Study

Climate neutrality for Austria by 2040

Contribution of Austrian industry

Abridged Version

Christian Diendorfer, Bernhard Gahleitner, Bernhard Dachs (AIT)
Thomas Kienberger, Peter Nagovnak (MUL)
Hans Böhm, Simon Moser (EI-JKU)
Gregor Thenius, Karina Knaus (AEA)

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1 Executive summary

Background to the study

In its current legislative program, the Austrian federal government is pursuing the ambitious target of completely decarbonising its energy sector and the whole of its economic system by 2040.

A consortium comprising the AIT Austrian Institute of Technology, the University of Leoben, the Energy Institute at the Johannes Kepler University Linz and the Austrian Energy Agency was commissioned by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) to prepare this scientific study to determine (i) how Austrian industry currently compares to other countries, (ii) what decarbonisation options are available to the individual sectors of Austrian industry, and (iii) what investment costs these technological options are estimated to involve. This study does not include a detailed economic or financial analysis of these costs or recommendations optimised for specific scenarios.

Current situation of Austrian industry compared to other countries

Some 110 TWh of energy is required every year within the scope for calculating the footprint that comprises all facilities and processes at Austria's industrial sites, equating to around 27% of gross domestic product (GDP). Greenhouse gas (GHG) emissions by Austrian industry have risen from 23.4 to 27.1 Mt CO_2e since 1990. The production of metals such as iron and steel, products made from stone and earth such as cement and bricks, and chemical products generates a particularly high level of GHG emissions. Austrian industry is closely integrated into international value creation chains. Industrial goods manufactured abroad "import" 15.3 Mt CO_2e of GHG emissions, slightly less than would be generated if production were to take place within Austria. Replacing domestic production with imports, in other words, would only reduce emissions by a marginal degree. The production of industrial goods for export accounts for 15 Mt CO_2e. In two sectors – iron and steel production and cement – a significant proportion of total emissions is generated by primary production, which makes up a relatively large part of the total compared to other countries. Whilst this puts Austria merely in the upper middle range in an European comparison of emissions in relation to value added, the processes used in primary production correspond consistently to the "best available technologies" in accordance with the European Union's sector-specific classification system.

Areas of technical decarbonisation potential for the 13 sectors of Austrian industry

Four decarbonisation strategies – *electrification*, *using carbon-neutral gases*, *carbon capture* and the *circular economy* – have been examined in order to study potential levers for decarbonisation by identifying areas of technical potential in the 13 industry sectors based on the IEA classification system, with a distinction made between energy- and process-related emissions. Process-related emissions are understood to mean all those generated in industrial conversion processes (e.g. blast furnaces) or by minerals required for production that are fed into the corresponding process. Energy-related emissions are generated by burning carbonaceous energy sources to meet the needs of the various categories of "useful energy".

In the **iron and steel production sector**, which consumes the most energy and generates the most emissions, merely using carbon-neutral gases could save up to 10 Mt of CO_2e per year – depending on the gas employed and the upstream chain required – by using direct reduced (or sponge) iron and electric arc furnaces. This shift in technology also offers a further benefit during the transition to climate-neutral steel production: should iron ore reduction capacity in Austria fall temporarily, a consistent quantity of high-quality steel could be produced using sponge iron available on the international market by rapidly expanding the electric arc furnaces that are planned. If this sector is to be more or less completely decarbonised, the decarbonisation of the applications that use process heat at high temperatures (>200°C) must also be stepped up alongside phasing out blast furnaces. The difference in temperature means that carbon-neutral gases will have to be used here too, which could reduce GHG emissions by between 1.4 and 1.9 Mt CO_2e. However, the need for upstream chains in the production of carbon-neutral gases means that a significant amount of extra energy must always be factored in, although this additional burden can be reduced significantly by recycling more scrap. It can be assumed that up to 50% scrap can be used while maintaining a consistent product portfolio. This use of scrap could minimise the quantity of pig iron to be produced via direct reduction and thus save an equivalent amount of both energy and raw material resources.

The **stone, earth and glass** sector is the second most emissions-intensive industrial sector in Austria, and the cement industry is responsible for roughly two thirds of the whole sector's emissions. The biggest challenge to decarbonising this sector is the geogenic emissions generated by processes to strip CO_2 from mineral compounds. The use of carbon capture technologies thus has a key role to play. Besides the established process of amine scrubbing, a wide range of options from this family of technologies are currently being tested in pilot facilities to determine their suitability for industrial use. The reduction in GHG emissions that can be achieved is around 90% due to leaks. This means that using technologies to avoid geogenic emissions could save about 2.5 Mt CO_2e a year provided that the captured CO_2 can be sequestered over the long term. Similar to the steel production industry discussed above, the high-temperature applications involving temperatures in excess of 200°C offer the second greatest level of potential in this sector too behind avoiding process emissions. In this context, getting the abovementioned carbon capture technologies established would enable energy-related emissions from the capturing process to be minimised as well. It must be pointed out that the Austrian cement industry already uses an above-average proportion of secondary fuels compared to other countries. Although these fuels (such as waste oil, scrap tyres and industrial waste) also generate GHG emissions, it should be noted that other options for use or recycling would have to be discussed if these energy sources were to be replaced. The increased use of recycled concrete in the cement industry, which could cut its emissions by up to a third while also conserving natural resources, is not currently the main focus of public debate.

The **decarbonisation potential in the remaining sectors** that could be leveraged is largely restricted to the energy-related emissions generated by burning carbonaceous fossil fuels. However, the chemicals industry and the paper and printing sector both have their own sector-specific characteristics that need to be taken into particular consideration:

In the **chemicals industry**, the third most significant sector in terms of GHG emissions, the current coupling of this sector with the energy sector (Schwechat refinery) is likely to fade in importance in the future. The replacement of refinery byproducts – key platform chemicals – that this will necessitate will usher in a new structure for the sector and could see GHG emissions shift from the energy to the industry sector.

The **paper industry** generates over 22 TWh and is thus the second most energy-intensive industrial sector in Austria. Many of its industrial combined heat and power (CHP) plants, which provide electricity and large quantities of necessary process steam, are run on biomass that is generated within the scope for calculating its footprint. The greatest potential for decarbonisation thus lies in supplying process heat and steam at temperatures above 200°C, which is currently still being done using natural gas. As well as increasing the proportion of biomass employed, using carbon-neutral gases could also conceivably serve as a simple replacement solution in the existing system.

In the remaining, **non-energy-intensive sectors**, electrification (heat pumps) and the use of carbon-neutral gases are potential ways forward at the technology level being considered and at temperatures up to 200°C. However, it must be pointed out that these differ significantly in some cases in terms of their implementation as a result of the installations, investments and upstream chains in energy generation required. Carbon-neutral gases are generally the tool of choice for being able to meet the relevant process requirements in the high-temperature range (above 200°C). Across all sectors, for example, using carbon-neutral gases to generate process heat above 200°C could save around 5 Mt CO_2e, i.e. 18% of total GHG emissions from industry. Using carbon-neutral gases to supply process heat below 200°C would enable a reduction of up to 2.4 Mt CO_2e, thus offering similar potential to electrification via heat pumps (around 2.2 Mt CO_2e).

Costs of the transformation

The relevant technology costs over the implementation period were analysed in order to be able to assess the amount of investment required to implement the decarbonisation strategies studied. Using carbon-neutral gases to reduce process-related emissions in the **iron and steel production sector** is expected to require between EUR 2.9 million and EUR 4.7 million of investment, with the lower threshold significantly dependent on scrap recycling and thus the reduced need for gas. Overall, using biomethane rather than hydrogen would be the least cost-intensive option in terms of the investments required for the decarbonisation strategy using carbon-neutral gases.

The level of investment required to deliver the decarbonisation strategy in the GHG-intensive **stone, earth and glass** sector is relatively low. The investment volume calculated for the two carbon capture options of amine scrubbing and burning oxyfuels is around EUR 370–620 million. However, these amounts only take account of the direct investment costs for capturing the CO_2 – there will be extra costs for downstream processes such as storage (CCS) and utilisation (CCU). Besides its resource efficiency, the circular economy approach, involving the use of more recycled concrete, is also a relatively low-cost option.

In addition, the largest investments are likely to be required in the non-energy-intensive sectors in particular for decarbonising room heating and air-conditioning systems and for process heat <200°C. Across all sectors, total investments of between EUR 1.3 billion and EUR 2.6 billion are to be expected for the areas of application involving temperatures up to 200°C, depending on which decarbonisation strategy is pursued. Here too, however, other factors besides the cost aspect also need to be taken into consideration when choosing the technology, such as exergy and resource efficiency, associated upstream chains and available areas of resource potential.

While the present study focuses primarily on simple investment costs for the various measures identified for decarbonising industry, operating costs must also be considered in order to achieve a holistic techno-economical assessment. Nevertheless, the findings indicate that significant investment will be required to take the individual decarbonisation measures. As such, they may also aid decision-making on any subsidies to be offered to individual measures depending on their decarbonisation potential.

Conclusions

The findings detailed in the report and summarised above thus reveal that:

- The decarbonisation of Austrian industry can be achieved by means of various technologies based on a number of decarbonisation strategies: electrification, using carbon-neutral gases, carbon capture and the circular economy. Implementing these strategies calls for a balanced analysis of the whole system and, based on this, a chain of measures that take account of the challenges and questions facing the sectors in terms of resource management, the predominant industrial processes and regional land use planning.
- Minimising process-related emissions is a particularly key lever for decarbonising Austrian industry, both for establishing the direct reduction route in primary steel production and for avoiding geogenic emissions from capture processes in the stone, earth and glass sector.
- The debate over carbon capture technologies as a way of reducing GHG emissions must also cover how it is to be subsequently used or stored. In this context, suitable framework conditions that facilitate cooperation between the sectors are essential and will help to strengthen Austria as a centre for industry.
- The decarbonisation of Austrian industry as presented here will require significant investment that needs to be supported by a mix of measures at regulatory and energy policy level (e.g. price signals for CO2, regulatory measures, new technologies, information-sharing and awareness-raising).

2 Introduction

2.1 Motivation

In its current legislative programme, the Austrian federal government is pursuing the ambitious target of completely decarbonising its energy sector and the whole of its economic system by 2040. The European Commission also made its climate targets more stringent in July 2021 and is now aiming to reduce net GHG emissions by at least 55% by 2030 from a 1990 baseline. By setting this interim objective, Europe intends to become the world's first climate-neutral continent by 2050.

Austria's industry will make a major contribution towards this journey to climate neutrality. Together with the energy sector, it is currently responsible for roughly 37% of national greenhouse gas (GHG) emissions. Some 110 TWh of energy is required every year within the scope for calculating the footprint that comprises all facilities and processes at Austria's industrial sites, equating to around 27% of gross domestic product (GDP). Climate-relevant GHG emissions by industry amounted to 27.1 Mt CO2e in 2019, as Figure 1 shows – up 15.8% on the 1990 baseline. This means that emissions will need to be cut by 61% by 2030 from 2019 levels in order to achieve the sector target of 10.5 Mt CO2e.[1]

However, it must not be forgotten that Austrian industries and the services attributable to it contribute over EUR 75 billion to the country's total gross value creation (Statistik Austria, 2021), or 34% of total value added in Austria. Industry, including the services attributable to it, provides a job for over 960,000 people, meaning that almost one in every three employees in Austria works in this sector. These critical contributions by industry to Austria's prosperity show that a decarbonisation strategy based on pushing out the industrial companies cannot be an expedient solution. Options must therefore be presented that permit the cost-efficient decarbonisation of these companies and thus avoid the risk of such an exodus.

