Energy cost and CO2 levy

The projections of final energy prices (see Fig. 5) for electricity and fuel for Swiss industry (CHF/GJ) until the year 2050 are adopted from the work done by Zuberi and Patel for the Swiss cement industry (Jibran S. Zuberi and Patel, 2017) and the Swiss chemical industry (Jibran S. Zuberi and Patel, 2018).

As described above, the Swiss F&B sector is dominated by SMEs and the majority (71%) of the sector’s current TFE demand is represented by companies collaborating with EnAW. Just as (nearly) all other companies, these companies automatically pay CO2 levy of 96 CHF/t while collaborating with EnAW. Just as (nearly) all other companies, these companies automatically pay CO2 levy of 96 CHF/t while collaborating with EnAW.

For the majority (71%) of the sector’s current TFE demand is represented by companies collaborating with EnAW (and likewise with the organisation ‘act’) are entitled to a refund of the CO2 levy (Swiss Federal Office of Environment (FOEN) 2019).

2.9. Discount rate and measure lifetime

Discount rates are used to discount the future cash flows to the present value in order to reflect both the time value of money and the risk involved in a specific project (Environmental Protection Agency (EPA) 1998). The hurdle rate for an individual project reflects the minimum rate of return at which the investment becomes profitable. In other words, the hurdle rate is used as a criterion for adopting or rejecting an EEM (US Environmental Protection Agency (EPA) 2008). The internal hurdle rate is chosen as a default discount rate (DR) for the discounted cash flow (DCF) analysis of an individual investment (Warfel, 1998). Rearranging Eq. 16 (see below, section 2.10) and setting CF to zero, the hurdle rate of each investment made for the implementation of an EEM in the EnAW database can be estimated for the given technical lifetimes of those particular technologies.

Although the net present value (NPV) is considered as a preferred way in microeconomics to evaluate the profitability of the investment, most of the companies in the Swiss industry prefer the criterion of simple payback time (SP) (Iten et al., 2017). Based on the techno-economic data received from EnAW it is also possible to estimate the SPs. Fig. 6 represents the correlation between the hurdle rates and the SPs for the EEMs implemented in EnAW database for the EE improvement in the Swiss F&B sector. Process-related EEMs with payback periods equal to or less than 4 years are considered cost-effective (or economic) for the Swiss industry (Energie-Agentur der Wirtschaft (EnAW) 2012). Based on the analysis of the EnAW database, the EEMs with an SP of 4 and 6 years have minimum hurdle rates of 21% and 10% respectively. In order to reflect the firm-level decision criteria for the adoption of EE technologies in the Swiss F&B sector, 21% is chosen as DR to analyze the base case and a lower DR of 10% is then chosen to analyze the effect of relaxing the economic criterion on the cost-effective potential. The discount rate chosen in this analysis implicitly considers the perceived risk of investment in energy efficiency improvement in the Swiss F&B sector.

The technical lifetimes of the cross-cutting EEMs reported in the EnAW database are estimated using the equipment life expectancy chart provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (Refrigerating and Air-Conditioning Engineers (ASHRAE) 2020). For core process related EEMs, lifetimes are either adopted from the literature (Innovation Center for U.S 2011) or they are estimated by rearranging Eq. 10.

2.10. Energy efficiency cost curves

Energy efficiency cost curves (EECC) are a convenient way to present the technical and economic EE improvement potential (Innovation Center for U.S 2007). In present work, EECCs are constructed by displaying the levelized cost of saved energy (and CO2 abatement) (CHF/GJ and CHF/t CO2) as a function of cumulative annual final energy savings (and cumulative annual CO2 abatement). In this definition, “cumulative” refers to the total first-year savings of all individual measures. While an EEM offers savings also in the second year, third year etc. the savings of one individual measure are not aggregated over time. The levelized cost of saved energy, is calculated by Eq. (12) and the respective value for CO2 abatement is determined using Eq. (13).

\[ C_{hit,y} = \frac{ANF \times NPV_y}{ES_y} \]  \hspace{1cm} (12)

