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# DECARBIN

## The impact of energy and climate policy on the decarbonization of industry in Switzerland: **Sector-Technology-Matrix**

| | Minerals – Cement | Minerals – Ceramics | Chemicals – Olefins | Chemicals – Other | Ferrous & non-ferrous metals | Food & Beverages |
|---|---|---|---|---|---|---|
| 1. Increase of process/ system efficiencies | ★★ | ★★ | ★★ | ★★ | ★★ | ★★ |
| 2. Shift to electricity | ★ | ★ | ★★★ | ★★★ | ★★ | ★★★ |
| 3. Shift to alternative fuels | ★★ | ★★★ | ★★★ | ★★ | ★★ | ★★★ |
| 4. Carbon capture and storage/use | ★★★ | ★ | ★ | ★ | ★ | ★ |
| 5. Shift to alternative feedstock | ★ | ★ | ★★ [1] | Not applicable | Not applicable | Not applicable |

1) Only relevant for scope 1 emissions if process is not fully electrified.

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Clausiusstrasse 37, CH-8092 Zürich
www.epg.ethz.ch

**Authors:**
Paul Tautorat, Swiss Federal Institute of Technology, paul.tautorat@gess.ethz.ch
Bjarne Steffen, Swiss Federal Institute of Technology, bjarne.steffen@gess.ethz.ch
Tobias S. Schmidt, Swiss Federal Institute of Technology, tobiasschmidt@ethz.ch

**SFOE project coordinators:**
Anne-Kathrin Faust, Anne-Kathrin.Faust@bfe.admin.ch

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# DECARBIN (**DECARB**onization of **IN**dustry in Switzerland)

## Sector-Technology-Matrix

*Financial support by the Swiss Federal Office of Energy through the Energy – Economy – Society (EES) research programme*

Paul Tautorat, Prof. Dr. Bjarne Steffen, Prof. Dr. Tobias Schmidt
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# Contents

# 1. Context

## 1.1. Relevance of emissions from the industrial sector

The Swiss Federal Council aims to achieve a climate-neutral Switzerland by 2050 [1]. While the decarbonization of the transport and building sectors is under way in Switzerland [2] and in many other industrialized countries, technologies for drastically reducing emissions in carbon- and energy-intensive industrial production are partly still in their infancy. Industry contributed about 18% of Swiss $CO_2$ emissions in 2018 [3] and consumed about 20% of final energy in Switzerland in 2020 [4]. At the same time, carbon- and energy-intensive industries are of significant importance for the Swiss economy. Major Swiss companies are engaged in industrial production in subsectors such as cement, chemicals, food & beverages and metals.

## 1.1. Compilation of the Sector-Technology-Matrix

The present Sector-Technology-Matrix summarizes the potential of different abatement options to contribute to the reduction of direct emissions from the most emission-intensive industry sectors in Switzerland.

First, using statistical data on emissions from the Swiss UNFCCC reporting tables for 2019 [5] we prioritized subsectors with a major contribution to direct emissions (i.e. scope 1 emissions) in Switzerland. Of all emissions reported as part of the relevant UNFCCC categories 1A2 (Energy > Fuel Combustion > Manufacturing Industry & Construction) and 2 (Industrial Processes and Product Use), we only considered sufficiently classified emissions that are emitted on site during the production process (cf. Figure 1). Furthermore, we de-prioritized subsectors if their yearly emissions did not exceed 100 kt $CO_2$eq. We also explicitly de-prioritized process emissions associated with the production of the food supplement Niacin, as they will be largely mitigated by the installation of a catalyst in the near future [6]. This left us with four prioritized industry sectors: (1) minerals (i.e., cement and ceramics), (2) chemicals (i.e., olefins and other chemicals and pharmaceuticals), (3) metals, and (4) food & beverages (cf. Figure 2). The indicated emissions, however, are subject to uncertainty as energy-related emissions (category 1A2) and process-related emissions (category 2) are reported in different product/sector groups and energy related emissions thus had to be allocated to industry sectors based on assumptions.

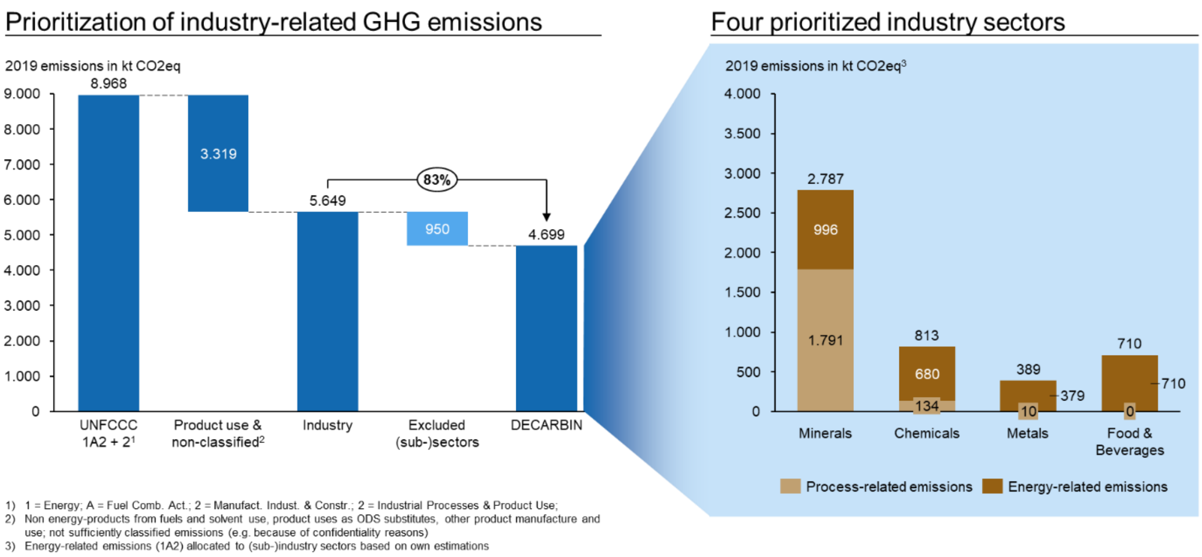
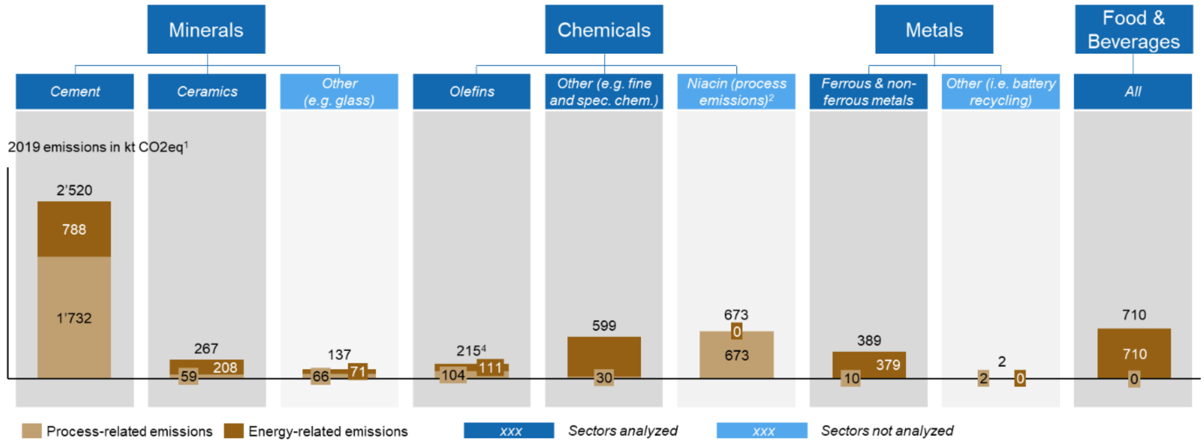



*Figure 1 Prioritization of industry-related GHG emissions*

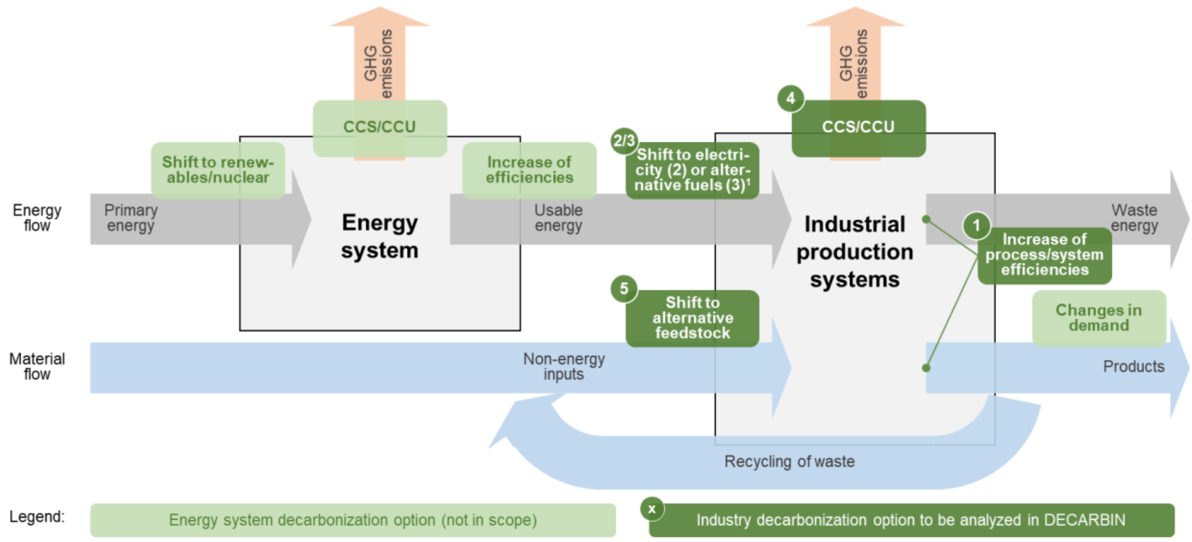



1) Energy-related emissions (1A2) allocated to (sub-)industry sectors based on own estimations
2) Process-related emissions from Lonza's Niacin production will be reduced significantly through the installation of a catalyst in the coming years
3) Activity and emissions data, for instance, are often only documented in the confidential version of the NIR
4) Overestimates actual emissions as the process-related emissions reported to UNFCCC include emissions from the Swiss Ammonia production and as energy-related are allocated based on process-related emissions (see footnote 1)

*Figure 2 Breakdown of industry-related GHG emissions by sub-sector*

Second, by conducting a review of existing studies on industry decarbonization options and results of recent and ongoing projects in European countries [7]–[9], we created a synthesis of available abatement options for the decarbonization of the prioritized subsectors. As illustrated in the DECARBIN framework in Figure 3, we focused on technological options beyond those typically covered in energy system analysis, namely: (1) Increase of process/system efficiencies, (2) shift towards electricity-based processes (electrification), (3) shift towards alternative fuels, (4) carbon capture and storage (CCS) or use (CCU), and (5) shift to alternative feedstock or intermediate products. Breaking down each of these five options further by differentiating underlying technical approaches gave us a list of available sub-options (cf. chapter 3).

At this point it must be highlighted that the matrix only considers scope 1 emissions from the industrial production system itself (see Figure 3). I.e., it covers neither upstream emissions associated with the production of the usable energy or feedstock used by the industrial production system, nor downstream emissions associated with the use of manufactured products or their end of life. As a result, when evaluating the decarbonization potential of an option, neither the current nor the future footprint of any energy or feedstock inputs is considered. As shown in Figure 3, changes of demand are not considered as an option to reduce emissions from the industrial production system. Furthermore, the impact of the options on the energy system – for instance due to increases of power/transmission demands – have not been analyzed. Also, resource efficiency was not investigated because we expect it to be less relevant for energy and climate policy to be modeled subsequently.




1) Including heating/cooling

*Figure 3 DECARBIN framework illustrating five options for the decarbonization of the industrial production system*

The scheme to assess each options relevance for the sectors studied is introduced in chapter 4. The identified abatement options are rated on a scale from 1 to 3 concerning (1) their diffusion potential for Switzerland, (2) the technical decarbonization potential and (3) the technology readiness. In addition, an overall score is derived aggregating the three individual scores.

In chapter 5 three items are presented per industry sector: (1) a set of industry-specific processes to be analyzed, (2) a table summarizing the assessments and (3) the detailed assessment per technical approach including short comments.

A summary of the results across the different industry sectors is given in chapter 6. References are indicated in square brackets next to the ratings (i.e. [#], [##], etc.) and are listed in chapter 7.

## 2. Conclusion

The present analysis indicates that per sector a multitude of different abatement options and technical approaches could potentially contribute to the deep decarbonization (see Figure 4). While from a technical perspective, increasing process/system efficiencies (option 1) and a shift to alternative fuels (option 3) could contribute significantly in all of the sectors, a shift in feedstock (option 5) is mainly applicable in the chemicals sector, a shift from fuel-based processes to electricity (option 2) in all but cement and minerals, and the capture and subsequent storage/use of carbon emissions (option 4) mainly in the cement industry. The economics as well as potential constraints of the analysed options (e.g., the availability of alternative fuels), however, have not been assessed yet, allowing for no concluding rating of the options' potential.

| | Minerals – Cement | Minerals – Ceramics | Chemicals – Olefins | Chemicals – Other | Ferrous & non-ferrous metals | Food & Beverages |
|---|---|---|---|---|---|---|
| 1. Increase of process/ system efficiencies | ★★ | ★★ | ★★ | ★★ | ★★ | ★★ |
| 2. Shift to electricity | ★ | ★ | ★★★ | ★★★ | ★★ | ★★★ |
| 3. Shift to alternative fuels | ★★ | ★★★ | ★★★ | ★★ | ★★ | ★★★ |
| 4. Carbon capture and storage/use | ★★★ | ★ | ★ | ★ | ★ | ★ |
| 5. Shift to alternative feedstock | ★ | ★ | ★★ [1] | Not applicable | Not applicable | Not applicable |

1) Only relevant for scope 1 emissions if process is not fully electrified.