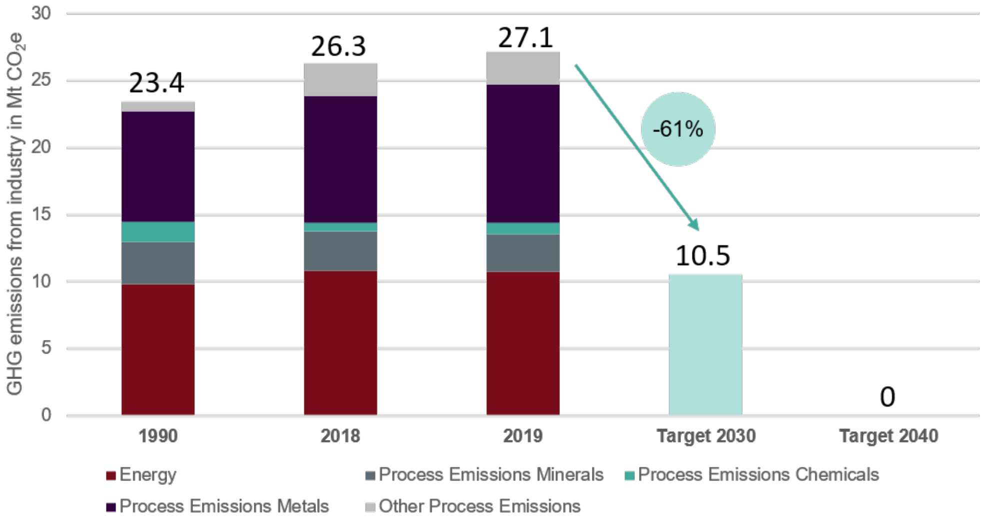

Figure 1: Trend in GHG emissions and GHG targets for Austrian industry for 2030 and 2040. Own chart based on (Umweltbundesamt, 2021)

As part of this scientific companion study, the AIT Austrian Institute of Technology was commissioned to illustrate how green Austria's industry already is and how Austrian companies can be supported through the transformation process and with the implementation of innovative transformation technologies. The content of this study was edited in cooperation with the University of Leoben, the Energy Institute at the Johannes Kepler University Linz and the Austrian Energy Agency. The AIT contributed knowledge from its Center for Energy and its Center for Innovation Systems and Policy as part of this collaboration. As well as project management, its work also focused on the technological assessment of the non-energy-intensive industry sectors as well as determining the current

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[1] This target applies on the assumption that industry is required to hit the -55% target exactly and there are no shifts between the individual sectors, e.g. agriculture and transport.

situation of Austrian industry in terms of the economy and net emissions, including in comparison to other countries. The analysis of the energy-intensive sectors of iron and steel production, paper and printing, and stone, earth and glass was performed at the University of Leoben, which was also responsible for the methodology used to calculate potential as well as for much of the structural work in this report. The Austrian Energy Agency and the Energy Institute at the Johannes Kepler University Linz calculated the investment costs associated with the areas of decarbonisation potential identified.

The present study investigates various future technologies in respect of their potential for reducing GHGs, their investment costs and their impact on the Austrian energy system, thus enabling the transformative potential of the technologies studied to be determined. The aim is to provide an extensive pool of data designed to enable the commissioning party to choose a number of targeted policy measures.

2.2 Methodology

2.2.1 Industry classification

The present study analyses the GHG emissions from the whole of the Austrian economy based on Eurostat's air emissions data (EUROSTAT, 2018) and the 2017 input-output table (EUROSTAT, kein Datum) using the ÖNACE and CPA[2] classification system. Both direct and indirect emissions generated by a sector are analysed, and the situation in Austria is compared with that in other countries. Emissions attributable to imports are also included (Section 3.3 – 3.3).

This is followed by a detailed investigation of the technical decarbonisation potential and decarbonisation options for the 13 sectors of Austrian industry, based on the IEA sectors[3] (Statistik Austria, 2013) reported in Statistics Austria's Energy Quantity Analysis (Statistik Austria, 2020) (Section 4.1) and of the associated investment costs (Section 5). The scope for calculating Austrian industry's footprint serves as the basis for these investigations.

N.B: The Energy Quantity Analysis shows the link between the energy sources used and the relevant categories of useful energy, allowing decarbonisation options to be calculated for specific applications. However, the Energy Quantity Analysis only indicates the amounts of energy actually used in the production process and does not factor in losses incurred within the scope for calculating industry's footprint. In this study, the amount of useful energy used is converted into CO2-equivalent emissions using specific emissions factors for each energy source. In order to integrate the losses not considered in the statistical data into the calculations as best possible, efficiency ratios specific to each category of useful energy are used and are factored into the calculation of GHG emissions for each energy source and category of useful energy. Nevertheless, this modelling approach gives rise to discrepancies with the emissions figures reported in the National Inventory Report (Umweltbundesamt, 2021)*. The emissions values shown in the National Inventory Report are to be regarded as the official figures.*

2.2.2 Scope for calculating industry's footprint

Within the industrial energy system, demand for energy and emissions of GHGs are generated both by the units that consume final energy to supply the various categories of useful energy as per Statistics Austria's Energy Quantity Analysis and by industrial energy conversion units as well as by feeding CO2-generating minerals into the system.

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[2] Emissions by class of goods are calculated based on the CPA classification system. CPA is fully compatible with NACE at two-digit level. For instance, CPA 17, Paper and paper products, corresponds to the activity NACE 17, Manufacture of paper and paper products.

[3] The IEA sectors largely overlap with ÖNACE. Detailed interrelationships are presented in the full version of the study.

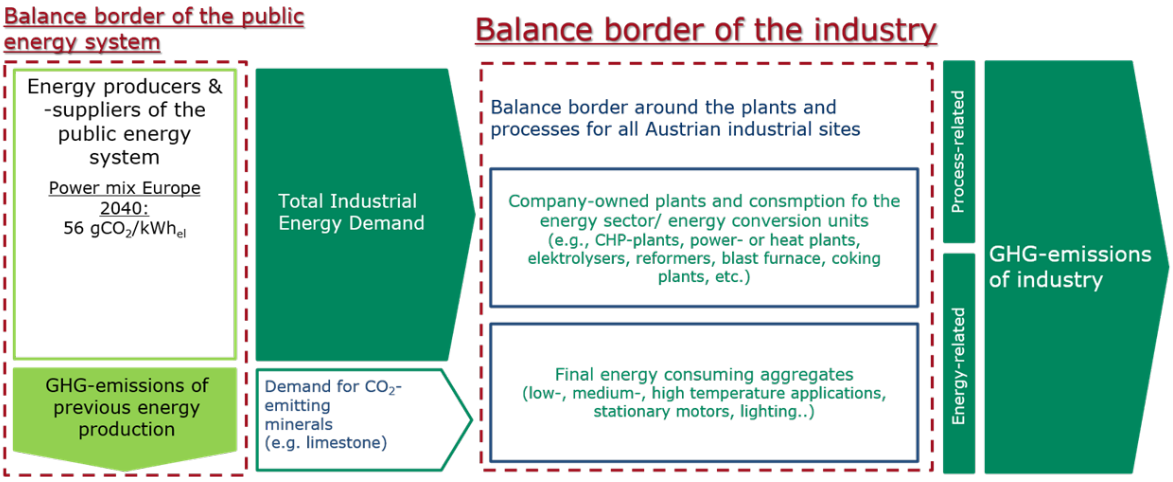

Figure 2: Illustration of the scope for calculating industry's footprint in accordance with (Nagovnak, Kienberger, Geyer, & Hainoun, 2021).CO_2 intensity in the European electricity mix in 2040 in accordance with (European Commission, 2020)

The scope for calculating industry's footprint shown in Figure 2 was defined as the facilities and processes for all the industrial sites in Austria. It must be borne in mind in this regard that the upstream production of the energy sources and minerals required for these processes can also generate emissions. Depending on the strategy pursued by the company concerned, these generation or conversion facilities (e.g. electrolysers) can be both within and outside the defined scope for calculating industry's footprint. This can have an impact on the energy and emissions footprint attributable directly to industry in terms of both composition (by energy source) and size. In consultation with the commissioning party, the GHG emissions caused by electrical generation facilities outside the scope for calculating the footprint have been included in the present study in each case. The Impact Assessment prepared by the European Commission is used for this purpose. In its MIX scenario, this assumes specific GHG emissions in the European electricity mix of 56 g/kWh in 2040 provided that the interim objective of a 55% cut in GHG emissions by 2030 compared with 1990 is achieved (European Commission, 2020).

The GHG emissions considered consist of energy- and process-related emissions, which are illustrated in Table 1:

Table 1: Illustration of energy- and process-related emissions

Energy-related emissions	Emissions generated from burning carbonaceous energy sources in the categories of useful energy identified in the Energy Quantity Analysis.
Process-related emissions	Emissions generated in industrial conversion processes (e.g. blast furnaces) or by minerals required for production that are fed into the corresponding process.

The technical decarbonisation potential of the four decarbonisation strategies – *electrification, using carbon-neutral gases, carbon capture and the circular economy* – for Austrian industry is to be investigated in the present study. This potential is understood as the maximum value (GHG emissions or energy usage in accordance with the scope for calculating industry's footprint) that can be achieved based on the current state of the art or, as appropriate, the state of the art foreseeable in the chosen target year (Deublein & Steinhauser, 2008), (Stanzer, et al., 2010), (Kaltschmitt, Hartmann, & Hofbauer, 2016), (Streicher, et al., 2010). Although the economic viability of the associated technical modifications is not considered, the premise applies that market positioning (volumes produced) and product quality must be maintained.

The present study only determines technical decarbonisation potential based on the current situation of Austrian production processes. In other words, no possible shifts in business areas or production volumes are investigated; neither are any economic considerations at this level of potential taken into account.

Whilst the present study considers direct investment costs for the respective measures identified for decarbonising industry, operating costs must also be factored in if a holistic techno-economic assessment is to be produced and a choice made between various alternative options.

Such a holistic evaluation of investment and operating costs over the entire life cycle of the technologies concerned would require separate detailed analyses that included macroeconomic calculations in various scenarios as well as the involvement of the relevant stakeholders (e.g. to identify typical investment cycles).