For calculating the levelized cost of CO2 abatement, \( ES_y \) is replaced with \( CA_y \).

\[ C_{hit,CO2,y} = \frac{ANF \times NPV_y}{CA_y} \]  \hspace{1cm} (13)

Where,
- \( ANF \) = Annuity factor calculated by Eq. (14) (%)
- \( NPV_y \) = Net present value of measure \( y \) calculated by Eq. (15) (CHF)
- \( ES_y \) = Final energy saving potential of measure (category) \( y \) calculated by Eq.s (3 or 4) (GJ/year)
- \( CA_y \) = CO2 abatement potential of measure (category) \( y \) calculated by Eq. (9) (kg CO2/year)

\[ ANF = \frac{(1 + r)^y \times r}{(1 + r)^y - 1} \]  \hspace{1cm} (14)

And

\[ NPV_y = \sum_{t=0}^{1y} CF_t \times (1 - r)^{-1+tr} \]  \hspace{1cm} (15)

Where,
- \( CF_t \) = Annual cash flow for year \( t \) calculated by Eq. (16) (CHF)

Fig. 5. Electricity and fuel prices for Swiss industry up to 2050 (Zuberi, 2017; (Jibran S. Zuberi and Patel, 2017)).
• $r$ = Real discount rate (%) (See section 2.9)
• $L_y$ = Lifetime of measure (years)
• $t$ = running year (e.g., 2019)
• $t_r$ = year of evaluation (i.e., 2017 in this case)

\[ CF_y = I_{y,a} + O&M_y - B_y \]  
(16)

Where,
• $I_{y,a}$ = Annualized initial investment for implementation of measure (or category) $y$ (calculated by multiplying $I_y$ from Eq. 11 with ANF from Eq. 14) (CHF)
• $O&M_y$ = Operation and maintenance cost of measure (or category) $y$ (CHF)
• $B_y$ = Annual benefits earned by implementing EE measure (or category) $y$ calculated by Eqs. (17 and 18) (CHF)

Similar to energy savings, CO2 abatement and initial investment, the values of annual benefits are also averaged across all the individual measures ($x$) reported in the EnAW database for particular EEM subcategory $y$ (only for cross cutting EEMs see footnote 8).

\[ B_x = \left( \sum_{x=1}^{n_x} B_x \right) / n_x \]  
(17)

Benefits for individual measure $x$ are then calculated as follows:

\[ B_x = (ES_{x,EnAW} \times P_e) + (FS_{x,EnAW} \times P_f) + (CA_y \times P_{CO2}) \]  
(18)

Where,
• $P$ = Price of electricity $e$, fuel $f$ (CHF/GJ) and CO2 (CHF/t CO2)

By combining Eqs. 14 to 17 with the Eqs. 12 and 13, the levelized cost of energy savings and of CO2 abatement can be expressed as follows:

\[ C_{n,t,Y} = \frac{I_y \times ANF + O&M_y - B_y}{ES_y} \]  
and \[ C_{n,t,CO2,Y} = \frac{I_y \times ANF + O&M_y - B_y}{CA_y} \]  
(19)

2.11. ODEX methodology

The ODEX methodology allows tracking the technical (physical) EE improvement based on the change in energy consumption and variation of physical activity data at the level of industry subsectors ( ODYSSEE-MURE 2020; see Eq. 20). Switzerland’s Energy Strategy 2050 is based on the scenario analyses prepared by PROGNOS AG, presented in a document referred to as Energy Perspectives 2050 (PROGNOS 2012). The Energy Strategy 2050 presents the overall targets for reduction in TFE consumption for each industry sector (50% reduction in total industry’s TFE consumption from its value in the year 2000) and projections of activity (PIP; see footnote 3) likewise for each industry sector. However, the document does not provide the breakdown of TFE reduction related to changes in structure, activity and EE improvement. Application of the ODEX methodology to the TFE reduction targets and physical activity projections for Swiss F&B sector presented in the Energy Perspectives 2050 (under the NEP target scenario) allows estimating the extent to which the energy savings due to physical EE improvement are expected to contribute to the sector’s overall TFE reduction target (Bhadbhade et al., 2019).