*Figure 4 High-level assessment of abatement options' relevance per prioritized industry sector*

# 3. Overview of abatement options

| **Level 1 – Abatement option** | **Level 2 – Underlying rationale** | **Level 3 – Technical approach** |
|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances *(e.g. pumps, motors, lighting, mills)* |
| | | 1.1.2. Process innovations for energy efficiency and process intensification *(e.g. better catalysts)* |
| | | 1.1.3. Waste heat recovery and use *(heat may be used for 2.1.1., 2.1.2. or 3.4)* |
| | 1.2. Reduction of non-energy production waste | |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity[1] | 2.1.1. Heat pumps and chillers |
| | | 2.1.2. Mechanical vapour recompression |
| | | 2.1.3. Electric boilers |
| | | 2.1.4. Infrared heaters |
| | | 2.1.5. Microwave & radio frequency heaters |
| | | 2.1.6. Induction furnaces |
| | | 2.1.7. Resistance furnaces |
| | | 2.1.8. Electric arc furnaces |
| | | 2.1.9. Plasma technology |
| | | 2.1.10. Other |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines |
| | | 2.2.2. Other |
| | 2.3. Enabling chemical reactions with electricity *(e.g. produce NH3 via electrical synthesis rather than through heat-driven Haber Bosch process; on-site hydrogen production via electrolysis)* | |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol |
| | | 3.1.2. Other liquid synthetic fuels |
| | | 3.1.3. Synthetic hydrogen |
| | | 3.1.4. Synthetic methane |
| | | 3.1.5. Other gaseous synthetic fuels |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels |
| | | 3.2.2. Liquid biofuels |
| | | 3.2.3. Gaseous biofuels |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil |
| | | 3.3.2. Other |
| | 3.4. Use of district heating/cooling | |
| 4. Carbon capture and storage/use[2] | 4.1. Pre-combustion | |
| | 4.2. Oxyfuel combustion | |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption |
| | | 4.3.2. Membrane separation |
| | | 4.3.3. Sorption by solids |
| | | 4.3.4. Carbonate looping |
| | 4.4. Direct capture in production process *(i.e. CALIX process for calcination during cement production)* | |
| 5. Shift to alternative feedstock or intermediate products | 5.1. Shift to alternative chemical agents *(e.g. replace coke/coal by hydrogen to produce sponge iron)* | |
| | 5.2. Shift to alternative non-reactive inputs *(e.g. use recycled aluminium, replace Portland by alternative cement with comparable properties)* | |

[1] Level 3 categorization based on [87]

[2] The storage/use part has not been evaluated

# 4. Assessment scheme

Abatement options are assessed regarding three different dimensions, namely (1) diffusion potential, (2) specific decarbonization potential and (3) technology readiness (see Table 1). On this basis, an "overall relevance" score is assigned based on a defined aggregation scheme (see Table 2).

*Table 1 Overview of assigned scores*

| | | | | | |
|---|---|---|---|---|---|
| ✚ | Low diffusion potential in Switzerland | TRL | Low technology readiness (TRL 1-3) | ? ? ? | No information gathered |
| ✚✚ | Medium diffusion potential in Switzerland | TRL TRL | Medium technology readiness (TRL 4-6) | | |
| ✚✚✚ | High diffusion potential in Switzerland | TRL TRL TRL | High technology readiness (TRL 7-9) | | |
| ☁ | Low specific decarbonisation potential | ★ | Low overall relevance | | |
| ☁☁ | Medium specific decarbonisation potential | ★★ | Medium overall relevance | | |
| ☁☁☁ | High specific decarbonisation potential | ★★★ | High overall relevance | | |

*Table 2 Rating scheme for the "overall relevance" score*

| Specific decarbonization potential | Technology readiness | Diffusion potential in Switzerland | Resulting overall relevance |
|---|---|---|---|
| ☁ | TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★ |
| | TRL TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★★ |
| | TRL TRL TRL | ✚ | ★ |
| | | ✚✚ | ★ |
| | | ✚✚✚ | ★★ |
| ☁☁ | TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★★ |
| | TRL TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★★ |
| | TRL TRL TRL | ✚ | ★ |
| | | ✚✚ | ★★ |
| | | ✚✚✚ | ★★ |
| ☁☁☁ | TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★★★ |
| | TRL TRL | ✚ | n/a (technologies with low TRL must have low diffusion) |
| | | ✚✚ | |
| | | ✚✚✚ | ★★★ |
| | TRL TRL TRL | ✚ | ★★ |
| | | ✚✚ | ★★★ |
| | | ✚✚✚ | ★★★ |

# 5. Sector-technology-matrix

## 5.1. Minerals industry

### *5.1.1. Cement*

#### 5.1.1.1. Overview of processes


Source: [10]–[13]

### 5.1.1.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | ●○○ | ●●● | ●●○ | ★☆☆ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | - | - | - | - |
| | | 1.1.3. Waste heat recovery and use | ●○○ | ●●● | ●●● | ★★☆ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity[3] | 2.1.1. Heat pumps and chillers | - | - | - | - |
| | | 2.1.2. Mechanical vapour recompression | - | - | - | - |
| | | 2.1.3. Electric boilers | - | - | - | - |
| | | 2.1.4. Infrared heaters | - | - | - | - |
| | | 2.1.5. Microwave & radio frequency heaters | - | - | - | - |
| | | 2.1.6. Induction furnaces | - | - | - | - |
| | | 2.1.7. Resistance furnaces | ●●○ | ●●○ | ●●● | ★★☆ |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | ●●○ | ●○○ | ●●● | ★★☆ |
| | | 2.1.10. Other | - | - | - | - |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | ●○○ | ●●○ | ●●● | ★★☆ |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | ●●○ | ●●○ | ●●● | ★★☆ |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | ●●○ | ●●○ | ●●● | ★★☆ |
| | | 3.1.4. Synthetic methane | ●●○ | ●●● | ●●● | ★★☆ |
| | | 3.1.5. Other gaseous synthetic fuels | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | ●●○ | ●●● | ●●○ | ★★☆ |
| | | 3.2.2. Liquid biofuels | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | ●●○ | ●●● | ●●● | ★★☆ |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | ●○○ | ●●● | ●●● | ★★☆ |
| | | 3.3.2. Other | ●○○ | ●●● | ●○○ | ★☆☆ |
| | 3.4. Use of district heating/cooling | | - | - | - | - |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | ●●● | ●●● | ●●● | ★★★ |
| | 4.2. Oxyfuel combustion | | ●●● | ●●● | ●●● | ★★★ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | ●●● | ●●● | ●●● | ★★★ |
| | | 4.3.2. Membrane separation | ●●● | ●●● | ●●● | ★★★ |
| | | 4.3.3. Sorption by solids | ●●● | ●●● | ●●● | ★★★ |
| | | 4.3.4. Carbonate looping | ●●● | ●●● | ●●● | ★★★ |
| | 4.4. Direct capture in production process | | ●●● | ●●● | ●●● | ★★★ |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | ●●○ | ●●● | ●●● | ★★☆ |
| | 5.2. Shift to alternative non-reactive inputs | | ●●○ | ●●● | ●●○ | ★★☆ |

[3] Level 3 categorization based on [87]

### 5.1.1.3. Detailed assessment

| | | |
|---|---|---|
| *Abatement option* | 1. Increase of process/system efficiencies | |
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Raw material preparation, clinker production, cement grinding | Clinker production |
| *Description* | • Energy efficiency measures widely applied in new plants and retrofitted to existing ones [14]<br>• Examples: Improved raw material and cement mills, mechanical transport systems and grate coolers | • Re-use of waste heat from high temperature processes for processes at lower temperatures<br>• Examples: Application of cyclone preheaters to increase temperature of feed entering the kiln by using heat from calcination and sintering process |
| *Abatement potential scope 1 emissions*[4] | • Limited to energy-related emissions<br>• Variable depending on type of efficiency measure | • Introducing cyclone preheaters and precalciners can reduce fuel demand by 0.9 GJ/t of clinker and $CO_2$ emissions by 0.064 $tCO_2$/t of clinker [14] |
| *Technology readiness level*[5] | 9 [14] | 9 [14], [10] |
| *Status in Switzerland* | • Diffusion of the different measurers varies between 16% (better separators for raw material) and 94% (replacing ball mills by vertical roller mills) [14] | • Solutions (e.g. preheaters and precalciners) are mature<br>• Usage of (more efficient) cyclone preheaters varies among Swiss cement plants [14], [10] |

[4] *The abatement potential is often a function of abatement cost, i.e. there is a trade-off between degree of decarbonization and investments or additional energy needed*

[5] *If multiple technologies or processes exist the highest available TRL is shown*

| *Abatement option* | 2. Shift to electricity | | | |
|---|---|---|---|---|
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | | 2.2. Provision of mechanical energy with electricity | 2.3. Enabling chemical reactions with electricity |
| *Technical approach* | 2.1.7. Resistance furnaces | 2.1.9. Plasma technology | 2.2.1. Electrification of combustion engines | |
| *Applicable processes* | Clinker production | Clinker production | Raw material preparation | Clinker production |
| *Description* | • Technical concept for the calcination of finely ground raw meal in electrically heated, steel reactors. Such reactors – compared to traditional kilns – allow for an indirect heating of the meal and thus an efficient direct capture of $CO_2$ (cf 4.4.) [15]<br>• Examples:<br>LEILAC 2 project investigates feasibility of electrifying a reactor located at HeidelbergCement plant in Lixhe, Belgium which currently heats the reactor using natural gas [15] | • Technical concept for heating the raw meal in the calciner or the kiln through plasma torches. Plasma torches use ionized gases (plasma) heated via electric arcs [16], [17]<br>• Examples:<br>Technical concept based on the working parameters of Cementa's cement plant in Slite, Sweden exists [16]. R&D program by the British Mineral Product Association to research the potential use of plasma in the cement and lime industry in more detail [17] | • Raw material typically transported from the quarry to the cement plant via transport belts and/or dumpers (depending on the geographical situation of the site). To date these dumpers are burning fossil fuels | • Lab scale electrochemical synthesis of calcium hydroxide ($Ca(OH)_2$) to produce alite ($3CaO \cdot SiO_2$), the main constituent of Portland cement [18] |
| *Relative abatement potential scope 1 emissions* | • Theoretically all energy-related emissions (up to ~40%)<br>• Theoretically full decarbonization possible by combination with direct capture | • Theoretically all energy-related emissions (up to ~40%) | • 130 t of $CO_2$ per year and dumper [19] | • Theoretically all energy-related emissions (up to ~40%) |
| *Technology readiness level* | 4 [15] | 2 [16], [17]<br>Plasma torches in general commercially available and applied e.g. in selected waste incineration plants | 7 [19] | 4 [18] |
| *Status in Switzerland* | • Low diffusion as not applied commercially yet (see TRL) | • Low diffusion as not applied commercially yet (see TRL) | • One of 40 dumpers in Switzerland electrified [20] in a demonstration project at Vigier quarry in Péry, CH [19] | • Low diffusion as not applied commercially yet (see TRL) |

| *Abatement option* | 3. Shift to alternative fuels | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | | 3.2. Use of biofuels | | 3.3. Use of low carbon fossil fuels | |
| *Technical approach* | 3.1.3. Synthetic hydrogen | 3.1.4. Synthetic methane | 3.2.1. Solid biofuels | 3.2.3. Gaseous biofuels | 3.3.1. Natural gas instead of hard coal or fuel oil | 3.3.2. Other |
| *Applicable processes* | Clinker production | Clinker production | Clinker production | Clinker production | Clinker production | Clinker production |
| *Description* | • Different initiatives to co-fire hydrogen in the burner<br>• <u>Examples</u>:<br>CEMEX Alicante [21] and Rugby plants [22]; Hanson UK port Talbot plant [23], [24] | • The burner can be run on different fuels including (synthetic) methane | • Different types of solid biomass co-fired in cement plants today – from waste wood to animal waste to sewage sludge | • Analog to natural gas (3.3.1.) the burner can be run on gaseous biofuels | • The burner can be run on different fuels including natural gas | • Different types of waste (as e.g. old tires or plastic waste) used globally as substitutes for fossil fuels |
| *Abatement potential scope 1 emissions* | • Theoretically all energy-related emissions (up to ~40%)<br>• In Switzerland coal/coke still make up ~31% of the fuel [25] | • 40% lower $CO_2$ emissions compared to coal in relation to primary energy content [26], [27] (see also 3.3.1.)<br>• In Switzerland coal/coke still make up ~31% of the fuel [25]<br>• Life-cycle emissions of synthetic fuels not considered in the DECARBIN project | • Due to the lower calorific value of biomass full substitution technically challenging [28], substitution above 50% would require changes to the plants [29]<br>• In Switzerland coal/coke still make up ~31% of the fuel [25] | • Theoretically all energy-related emissions (up to ~40%)<br>• In Switzerland coal/coke still make up ~31% of the fuel [25] | • 40% lower $CO_2$ emissions compared to coal in relation to primary energy content [26]<br>• In Switzerland coal/coke still make up ~31% of the fuel [25] | • The abatement potential depends on the baseline fuel mix and the mix of the alternative fuel – in Switzerland coal/coke still make up ~31% of the fuel [25] |
| *Technology readiness level* | >6 [21], [22], [23], [24], [30]<br>TRL TRL TRL | 9 [14], [31], [32]<br>TRL TRL TRL | 9 [25]<br>TRL TRL TRL | 9 [25]<br>TRL TRL TRL | 9 [14], [31], [32]<br>TRL TRL TRL | 9 [25]<br>TRL TRL TRL |
| *Status is Switzerland* | • Low diffusion as not applied commercially yet [25] | • Limited use of gas in Swiss plants [14], [25]<br>• Synthetic methane not used in Switzerland yet [14] | • 16% of the fuel used in Switzerland are solid biofuels (7.5% waste wood, 4.5% dry sewage sludge, 4.2% animal fats and meal), its share has been increasing since 2009 [25] | • Low diffusion as not applied commercially yet [25] | • Limited use of natural gas in Swiss plants [14], [25] | • Widely applied in Swiss plants [25]<br>• Alternative fuels (excl. biofuels) make up 52% [25] |

| *Abatement option* | 4. Carbon capture and storage/use[6] | | | | | | |
|---|---|---|---|---|---|---|---|
| *Underlying rationale* | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | | 4.4. Direct capture in production process |
| *Technical approach* | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4. Carbonate looping | |
| *Applicable processes* | Clinker production | Clinker production | Clinker production | Clinker production | Clinker production | Clinker production | Clinker production |
| *Description* | • On-site production of $CO_2$ and $H_2$ from the original fuel. While the pure $H_2$ can be used as fuel in the burner, the $CO_2$ is captured using physical or chemical absorption technologies (see 4.3.) [33]<br>• Pre-combustion technologies do not bear the potential to capture process-related emissions | • Combustion of fuel in pure $O_2$ leading to higher $CO_2$ concentrations compared to combustion in ambient air improving the efficiency of post combustion processes<br>• Examples:<br>CEMCAP project [34]; ECRA project [35] | • Aqueous solution (e.g. amine or ammonium) used to separate $CO_2$ from flue gas which is regenerated in a second step to release the purified $CO_2$<br>• Alternatively, aqueous solution used to produce by-products from the captured $CO_2$ (e.g. baking soda ($NaHCO_3$) based on a sodium hydroxide solution)<br>• Examples:<br>Capital Aggregates plant, US; Norcem plant, NO; Anhui Conch plant, CN; Dalmia Cement plant, IN [36]; CEMCAP project [34] | • Cascade of membranes used to separate $CO_2$ from the flue gas based on differences in diffusivity<br>• Examples:<br>Norcem plant, NO; MemCCC project, NO [36]; CEMCAP project [34] | • A solid material adsorbs $CO_2$ on its surface and releases it during regeneration<br>• Examples:<br>Norcem plant, NO; LH CO2MENT Colorado project, US; CO2MENT project, CA [36] | • $CO_2$ captured based on reversible carbonation reaction, most commonly the looping of calcium ($CaO + CO_2$ <-> $CaCO_3$)<br>• Examples:<br>Taiwan Cement Company plant, TW; Norcem plant, NO [36]; CEMCAP project[34]; CLEANKER project [34] | • Technical concept for the calcination of finely ground raw meal in electrically heated, steel reactors. Such reactors – compared to traditional kilns – allow for an indirect heating of the meal and thus an efficient direct capture of $CO_2$ [15]<br>• Examples:<br>LEILAC 1 & 2 projects [15] |
| *Abatement potential scope 1 emissions* | • 90% [37] of energy related emissions | • 90% [36], [38] | • 90% [38] | • 90% [36], [38] | • >80% [36] | • 90% [36], [38] | • 95% of process-related emissions are targeted |
| *Technology readiness level* | 9 [33] | 7 [36] | Cement industry: 7 [36]<br>In general: Up to 7 [39] | Cement industry: 8 [36]<br>In general: 9 [40], [39] | Cement industry: 4 [36]<br>In general: Up to 9 [39] | Cement industry: 6 [36]<br>In general: Up to 9 [39] | 7 [15] |
| *Status in Switzerland* | • Low diffusion as not applied commercially yet | | | | | | |