3 Austrian industry in detail – current situation

3.1 GHG emissions by the Austrian economy

First of all, the analysis will look at direct, or production-related, emissions. Overall, GHG emissions attributable to the Austrian economy in 2018 totaled 60.1 Mt CO_2e according to Eurostat. Of this amount, 9 Mt CO_2e come from agriculture, 26 Mt CO_2e from industry (tangible goods production) and around 25 Mt CO_2e from the various segments of the services sector, including construction, transport, energy and waste disposal. Within the service sector, energy supply generates 10.3 Mt CO_2e of GHG emissions, with 6.3 Mt CO_2e produced by various transport services and 1.5 Mt CO_2e by retail and wholesale. The Austrian Institute of Economic Research (WIFO) is anticipating a slight rise in emissions for 2019, with a fall of over 7% likely for 2020 as a result of the coronavirus crisis (Sommer, Sinabell, & Streicher, 2021).

The figure below illustrates emissions per EUR million of output and value added.[4] Only industrial production at this level is shown, as this is the focus of this study. The data reveals that emissions are distributed very unevenly. The production of petroleum products and metals, glass, ceramics, stone and earth as well as paper and paper products generates significantly higher emissions in terms of both value added and output.

By contrast, vehicle construction and the manufacture of pharmaceutical products have a much smaller footprint. Less emissions-intensive[5] sectors have been put into a chart underneath Figure 3 to improve legibility by using a different scale. Overall, however, tangible goods production is much more GHG-intensive than services: to generate EUR 1 million in added value, an average of 500 t is emitted in the production of tangible goods, compared with just 88 t in the provision of services.

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[4] Output comprises all the necessary inputs of other goods that are required to produce a particular good plus value added. "Value added" here is defined as the total of all wages, salaries, interest, dividend and profit that can be attributed to the production of a good.

[5] How emissions-intensive a sector is depends on its GHG emissions in tonnes per EUR million of value added.

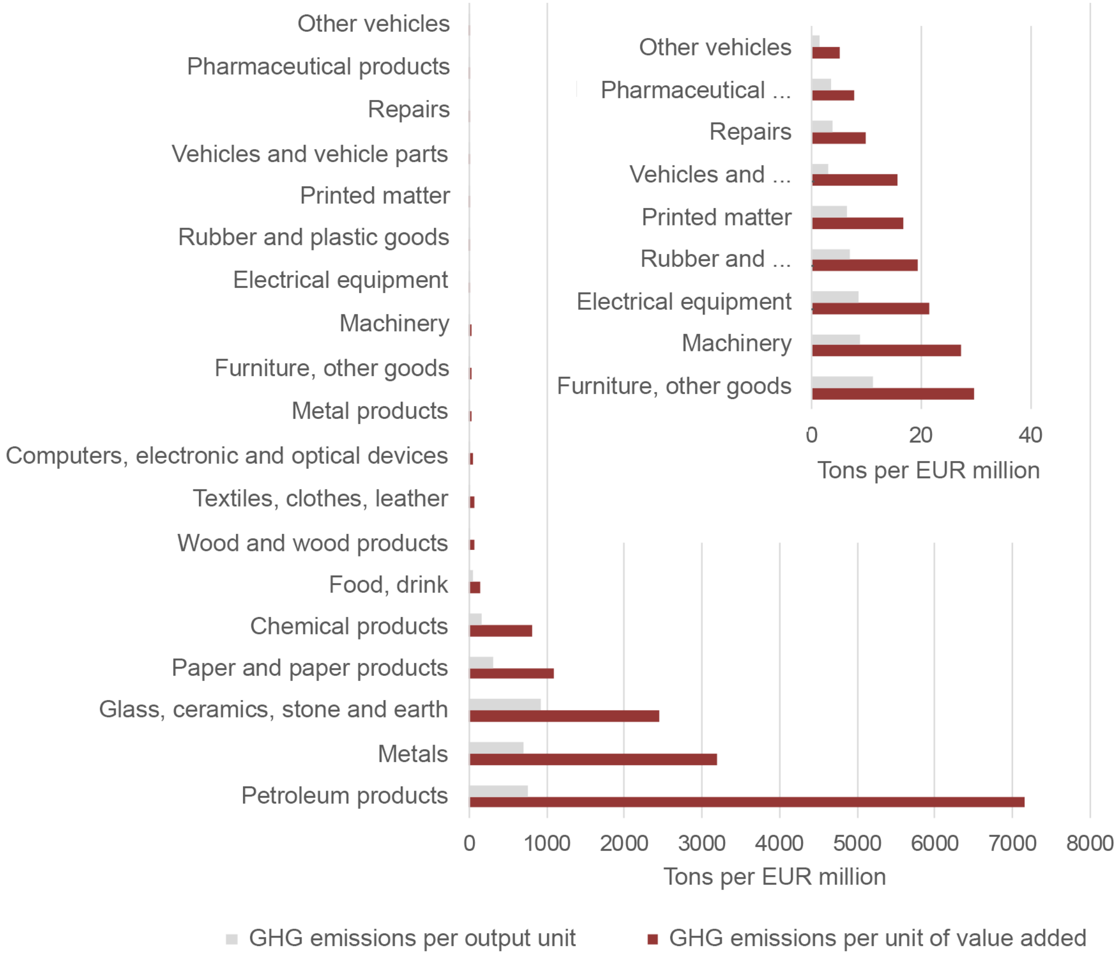

Figure 3: GHG gas emissions relative to output and value added, 2018. Own chart based on [3], [14] and own calculations

It must also be borne in mind when assessing emissions intensities that many of the goods produced are exported or used as intermediate products for creating other goods rather than being consumed straight away. Of the roughly 60 Mt CO_2e generated by the Austrian economy, 10.5 Mt CO_2e can be attributed to final consumption and 30.7 Mt CO_2e to the production of intermediate products for the Austrian economy. The supply of products and services for customers outside Austria generates 18.7 Mt CO_2e, which is thus exported; see Figure 4.

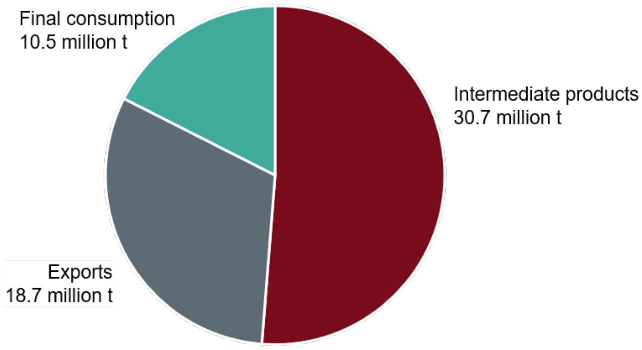

Figure 4: Breakdown by destination of GHG emissions generated by the Austrian economy, 2018. Own chart based on (EUROSTAT, 2018), (Statistik Austria, 2020) and own calculations

If one considers only the GHG emissions from Austrian industry (see Figure 5), 1.7 Mt CO_2e of the approximately 26 Mt CO_2e generated can be attributed to final consumption and 9.4 Mt CO_2e to the production of intermediate products. Production for export accounts for 15 Mt CO_2e of emissions.

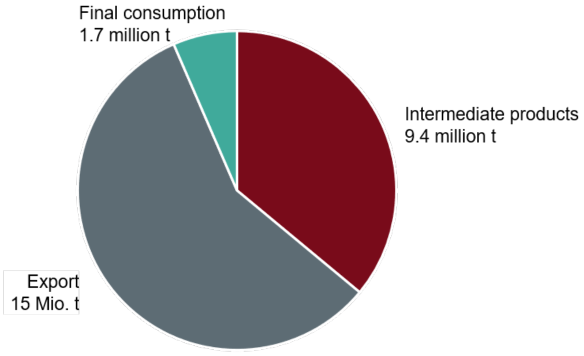

Figure 5: Breakdown by destination of GHG emissions generated by Austrian industry, 2018. Own chart based on (EUROSTAT, 2018), (Statistik Austria, 2020) and own calculations

3.2 Austrian industry in an international comparison

The fact that the Austrian economy is closely intertwined with international markets poses the question of how much GHG emissions the various sectors generate compared with other countries. Figure 7 is an attempt to answer this question using Eurostat (EUROSTAT, 2018) data. Austria is roughly in the middle. On average, Austria's industry is more emissions-intensive than that of Germany, the Nordic countries and its main trading partners Italy and Switzerland.

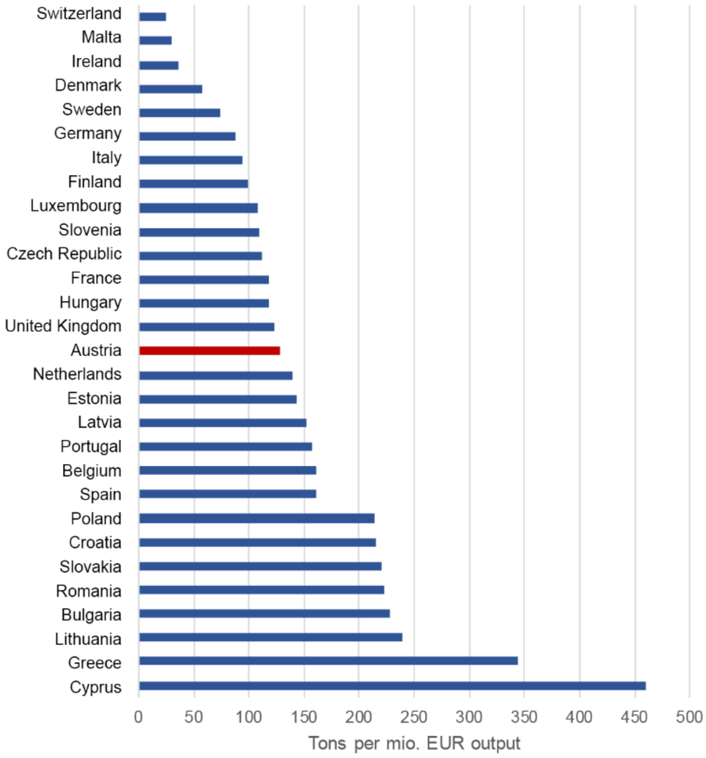

Figure 6: GHG emissions by industry in tonnes per EUR million of output in various European countries, 2018. Source: Eurostat (EUROSTAT, 2018)

Whole-industry comparisons are only of limited informative value, however, as they fail to account for how industry is structured in the individual countries. A country with a large steel industry might report much higher levels of emissions intensity even though the production by the steel industry in this country is much more emissions-efficient than those in other countries.

Figure 7 compares the emissions of various countries at individual sector level based on emissions per euro of output. The comparative data from these countries has been standardised to the equivalent sector in Austria. If the value for another country is less than one in the chart, the sector in question will be more emissions-intensive in Austria than in the other country.

Overall, the Austrian economy is more emissions-intensive than other countries in the petroleum processing, paper and paper products, and metal production sectors and much less emissions-intensive in the production of glass, ceramics and goods made from stone and earth, in the chemicals industry and in the food industry.