\[ I_t = \frac{EC_{t_0}PI_t}{EC_{t_0}PI_{t_0}} \]  
(20)

Where,
• $I_t$ = physical EE index for year $t$ (also referred to as ODEX)
• $EC_t$ and $EC_{t_0}$ = Energy consumption of the sector for base year $t_0$ and year $t$ respectively (TJ)
• $PI_{t_0}$ and $PI_t$ = Production index for the base year $t_0$ and year $t$ respectively

Energy savings can be estimated based on Eq. 21

\[ ES_t = \left[ 1 - \left( \frac{I_t}{I_{t-1}} \right) \right] \times EC_t \]  
(21)

Where,
• $ES_t$ = Energy savings for year $t$ (TJ)
• $I_t$ and $I_{t-1}$ = Physical EE indices for current year $t$ and previous year $t-1$ respectively (i.e., the ratio represents the change of the ODEX)

3. Results and discussion

Based on the EnAW database the cost-effective EE improvement potential of currently commercially available technologies in the Swiss F&B sector is estimated in this study and compared with the targeted EE improvement and the technical potential. Fig. 7 presents the various levels of overall sector-wide EE improvement potentials estimated in the present analysis for the Swiss F&B sector. Our estimate of the energy savings to be achieved by physical EE improvement in order to reach the 2050 targets of the Energy Strategy is 26% of the sector’s current (2017) TFE demand. The related technical EE improvement potentials by product group of the Swiss F&B sector are presented in Table 1 along with current SECs of the products in the Swiss F&B sector, reference

![Fig. 6. Simple payback period and corresponding hurdle rates for the Swiss F&B sector (based on EnAW database).](image)

![Fig. 7. Various levels of EE improvement potential for Swiss F&B sector relative to the year 2017.](image)
SECs based on the best available techniques (BAtS) and the shares of product groups in TFE of the Swiss F&B sector. The total sector-wide process-related technical EE improvement potential estimated by comparing SECs for the Swiss products with those of reference SECs represents 25% of the sector’s current TFE demand (fifth column of Table 1). The potential represented by the commercially available EE improvement technologies in the Swiss F&B sector is estimated at 18% and the cost-effective technologies represent 16% and 14% EE improvement potential of the sector’s current TFE demand under the economic criteria of 6 and 4-year SP respectively (top two bars in Fig. 7, for discount rates of 21% and 10%). The gap between EE potential represented by currently available technologies and the technical EE potential is expected to be filled by the emerging technologies (see Table 2 for energy saving estimates). Across all subsectors, approximately 61% of technical potential can be realized by the implementation of currently available technologies in Switzerland (grey bar in Fig. 7), while the part of remaining 39% can be realized by the emerging technologies. However, the emerging technologies are excluded from the EECC due to the lack of economic data. The dairy industry represents the largest share of technical EE improvement potential in the Swiss F&B sector, followed by the meat processing industry (see Fig. 8).

Table 2 presents an extensive list of technology modifications for EE improvement (EEMs) applicable to the Swiss F&B sector along with the techno-economic data and levelized costs estimated based on the EnAW database. In addition to the broad classification of EEMs into categories according to the end-uses to which they are implemented, EEMs are further classified as fuel or electricity saving measures based on the energy carrier saved by the implementation of the EEM. EEMs in each category are organized in descending order of sector-wide EE improvement potential.

While Fig. 7 and Table 1 present the overall technical EE improvement potentials including both process-specific and cross-cutting technologies, the results of cost-effectiveness analysis are presented separately for both categories using the energy efficiency and CO₂ abatement cost curves. This allows to take into account the large difference in the scales of initial investment costs. The calculation of levelized costs using Eq. 19 implies that the EEMs with negative levelized cost (i.e. EEMs lying below the X-axis on the EECC) are cost-effective and the point at which the curve intersects the x-axis represents the cumulative sector-wide cost-effective potential for that category of EEMs. The core process-specific technologies and cross-cutting technologies represent cost-effective EE potentials of 4% and 10% respectively relative to the sector’s current TFE demand.