[6] The storage/use part is not analysed in detail here

| *Abatement option* | 5. Shift to alternative feedstock or intermediate products | |
|---|---|---|
| *Underlying rationale* | 5.1. Shift to alternative chemical agents | 5.2. Shift to alternative non-reactive inputs |
| *Technical approach* | 5.1.1 Alternative binders<br>(e.g. alkali-activated & belite-rich Portland) | 5.2.1. Supplementary<br>cementitious materials |
| *Applicable processes* | / | / |
| *Description* | • Replace the clinker and its function rather than trying to reduce the cement's clinker content as done through supplementary cementitious materials (see 5.2.1.)<br>• Produced in a similar way as clinker but from different raw materials reducing the $CO_2$ emissions in the production [41] | • Reducing the $CO_2$ intense clinker content in cement reduces its $CO_2$ intensity<br>• Traditional CEM I Portland cement has a clinker content of 95-100%. CEM II/A and CEM II/B, Portland composite cements, have lower clinker contents of 80-94% and 65-79%, respectively. CEM III blast furnace cement, CEM IV Pozzolanic cements and CEM V Composite cements can have even lower clinker contents [42]<br>• Globally large regional differences observed connected with the availability of supplementary materials |
| *Abatement potential scope 1 emissions* | • Variable depending on type of binder | • Variable depending on mixture of cement: CEM II/A and II/B reduce emission by up to 20 and 35%, respectively, CEM V composite cements even up to 80% [43]<br>• Note: Replacement materials (as e.g. fly-ash) not always available in the regions of cement production, and the different cement types can differ significantly in their properties, e.g. in their strength [42] |
| *Technology readiness level* | 9 [25] | 9 [25] |
| *Status in Switzerland* | • Low diffusion (<3% [25]) | • Use of CEM II/A and II/B in Switzerland has been growing in the past [25], only 7% of the cement produced today is of CEM I type |

### *5.1.2. Ceramics (limited to brick and tile production)*

#### 5.1.2.1. Overview of processes


Source: [44]–[46]

### 5.1.2.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | ●○○ | ●●● | ? ? ? | ★☆☆ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | ●○○ | ●●● | ? ? ? | ★☆☆ |
| | | 1.1.3. Waste heat recovery and use | ●○○ | ●●● | ? ? ? | ★☆☆ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | ●●○ | ●●● | ? ? ? | ★★☆ |
| | | 2.1.2. Mechanical vapour recompression | ●●○ | ●●● | ? ? ? | ★★☆ |
| | | 2.1.3. Electric boilers | - | - | - | - |
| | | 2.1.4. Infrared heaters | - | - | - | - |
| | | 2.1.5. Microwave & radio frequency heaters | ●●○ | ●○○ | + + + | ★★☆ |
| | | 2.1.6. Induction furnaces | - | - | - | - |
| | | 2.1.7. Resistance furnaces | - | - | - | - |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | - | - | - | - |
| | | 2.1.10. Other | ●●○ | ●○○ | + + + | ★★☆ |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | - | - | - | - |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | ●●● | ? ? ? | + + + | ★★★ |
| | | 3.1.2. Other liquid synthetic fuels | ●●● | ? ? ? | + + + | ★★★ |
| | | 3.1.3. Synthetic hydrogen | ●●● | ? ? ? | + + + | ★★★ |
| | | 3.1.4. Synthetic methane | ●●● | ●●● | + + + | ★★★ |
| | | 3.1.5. Other gaseous synthetic fuels | ●●● | ? ? ? | + + + | ★★★ |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | - | - | - | - |
| | | 3.2.2. Liquid biofuels | ●●● | ? ? ? | + + + | ★★★ |
| | | 3.2.3. Gaseous biofuels | ●●● | ●●● | + + + | ★★★ |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | - | - | - | - |
| | | 3.3.2. Other | - | - | - | - |
| | 3.4. Use of district heating/cooling | | - | - | - | - |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | ●●○ | ●●● | + + + | ★★☆ |
| | 4.2. Oxyfuel combustion | | ●●○ | ●●● | + + + | ★★☆ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | ●●○ | ●●● | + + + | ★★☆ |
| | | 4.3.2. Membrane separation | ●●○ | ●●● | + + + | ★★☆ |
| | | 4.3.3. Sorption by solids | ●●○ | ●●● | + + + | ★★☆ |
| | | 4.3.4. Carbonate looping | ●●○ | ●●● | + + + | ★★☆ |
| | 4.4. Direct capture in production process | | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | ●●○ | ●●● | ? ? ? | ★★☆ |
| | 5.2. Shift to alternative non-reactive inputs | | ●●○ | ●●● | ? ? ? | ★★☆ |

### 5.1.2.3. Detailed assessment

| | | | |
|---|---|---|---|
| *Abatement option* | 1. Increase of process/system efficiencies | | |
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.2. Process innovation for energy efficiency and process intensification | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Burning | Burning, drying | Burning |
| *Description* | • Optimization of kiln furniture for production of roof tiles [47] as lighter equipment leads to less heat leaving the kiln | • Separation of burner and dryer allowing for electrification of drying process and lowering energy demand for burning (in combination with heat pumps, cf. 2.1.1.) [47] | • Preheating of combustion air to reduce fuel demand [47], [48] |
| *Abatement potential scope 1 emissions* | • Only incremental improvements for energy-related emissions | • Only incremental improvements for energy-related emissions | • Incremental improvements for energy-related emissions [48] |
| *Technology readiness level* | 9 [47] | 9 [47] | 9 [47] |
| *Status in Switzerland* | • No information available | • No information available | • No information available |

| *Abatement option* | 2. Shift to electricity | | | |
|---|---|---|---|---|
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | | | |
| *Technical approach* | 2.1.1. Heat pumps and chillers | 2.1.2. Mechanical vapour recompression | 2.1.5. Microwave and radio frequency heaters | 2.1.10. Other |
| *Applicable processes* | Drying | Drying | Drying | Burning |
| *Description* | • Electrification of drying of wet, pressed bricks and tiles reduces fuel demand in the burner section as hot air can be reused in the burner instead of being fed into the dryer [49] | • Used to upgrade waste steam | • Microwave heating allows for an electrification of the drying process for simple geometries [50], [46], [44], [51] | • Electrification of the burning process. No commercial or pilot projects [46], [52]<br>• Different electrifications pathways are conceivable, e.g. resistance furnaces (cf. 2.1.7.), including hybrid solutions in combination with alternative fuels (cf 4.) [47] |
| *Relative abatement potential scope 1 emissions* | • Reduction of burner's fuel demand [49]<br>$CO_2$ $CO_2$ $CO_2$ | • Variable – parts of the energy related emissions<br>$CO_2$ $CO_2$ $CO_2$ | • Reduction of burner's fuel demand<br>$CO_2$ $CO_2$ $CO_2$ | • Elimination of burner's fuel demand<br>$CO_2$ $CO_2$ $CO_2$ |
| *Technology readiness level* | Depending on temperature level<br>9 [53]<br>TRL TRL TRL | 9<br>TRL TRL TRL | 1-3 [46]<br>TRL TRL TRL | 2 [52]<br>TRL TRL TRL |
| *Status in Switzerland* | • No information available<br>? ? ? | • No information available<br>? ? ? | • Low diffusion as not applied commercially yet (see TRL) | • Low diffusion as not applied commercially yet (see TRL) |

| *Abatement option* | 3. Shift to alternative fuels | | | | | | |
|---|---|---|---|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | | | | | 3.2. Use of biofuels | |
| *Technical approach* | 3.1.1. Synthetic methanol | 3.1.2. Other liquid synthetic fuels | 3.1.3. Synthetic hydrogen | 3.1.4. Synthetic methane | 3.1.5. Other gaseous synthetic fuels | 3.2.2. Liquid biofuels | 3.2.3. Gaseous biofuels |
| *Applicable processes* | Burning, drying | Burning, drying | Burning, drying | Burning, drying | Burning, drying | Burning, drying | Burning, drying |
| *Description* | • Replacing the current fuel (mostly gas) by any synthetic liquid or gaseous fuel<br>• Depending on the fuel, changes to the process have to be made to counteract unintended effects as e.g. changes in colour | | | | | • Replacing the current fuel (mostly gas) by any liquid or gaseous biofuel<br>• Depending on the fuel, changes to the process have to be made to counteract unintended effects as e.g. changes in colour | |
| *Abatement potential scope 1 emissions* | • All energy-related emissions | | | | | | |
| *Technology readiness level* | ? ? ? | ? ? ? | ? ? ? | 9 [46], [45]<br>TRL TRL TRL | ? ? ? | ? ? ? | 9<br>TRL TRL TRL |
| *Status is Switzerland* | • Low diffusion as not applied commercially yet<br>• Today, fuel mix is dominated by gas and fuel oil leading to emissions of ca. 0.2 t of $CO_2$ per t of brick produced [25], [54], [55], [56] | | | | | • Low diffusionToday, fuel mix is dominated by gas and fuel oil leading to emissions of ca. 0.2 t of $CO_2$ per t of brick produced[25], [54], [55], [56] | |

| *Abatement option* | 4. Carbon capture and storage/use | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | |
| *Technical approach* | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4 Calcium looping |
| *Applicable processes* | Burning, drying | Burning, drying | Burning, drying | Burning, drying | Burning, drying | Burning, drying |
| *Description* | • The CCS solutions discussed in 4.1.-4.3. for the cement industry can be similarly applied to the ceramics industry and more specifically to the production of bricks and tiles. Compared to the cement industry, however, the flue gases typically have lower $CO_2$ contents leading to higher specific energy demands for the regeneration. As for the cement industry, low-temperature waste energy is available for recovery [48], [57]. Due to in average smaller installations, economics of CCS in the ceramics industry are expected less favourable<br>• Note: The applicability of CCS to the flue gas stream of different industry processes mainly depends on its $CO_2$ concentration, temperature and the concentration of impurities [58] as well as the availability of waste heat and the dispersion of the flue gas sources | | | | | |
| *Abatement potential scope 1 emissions* | • Typically 90% or more [36], [37] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | • Typically 90% or more [36], [37] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size |
| *Technology readiness level* | In general (not specific to ceramics production): 9 [33] | In general (not specific to ceramics production): 7 [36] | In general (not specific to ceramics production): 9 [40], [39] | In general (not specific to ceramics production): Up to 9 [39] | In general (not specific to ceramics production): Up to 9 [39] | In general (not specific to ceramics production): Up to 7 [39] |
| *Status is Switzerland* | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet |

| *Abatement option* | 5. Shift to alternative feedstock or intermediate products | |
|---|---|---|
| *Underlying rationale* | 5.1. Shift to alternative chemical agents | 5.2. Shift to alternative non-reactive inputs |
| *Technical approach* | 5.1.1. Biogenic pore-forming agents | 5.2.1. Alternative tones |
| *Applicable processes* | Burning | Burning |
| *Description* | • In brick manufacturing pore-forming agents used to reduce thermal conductivity. Today both fossil (e.g. polystyrene-based) and renewable (e.g. sawdust) agents used [47], [59], [60] | • Reduces process-related emissions from calcination (cf. cement production) and subsequently leads to lower energy-related emissions as less energy for calcination is needed [47] |
| *Abatement potential scope 1 emissions* | • Depends on the currently used agents | • Depends on the currently used tones and its replacement |
| *Technology readiness level* | 9 [47], [59], [60]<br>TRL TRL TRL | 9 (see 5.1.2)<br>TRL TRL TRL |
| *Status in Switzerland* | • No information available<br>? ? ? | • No information available<br>? ? ? |

## 5.2. Chemicals industry

### *5.2.1. Lower olefins*

#### 5.2.1.1. Overview of processes


Source: [61], [62]

### 5.2.1.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | 1/3 | 3/3 | +++ | ★★☆ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | 2/3 | 2/3 | +++ | ★★☆ |
| | | 1.1.3. Waste heat recovery and use | 1/3 | 3/3 | ??? | ★☆☆ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | 1/3 | 3/3 | ??? | ★☆☆ |
| | | 2.1.2. Mechanical vapour recompression | 1/3 | 3/3 | ??? | ★☆☆ |
| | | 2.1.3. Electric boilers | - | - | - | - |
| | | 2.1.4. Infrared heaters | - | - | - | - |
| | | 2.1.5. Microwave & radio frequency heaters | - | - | - | - |
| | | 2.1.6. Induction furnaces | - | - | - | - |
| | | 2.1.7. Resistance furnaces | - | - | - | - |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | 3/3 | 2/3 | +++ | ★★★ |
| | | 2.1.10. Other | 3/3 | 2/3 | +++ | ★★★ |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | 3/3 | 1/3 | +++ | ★★★ |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | 3/3 | 3/3 | +++ | ★★★ |
| | | 3.1.4. Synthetic methane | - | - | - | - |
| | | 3.1.5. Other gaseous synthetic fuels | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | - | - | - | - |
| | | 3.2.2. Liquid biofuels | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | - | - | - | - |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | - | - | - | - |
| | | 3.3.2. Other | - | - | - | - |
| | 3.4. Use of district heating/cooling | | - | - | - | - |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | 2/3 | 3/3 | +++ | ★★☆ |
| | 4.2. Oxyfuel combustion | | 2/3 | 3/3 | +++ | ★★☆ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | 2/3 | 3/3 | +++ | ★★☆ |
| | | 4.3.2. Membrane separation | 2/3 | 3/3 | +++ | ★★☆ |
| | | 4.3.3. Sorption by solids | 2/3 | 3/3 | +++ | ★★☆ |
| | | 4.3.4. Carbonate looping | 2/3 | 3/3 | +++ | ★★☆ |
| | 4.4. Direct capture in production process | | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | 5.1.1. Ethane | 2/3 | 3/3 | ??? | ★★☆ |
| | | 5.1.2. Methanol | 1/3 | 3/3 | +++ | ★★☆ |
| | 5.2. Shift to alternative non-reactive inputs | | - | - | - | - |