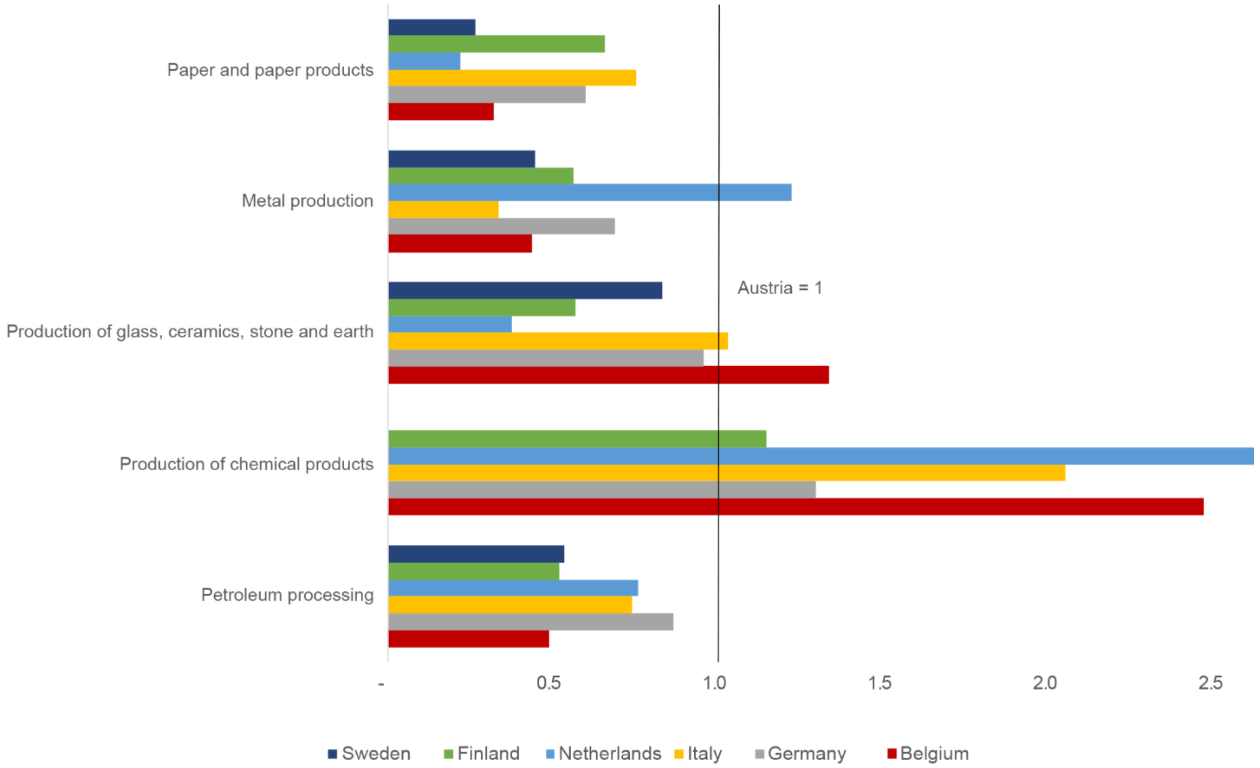

Figure 7: Emissions intensity of various sectors in an international comparison, 2018. Source: Eurostat (EUROSTAT, 2018)

A comparison of industrial processes using the European Union's BAT reference documents (BREFs)[6] shows that the processes used in primary production consistently represent the best available technologies. Production in China, India and South Korea, by contrast, is significantly more emissions-intensive than Austria's. Higher imports from these countries would increase the overall GHG footprint of Austria's industry and thus of the economy as a whole.

3.3 The emissions content of Austrian imports

As a highly internationalised economy, Austria imports many intermediate products and goods from abroad for consumption within its borders. As might be expected, the most-imported goods are textiles and clothes, fuels, vehicles, chemical products, computers, electronics and electrical equipment, with less services than tangible goods being imported on average. There are some good reasons for adding the emissions generated by the production of these imports to the Austrian economy's GHG footprint. These emissions may never have been produced were it not for the demand from Austrian companies or consumers, In addition, the products in question are used in manufacture, just like intermediate products made in Austria – which have been added to the GHG footprint.

The lion's share of imported emissions is attributable to the production of metals (5.3 million t), chemical products (2.4 million t) and glass, ceramics, stone and earth (2.2 million t). Imported emissions exceed domestic emissions in the case of some goods, such as textiles and clothes, chemical products, machinery, vehicles and vehicle parts. Amongst Austria's trading partners, imported emissions come primarily from Germany (around 5 million t), Slovakia (1.5 million t) and China (1.3 million t). The high figure for Slovakia is mainly due to the import of metals and the high emissions intensity required to extract them in that country.

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[6] https://eippcb.jrc.ec.europa.eu/reference

3.4 Sector-by-sector analysis of Austrian industry

Table 2 shows some of the key structural and performance data for the 13 industry sectors analysed with regard to the number of companies and number of employees per sector, their total gross value creation and the number of significant single emitters and their GHG emissions for 2019. The number of companies listed in the ETS varies considerably from sector to sector. However, the mere number is clearly by no means an indicator of a sector's GHG emissions as recorded in the ETS. Whereas, for example, 19 companies in the paper industry generate some 1,400 kt CO_2e, iron and steel production, with only three companies, is responsible for around 12,000 kt – making it the largest emitter of GHGs across the whole of Austrian industry.

Table 2: Key figures for Austria's industry sectors 2019 (Statistik Austria, 2021)

Sector	Companies	Significant single emitters[7]	Emissions from single emitters in kt CO_2e	Employees	Total gross value creation in EUR million
Construction	37,923	0	-	318,776	19,183
Mining[8]	318	2	264	approx. 6,000	approx. 627
Chemicals and petrochemicals	520	10	1,631	35,051	4,791
Printing	819	0	-	10,832	755
Iron and steel production	52	3	12,016	24,642	2,757
Vehicle construction	333	2	24	51,695	4,897
Wood processing	2,667	0	-	34,259	2,742
Mechanical engineering	6,349	2	43	240,209	21,519
Food, beverages and tobacco	4,078	2	257	88,036	6,396
Non-ferrous metals	85	2	132	13,480	1,328
Paper and paper products	138	19	1,432	16,626	2,036
Other production	5,843	1	16	77,128	4,910
Stone, earth and glass	1,329	33	4,118	31,355	2,538

The ten largest industrial emitters are shown in Figure 8 and belong to the following sectors: iron and steel production; stone, earth and glass; and paper and printing.

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[7] Significant single emitters" in this context means those companies listed in the ETS. Subsidiaries of corporate groups have been included with their parent company.

[8] No data is published on the "mining of metal ores" subsector (NACE 07) as so few companies are active in this subsector. The values for the three companies in this sector have been included based on own research and extrapolations.

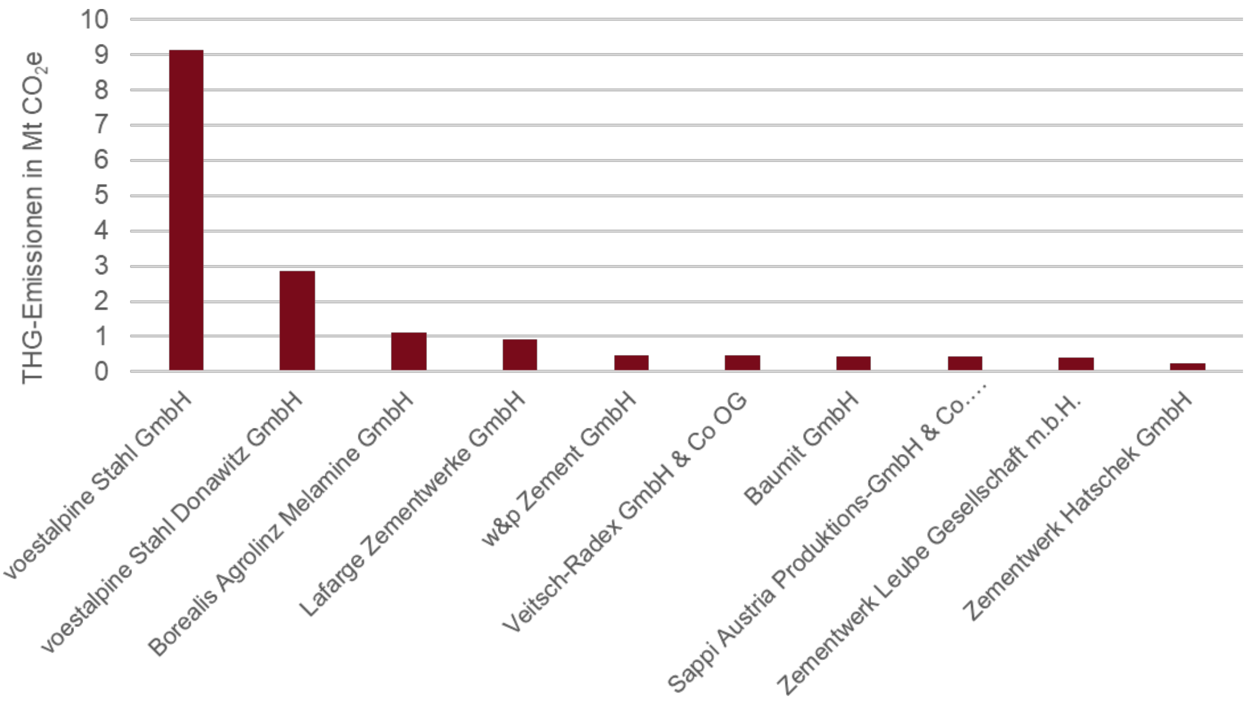


Figure 8: The ten largest emitters in Austrian industry according to the ETS database 2019 (European Commission, 2020)

Figure 9 breaks down GHG emissions from the 13 sectors by the energy source responsible. Generating 9.6 Mt CO_2e, the use of coal and coke in the iron and steel production sector is noticeably prominent. Geogenic (process-related) CO_2 emissions from the stone, earth and glass sector also contribute a significant 2.9 Mt CO_2e to Austrian industry's GHG emissions as a single item. Final energy supplied via natural gas results in overall emissions of 7 Mt CO_2e, while the use of electrical energy in industry is responsible for indirect emissions of 7 Mt CO_2e. However, these emissions are attributed to the energy sector rather than industry in official publications by the Federal Environment Agency and Statistics Austria.

Figure 10 breaks down GHG emissions by category of useful energy. Transformation processes are by far the largest source of GHGs, accounting for around 12.5 Mt CO_2e. A comparison with Figure 9 reveals that this is mainly due to coal and coke being used in the iron and steel sector as a reducing agent for iron ore as well as geogenic emissions in the stone, earth and glass sector. In the chemicals and petrochemicals sector, natural gas is used as a raw material for downstream products, meaning that GHG emissions are generated via transformation processes in this sector too. The final energy required to supply process heat above 200°C is responsible for some 7.3 Mt CO_2e of emissions. The final energy used to run stationary engines generates emissions in the amount of 5.8 Mt CO_2e, with as much as 86% of the final energy needed being supplied by electricity. This category of useful energy thus largely generates indirect emissions in the energy sector. Process heat under 200°C generates 3.0 Mt CO_2e in emissions.