3.1. Energy efficiency cost curve for core process-specific EE improvement

Core process-specific EEMs are the technology modifications implemented to reduce the energy consumption of core production processes. These technology modifications represent 30% of total sector-wide EE improvement potential for all the commercially available EEMs in the Swiss F&B sector (the remaining 70% is represented by cross-cutting technologies). Although the cost-effective EEMs related to dairy represent only 43% of overall EE improvement potential of all commercially available technology modifications in Swiss dairy (see Fig. 9 (a)), these EEMs represent the largest share (33%) of overall sector-wide cost-effective potential for core process-specific EE improvement (see Fig. 9 (b)).

According to Fig. 9 (a) representing commercially available core process specific EEMs in Switzerland, the percentage of cost effective potential out of total EE potential ranges from 43% for “dairy” to 100% for “other foods”. Across all subsectors, 19 out of 25 EEMs identified as core process-specific EEMs were found to be cost-effective based on the criteria of 4-year SP or (21% DR). As shown in Fig. 10, “Use of dry pulp pelletizing (SPR3)” is found to be the most cost effective EEM among commercially available technologies in Swiss F&B sector. However, since its application being limited to the beet pulp drying process in sugar manufacturing, SPR3 has a negligible sector-wide EE potential.

“Optimization of process scheduling (PR1)” closely follows SPR3 in terms of cost-effectiveness whereas “Replacing batch autoclave with continuous pasteurization (DPR6)” was found to be the most expensive EEM. Unlike the majority of other EEMs in this category, PR1 can be implemented across all the product groups of Swiss F&B sector explaining why it has the largest sector-wide EE potential (i.e. largest horizontal step; see step 2 in Fig. 10) in this category despite having low relative EE potential (see Table 2).

Due to the heterogeneous nature of the sector, the sector-wide EE improvement potentials of EEMs depend more on the share of the product group and the end use (or production step) in the sector’s TFE demand than their relative EE improvement potential. “Replacing steam ejectors by vacuum pumps in vacuum dryer (CPR2)” and “modifying the conching temperature (CPR3)” have the largest relative EE improvement potentials, i.e. they can save approximately 40% and 30% of the energy consumed for drying and conching respectively in cocoa in a chocolate processing (see Table 2). However, due to its implementation being limited to the chocolate and cocoa processing, CPR2 and CPR3 have relatively small sector-wide EE improvement potentials. It should, however, be noted that due to lack of information regarding the diffusion of vacuum drying in other industrial sectors of Swiss F&B sector (e.g. coffee & tea and temperature sensitive products of dairy speciality (European Integrated Pollution Prevention Control Bureau (IPPC) 2018)), the sector-wide EE improvement potential of

![Fig. 8. Share of technical EE potential by product groups for Swiss F&B.](image-url)
CPR2 is underestimated.

While commercially available core process-specific EEMs are displayed in Fig. 10, emerging technologies identified in the international literature are presented in Table 2. These EEMs are not included in the EECC due to lack of economic data. Out of all the emerging technologies reviewed, “pulse electric pasteurization (EMR5)” is the most promising EE improvement technology for Swiss F&B sector since it can potentially be implemented to completely replace the thermal demand for the pasteurization in dairy, vegetable and fruit juice manufacturing and beverage manufacturing (Lung et al., 2020) (product groups responsible for approximately 35% of sector’s current TFE).