### 5.2.1.3. Detailed assessment

| *Abatement option* | 1. Increase of process/system efficiencies | | |
|---|---|---|---|
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.2. Process innovation for energy efficiency and process intensification | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Pyrolysis, primary fractionation, gas clean-up, co-product fractionation | Pyrolysis | Pyrolysis, primary fractionation, gas clean-up, co-product fractionation |
| *Description* | • Typically ethylene ($C_2H_4$) and other olefins produced through thermal cracking of fossil feedstock by steam at temperatures of up 1000°C produced through burning of fossil fuels<br>• Production takes place in complex multi-stage facilities which can be divided into four stages: (1) pyrolysis, (2) primary fractionation, (3) gas clean-up and (4) co-product fractionation [62]<br>• All European steam crackers apply any form of insulation to reduce energy consumption and all operators claim to use efficient fractionation columns [62]<br>• Level of efficiency not only depends on the equipment used but also on how the plants are operated | • Catalytic cracking applied globally as alternative to the traditional thermal steam cracking [63], [64], especially for the cracking of crude oil<br>• Different catalytic processes lead to different ethylene – propylene ratios | • Hydrocarbons fed into steam cracker typically preheated in heat exchangers using waste heat [62]<br>• All European steam crackers make use of condensate recycling to reduce energy demand associated with steam production [62]<br>• Reduction of energy demand through preheating of combustion air [62] |
| *Abatement potential scope 1 emissions* | • Significant room for improvement in terms of fuel consumption for refinery processes in Switzerland when comparing consumption to best available technologies (BAT) [65] | • Significant abatement potential (10-20% [63]) | • Fuel saving potential of up to 62% for refining processes in Switzerland with the majority of savings going back to heat recovery [65] |
| *Technology readiness level* | 9 [62], [66] | 9 [63], [67] | 9 [65] |
| *Status in Switzerland* | • Past reduction of energy demand of Lonza's Visp cracker by 6800 MWh/a [68]<br>• Though thermal steam cracking will always be energy intense due to the high temperatures needed to crack long hydrocarbons, the discrepancy with the BAT mentioned in [65] points towards an abatement potential in Switzerland | • Low diffusion as not applied commercially yet | • No information available |

| *Abatement option* | 2. Shift to electricity | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | | | | | 2.3. Enabling chemical reactions with electricity |
| *Technical approach* | 2.1.1. Heat pumps and chillers | 2.1.2. Mechanical vapour recompression | 2.1.9. Plasma technology | 2.1.10. Others | | |
| *Applicable processes* | Pyrolysis, primary fractionation, gas clean-up, co-product fractionation | Pyrolysis, primary fractionation, gas clean-up, co-product fractionation | Pyrolysis | Pyrolysis | Pyrolysis | Pyrolysis |
| *Description* | • Heat pumps used to pre-heat feedstock and other material streams (see also 1.1.3.) | • Used to upgrade waste steam [62] | • Plasma-assisted production of olefins from rich-in-methane gas can yield lower (life cycle) emissions than traditional production via steam cracking of naphtha<br>• Plasma-assisted electrification of cracking process demonstrated on lab scale [69] | • Contrary to traditional steam cracking process, the RDR technology developed by the company Coolbrook uses an electricity propelled turbomachine for direct heating of the feed [70], [71]<br>• Pilot currently built in Geleen, NL | • BASF eFurnace process supposed to electrify the steam cracking process [72]<br>• DOW and Shell work on electric cracking processes as well [73] | • Instead of breaking bonds using thermal energy (steam cracking), electrochemical processes foresee breaking the hydrocarbons electrochemically resulting in a switch to electricity [74] |
| *Abatement potential scope 1 emissions* | • Variable – parts of the energy related emissions | • Variable – parts of the energy related emissions | • Theoretically all energy-related emissions<br>• Potential limited based on flue gas concentration and avg. installation size | • All energy-related emissions<br>• Potential limited based on flue gas concentration and avg. installation size | • All energy-related emissions<br>• Potential limited based on flue gas concentration and avg. installation size | • All energy-related emissions<br>• Potential limited based on flue gas concentration and avg. installation size |
| *Technology readiness level* | Depending on temperature level<br>9 [53] | 9 [62] | 4 [75] | 4 [70], [71] | n/a [72], [73]<br>? ? ? | 1-3 [74] |
| *Status in Switzerland* | • No information available<br>? ? ? | • No information available<br>? ? ? | • Low diffusion as not applied commercially yet (see TRL) | • Low diffusion as not applied commercially yet (see TRL) | • Low diffusion as not applied commercially yet (see TRL) | • Low diffusion as not applied commercially yet (see TRL) |

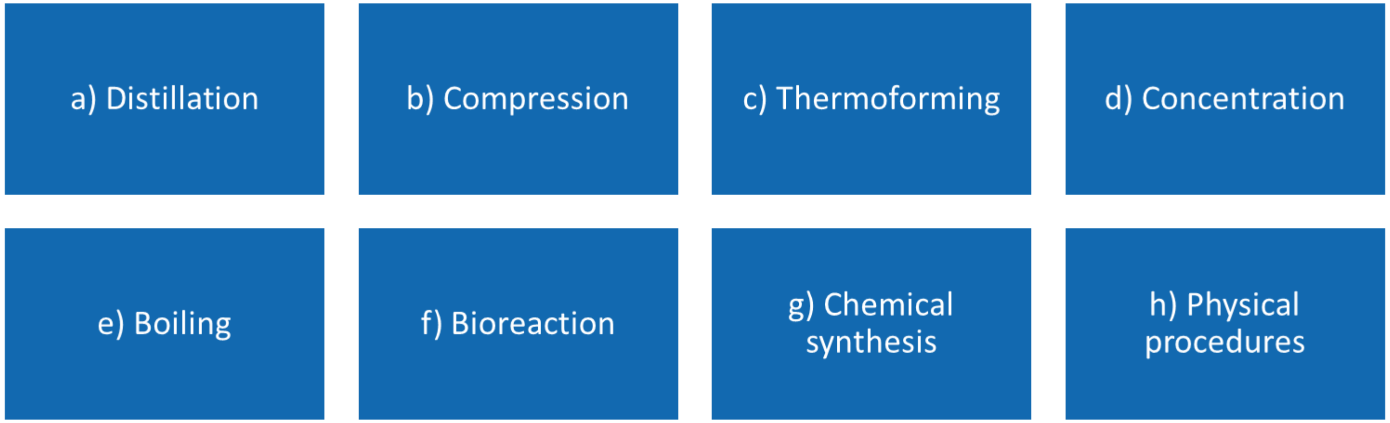
| *Abatement option* | 3. Shift to alternative fuels | 4. Carbon capture and storage/use | | | | | |
|---|---|---|---|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | |
| *Technical approach* | 3.1.3. Synthetic hydrogen | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4 Calcium looping |
| *Applicable processes* | Pyrolysis | Pyrolysis | Pyrolysis | Pyrolysis | Pyrolysis | Pyrolysis | Pyrolysis |
| *Description* | • Typically, by-products from the steam cracking process are recycled to be used as fuel in the cracking process, i.e. hydrogen and fuel gases are separated from the desired products (e.g. ethylene) and then fed back to the burner, where they are combusted emitting greenhouse gases<br>• To date no steam cracker operates on 100% hydrogen (though 100% hydrogen burners in principle available). In case of a hydrogen share of 100%, alternatives for the non-hydrogen by-products have to be identified | • The CCS solutions discussed in 4.1.-4.3. for the cement industry can be similarly applied to the chemicals industry and more specifically to the production of olefins in steam crackers. Compared to the cement industry, however, the flue gases from steam crackers typically have lower $CO_2$ contents – depending on the fuel used – leading to higher specific energy demands for the regeneration. As for the cement industry, low-temperature waste energy is available for recovery [57], [76]<br>• Note: The applicability of CCS to the flue gas stream of different industry processes mainly depends on its $CO_2$ concentration, temperature and the concentration of impurities [58] as well as the availability of waste heat and the dispersion of the flue gas sources | | | | | |
| *Abatement potential scope 1 emissions* | • Significant reduction of greenhouse gases possible [77] esp. given the high temperatures (~850°C) at which steam crackers are operated and the enormous energy demand associated with the provision of this thermal energy<br>• Replacing fuel gases by hydrogen reduces energy related emissions to zero | • Typically 90% or more [36], [37], [38] (see chapter on cement industry) | | | | | |
| *Technology readiness level* | 9 (though not demonstrated for steam cracker) | In general (not specific to olefin production): 9 [33] | In general (not specific to olefin production): 7 [36] | In general (not specific to olefin production): 9 [39], [40] | In general (not specific to olefin production): Up to 9 [39] | In general (not specific to olefin production): Up to 9 [39] | In general (not specific to olefin production): Up to 7 [39] |
| *Status is Switzerland* | • Not yet applied in Switzerland so far<br>• The Swiss Visp cracker uses by-products from the cracking process to fuel its burner [27] | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet |

| *Abatement option* | 5. Shift to alternative feedstock or intermediate products | |
|---|---|---|
| *Underlying rationale* | | |
| *Technical approach* | 5.1.1. Ethane | 5.1.2. Methanol |
| *Applicable processes* | Pyrolysis | Pyrolysis |
| *Description* | • Today the choice of feedstock for the olefin production depends heavily on its abundance and price. While naphtha is the predominant feedstock in e.g. Europe and China, in the US and the Middle East ethane is dominating [78], [79]<br>• It is important to note that the type of feedstock influences the yield of ethylene and by-products. Steam cracking of ethane is reported to yield 80-84 wt% ethylene and typically 82 wt% high value chemicals (HVCs) whereas naphtha crackers only yield 29-34 wt% ethylene and 55 wt% HVCs [61] | • The methanol-to-olefins (MTO) process is a catalytic process to produce olefins. Though not used in Europe, ca. 20% of China's ethylene capacity is MTO based with parts of the methanol produced from coal (coal-to-olefins or CTO) [80] |
| *Abatement potential scope 1 emissions* | • Specific $CO_2$ emissions (t $CO_2$/ t HVC) of olefins production via ethane roughly 30% lower compared to the production via naphtha (1.0-1.2 compared to 1.6-1.8 t $CO_2$/ t HVCs) [61] | • The specific energy consumption of state-of-the-art conversion of methanol to HVCs (5-8 GJ/t HVCs) can be lower than that of the steam cracking process based on naphtha (8 GJ/t HVCs) or ethane (9 GJ/t HVCs) [81]<br>• Though the MTO route allows to reduce life cycle emissions of olefin production significantly through low $CO_2$ methanol (see e.g. 5.1.3.), the abatement potential for the industrial production system is limited |
| *Technology readiness level* | 9 [78], [79] | 9 [77] |
| *Status in Switzerland* | • The only Swiss steam cracker can run on butane, naphtha or propane. No detailed information on fuel use available [82]<br>? ? ? | • Neither deployed in Switzerland nor in the rest of Europe [83] |

### *5.2.2. Other chemicals*

#### 5.2.2.1. Overview of processes (excluding olefins and Niacin)

While for the other examined industries, the high homogeneity of products and small number of processes allows for an analysis of specific processes (e.g. shaping, drying and burning for ceramics), this approach reaches its limits for the chemicals industry which is characterized by a high heterogeneity of products and processes. For chemicals, we are instead looking at a set of generic processes (e.g. distillation) that are part of many different process chains used to produce a multitude of products.




Source: [84]–[86]

### 5.2.2.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | ●●○ | ●●● | ●●● | ★★★ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | - | - | - | - |
| | | 1.1.3. Waste heat recovery and use | ●●○ | ●●● | ●●● | ★★★ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | ●●● | ●●● | ●●● | ★★★ |
| | | 2.1.2. Mechanical vapour recompression | ●●● | ●●● | ●●● | ★★★ |
| | | 2.1.3. Electric boilers | ●●● | ●●● | ●●● | ★★★ |
| | | 2.1.4. Infrared heaters | - | - | - | - |
| | | 2.1.5. Microwave & radio frequency heaters | - | - | - | - |
| | | 2.1.6. Induction furnaces | - | - | - | - |
| | | 2.1.7. Resistance furnaces | ●●● | ●●● | ●●● | ★★★ |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | - | - | - | - |
| | | 2.1.10. Other | | | | |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | 2.3.1. Electrolysis | ●●● | ●●● | ●●● | ★★★ |
| | | 2.3.2. Electrochemical processes | ●●● | ●○○ | ●●● | ★★★ |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | ●●● | ●●● | ●●● | ★★★ |
| | | 3.1.4. Synthetic methane | ●●● | ●●● | ●●● | ★★★ |
| | | 3.1.5. Other gaseous synthetic fuels | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | ●●○ | ●●● | ●●● | ★★★ |
| | | 3.2.2. Liquid biofuels | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | ●●● | ●●● | ●●● | ★★★ |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | ●○○ | ●●● | ●○○ | ★★☆ |
| | | 3.3.2. Other | - | - | - | - |
| | 3.4. Use of district heating/cooling | | ●●● | ●●● | ●○○ | ★★☆ |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | ●●○ | ●●● | ●●● | ★★☆ |
| | 4.2. Oxyfuel combustion | | ●●○ | ●●● | ●●● | ★★☆ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | ●●○ | ●●● | ●●● | ★★☆ |
| | | 4.3.2. Membrane separation | ●●○ | ●●● | ●●● | ★★☆ |
| | | 4.3.3. Sorption by solids | ●●○ | ●●● | ●●● | ★★☆ |
| | | 4.3.4. Carbonate looping | ●●○ | ●●● | ●●● | ★★☆ |
| | 4.4. Direct capture in production process | | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | - | - | - | - |
| | 5.2. Shift to alternative non-reactive inputs | | - | - | - | - |