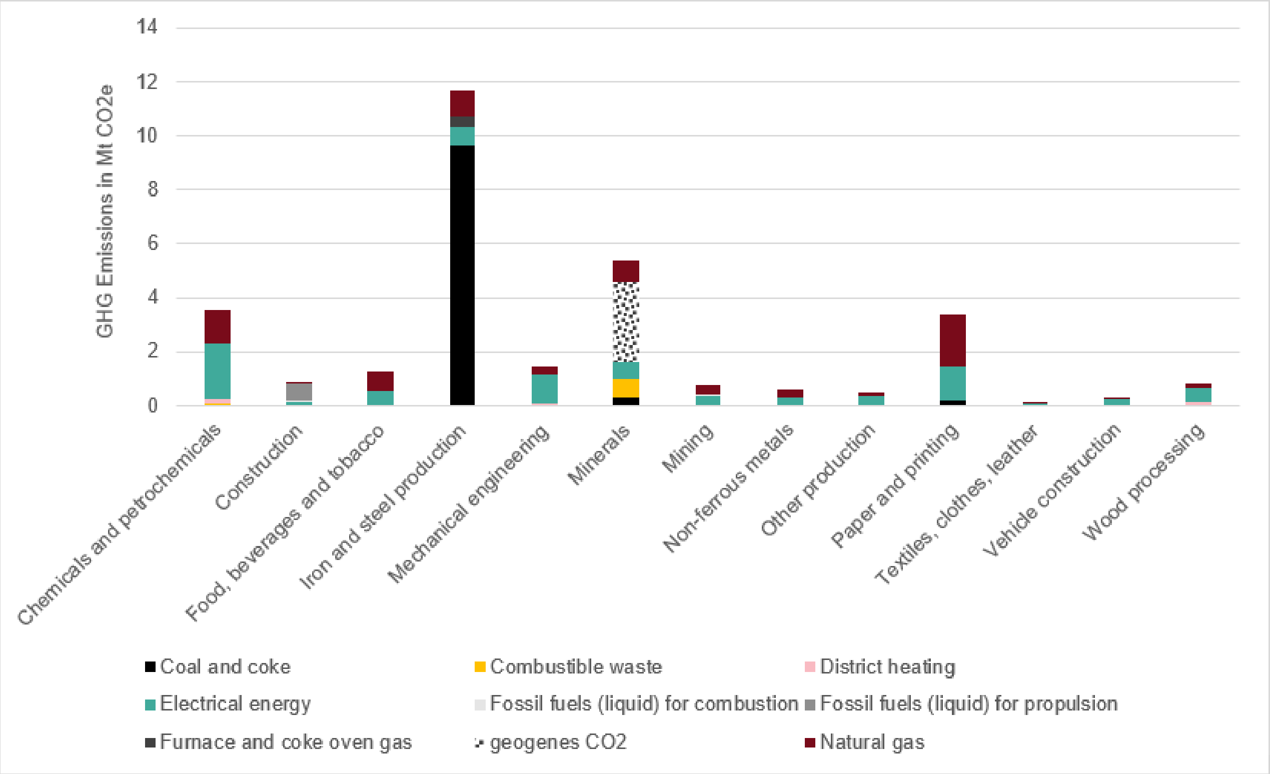


Figure 9: GHG emissions generated by the 13 IEA sectors by energy source, 2019. Own chart based on (Statistik Austria, 2020), (Umweltbundesamt, 2021) and own calculations.

The energy-intensive sectors of iron and steel production, stone, earth and glass, chemicals and petrochemicals, and paper and printing will now be described in detail below. See the long version of this study for a full description of all 13 Austrian industry sectors.

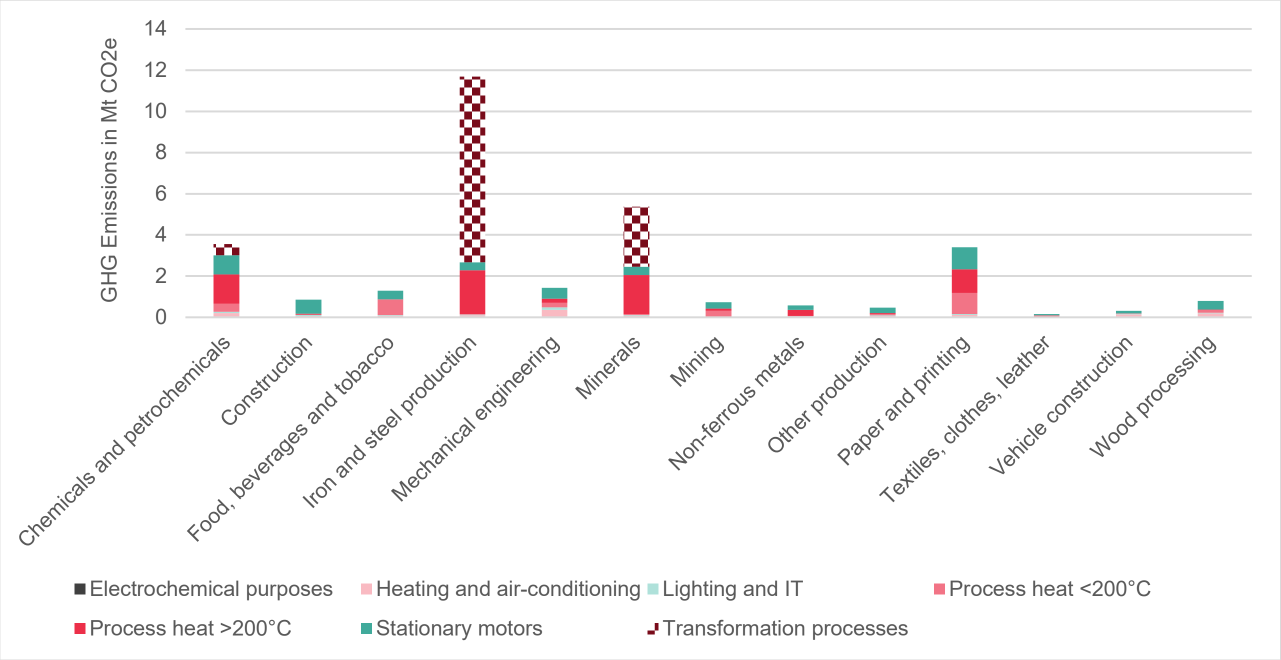


Figure 10: GHG emissions generated by the 13 IEA sectors by category of useful energy, 2019. Own chart based on (Statistik Austria, 2020), (Umweltbundesamt, 2021) and own calculations.

3.4.1 Iron and steel production

Austria’s iron and steel production sector is concentrated around 52 companies employing 24,642 people between them. Their total gross value creation amounts to some EUR 2.8 billion. Iron and steel production is the most emissions- and energy-intensive sector in Austria, generating approximately 12 Mt CO2e and requiring total energy of some 33 TWh in 2018. Essentially, all the sector’s emissions are included in the ETS. The emissions are generated by 3 companies, with Voestalpine AG and its subsidiaries accounting for over 99%.

Number of companies	52
Employees	24,642
Value added in EUR million	2,757
GHG emissions in Mt CO_2e	11.9
Sectoral GHG emissions as a percentage of the industry total	46.0%

The sector can be further subdivided into the primary and secondary steel production segments.

Its energy flows are shown in the Sankey diagram presented as Figure 12. More than 25 TWh of coal and coke is required to make between 6 and 7 Mt of steel via blast furnaces (currently the only primary steel production method used in Austria). To be able to extract the iron tied up in oxygen compounds as Fe_xO_y in the blast furnace, the carbon it contains is used as a reducing agent. The reaction between the oxygen originally present in the iron ore and the carbon that is introduced produces the greenhouse gas CO_2 once all the relevant reactions have taken place.

Together with the use of fossil energy sources in the amount of 7 TWh to meet the final energy needs of the categories of useful energy shown in Figure 11, primary steel production contributed over 11.4 Mt CO_2e to Austria’s GHG footprint in 2018. The bulk – 9.4 Mt – was caused by the reduction process described above.

Secondary steel production uses electric arc furnaces and a few gas-powered melters to melt around 1 Mt of steel fed in as scrap steel, which then undergoes secondary metallurgical treatment. The energy that this requires and the CO_2 that it generates are both parameters that are exclusively attributable to the final energy needs of the categories of useful energy shown in Figure 11. Final energy consumption and the resulting GHG emissions from secondary steel production are included as part of the sector as a whole in the diagram below.

In the same way as for the other sectors, Figure 11 shows the final energy use and associated GHG emissions from the sector. As a relatively large amount of coal and coke is used to reduce iron ore, however, this is of much less informative value for this sector. Nevertheless, Figure 11 also illustrates that final energy is primarily used to supply process heat at high temperatures in iron and steel production.

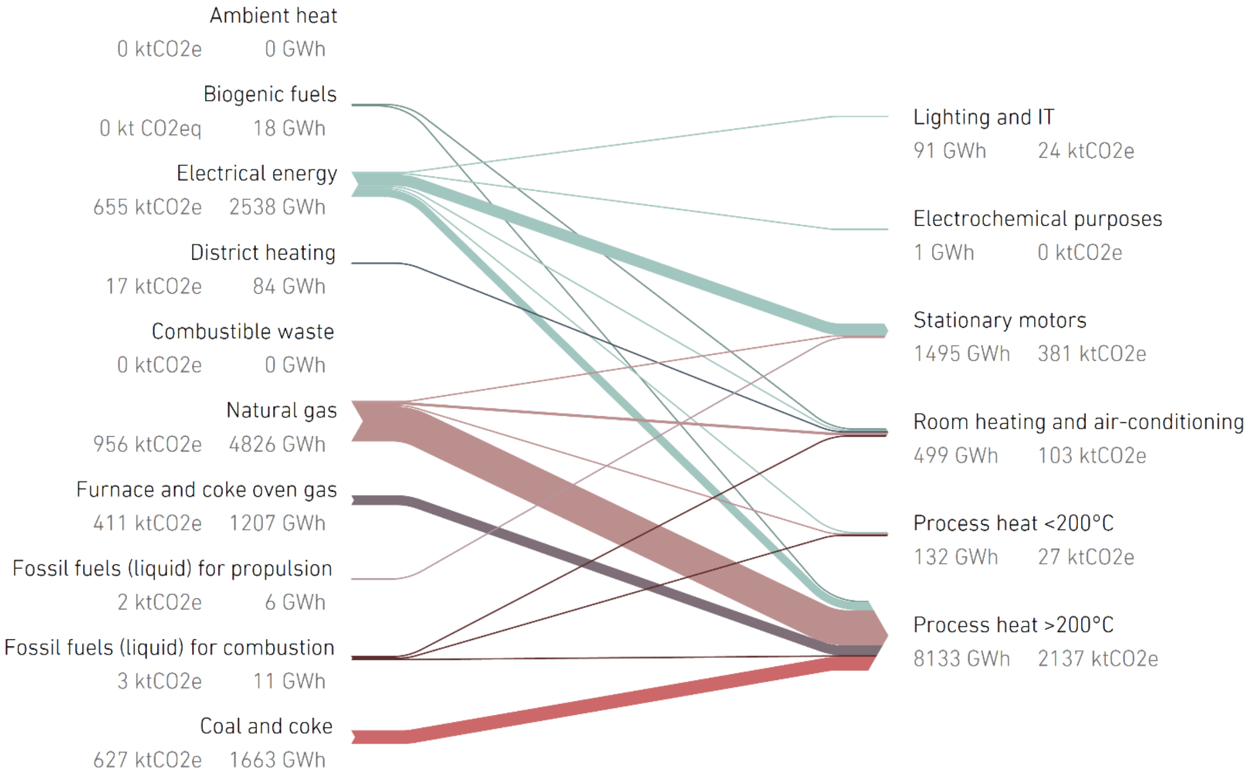


Figure 11: Final energy and GHG intensity for supplying the various categories of useful energy in the “Iron and steel production” sector. Whole of Austria 2019 (own chart based on (Statistik Austria, 2020), (Sejkora, Kühberger, Radner, Trattner, & Kienberger, 2020))