3.2. Energy efficiency cost curve for cross-cutting technologies

Measures related to end-uses such as EMDS, RFG, SS as well as WHR, which are implementable across all the product groups of Swiss F&B sector, are categorized as cross-cutting EEMs. Commercially available cross-cutting EEMs represent 70% of total EE improvement potential for Swiss F&B sector. Although the technology modifications related to WHR represent the largest share of total sector-wide EE improvement potential for currently available EEMs in Switzerland, the EEMs related to refrigeration have the largest share of cost-effective EE improvement potential for cross-cutting technologies (see Fig. 11 (b) and (c); and horizontal steps 4, 12 and 14 in Fig. 12). (For abbreviations see Table 2)

All commercially available EEMs related to EMDS and refrigeration are cost effective whereas the cost effective EE represents 78% share of total EE improvement potential for EEMs related WHR and SS each (see Fig. 11 (a)). Overall, out of a total 18 EEMs identified for cross-cutting technologies, 15 measures are found to be cost-effective based on the criterion of a 4-year payback period (or 21% DR). As shown in Fig. 12, “Substitution of fossil fuels by industrial waste (SS2)” is found to be the most cost-effective EEM followed by another fuel substitution measure “Substitution of fuel oil by natural gas boiler (SS1)”. However, due to the limited availability of industrial waste (Jibran S. Zuberi and Patel, 2017, Swiss Federal Office of Environment (FOEN) 2018) and low calorific value impeding its applicability for high temperature heat demand, SS2 has a limited sector-wide EE improvement potential. “Process heat integration (WHR1)” has the largest sector-wide EE improvement potential (see horizontal step no 13 in Fig. 12). The sector-wide diffusion potential of “low temperature heat pump integration (WHR3)” is limited to 50% of the sector’s TFE (third largest among WHR EEMs;
Fig. 11. (a) Percentage of EE potential represented by commercially available cost-effective EEMs in Swiss F&B industry for individual end uses (b) Shares of individual end uses in cost effective EE potential represented by cross-cutting EEMs in Swiss F&B sector (c) Shares of individual end uses in total EE potential represented by all commercially available cross-cutting EEMs in Swiss F&B sector. (See Table 2 for abbreviations; numbering in legends represents ranking with the most cost-effective measures being mentioned first)

Fig. 12. Energy efficiency cost curve for cross-cutting EEMs for Swiss F&B sector.
50% heat demand is required at temperatures <100°C (Naegler et al., 2015) demand despite having the largest relative EE improvement potential (18%) and the possibility of implementation across all the product groups of F&B sector.

Emerging technologies such as “high temperature heat pumps (HTHP) (EMR1)” and “steam generation from waste heat (by low pressure evaporation and vapour compression; LPE&VC) (EMR2)” display a large sector-wide technical potential for the implementation (see Table 2). However, these technologies are still in a relatively nascent stage and the cost-effectiveness is very site-specific, i.e. it depends on the temperature at which the excess heat is available, the flow rate of steam demand and the plant topology (Jibran S. Zuberi et al., 2018, Bless et al., 2017). As a result, the cost-effectiveness of these technologies could not be reasonably generalized for the entire sector and are excluded from the EECCs.

3.3. Cost curve for CO2 abatement

Natural gas, fuel oil and coal together cover approximately 56% TFE demand of the Swiss F&B sector (see Fig. 2(b)(25)). The EEMs implemented for the reduction of fuel consumption and the measures of fuel substitution result in the abatement of associated CO2 emissions. In combination, they offer the potential to reduce 24% of current CO2 emission levels of the Swiss F&B sector. Overall, out of 30 measures allowing to reduce the CO2 emissions, 21 measures were found to be cost-effective based on the criterion of a 4-year SP (or 21% DR), representing a cost-effective CO2 emission reduction potential of 18% (relative to current emission levels, see Fig. 13).

“Substitution of fuel oil by natural gas boiler (SS1)” is found to be the most cost-effective EEM as well as the EEM with the largest sector-wide potential for CO2 abatement in Swiss F&B sector (see horizontal step 1 in Fig. 13). Fuel oil has a CO2 emission factor of 73 tCO2/TJ whereas the emission factor of natural gas is 56 tCO2/TJ (Swiss Federal Office of Environment (FOEN) 2018). On the other hand, “Solar thermal integration (SS3)” is found to be the most expensive EEM for CO2 abatement in Swiss food and beverage industry. Core process-specific EEMs represent 60% of cost-effective CO2 emission reduction potential whereas the cross-cutting EEMs represent the remaining 40% of CO2 abatement potential.