### 5.2.2.3. Detailed assessment

| | | |
|---|---|---|
| *Abatement option* | 1. Increase of process/system efficiencies | |
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Distillation, compression, thermoforming, concentration, boiling, bioreactions, other physical procedures | Distillation, compression, thermoforming, concentration, boiling, other physical procedures |
| *Description* | • Fuel savings through use of more efficient heating and steam production (e.g. burners, boilers and insulation) | • Fuel savings through heat recovery from among others flue gases, product streams and motor systems [66] (see also 2.1.1. and 2.1.2.) |
| *Abatement potential scope 1 emissions* | • Depends on the specific measure and the fuel used today<br>$CO_2$ $CO_2$ $CO_2$ | • Depends on the specific measure and the fuel used today (see also 2.1.1. and 2.1.2.)<br>$CO_2$ $CO_2$ $CO_2$ |
| *Technology readiness level* | 9 [66]<br>TRL TRL TRL | 9 [66]<br>TRL TRL TRL |
| *Status in Switzerland* | • 26% (~1400 TJ p.a.) of the total energy efficiency potential in the Swiss chemical and pharmaceutical industry [66] | • 34% (~1400 TJ p.a.) of the total energy efficiency potential in the Swiss chemical and pharmaceutical industry [66] |

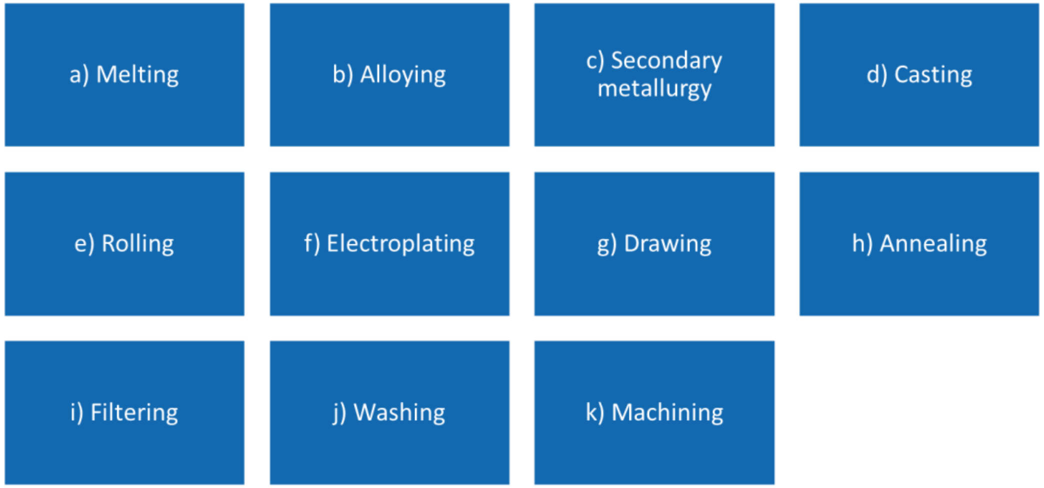
| *Abatement option* | 2. Shift to electricity | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | | | | 2.3. Enabling chemical reactions with electricity | |
| *Technical approach* | 2.1.1. Heat pumps and chillers | 2.1.2. Mechanical vapour recompression | 2.1.3. Electric boilers | 2.1.7. Resistance furnaces | 2.3.1. Electrolysis | 2.3.2. Electrochemical processes |
| *Applicable processes* | Distillation (100 °C - 300 °C), compression (110 °C - 170 °C), thermoforming (130 °C - 160 °C), concentration (120 °C - 140 °C), boiling (80 °C - 110 °C), bioreactions (20 °C - 60 °C), other physical procedures [53] | | | Distillation (100 °C - 300 °C), compression (110 °C – 170 °C), thermoforming (130 °C - 160 °C) [53] | Chemical synthesis | Chemical synthesis |
| *Description* | • Heat pumps used to provide heat for chemical reactions or physical procedures using waste heat, ambient heat from the air or the ground as well as solar heat produced for this purpose | • Used to upgrade waste steam [62] | • Substitution of fossil fuel based heat and steam provision by electric boilers | • Substitution of fossil fuel based heat provision by resistance furnaces | • On-site production of hydrogen via electrolysis instead of steam methane reforming which is highly endothermic and produces process-related $CO_2$ emissions (water-gas shift reaction)[73] [73] | • E.g. electrochemical rather than thermochemical synthesis of ammonia [74] |
| *Abatement potential scope 1 emissions* | • Variable – parts of the energy related emissions<br>• Potential depends on process | • Variable – parts of the energy related emissions<br>• Potential depends on process | • Variable – parts of the energy related emissions<br>• Potential depends on process | • Variable – parts of the energy related emissions Potential depends on process | • Both energy- and process-related emissions | • Parts of the energy related emissions |
| *Technology readiness level* | Depending on temperature level<br>9 [53], [87]<br>TRL TRL TRL | 9 [62][62], [87]<br>TRL TRL TRL | 9 [87]<br>TRL TRL TRL | 9 [87]<br>TRL TRL TRL | 9<br>TRL TRL TRL | 1-3 [74]<br>TRL TRL TRL |
| *Status in Switzerland* | • So far only 35% of the sectors total energy demand is provided by electricity [88]<br>• Today, thermal energy supply is dominated by gas, district heating and biomass [56]<br>• Heat pumps not widely applied in Switzerland yet | | • So far only 35% of the sectors total energy demand is provided by electricity [88]<br>• Today, fuel mix is dominated by electricity, gas, district heating and biomass [56] | | | |

| *Abatement option* | 3. Shift to alternative fuels | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | | 3.2. Use of biofuels | | 3.3. Use of low carbon fossil fuels | 3.4. District heating /cooling |
| *Technical approach* | 3.1.3. Synthetic hydrogen | 3.1.4. Synthetic methane | 3.2.1. Solid biofuels | 3.2.3. Gaseous biofuels | 3.3.1. Natural gas instead of hard coal or fuel oil | |
| *Applicable processes* | Distillation, compression, thermoforming, concentration, boiling, bioreactions | | | | | |
| *Description* | • Replacement of fossil fuels by hydrogen for heat and steam generation | • Replacement of natural gas (~55% of thermal energy in the chemicals industry in 2019) or industrial waste (~28% of thermal energy) by synthetic methane [88] | • Replacement of natural gas (~55% of thermal energy in the chemicals industry in 2019) or industrial waste (~28% of thermal energy) by solid biofuels via on-site cogeneration plants [88] | • Replacement of natural gas (~55% of thermal energy in the chemicals industry in 2019) or industrial waste (~28% of thermal energy) by gaseous biofuels [88] | • Replacement of fuel oil (~4% of thermal energy in chemicals industry in 2019) by natural gas [88] | • Replacement of local fossil fuel based heat and steam production by district heating |
| *Abatement potential scope 1 emissions* | • Full abatement of all energy related emissions (though associated with changes in infrastructure when switching from gas) | • Full abatement of all energy related emissions | • Potential limited by the size of the industrial site<br>• Potential limited to production in cogeneration plant. Individual gas burners cannot be switched to solid biomass | • Full abatement of all energy related emissions | • ~25% lower $CO_2$ emissions for natural gas compared to fuel oil [27] | • Full abatement of the energy related emissions of rather low temperature processes<br>• $CO_2$ emissions from cogeneration plants outside the industrial production system not taken into account in the DECARBIN project [88] |
| *Technology readiness level* | 9 | 9 | 9 | 9 | 9 | 9 |
| *Status is Switzerland* | • 55% of thermal energy in chemicals industry provided by natural gas and 28% by industrial waste [88]<br>• Low diffusion as not applied in Switzerland yet | • 55% of thermal energy in chemicals industry provided by natural gas and 28% by industrial waste [88] | • 55% of thermal energy in chemicals industry provided by natural gas and 28% by industrial waste [88] | • 55% of thermal energy in chemicals industry provided by natural gas and 28% by industrial waste [88] | • 4% of thermal energy in the chemicals industry provided by fuel oil [88] | • Potential depends on the temperature levels needed and the temperature levels at which district heating networks can provide steam |

| *Abatement option* | 4. Carbon capture and storage/use | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | |
| *Technical approach* | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4 Calcium looping |
| *Applicable processes* | Distillation, compression, thermoforming, concentration, boiling, bioreactions | | | | | |
| *Description* | • The CCS solutions discussed in 4.1.-4.3. for the cement industry can be similarly applied to the chemicals and pharmaceuticals industry. Compared to the cement industry, however, the flue gases typically have lower $CO_2$ contents leading to higher specific energy demands for the regeneration. Due to in average smaller installations, economics of CCS in the ceramics industry are expected less favourable<br>• Note: The applicability of CCS to the flue gas stream of different industry processes mainly depends on its $CO_2$ concentration, temperature and the concentration of impurities [58] as well as the availability of waste heat and the dispersion of the flue gas sources | | | | | |
| *Abatement potential scope 1 emissions* | • Typically 90% or more [36], [37] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | • Typically 90% or more [36], [37] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat |
| *Technology readiness level* | In general (not specific to chemicals production): 9 [33] | In general (not specific to chemicals production): 7 [36] | In general (not specific to chemicals production): 9 [40], [39] | In general (not specific to chemicals production): Up to 9 [39] | In general (not specific to chemicals production): Up to 9 [39] | In general (not specific to chemicals production): Up to 7 [39] |
| *Status is Switzerland* | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet | • Low diffusion as not applied commercially yet |

## 5.3. Metals industry

### 5.3.1.1. Overview of processes




Source: [89]–[91]

### 5.3.1.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | ●●○ | ●●● | ●●● | ●●○ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | ●●○ | ●●● | ●●● | ●●○ |
| | | 1.1.3. Waste heat recovery and use | ●●○ | ●●● | ●○○ | ●○○ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | - | - | - | - |
| | | 2.1.2. Mechanical vapour recompression | - | - | - | - |
| | | 2.1.3. Electric boilers | - | - | - | - |
| | | 2.1.4. Infrared heaters | - | - | - | - |
| | | 2.1.5. Microwave & radio frequency heaters | - | - | - | - |
| | | 2.1.6. Induction furnaces | ●●● | ●●● | ●○○ | ●●○ |
| | | 2.1.7. Resistance furnaces | - | - | - | - |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | ●●○ | ●○○ | ●●● | ●●○ |
| | | 2.1.10. Other | - | - | - | - |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | - | - | - | - |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | ●●● | ●●● | ●●● | ●●● |
| | | 3.1.4. Synthetic methane | ●●● | ●●● | ●●● | ●●● |
| | | 3.1.5. Other gaseous synthetic fuels | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | - | - | - | - |
| | | 3.2.2. Liquid biofuels | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | ●●● | ●●● | ●●● | ●●● |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | - | - | - | - |
| | | 3.3.2. Other | - | - | - | - |
| | 3.4. Use of district heating/cooling | | - | - | - | - |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | ●●○ | ●●● | ●●● | ●●○ |
| | 4.2. Oxyfuel combustion | | ●●○ | ●●● | ●●● | ●●○ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | ●●○ | ●●● | ●●● | ●●○ |
| | | 4.3.2. Membrane separation | ●●○ | ●●● | ●●● | ●●○ |
| | | 4.3.3. Sorption by solids | ●●○ | ●●● | ●●● | ●●○ |
| | | 4.3.4. Carbonate looping | ●●○ | ●●● | ●●● | ●●○ |
| | 4.4. Direct capture in production process | | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | - | - | - | - |
| | 5.2. Shift to alternative non-reactive inputs | | - | - | - | - |

### 5.3.1.3. Detailed assessment

| | | | |
|---|---|---|---|
| *Abatement option* | 1. Increase of process/system efficiencies | | |
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.2. Process innovation for energy efficiency and process intensification | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Melting, casting, rolling, machining (selection) | Casting | Melting, casting, rolling, machining (selection) |
| *Description* | • A number of efficiency measures could potentially lower the electricity and fuel demand in Swiss facilities, e.g. improved kilns, furnaces and burners [89] | • Near net shape casting allows saving energy associated with reheating and rolling of the metal, one example being strip casting where the metal is cast into a thin strip, eliminating the need for rolling [89] | • A number of efficiency measures could potentially lower the electricity and fuel demand in Swiss facilities, e.g. recuperative burners, scrap preheating [89] |
| *Abatement potential scope 1 emissions* | • Depends on type of measure and the baseline technology used<br>• In a comparison with secondary steel facilities in other European countries, the Swiss metals sector is relatively energy efficient [89] | • Depends on the current energy demand associated with reheating and rolling | • Depends on type of measure and the baseline technology used<br>• In a comparison with secondary steel facilities in other European countries, the Swiss metals sector is relatively energy efficient [89] |
| *Technology readiness level* | 9 [89] | 9 [89] | 9 [89] |
| *Status in Switzerland* | • Low diffusion as often not applied in Switzerland<br>• Depends on type of measure<br>• No information available for some measures | • Low diffusion as not applied in Switzerland yet [89] | • Depends on type of measure<br>• No information available for some measures |

| | | |
|---|---|---|
| *Abatement option* | 2. Shift to electricity | |
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | |
| *Technical approach* | 2.1.6. Induction furnace | 2.1.9. Plasma technology |
| *Applicable processes* | Melting | Melting, annealing (selection) |
| *Description* | • Replacement of coal-based cupola furnaces by induction furnaces in foundries [89] | • Plasma torches could replace fossil fuel burners at different production steps in the metals industry |
| *Abatement potential scope 1 emissions* | • All energy-related emissions of respective processes possible | • Large parts of the energy-related emissions |
| *Technology readiness level* | 9 [89] | 2 [16], [17]<br>Plasma torches in general are commercially available but not used in the metals industry |
| *Status in Switzerland* | • Ca. 75% of the 14 Swiss iron foundries already use induction furnaces [27] | • Not applied commercially (see TRL) |

| *Abatement option* | 3. Shift to alternative fuels | | |
|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | | 3.2. Use of biofuels |
| *Technical approach* | 3.1.3. Synthetic hydrogen | 3.1.4. Synthetic methane | 3.2.3. Gaseous biofuels |
| *Applicable processes* | Melting, annealing (selection) | Melting, annealing (selection) | Melting, annealing (selection) |
| *Description* | • Hydrogen could replace fossil fuels in burners at different production steps in the metals industry | • Synthetic methane could replace fossil fuels in burners at different production steps in the metals industry | • Gaseous biofuels could replace fossil fuels in burners at different production steps in the metals industry |
| *Abatement potential scope 1 emissions* | • All energy-related emissions going back to burners | • All energy-related emissions going back to burners | • All energy-related emissions going back to burners |
| *Technology readiness level* | 9 (though not demonstrated for metals production) | 9 | 9 |
| *Status is Switzerland* | • Low diffusion as not applied in Switzerland yet<br>• Today, fuel mix is dominated by electricity, gas and coal [56] | | |

| *Abatement option* | 4. Carbon capture and storage/use | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | |
| *Technical approach* | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4 Calcium looping |
| *Applicable processes* | Melting, annealing (selection) | Melting, annealing (selection) | Melting, annealing (selection) | Melting, annealing (selection) | Melting, annealing (selection) | Melting, annealing (selection) |
| *Description* | • The CCS solutions discussed in 4.1.-4.3. for the cement industry can be similarly applied to the metals industry. Compared to the cement industry, however, the flue gases have lower CO2 contents leading to higher specific energy demands for the regeneration. As for the cement industry, low-temperature waste energy is available for recovery. Due to in average smaller installations, economics of CCS in the metals industry are expected less favourable<br>• Note: The applicability of CCS to the flue gas stream of different industry processes mainly depends on its CO2 concentration, temperature and the concentration of impurities [58] as well as the availability of waste heat and the dispersion of the flue gas sources | | | | | |
| *Abatement potential scope 1 emissions* | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration and avg. installation size | | | | | |
| *Technology readiness level* | In general (not specific to metals production): 9 [33] | In general (not specific to metals production): 7 [36] | In general (not specific to metals production): 9 [39], [40] | In general (not specific to metals production): Up to 9 [39] | In general (not specific to metals production): Up to 9 [39] | In general (not specific to metals production): Up to 7 [39] |
| *Status is Switzerland* | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet |

## 5.4. Food and beverages industry

### 5.4.1.1. Overview of processes

- a) Preparation
- b) Size reduction, mixing and forming
- c) Separation
- d) Product processing
- e) Heat processing
- f) Concentration
- g) Processing by removal of heat
- h) Post-processing by operations
- i) Utility processes

Sub-processes:

a) Preparation
   a. Sorting/screening, grading, dehulling, destemming/destalking and trimming
   b. Peeling
   c. Washing
   d. Thawing

b) Size reduction, mixing and forming
   a. Cutting, slicing, chopping, mincing, pulping and pressing
   b. Mixing/blending, homogenisation and conching
   c. Grinding/milling and crushing
   d. Forming/moulding and extruding

c) Separation techniques
   a. Extraction
   b. Deionisation
   c. Fining
   d. Centrifugation and sedimentation
   e. Filtration
   f. Membrane separation
   g. Crystallisation
   h. Removal of free fatty acids by neutralisation
   i. Bleaching
   j. Deodorisation by stream stripping
   k. Decolourisation
   l. Distillation

d) Product processing technology
   a. Soaking
   b. Dissolving
   c. Solubilisation/alkalising
   d. Fermentation
   e. Coagulation

e) Heat processing
   a. Melting
   b. Blanching
   c. Cooking and boiling
   d. Baking
   e. Roasting
   f. Frying
   g. Tempering
   h. Pasteurisation, sterilisation and UHT processing

f) Concentration by heat
   a. Evaporation
   b. Drying
   c. Dehydration

g) Processing by removal of heat
   a. Cooling, chilling and cold stabilisation
   b. Freezing
   c. Freeze-drying/lyophilisation

h) Post-processing by operations
   a. Packing and filling
   b. Gas flushing and storage under gas

i) Utility processes
   a. Cleaning and disinfection
   b. Energy generation and consumption
   c. Water treatment
   d. Vacuum generation
   e. Refrigeration
   f. Compressed air generation

Source: [92], [93]

### 5.4.1.2. Summary of assessment

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Abatement potential | Technology readiness | Potential in Switzerland | Overall relevance |
|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | 2/3 | 3/3 | 2/3 | 2/3 |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | 2/3 | 3/3 | 3/3 | 2/3 |
| | | 1.1.3. Waste heat recovery and use | 1/3 | 3/3 | 2/3 | 1/3 |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | 3/3 | 3/3 | 3/3 | 3/3 |
| | | 2.1.2. Mechanical vapour recompression | 3/3 | 3/3 | 3/3 | 3/3 |
| | | 2.1.3. Electric boilers | 3/3 | 3/3 | ? ? ? | 3/3 |
| | | 2.1.4. Infrared heaters | 3/3 | 3/3 | ? ? ? | 3/3 |
| | | 2.1.5. Microwave & radio frequency heaters | 3/3 | 3/3 | ? ? ? | 3/3 |
| | | 2.1.6. Induction furnaces | 3/3 | 3/3 | ? ? ? | 3/3 |
| | | 2.1.7. Resistance furnaces | 3/3 | 3/3 | ? ? ? | 3/3 |
| | | 2.1.8. Electric arc furnaces | - | - | - | - |
| | | 2.1.9. Plasma technology | - | - | - | - |
| | | 2.1.10. Other | 3/3 | 3/3 | 3/3 | 3/3 |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | - | - | - | - |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | 3/3 | 3/3 | 3/3 | 3/3 |
| | | 3.1.4. Synthetic methane | 3/3 | 3/3 | 3/3 | 3/3 |
| | | 3.1.5. Other gaseous synthetic fuels | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | 3/3 | 3/3 | 3/3 | 3/3 |
| | | 3.2.2. Liquid biofuels | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | 3/3 | 3/3 | 3/3 | 3/3 |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | - | - | - | - |
| | | 3.3.2. Other | 1/3 | 3/3 | 2/3 | 2/3 |
| | 3.4. Use of district heating/cooling | | 3/3 | 3/3 | 1/3 | 2/3 |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | 1/3 | 3/3 | 3/3 | 1/3 |
| | 4.2. Oxyfuel combustion | | 1/3 | 3/3 | 3/3 | 1/3 |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | 1/3 | 3/3 | 3/3 | 1/3 |
| | | 4.3.2. Membrane separation | 1/3 | 3/3 | 3/3 | 1/3 |
| | | 4.3.3. Sorption by solids | 1/3 | 3/3 | 3/3 | 1/3 |
| | | 4.3.4. Carbonate looping | 1/3 | 3/3 | 3/3 | 1/3 |
| | 4.4. Direct capture in production process | | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | - | - | - | - |
| | 5.2. Shift to alternative non-reactive inputs | | - | - | - | - |

### 5.4.1.3. Detailed assessment

| | | | |
|---|---|---|---|
| *Abatement option* | 1. Increase of process/system efficiencies | | |
| *Underlying rationale* | 1.1. Reduction of (non-recovered) waste energy | | |
| *Technical approach* | 1.1.1. More efficient machines/appliances | 1.1.2. Process innovation for energy efficiency and process intensification | 1.1.3. Waste heat recovery/use |
| *Applicable processes* | Heat processing, concentration by heat, processing by removal of heat (selection) | Pasteurization, drying (selection) | Heat processing, utility processes like compressed air generation (selection) |
| *Description* | • Potential for energy efficiency measures exist leading to either fuel or electricity savings [93]<br>• Examples: Insulation of various process equipment (e.g. ovens) [93] | • Pulse electric field (PEF) processing can reduce the energy demand for pasteurization<br>• Reduced energy demand in subsequent processing steps (e.g. cutting, drying, evaporation) [94] | • Waste heat from different process equipment and flue gases is recovered |
| *Abatement potential scope 1 emissions* | • Relative energy saving potential varies by measure between 1% (e.g. replacing steam humidifier with air humidifier) and 40% (e.g. replacing steam ejectors by vacuum pumps) [93] | • Efficiency improvements compared to thermal processes<br>• Additional abatement potential by reduction of waste | • Relative energy saving potential varies by measure |
| *Technology readiness level* | 9 [93] | 9 [94] | 9 [93] |
| *Status in Switzerland* | • Diffusion varies by measure between 30% (e.g. installing more efficient motors ) and 99% (e.g. replacing steam humidifier with air humidifier) [93] | • Low diffusion as not applied in Switzerland yet [93] | • Diffusion varies by measure between 31% (e.g. waste heat recovery from compressor) and 35% (e.g. waste heat recovery from process equipment) [93] |

| *Abatement option* | 2. Shift to electricity | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Underlying rationale* | 2.1. Provision of heat and cold with electricity | | | | | | | |
| *Technical approach* | 2.1.1. Heat pumps and chillers | 2.1.2. Mechanical vapour recompression | 2.1.3. Electric boilers | 2.1.4. Infrared heaters | 2.1.5. Microwave & radio frequency heaters | 2.1.6. Induction furnaces | 2.1.7. Resistance furnaces | 2.1.10. Other |
| *Applicable processes* | Heat processing, concentration by heat (selection) | Heat processing, concentration by heat (selection) | Heat processing, concentration by heat (selection) | Roasting, drying, baking (selection) | Evaporation, drying (selection) | Heat processing (selection) | Roasting, drying, baking (selection) | Pasteurization, drying (selection) |
| *Description* | • Provision of heat via (high temperature) heat pumps [53], [93], [95], [96], [97] | • Recovery of waste heat to heat up steam [93], [97], [87] | • Electricity based steam and hot water production | • Indirect heating of treated food's surface by electrically produced infrared radiation | • Interaction of electromagnetic waves with molecules heats the treated food from the inside | • Heating of food via metal pipes or vessels which are heated through magnetic fields produced via coils | • Heating of food via convection and radiation as done in standard household ovens | • Pulse electric field (PEF) processing can replace certain thermal processing steps (e.g. pasteurization); see also 1.1.2 [94] |
| *Relative abatement potential scope 1 emissions* | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Significant potential through replacement of fossil fuel based processes<br>$CO_2$ $CO_2$ $CO_2$ | • Efficiency improvements compared to thermal processes<br>• Additional abatement potential by reduction of waste<br>$CO_2$ $CO_2$ $CO_2$ |
| *Technology readiness level* | Depending on temperature level 9 [53]<br>TRL TRL TRL | Depending on temperature level 9 [93], [87]<br>TRL TRL TRL | 9 [87]<br>TRL TRL TRL | 9 [97], [87]<br>TRL TRL TRL | 9 [93], [97], [87]<br>TRL TRL TRL | 9 [97]<br>TRL TRL TRL | 9 [97]<br>TRL TRL TRL | 9 [94]<br>TRL TRL TRL |
| *Status in Switzerland* | • Low diffusion (depending on temperature level) [93] | • Low diffusion as no widespread use in Switzerland yet | • No information available<br>? ? ? | • No information available<br>? ? ? | • No information available<br>? ? ? | • No information available<br>? ? ? | • No information available<br>? ? ? | • Low diffusion as not applied in Switzerland yet [93] |

| *Abatement option* | 3. Shift to alternative fuels | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 3.1. Use of synthetic fuels | | 3.2. Use of biofuels | | 3.3. Use of lower carbon fossil fuels | 3.4. District heating/cooling |
| *Technical approach* | 3.1.3. Synthetic hydrogen | 3.1.4. Synthetic methane | 3.2.1. Solid biofuels | 3.2.3. Gaseous biofuels | 3.3.2. Other | |
| *Applicable processes* | Heat processing like cooling and baking (selection) | Heat processing like cooling and baking (selection) | Heat processing like cooling and baking (selection) | Heat processing like cooling and baking (selection) | Heat processing like cooling and baking (selection) | Heat processing like cooling and baking (selection) |
| *Description* | • Replacement of fossil fuels (as e.g. natural gas or fuel oil) by hydrogen | • Replacement of fossil fuels (as e.g. natural gas or fuel oil) by synthetic methane | • Replacement of fossil fuels (as e.g. natural gas or fuel oil) by solid biofuels | • Replacement of fossil fuels (as e.g. natural gas or fuel oil) by gaseous biofuels | • Replacement of light fuel oil by natural gas | • Replacement of local fossil fuel based heat and steam production by district heating |
| *Abatement potential scope 1 emissions* | • Significant potential through replacement of fossil fuel based processes | • Significant potential through replacement of fossil fuel based processes | • Significant potential through replacement of fossil fuel based processes | • Significant potential through replacement of fossil fuel based processes | • Significant potential through replacement of fossil fuel based processes | • Full abatement of the energy related emissions of rather low temperature processes<br>• $CO_2$ emissions from cogeneration plants outside the industrial production system not taken into account in the DECARBIN project [88] |
| *Technology readiness level* | 9 | | 9 | 9 | | 9 |
| *Status is Switzerland* | • Low diffusion as no widespread use in Switzerland yet<br>• Today, fuel mix is dominated by electricity, gas and fuel oil [56] | | | | | • Potential depends on the temperature levels needed and the temperature levels at which district heating networks can provide steam |

| *Abatement option* | 4. Carbon capture and storage/use | | | | | |
|---|---|---|---|---|---|---|
| *Underlying rationale* | 4.1. Pre-combustion | 4.2. Oxyfuel combustion | 4.3. Post-combustion | | | |
| *Technical approach* | | | 4.3.1. Chemical absorption | 4.3.2. Membrane separation | 4.3.3. Sorption by solids | 4.3.4 Calcium looping |
| *Applicable processes* | Heat processing, concentration by heat | Heat processing, concentration by heat | Heat processing, concentration by heat | Heat processing, concentration by heat | Heat processing, concentration by heat | Heat processing, concentration by heat |
| *Description* | • The CCS solutions discussed in 4.1.-4.3. for the cement industry can be similarly applied to the food and beverages industry. Compared to the cement industry, however, the flue gases have lower CO2 contents leading to higher specific energy demands for the regeneration. Due to in average smaller installations (more than 200 sites contribute to the sector's emissions), economics of CCS in the food and beverages industry are expected less favourable<br>• Note: The applicability of CCS to the flue gas stream of different industry processes mainly depends on its CO2 concentration, temperature and the concentration of impurities [58] as well as the availability of waste heat and the dispersion of the flue gas sources | | | | | |
| *Abatement potential scope 1 emissions* | • Typically 90% or more [36], [37], [38] (see chapter on cement industry)<br>• Potential limited based on flue gas concentration, avg. installation size and availability of waste heat | | | | | |
| *Technology readiness level* | In general (not specific to food production): 9 [33] | In general (not specific to food production): 7 [36] | In general (not specific to food production): 9 [40], [39] | In general (not specific to food production): Up to 9 [39] | In general (not specific to food production): Up to 9 [39] | In general (not specific to food production): Up to 7 [39] |
| *Status is Switzerland* | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet | • Low diffusion as not applied in Switzerland yet |