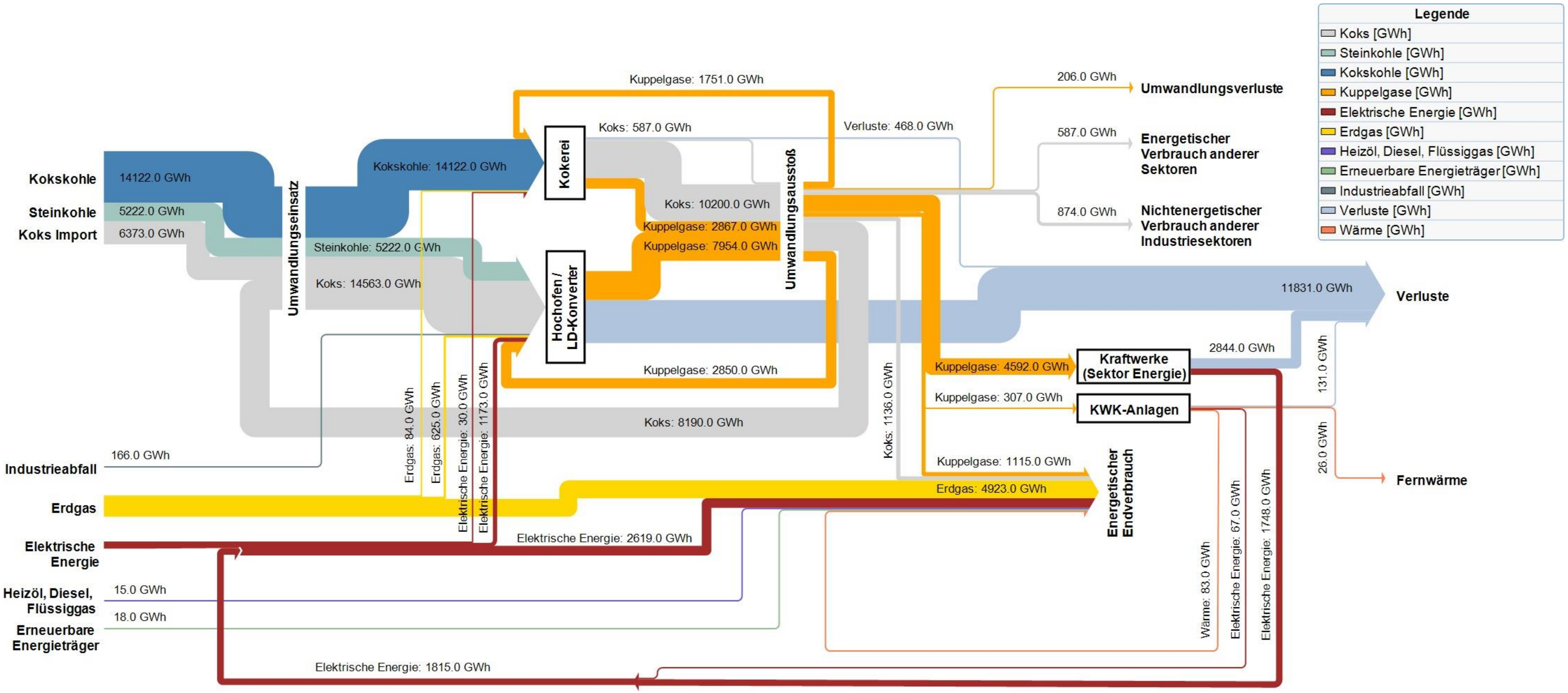


Figure 12: Energy flow diagram for iron and steel production

3.4.2 Stone, earth and glass

Number of companies	1,329
Employees	31,355
Value added in EUR million	2,538
GHG emissions in Mt CO_2e	5.27
Sectoral GHG emissions as a percentage of the industry total	20.4%

Austria's stone, earth and glass sector encompasses 1,329 companies employing over 31,355 people between them. Their total gross value creation amounts to some EUR 2.5 billion. The stone, earth and glass sector is responsible for a total of 5.3 Mt CO_2e of climate-relevant GHG emissions. Contributing 20% of total industrial emissions, it is the second most emissions-intensive sector in Austria. Thirty-three companies in the sector are listed in the ETS and generate 4.1 Mt CO_2e of emissions between them. Cement manufacture is responsible for over 60% of the emissions reported in the ETS.

Process-related emissions account for 63% of the sector's emissions and are caused by the conversion of the mineral raw materials used (e.g. converting limestone (CaCO3) into quicklime (CaO) and CO2). The sector thus represents a particular challenge to the decarbonisation of Austrian industry. As Table 3 illustrates, the sector is divided into seven subsectors, with the cement industry once again generating the lion's share of process-related emissions at 63%. For this reason, it will be used as an example for the sector as a whole in the following section (Umweltbundesamt, 2021).

Table 3: Process-related GHG emissions in the stone, earth and glass sector and its subsectors (Anderl, et al., 2020)

2018	Cement	Lime	Magnesite	Glass	Brick	Dolomite	Na_2CO_3	Sector total
Process-related emissions in kt CO_2e	1,827	544	365	38	105	19	10	2,908
% of sectoral process-related emissions	63%	19%	13%	1%	4%	<1%	<0.5%	100%

The energy-related emissions from the cement industry that were generated in addition to the process-related emissions detailed above amounted to 904 kt CO_2e in 2018 and thus make up only around one third of the subsector's total emissions. As Figure 13 illustrates, the percentage of refuse-derived fuels in the cement subsector's energy mix is amongst the highest in Europe, with the thermal recovery of plastics and scrap tyres playing an especially important role.

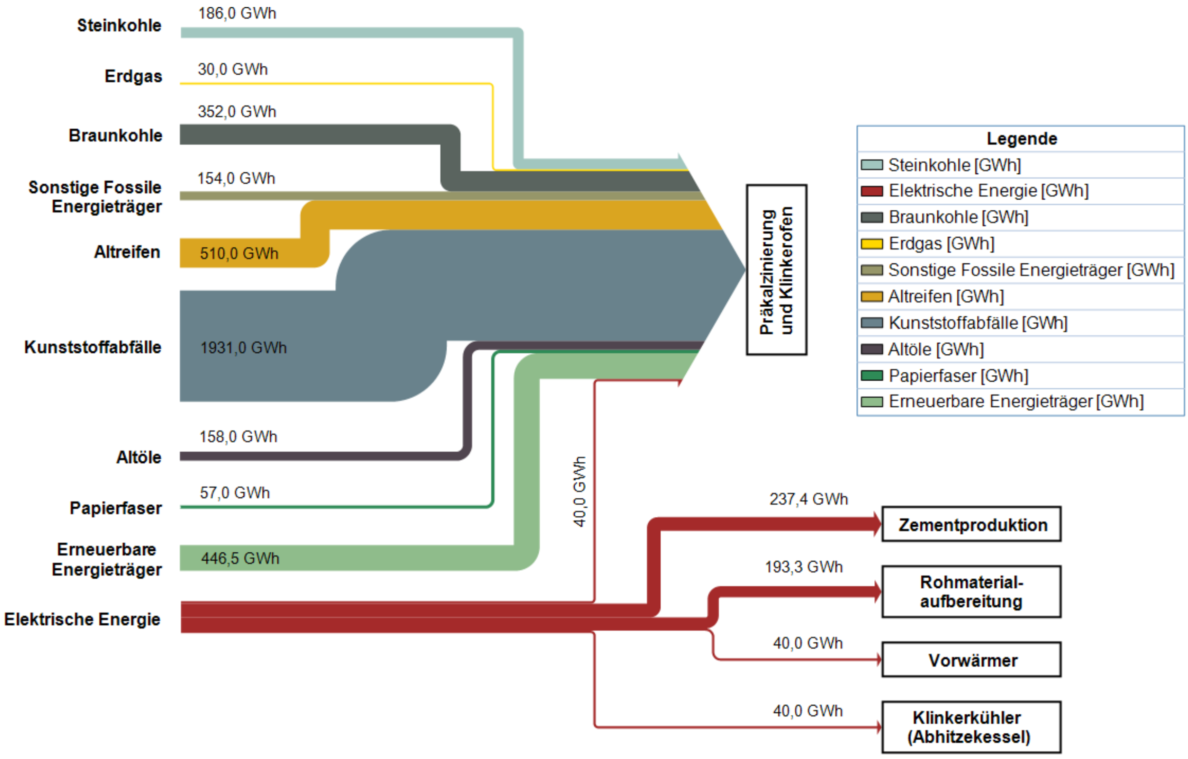


Figure 13: Energy flow diagram for the cement industry

These find particular use in clinker production in rotary kilns at temperatures in excess of 1,200°C. The (geogenic) carbon dioxide contained in the raw material – in this case calcium carbonate ($CaCO_3$) – is driven out by the high temperatures, thus producing the CaO required for cement production. The CO_2 that is expelled then escapes from the kiln.

This process whereby (geogenic) CO_2 tied up in the raw material is driven out at high temperatures is also responsible for the process-related emissions in most of the other abovementioned subsectors of the stone, earth and glass sector. The energy-related emissions and the underlying energy demand per energy source and category of useful energy can be seen in Figure 14. This shows that the supply of heat at high temperatures makes up a particularly significant proportion of the final energy needs. Natural gas, combustible waste and coal and coke are used as the energy sources here. Although all these sources generate climate-relevant GHG emissions, replacing the refuse-derived fuels currently used would also mean having to decide whether to recycle the corresponding waste in another way or dispose of it.