Among the emerging technologies according to Table 2, “Pulse electric pasteurization (EMR5)” offers the largest sector-wide CO2 abatement potential followed by “high temperature heat pumps (EMR1)”.

3.4. Sensitivity analysis

The sector-wide cost-effective potential is a function of initial investment, energy costs, discount rate and CO2 levy. Apart from the initial investment cost, also the other variables are inherently uncertain. A sensitivity analysis presents the effect of changes in the exogenous variables on the overall sector-wide cost-effective EE improvement potential and the CO2 emissions reduction potential.

3.5. Energy prices

The energy prices selected for the base case in the current analysis are estimated prices of energy for the overall industry sector for the year 2017 (41 CHF/GJ for electricity and 16 CHF/GJ for fuel; see section 2.8). However, large energy consumers can negotiate low network charges and get tax exemptions (Ecofys CEPS, Economistiassociati 2016) which may result in them paying energy prices of only 50% of the base case. Electricity and fuel prices in Swiss industry are projected to rise by 30% and 60% until 2050 (see Fig. 5). In order to account for the heterogeneity and uncertainty, the sensitivity of the cost-effective EE improvement potential is tested for 50% higher and 50% lower energy prices.

Overall cost-effective EE improvement potential for the base case of 4-year SP (or 21% DR) decreases from 14% for the base case energy prices to 7% for 50% lower energy prices. For large consumers which can negotiate lower energy prices, in total, 20 EEMs become
economically unattractive (10 EEMs are non-cost-effective for the base case). On the other hand, for a 50% rise in the energy prices, the overall sector-wide cost-effective EE improvement potential increases to 16% of the sector’s current TFE demand. Results of sensitivity analysis under various energy prices and discount rate scenarios are presented in Table 3. The cost-effective EE improvement potential for cross-cutting technologies is more sensitive to the energy price changes than the cost effective potential for core process-specific technologies (see Table 3). The overall cost-effective EE improvement potential is relatively less sensitive to energy prices under less stringent economic criteria of 6-year SP. However, due to the lack of data availability related to core-process specific EEMs for some product groups (see footnote 14), the sensitivity of the cost-effectiveness of EEMs is underestimated and the results for this category should be interpreted with care.

3.6. Effect of discount rate

The hurdle rate of 21% represents the real investment behaviour of companies of the Swiss F&B sector for an SP of 4 years and was therefore chosen as the base case discount rate for DCF analysis. However, the sensitivity of the cost-effective EE improvement potential is also tested for the less stringent economic criterion of 6-year SP. Corresponding hurdle rate for 6-year SP is chosen as the minimum DR for this scenario. The cost-effective EE improvement potential for the base case energy prices increases from 14% for 4-year SP to 16% for 6-years SP. The overall cost-effective EE improvement potential for 6-year SP (i.e. 10% DR) decreases from 16% to 14% of the sector’s current TFE demand for the 50% lower energy prices than in the base case and for 50% higher energy prices, it increases to 17% of the sector’s current TFE demand. While the cost-effective EE improvement potential for the cross-cutting measures is relatively less sensitive to energy price changes for less stringent economic criteria of 10% DR, the cost-effective EE potential remains unchanged for the core process-specific technologies under this scenario (see Table 3).