# 6. Overall relevance ratings per abatement option

## 6.1. Level 3 – Technical approach

| Level 1 – Abatement option | Level 2 – Underlying rationale | Level 3 – Technical approach | Minerals: Cement | Minerals: Ceramics | Chemicals: Olefins | Chemicals: Other | Metals | Food & Bev. |
|---|---|---|---|---|---|---|---|---|
| 1. Increase of process/system efficiencies | 1.1. Reduction of (non-recovered) waste energy | 1.1.1. More energy-efficient machines/appliances | ★☆☆ | ★☆☆ | ★★☆ | ★★★ | ★★☆ | ★★☆ |
| | | 1.1.2. Proc. innov. for energy effic. and process intensific. | - | ★☆☆ | ★★☆ | - | ★★☆ | ★★☆ |
| | | 1.1.3. Waste heat recovery and use | ★★☆ | ★☆☆ | ★☆☆ | ★★★ | ★☆☆ | ★☆☆ |
| | 1.2. Reduction of non-energy production waste | | - | - | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | 2.1.1. Heat pumps and chillers | - | ★★☆ | ★☆☆ | ★★★ | - | ★★★ |
| | | 2.1.2. Mechanical vapour recompression | - | ★★☆ | ★☆☆ | ★★★ | - | ★★★ |
| | | 2.1.3. Electric boilers | - | - | - | ★★★ | - | ★★★ |
| | | 2.1.4. Infrared heaters | - | - | - | - | - | ★★★ |
| | | 2.1.5. Microwave & radio frequency heaters | - | ★★☆ | - | - | - | ★★★ |
| | | 2.1.6. Induction furnaces | - | - | - | - | ★★☆ | ★★★ |
| | | 2.1.7. Resistance furnaces | ★★☆ | - | - | ★★★ | - | ★★★ |
| | | 2.1.8. Electric arc furnaces | - | - | - | - | - | - |
| | | 2.1.9. Plasma technology | ★★☆ | - | ★★★ | - | ★★★ | - |
| | | 2.1.10. Other | - | ★★☆ | ★★★ | | - | ★★★ |
| | 2.2. Provision of mechanical energy with electricity | 2.2.1. Electrification of combustion engines | ★★☆ | - | - | - | - | - |
| | | 2.2.2. Other | - | - | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | | ★★☆ | - | ★★★ | ★★★ | - | - |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | 3.1.1. Synthetic methanol | - | ★★★ | - | - | - | - |
| | | 3.1.2. Other liquid synthetic fuels | - | ★★★ | - | - | - | - |
| | | 3.1.3. Synthetic hydrogen | ★★☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| | | 3.1.4. Synthetic methane | ★★☆ | ★★★ | - | ★★★ | ★★★ | ★★★ |
| | | 3.1.5. Other gaseous synthetic fuels | - | ★★★ | - | - | - | - |
| | 3.2. Use of biofuels | 3.2.1. Solid biofuels | ★★☆ | - | - | ★★★ | - | ★★★ |
| | | 3.2.2. Liquid biofuels | - | ★★★ | - | - | - | - |
| | | 3.2.3. Gaseous biofuels | ★★☆ | ★★★ | - | ★★★ | ★★★ | ★★★ |
| | 3.3. Use of lower carbon fossil fuels | 3.3.1. Natural gas instead of hard coal or fuel oil | ★★☆ | - | - | ★★☆ | - | - |
| | | 3.3.2. Other | ★☆☆ | - | - | - | - | ★★☆ |
| | 3.4. Use of district heating/cooling | | - | - | - | ★★☆ | - | ★★☆ |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.2. Oxyfuel combustion | | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.3. Post-combustion | 4.3.1. Chemical absorption | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | | 4.3.2. Membrane separation | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | | 4.3.3. Sorption by solids | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | | 4.3.4. Carbonate looping | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.4. Direct capture in production process | | ★★★ | - | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | | ★★☆ | ★★☆ | ★★☆ | - | - | - |
| | 5.2. Shift to alternative non-reactive inputs | | ★★☆ | ★★☆ | - | - | - | - |

### 6.2. Level 2 – Underlying rationale[7]

| Level 1 – Abatement option | Level 2 – Underlying rationale | Minerals: Cement | Minerals: Ceramics | Chemicals: Olefins | Chemicals: Other | Metals | Food & Bev. |
|---|---|---|---|---|---|---|---|
| 1. Increase of process/ system efficiencies | 1.1. Reduction of (non-recovered) waste energy | ★★☆ | ★☆☆ | ★★☆ | ★★★ | ★★☆ | ★★☆ |
| | 1.2. Reduction of non-energy production waste | - | - | - | - | - | - |
| 2. Shift to electricity | 2.1. Provision of heat and cold with electricity | ★★☆ | ★★☆ | ★★☆ | ★★★ | ★★★ | ★★★ |
| | 2.2. Provision of mechanical energy with electricity | ★★☆ | - | - | - | - | - |
| | 2.3. Enabling chemical reactions with electricity | ★★☆ | - | ★★★ | ★★★ | - | - |
| 3. Shift to alternative fuels | 3.1. Use of synthetic fuels | ★★☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| | 3.2. Use of biofuels | ★★☆ | ★★★ | - | ★★★ | ★★★ | ★★★ |
| | 3.3. Use of lower carbon fossil fuels | ★★☆ | - | - | ★★☆ | - | ★★☆ |
| | 3.4. Use of district heating/cooling | - | - | - | ★★☆ | - | ★★☆ |
| 4. Carbon capture and storage/use | 4.1. Pre-combustion | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.2. Oxyfuel combustion | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.3. Post-combustion | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| | 4.4. Direct capture in production process | ★★★ | - | - | - | - | - |
| 5. Shift to alternat. feed-stock or interm. products | 5.1. Shift to alternative chemical agents | ★★☆ | ★★☆ | ★★☆ | - | - | - |
| | 5.2. Shift to alternative non-reactive inputs | ★★☆ | ★★☆ | ★★☆ | - | - | - |

### 6.3. Level 1 – Abatement option[8]

| Level 1 – Abatement option | Minerals: Cement | Minerals: Ceramics | Chemicals: Olefins | Chemicals: Other | Metals | Food & Bev. |
|---|---|---|---|---|---|---|
| 1. Increase of process/ system efficiencies | ★★☆ | ★☆☆ | ★★☆ | ★★★ | ★★☆ | ★★☆ |
| 2. Shift to electricity | ★★☆ | ★★☆ | ★★★ | ★★★ | ★★☆ | ★★★ |
| 3. Shift to alternative fuels | ★★☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| 4. Carbon capture and storage/use | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| 5. Shift to alternat. feed-stock or interm. products | ★★☆ | ★★☆ | ★★☆ | - | - | - |

[7] Level 2 score was aggregated by taking the average of the Level 3 scores
[8] Level 1 score was aggregated by taking the average of the Level 2 scores

These bottom-up derived score per abatement option in the following were validated and adjusted based on expert interviews, leading to slightly different results (cf. Section 6.4).

## 6.4. Level 1 – Abatement option (triangulated in interviews)

| Level 1 – Abatement option | Minerals: Cement | Minerals: Ceramics | Chemicals: Olefins | Chemicals: Other | Metals | Food & Bev. |
|---|---|---|---|---|---|---|
| 1. Increase of process/ system efficiencies | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ |
| 2. Shift to electricity | ★☆☆ | ★☆☆ | ★★★ | ★★★ | ★★☆ | ★★★ |
| 3. Shift to alternative fuels | ★★☆ | ★★★ | ★★★ | ★★☆ | ★★☆ | ★★★ |
| 4. Carbon capture and storage/use | ★★★ | ★☆☆ | ★☆☆ | ★☆☆ | ★★☆ | ★☆☆ |
| 5. Shift to alternat. feed-stock or interm. products | ★☆☆ | ★☆☆ | ★★☆ | - | - | - |

# 7. References


[1] Bundesrat, “Medienmitteilung vom 28. August 2019 zum Klimaziel 2050 (Netto-Null Emissionen) der Schweiz,” Aug. 28, 2019. https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-76206.html (accessed Oct. 05, 2021).

[2] Bundesrat, “Langfristige Klimastrategie der Schweiz,” Jan. 2021. Accessed: Oct. 05, 2021. [Online]. Available: https://www.newsd.admin.ch/newsd/message/attachments/65874.pdf.

[3] BAFU, “Kenngrössen zur Entwicklung der Treibhausgasemissionen in der Schweiz 1990-2018,” 2020.

[4] BFE, “Schweizerische Gesamtenergiestatistik 2020,” 2021.

[5] UNFCCC, “Swiss National Inventory Submissions 2021,” 2021. Accessed: Oct. 26, 2021. [Online]. Available: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2019.

[6] BAFU, “Treibhausgasemissionen des Schweizer Industriesektors höher als angenommen,” 2020. https://www.bafu.admin.ch/bafu/de/home/dokumentation/medienmitteilungen/anzeige-nsb-unter-medienmitteilungen.msg-id-78041.html.

[7] BMWi, “Energiewende in der Industrie.” 2020.

[8] Agora Energiewende, “Klimaneutrale Industrie,” 2019.

[9] PBL Netherlands Environmental Assessment Agency, “MIDDEN: Manufacturing Industry Decarbonisation Data Exchange Network ,” 2021. https://www.pbl.nl/en/middenweb (accessed Oct. 14, 2021).

[10] M. D. Obrist, R. Kannan, T. J. Schmidt, and T. Kober, “Decarbonization pathways of the Swiss cement industry towards net zero emissions,” *J. Clean. Prod.*, vol. 288, p. 125413, Mar. 2021, doi: 10.1016/j.jclepro.2020.125413.

[11] M. J. S. Zuberi and M. K. Patel, “Bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials in the Swiss cement industry,” *J. Clean. Prod.*, vol. 142, pp. 4294–4309, Jan. 2017, doi: 10.1016/j.jclepro.2016.11.178.

[12] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, “Carbon Dioxide Emissions from the Global Cement Industry,” *Annu. Rev. Energy Environ.*, vol. 26, no. 1, pp. 303–329, Nov. 2001, doi: 10.1146/annurev.energy.26.1.303.

[13] F. Schorcht, I. Kourti, B. M. Scalet, S. Roudier, and L. Delgado Sancho, “Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide,” Seville, 2013. Accessed: Sep. 15, 2021. [Online]. Available: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf.

[14] M. J. S. Zuberi and M. K. Patel, “Bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials in the Swiss cement industry,” *J. Clean. Prod.*, vol. 142, pp. 4294–4309, Jan. 2017, doi: 10.1016/j.jclepro.2016.11.178.

[15] Calix Europe SARL, “LEILAC2 project website.” https://www.project-leilac.eu/leilac2-project (accessed Jul. 20, 2021).

[16] T. Burman and J. Engvall, “Evaluation of usage of plasma torches in cement production – A heat transfer modelling study,” Chalmers University of Technology, Gothenburg, 2019.

[17] L. Fluentes, “Will be in UK the 1st Cement Plant with Zero CO2 emissions?,” May 29, 2020. https://www.linkedin.com/pulse/uk-1st-cement-plant-zero-co2-emissions-luis-fuentes (accessed Jul. 20, 2021).

[18] L. D. Ellis, A. F. Badel, M. L. Chiang, R. J-Y Park, and Y.-M. Chiang, “Toward electrochemical synthesis of cement - An electrolyzer-based process for decarbonating CaCO 3 while producing useful gas streams,” doi: 10.1073/pnas.1821673116.

[19] Empa, “Start of work for the world’s largest electric truck,” Apr. 19, 2018. https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-70487.html (accessed Jul. 19, 2021).

[20] C. Werwitzke, “E-Muldenkipper der Superlative nimmt seine Arbeit auf,” Apr. 23, 2018. https://www.electrive.net/2018/04/23/e-muldenkipper-der-superlative-nimmt-seine-arbeit-auf/ (accessed Jul. 20, 2021).

[21] CEMEX SAB, “CEMEX successfully deploys hydrogen-based ground-breaking technology,” Feb. 22, 2021. https://www.cemex.com/-/cemex-successfully-deploys-hydrogen-based-ground-breaking-technology (accessed Jul. 20, 2021).

[22] J. Pérez, “CEMEX invests US$25 million to phase out fossil fuels at Rugby cement plant in the UK - CEMEX invests US$25 million to phase out fossil fuels at Rugby cement plant in the UK ,” Mar. 09, 2021. https://www.cemex.com/-/cemex-invests-us-25-million-to-phase-out-fossil-fuels-at-rugby-cement-plant-in-the-uk (accessed Jul. 20, 2021).

[23] Hanson UK, “Collaboration on green hydrogen research,” Feb. 11, 2021. https://www.hanson.co.uk/en/news-and-events/green-hydrogen-research (accessed Jul. 19, 2021).

[24] Swansea University, “RICE project website,” Oct. 28, 2020. https://www.rice.cymru/en/hydrogen-hanson (accessed Jul. 19, 2021).

[25] cemsuisse, “Kennzahlen 2020,” Bern, 2020. Accessed: Jul. 19, 2021. [Online]. Available: https://www.cemsuisse.ch/app/uploads/2020/05/Cemsuisse_Kennzahlen_2020_RZ.pdf.

[26] V. Quaschning, “Spezifische Kohlendioxidemissionen verschiedener Brennstoffe,” 2021. https://www.volker-quaschning.de/datserv/CO2-spez/index.php (accessed Jul. 20, 2021).

[27] “Switzerland’s Greenhouse Gas Inventory 1990-2019. National Inventory Report,” Bern, Apr. 2021. Accessed: Aug. 12, 2021. [Online]. Available: https://unfccc.int/documents/271462.

[28] European Commission Joint Research Centre, “Deep decarbonisation of industry: The cement sector,” 2020.

[29] A. Murray and L. Price, “Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector,” Berkeley, Jun. 2008.

[30] V. Schneider, R. Van der Meer, and J. Hammes, “Wasserstoff als Brennstoff in der Zementherstellung,” Jan. 21, 2016.

[31] S. S. Akhtar, E. Ervin, S. Raza, and T. Abbas, “From coal to natural gas: Its impact on kiln production, Clinker quality and emissions,” *IEEE Cem. Ind. Tech. Conf.*, 2013, doi: 10.1109/CITCON.2013.6525276.

[32] L. J. Hanle, K. R. Jayaraman, and J. S. Smith, “CO 2 Emissions Profile of the U.S. Cement Industry,” Washington DC, 2004.

[33] Department of Energy, “Pre-Combustion Carbon Capture Research.” https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-

research/carbon-capture-rd/pre-combustion-carbon (accessed Jul. 20, 2021).

[34] SINTEF Energy Research, "CEMCAP project website." https://www.sintef.no/projectweb/cemcap/ (accessed Jul. 20, 2021).

[35] Europea Cement Research Academy ECRA, "ECRA CCS Project: Report on Phase IV.A," Duesseldorf, 2016. Accessed: Jul. 20, 2021. [Online]. Available: www.ecra-online.org.

[36] M. G. Plaza, S. Martínez, and F. Rubiera, "CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations," *Energies*, vol. 13, no. 21, p. 5692, Oct. 2020, doi: 10.3390/en13215692.

[37] R. T. J. Porter, M. Fairweather, C. Kolster, N. Mac Dowell, N. Shah, and R. M. Woolley, "Cost and performance of some carbon capture technology options for producing different quality CO 2 product streams."