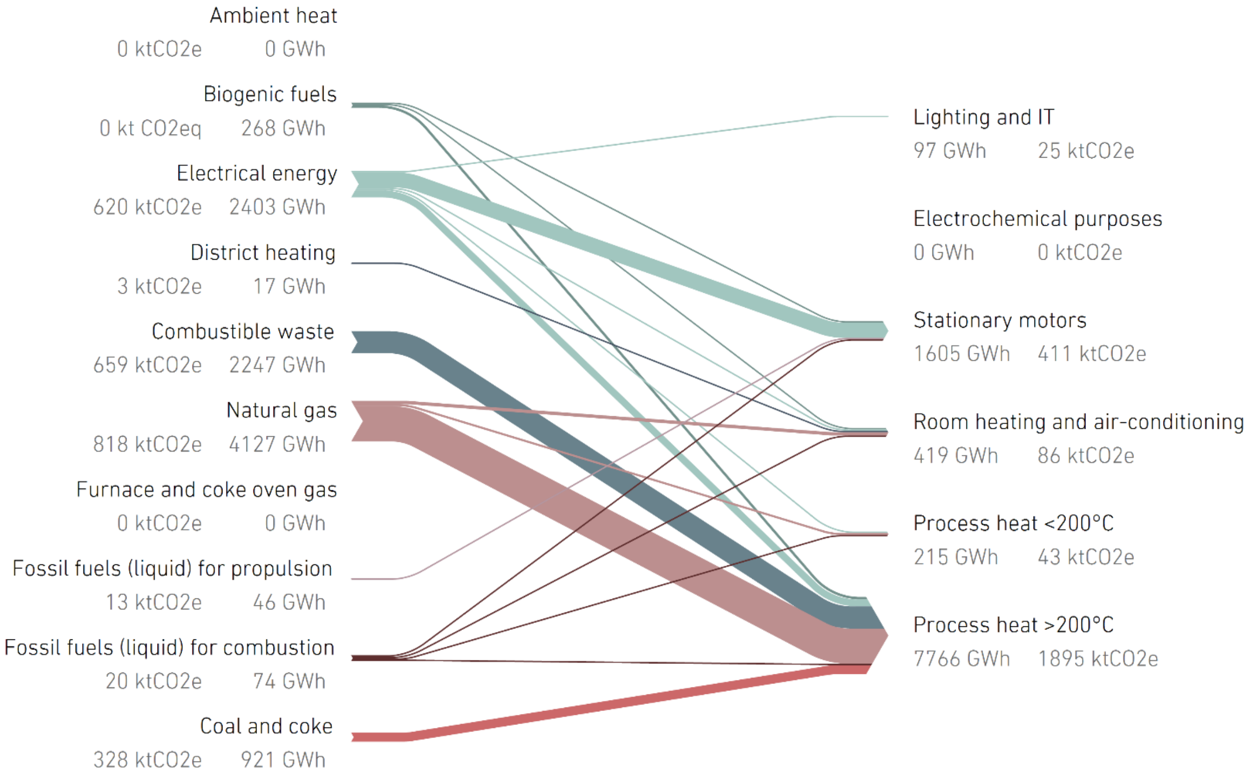


Figure 14: Final energy and GHG intensity for supplying the various categories of useful energy in the “Stone, earth and glass” sector. Whole of Austria 2019 (own chart based on (Statistik Austria, 2020), (Sejkora, Kühberger, Radner, Trattner, & Kienberger, 2020))

3.4.3 Chemicals and petrochemicals

Number of companies	520
Employees	35,051
Value added in EUR million	4,791
GHG emissions in Mt CO_2e	2.17
Sectoral GHG emissions as a percentage of the industry total	8.4%

The chemicals and petrochemicals sector encompasses 520 companies employing 35,000 people between them. Their total gross value creation amounts to some EUR 4.8 billion. Ten chemicals companies are listed in the ETS and emit a combined total of some 1.8 Mt CO_2e, putting this sector third. Over 60% of the emissions reported in the ETS (1.1 Mt CO_2e) relate to the production of fertiliser and nitrogen compounds.

It must be expressly pointed out here that the international definition classifies petroleum processing (e.g. the Schwechat refinery) as part of the energy sector rather than the chemicals and petrochemicals sector.

Figure 15 shows the final energy use and associated GHG emissions from the “Chemicals and petrochemicals” sector. In this sector, final energy is chiefly required for supplying process heat above 200°C, with electrical energy largely being used for this purpose. Many stationary motors have also already been electrified. Natural gas is the most important fossil energy source at 3.5 TWh and is used primarily to supply heat. In addition, 2.8 TWh of natural gas is used as a raw material for transformation processes. This use of the material is not shown in the energy flow diagram. As was also illustrated in Figure 1, the sector’s process-related emissions amounted to 851 kt CO_2e in 2019.

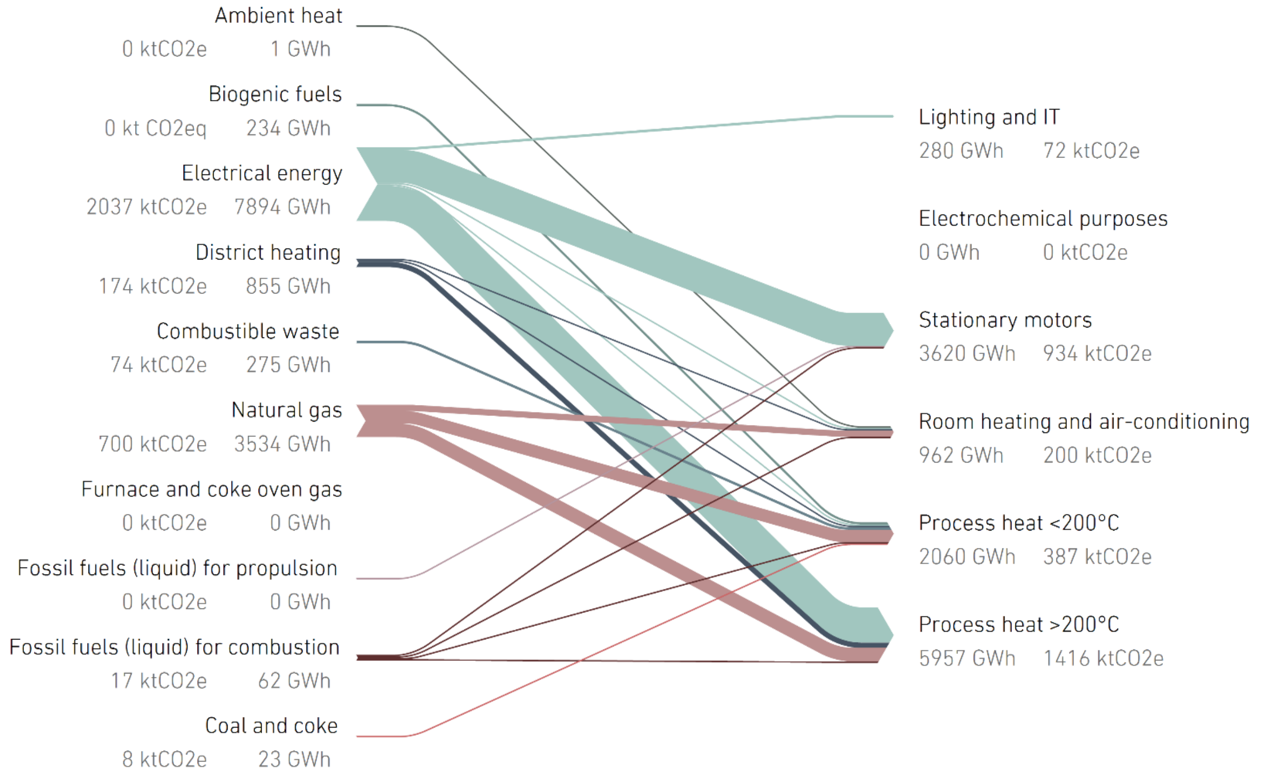


Figure 15: Final energy and GHG intensity for supplying the various categories of useful energy in the “Chemicals and petrochemicals” sector. Whole of Austria 2019 (own chart based on (Statistik Austria, 2020), (Sejkora, Kühberger, Radner, Trattner, & Kienberger, 2020))

3.4.4 Paper and printing

The paper and printing sector includes the manufacture of paper, cardboard and other paper products as well as the production of printed matter, with the manufacture of paper and cardboard accounting for 99.9% of fossil GHG emissions (Statistik Austria, 2020). The production of paper and cardboard involves 138 companies employing 31,355 people and creating total gross value of EUR 2 billion. Nineteen companies in the sector are listed in the ETS and emit over 1.4 Mt CO2e in all.

Number of companies	957
Employees	27,458
Value added in EUR million	2,791
GHG emissions in Mt CO_2e	1.98
Sectoral GHG emissions as a percentage of the industry total	7.7%

The paper and printing sector is responsible for a total of some 2 Mt CO_2e and is thus the fourth most emissions-intensive sector, contributing 7.7% of overall industrial emissions.

The sector is also the second most energy-intensive in Austria, requiring 22 TWh of energy in total. Although all GHG emissions in the paper and printing sector are energy-related, the sector occupies a unique position in terms of its GHG emissions. This is because, for the purposes of energy statistics, black liquor – a byproduct of chemical wood pulping – is not deemed to be produced as waste and become an energy source until it is within the scope of calculation for the sector. This is then used to generate electricity and heat in companies’ own CHP plants. This peculiarity of the sector, which is illustrated in Figure 17 and which currently obviates the need to buy in significant volumes of energy from outside, has to be factored into any consideration of decarbonisation.

Over half of the sector’s total energy requirement in 2018 – approximately 22,300 GWh – was able to be met using the black liquor described above within the scope for calculating the sector’s footprint. Climate-relevant energy-related GHG emissions in the amount of some 1,700 kt CO_2e are generated mainly by burning fossil natural gas, as illustrated in the sector-specific Sankey diagrams presented below as Figure 17 and Figure 17. According to information from Sappi Gratkorn, which has been the largest consumer to date, the coal that is currently still listed in the statistics has been and is being replaced by a mix of biomass and CH_4 in 2020 and 2021.

It must also be borne in mind that the statistics distinguish between using fuel in CHP plants

To make steam and to generate electricity. For the purpose of studying the various decarbonisation strategies, the production of heat and electricity inside the CHP plant – which actually happens together – is considered separately so that the vastly different requirements for generating electricity and steam can be taken into account.

Applying this methodology to the statistics means that the analysis of useful energy presented in Figure 16 only shows the use of energy sources for the production of steam (which includes the production of steam inside CHP plants), not the use of energy required to generate electricity. The electrical energy obtained in companies' own plants is only implicitly discernible in the analysis of useful energy in the form of a lower energy requirement.