3.7. Effect of CO2 levy

The CO2 reduction potential for the base case scenario is estimated using the current (2018) value of CO2 levy (i.e. 96 CHF/t CO2). In order to take into account the effect of higher CO2 levies anticipated in future, the sensitivity of CO2 reduction potential is tested for 150 CHF/t CO2 (projected until 2035) and 250 CHF/t CO2 (projected until 2050) (PROGNOS 2012) under various energy price and discount rate scenarios. Fig. 14 presents the results of the sensitivity analysis of the CO2 abatement potential for anticipated values of CO2 levy under different scenarios of energy prices and economic criteria. For the base case energy prices and 4-year SP, the CO2 abatement potential increases from 18% for the current CO2 levy to 21% of the sector’s current CO2 emissions for 2050 projected value of the CO2 levy. In contrast, the CO2 abatement potential remains unchanged at 21% of the sector’s current CO2 emissions under more relaxed economic criteria of 6-year SP for all the projected values of CO2 levy. CO2 emission reduction potential drops to 12% in case of 50% lower energy prices for current CO2 levy but increases up to 19% for higher CO2 levy (see Fig. 14). For less stringent economic criteria however, CO2 emission reduction potential remains almost unchanged for all the projected values of CO2 levy. At 50% higher energy prices, CO2 abatement potential displays the least sensitivity to both changes in CO2 levy as well as relaxed the economic criteria.

4. Conclusion

In the period from 2004 to 2017, the growth of energy consumption was somewhat above the growth rate of production, implying a slight
deterioration in the energy efficiency (EE) of the Swiss food and beverage (F&B) industry. On the other hand, the growing share of electricity in the fuel mix has resulted in a drop in CO2 emissions intensity of the Swiss F&B sector during the same period. The present study identifies various levels of energy efficiency (EE) improvement (see Fig. 7) and corresponding CO2 abatement potentials for the Swiss F&B sector. Based on the application of ODEX methodology to the projected total final energy (TFE) demand and the physical production index of Swiss F&B sector, the energy efficiency improvement (excluding the effect of structure and activity change) which is required in order to reach the new energy policy (NEP) scenario of the Swiss energy strategy 2050 is estimated at 26% of the sector's current TFE demand. The process related technical potential based on the comparison of specific energy consumption (SEC; GJ/t product) values of Swiss products with that of reference SECs (based on the best available techniques from literature) is estimated at 25% of the sector's current TFE. Today's commercially available EE technologies in Swiss F&B sector can potentially reduce 18% of the sector's current TFE demand out of which, the cost-effective technologies represent an EE improvement potential of 14% under the base case scenario and the corresponding CO2 abatement potential is estimated at 18% of the sector's current CO2 emissions. In the coming decades, the economic potential must be nearly doubled (from today 14% of the current energy use) in order to achieve Swiss F&B sector's EE target of 26% (based on the validity of all other assumptions, e.g. about growth, the production index etc.).

Today's cost-effective EE improvement potential of 14% can be broken down into 4% related to core process-specific measures and 10% of cross-cutting technologies (under the base case scenario). However, the cost effectiveness of cross-cutting technologies drops to 4% for lower energy prices thus, indicating lower energy prices to be the major barrier for the adoption of cross-cutting technologies.

The dairy industry has the largest potential for reducing Swiss F&B sector's TFE demand (since it represents the largest share of technical potential). Based on the analysis of commercially available technologies, EEMs related to the dairy production represent the largest share of cost-effective EE improvement potential for core process-specific technologies whereas the EEMs related to refrigeration systems dominate the cost-effective potential for cross-cutting technologies. The largest potential for EE improvement lies in heat recovery, heat supply and refrigeration. The relatively low temperature levels (compared to other industries) and low temperature differentials making this sector particularly relevant for new technologies.

Most of the emerging technologies developed within and outside of Switzerland reviewed in this analysis are either applicable to multiple sectors (e.g. pulse electric pasteurization) or they are cross-cutting (e.g. high temperature heat pumps and steam production from excess heat) representing large sector wide diffusion potentials. While currently commercially available EE improvement technologies fall short of realizing the estimated technical potential, the estimates of energy-saving potentials of the emerging technologies provide an indication of available options to close the gap, albeit so far without understanding the economics.

5. CRediT author statement

Navdeep Bhadbhade: Conceptualization, methodology, Formal analysis, Data curation, Writing-Original draft, Visualization. Martin K. Patel: Writing-Review and editing, Supervision, Project administration, Funding acquisition

Declaration of Competing Interest

None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper.

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Supplementary materials

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