[38] M. Voldsund *et al.*, "Comparison of technologies for CO 2 capture from cement production—Part 1: Technical evaluation," *Energies*, vol. 12, no. 3, p. 559, Feb. 2019, doi: 10.3390/en12030559.

[39] D. Kearns, H. Liu, and C. Consoli, "Technology readiness and costs of CCS," 2021.

[40] M. Haines, "Assessment of emerging CO2 capture technologies and their potential to reduce costs," Dec. 2014. Accessed: Jul. 23, 2021. [Online]. Available: https://ieaghg.org/docs/General_Docs/Reports/2014-TR4.pdf.

[41] A. Naqi and J. G. Jang, "Recent progress in green cement technology utilizing low-carbon emission fuels and raw materials: A review," *Sustainability (Switzerland)*, vol. 11, no. 2. MDPI AG, Jan. 21, 2019, doi: 10.3390/su11020537.

[42] DIN Deutsches Institut für Normung e. V., "DIN EN 197-1:2011-11," Berlin, 2011. doi: https://dx.doi.org/10.31030/1758792.

[43] B. Zeschmar-Lahl, H. Schönberger, and J. Waltisberg, "Abfallmitverbrennung in Zementwerken Sachverständigengutachten," Dessau-Roßlau, 2020. Accessed: Jul. 22, 2021. [Online]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2020_11_05_texte_202_2020_abfallverbrennung_zementwerke_1.pdf.

[44] C. Agrafiotis and T. Tsoutsos, "Energy saving technologies in the European ceramic sector: a systematic review," *Appl. Therm. Eng.*, vol. 21, no. 12, pp. 1231–1249, Aug. 2001, doi: 10.1016/S1359-4311(01)00006-0.

[45] J. Besier and M. Marsidi, "Decarbonisation options for the dutch ceramic industry," The Hague, Dec. 2020. Accessed: Aug. 04, 2021. [Online]. Available: www.pbl.nl/en.

[46] European Commission, "Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry," Aug. 2007. Accessed: Aug. 05, 2021. [Online]. Available: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/cer_bref_0807.pdf.

[47] R. Geres, J. Lausen, and S. Weigert, "Roadmap für eine treibhausgasneutrale Ziegelindustrie in Deutschland," 2021, Accessed: Aug. 03, 2021. [Online]. Available: www.ziegel.de.

[48] T. Redemann and E. Specht, "Simulation des Brandes von keramischem Gut Teil 2: Roadmap zur CO2-freien Herstellung von Ziegeln bis 2050," *Brick Tile Ind. Int.*, vol. 4, 2020, [Online]. Available: https://www.zi-online.info/de/artikel/zi_Simulation_des_Brandes_von_keramischem_Gut_Teil_2_Roadmap_zur_CO2-freien_3551341.html.

[49] E. Rimpel, "Use of heat pumps in brick drying," *Brick Tile Ind. Int.*, vol. 8, 2015, Accessed: Aug. 04, 2021. [Online]. Available: https://www.zi-online.info/en/artikel/zi_Use_of_heat_pumps_in_brick_drying_2465278.html.

[50] N. Vorhauer, A. Tretau, A. Bück, and M. Prat, "Microwave drying of wet clay with intermittent heating," *Dry. Technol.*, vol. 37, no. 5, pp. 664–678, Apr. 2019, doi: 10.1080/07373937.2018.1547740.

[51] V. G. Karayannis, "Microwave sintering of ceramic materials," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 161, no. 1, p. 012068, Nov. 2016, doi: 10.1088/1757-899X/161/1/012068.

[52] J. Besier, "Decarbonisation of the Dutch ceramic industry," Delft University of Technology, 2021.

[53] C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann, and S. S. Bertsch, "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials," *Energy*, vol. 152. Elsevier Ltd, pp. 985–1010, Jun. 01, 2018, doi: 10.1016/j.energy.2018.03.166.

[54] T. Hübner, A. Guminski, and S. von Roon, "Energiewende in der Industrie: Potenziale und Wechselwirkungen mit dem Energiesektor - Branchensteckbrief der Keramikindustrie," Aug. 2019.

[55] p + f Sursee (Prüf- und Forschungsinstitut), "Umweltproduktdeklaration (EPD) Backsteine 'SwissModul,'" Sursee, 2018. Accessed: Dec. 10, 2021. [Online]. Available: http://www.pfsursee.ch/.

[56] Bundesamt für Statistik, "Aufkommens- und Verwendungstabellen für Energieflüsse - 2010-2019 | Tabelle | Bundesamt für Statistik," Sep. 2021. Accessed: Dec. 10, 2021. [Online]. Available: https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken/tabellen.assetdetail.18845931.html.

[57] P. Bains, P. Psarras, and J. Wilcox, "CO2 capture from the industry sector," *Prog. Energy Combust. Sci.*, vol. 63, pp. 146–172, Nov. 2017, doi: 10.1016/J.PECS.2017.07.001.

[58] H. Pilorgé *et al.*, "Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector," *Environ. Sci. Technol.*, vol. 54, no. 12, pp. 7524–7532, Jun. 2020, doi: 10.1021/acs.est.9b07930.

[59] C. Bories, M. E. Borredon, E. Vedrenne, and G. Vilarem, "Development of eco-friendly porous fired clay bricks using pore-forming agents: A review," *J. Environ. Manage.*, vol. 143, pp. 186–196, Oct. 2014, doi: 10.1016/J.JENVMAN.2014.05.006.

[60] B. Walter and M. Tesar, "Porosierungsmittel in der Österreicherischen Ziegelindustrie - Herkunft und Einsatz," Wien, 2009. Accessed: Aug. 05, 2021. [Online]. Available: https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0244.pdf.

[61] T. Ren, M. Patel, and K. Blok, "Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes," *Energy*, vol. 31, no. 4, pp. 425–451, 2006, doi: 10.1016/j.energy.2005.04.001.

[62] H. Falcke *et al.*, "Best Available Techniques (BAT) Reference Document for the Production of Large Volume Organic Chemicals," Luxembourg, 2017. doi: 10.2760/77304.

[63] iea, "Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes," 2013.

[64] J. G. Speight, "Catalytic cracking," in *The Refinery of the Future*, Elsevier, 2020, pp. 197–226.

[65] J. Zuberi, X. Li, S. A. Wallerand, F. Maréchal, and M. Patel, "Joint Activity Scenarios and Modelling - Energy Efficiency in Industry Sector," 2020.

[66] M. J. S. Zuberi and M. K. Patel, "Cost-effectiveness analysis of energy efficiency measures in the Swiss chemical and pharmaceutical industry," *Int. J. Energy Res.*, vol. 43, no. 1, pp. 313–336, Jan. 2019, doi: 10.1002/ER.4267.

[67] G. Zhu, C. Xie, Z. Li, and X. Wang, "Catalytic processes for light olefin production," in *Springer Handbooks*, vol. PartF1, Springer, 2017, pp. 1063–1079.

[68] Lonza Group Ltd, "Lonza Annual Report 2014," Basel, 2015. Accessed: Jul. 19, 2021. [Online]. Available: https://www.lonza.com/investor-relations/-/media/485F47DC7B424A6F9B5055980FB10C77.ashx.

[69] E. Delikonstantis, E. Igos, M. Augustinus, E. Benetto, and G. D. Stefanidis, "Life cycle assessment of plasma-assisted ethylene production from rich-in-methane gas streams," *Sustain. Energy Fuels*, vol. 4, no. 3, pp. 1351–1362, Mar. 2020, doi: 10.1039/C9SE00736A.

[70] I. Amghizar, J. N. Dedeyne, D. J. Brown, G. B. Marin, and K. M. Van Geem, "Sustainable innovations in steam cracking: CO2 neutral olefin production," *React. Chem. Eng.*, vol. 5, no. 2, pp. 239–257, Feb. 2020, doi: 10.1039/C9RE00398C.

[71] H. Johannesdahl, "(129a) Rdr - Revolution in Ethylene Yield," 2018, Accessed: Jul. 20, 2021. [Online]. Available: https://www.aiche.org/conferences/aiche-spring-meeting-and-global-congress-on-process-safety/2018/proceeding/paper/129a-rdr-revolution-ethylene-yield.

[72] BASF SE, "BASF, SABIC and Linde join forces to realize the world's first electrically heated steam cracker furnace," 2021. https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2021/basf-sabic-and-linde-join-forces-to-realize-wolds-first-electrically-heated-steam-cracker-furnace.html (accessed Jul. 19, 2021).

[73] The Dow Chemical Company, "Dow and Shell demonstrate progress in joint technology development for lower CO2 emission crackers," Jun. 17, 2021. https://nl.dow.com/en-us/news/dow-and-shell-electrified-cracker-lowers-emissions.html (accessed Jul. 19, 2021).

[74] Z. J. Schiffer and K. Manthiram, "Electrification and Decarbonization of the Chemical Industry," *Joule*, vol. 1, no. 1. Cell Press, pp. 10–14, Sep. 06, 2017, doi: 10.1016/j.joule.2017.07.008.

[75] E. Delikonstantis, M. Scapinello, and G. D. Stefanidis, "Low energy cost conversion of methane to ethylene in a hybrid plasma-catalytic reactor system," *Fuel Process. Technol.*, vol. 176, pp. 33–42, Jul. 2018, doi: 10.1016/J.FUPROC.2018.03.011.

[76] M. C. Weikl, "Carbon Capture in Cracking Furnaces," 2010, Accessed: Jul. 19, 2021. [Online]. Available: https://www.researchgate.net/publication/263272524.

[77] C. Oliveira and T. van Dril, "Decarbonisation options for Large Volume Organic Chemicals production, SABIC Geleen," The Hague, 2021. Accessed: Jul. 13, 2021. [Online]. Available: www.pbl.nl/en.

[78] D. Dickson, A. Hussain, and B. Kumpf, "The future of petrochemicals: Growth Surrounded by Uncertainty," 2019.

[79] Q. Chen, M. Lv, D. Wang, Z. Tang, W. Wei, and Y. Sun, "Eco-efficiency assessment for global warming potential of ethylene production processes: A case study of China," *J. Clean. Prod.*, vol. 142, pp. 3109–3116, Jan. 2017, doi: 10.1016/J.JCLEPRO.2016.10.156.

[80] K. Cui, "Can China's CTO and MTO industries survive the threat of massive steam cracker investment?," Sep. 06, 2019. https://www.woodmac.com/news/can-chinas-cto-and-mto-industries-survive-the-threat-of-massive-steam-cracker-investment/ (accessed Jul. 20, 2021).

[81] T. Ren, M. K. Patel, and K. Blok, "Steam cracking and methane to olefins: Energy use, CO2 emissions and production costs," *Energy*, vol. 33, no. 5, pp. 817–833, May 2008, doi: 10.1016/j.energy.2008.01.002.

[82] Lonza Group Ltd, "Lonza Annual Report 2019," Basel, 2020. Accessed: Jul. 19, 2021. [Online]. Available: https://www.lonza.com/investor-relations/-/media/CF4F40C6AD9045228FBD4A45D6A00431.ashx.

[83] A. M. Bazzanella and F. Ausfelder, "Low carbon energy and feedstock for the European chemical industry," Frankfurt am Main, Jun. 2017. Accessed: Jul. 20, 2021. [Online]. Available: www.dechema.de.

[84] European Commission, "Reference Document on Best Available Techniques for the Manufacture of Organic Fine Chemicals," Sevilla, Aug. 2006. Accessed: Sep. 16, 2021. [Online]. Available: http://eippcb.jrc.es.

[85] European Commission, "Reference Document on Best Available Techniques for the Production of Speciality Inorganic Chemicals," Sevilla, Aug. 2007. Accessed: Sep. 16, 2021. [Online]. Available: http://eippcb.jrc.es.

[86] European Commission, "Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Solids and Others industry," Seville, Aug. 2007. Accessed: Sep. 16, 2021. [Online]. Available: http://eippcb.jrc.es.

[87] S. Madeddu *et al.*, "The CO2reduction potential for the European industry via direct electrification of heat supply (power-to-heat)," *Environ. Res. Lett.*, vol. 15, no. 12, p. 124004, Dec. 2020, doi: 10.1088/1748-9326/abbd02.

[88] C. Del Taglia, R. Scherer, M. Ferster, and N. Stamm, "Energieverbrauch in der Industrie und im Dienstleistungssektor - Resultate 2019," Bern, 2020.

[89] N. Bhadbhade, M. J. S. Zuberi, and M. K. Patel, "A bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials for the swiss metals sector," *Energy*, vol. 181, pp. 173–186, Aug. 2019, doi: 10.1016/j.energy.2019.05.172.

[90] E. Worrell, L. Price, and N. Martin, "Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector," *Energy*, vol. 26, no. 5, pp. 513–536, May 2001, doi: 10.1016/S0360-5442(01)00017-2.

[91] "Reference Document on Best Available Techniques in the Smitheries and Foundries Industry," May 2005.

[92] G. Giner Santonja, T. Brinkmann, K. Raunkjær Stubdrup, P. Karlis, and S. Roudier, "Best Available Techniques (BAT) reference document for the food, drink and milk industries," 2019. Accessed: Aug. 27, 2021. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/ef80e416-329c-11ea-ba6e-01aa75ed71a1/language-en.

[93] N. Bhadbhade and M. K. Patel, "Analysis of energy efficiency improvement and carbon dioxide abatement potentials for Swiss Food and Beverage sector," *Resour. Conserv. Recycl.*, vol. 161, p. 104967, Oct. 2020, doi: 10.1016/J.RESCONREC.2020.104967.

[94] K. Nowosad, M. Sujka, U. Pankiewicz, and R. Kowalski, "The application of PEF technology in food processing and human nutrition," *J. Food Sci. Technol.*, vol. 58, no. 2, pp. 397–411, Feb. 2021, doi: 10.1007/S13197-020-04512-4/TABLES/2.

[95] F. Bühler, B. Zühlsdorf, T. Van Nguyen, and B. Elmegaard, "A comparative assessment of

electrification strategies for industrial sites: Case of milk powder production," *Appl. Energy*, vol. 250, pp. 1383–1401, Sep. 2019, doi: 10.1016/j.apenergy.2019.05.071.

[96] B. Zühlsdorf, F. Bühler, M. Bantle, and B. Elmegaard, "Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C," *Energy Convers. Manag. X*, vol. 2, p. 100011, Apr. 2019, doi: 10.1016/j.ecmx.2019.100011.

[97] J. Atuonwu and S. Tassou, "Decarbonisation of food manufacturing by the electrification of heat: A review of developments, technology options and future directions," *Trends in Food Science and Technology*, vol. 107. Elsevier Ltd, pp. 168–182, Jan. 01, 2021, doi: 10.1016/j.tifs.2020.10.011.