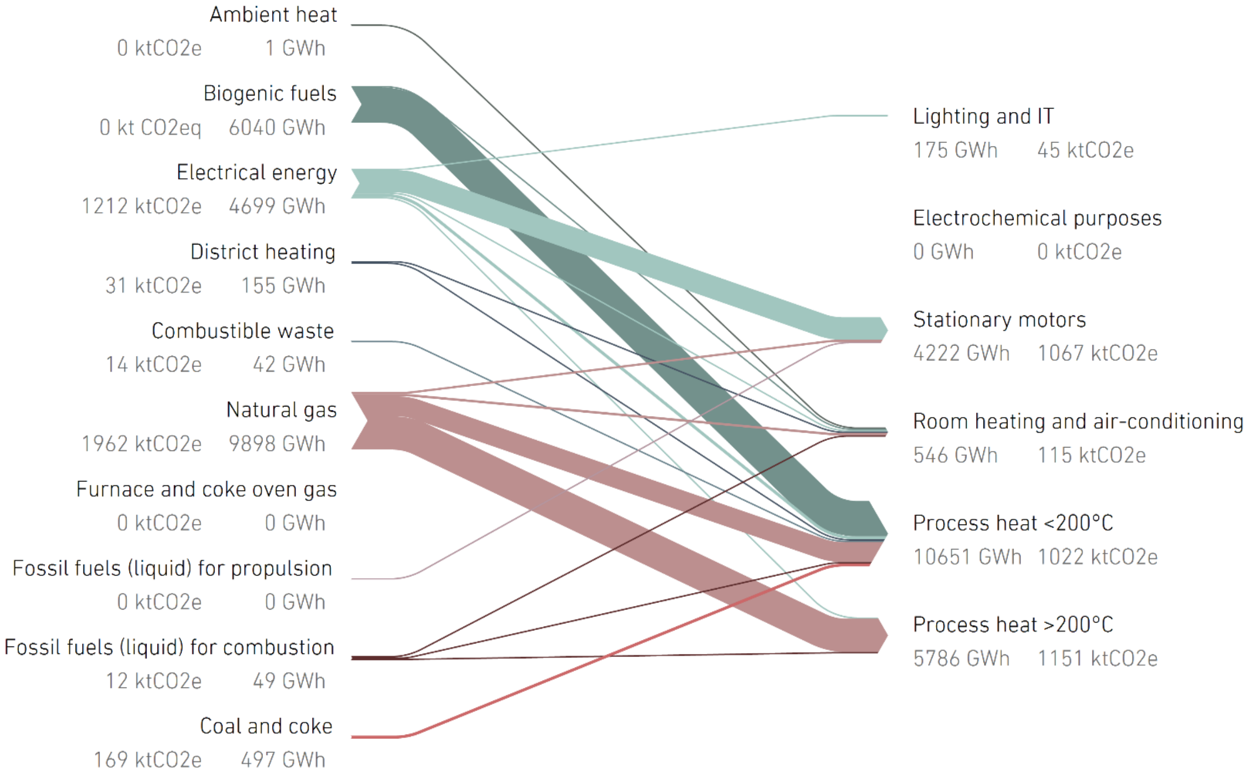


Figure 16: Final energy and GHG intensity for supplying the various categories of useful energy in the "Paper and printing" sector. Whole of Austria 2019 (own chart based on (Statistik Austria, 2020), (Sejkora, Kühberger, Radner, Trattner, & Kienberger, 2020))

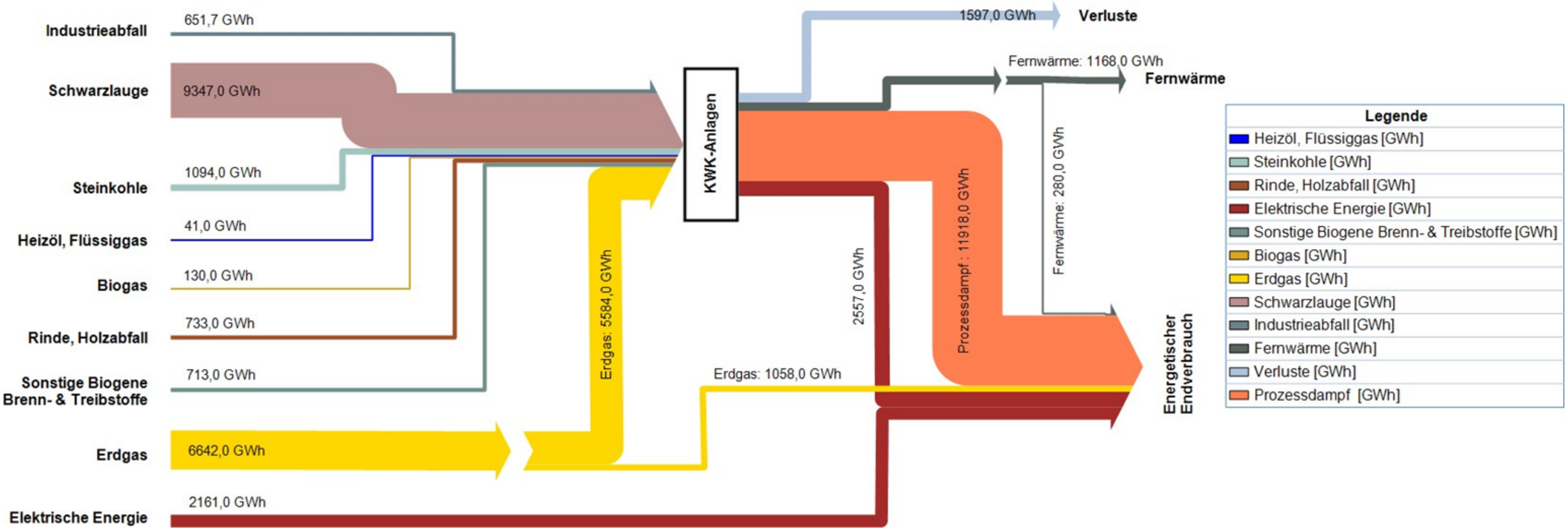


Figure 17: Energy flow diagram for the paper and printing sector. Own chart

4 Technical decarbonisation potential

This section takes a detailed look at the areas of technical decarbonisation potential determined for the four sectors described above, which generate the most GHG emissions. A full analysis of all 13 sectors can be found in the long version of this study.

To support the complete decarbonisation of Austrian industry and indicate potential decarbonisation strategies, the technical decarbonisation potential in each sector is illustrated based on the following four decarbonisation strategies:

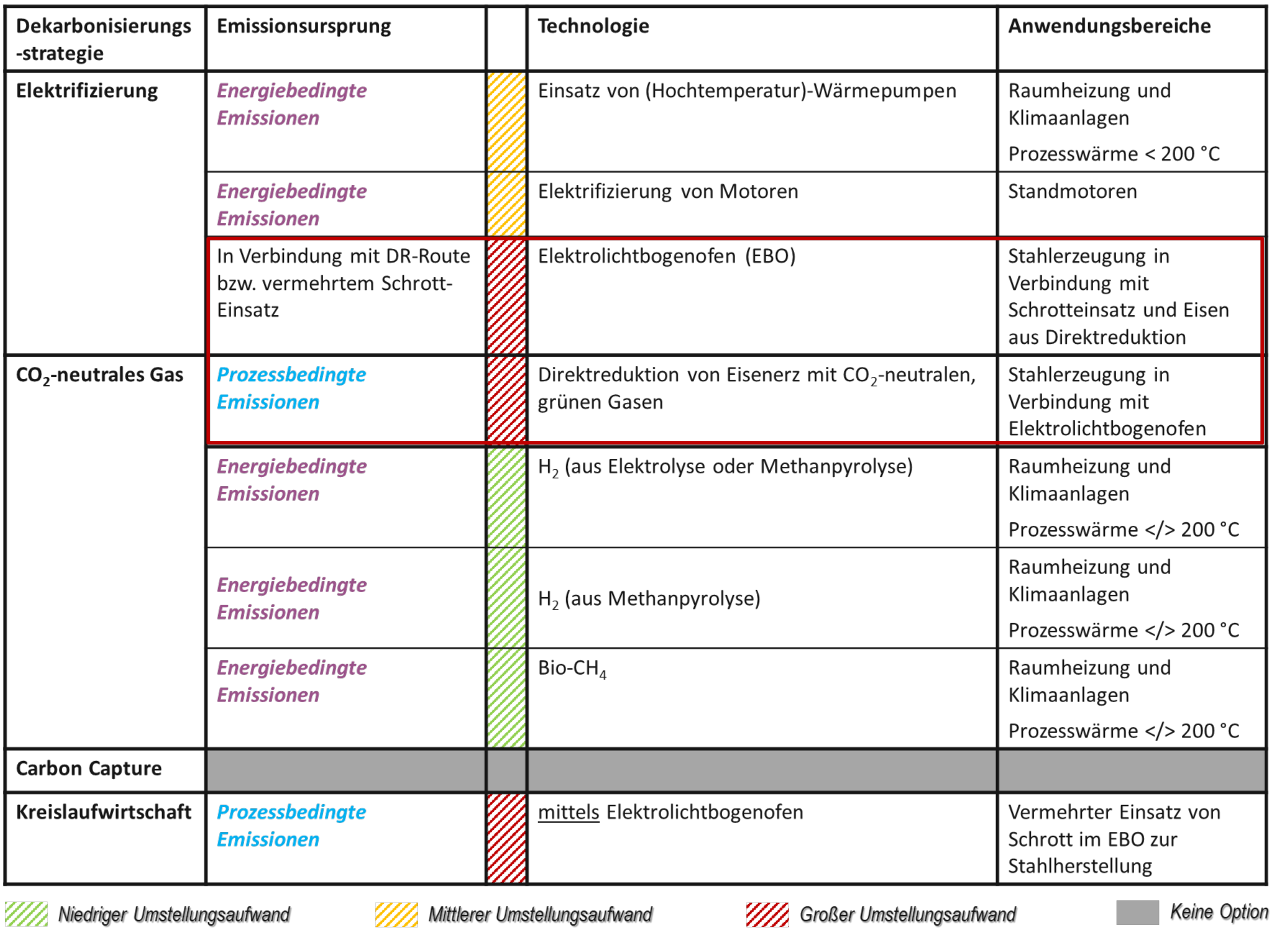
- **Electrification**
    - Heat pumps for room heating and air-conditioning systems (COP 3) and process heat below 200°C (COP 2.5)
    - Electrically powered stationary motors
- **Carbon-neutral gases**
    - Hydrogen (from electrolysis or methane pyrolysis) and bio-CH4 for room heating and air-conditioning systems as well as process heat below/above 200°C and sector-specific technologies in line with process requirements
- **Carbon capture**
    - Sector-specific technologies
- **Circular economy** (for selected emissions-intensive sectors)
    - Increased use of end-of-life products in sector-specific production processes

4.1 Areas of technical decarbonisation potential in the various sectors

4.1.1 Iron and steel production

All decarbonisation strategies studied for iron and steel production are based on avoiding both energy- and process-related emissions to a greater or lesser extent. The fact that an alternative technology already exists in the form of direct reduction/electric arc furnaces (abbreviated as DRI/ERF; outlined in red in Figure 18) means that the use of carbon capture technologies is to be considered only in the background in this study as far as this sector is concerned.

The decarbonisation of the categories of useful energy shown in Figure 18 would require a modest outlay for conversion work in the case of electrification, while using carbon-neutral gases would require minimal outlay within the scope being considered. Technologies such as the direct reduction of iron ore combined with electric arc furnaces require a root-and-branch transformation of the production process and would involve a significant outlay for conversion work.



Dekarbonisierungs-strategie	Emissionsursprung		Technologie	Anwendungsbereiche
Elektrifizierung	***Energiebedingte Emissionen***	🟨	Einsatz von (Hochtemperatur)-Wärmepumpen	Raumheizung und Klimaanlagen Prozesswärme < 200 °C
	Energiebedingte Emissionen	🟨	Elektrifizierung von Motoren	Standmotoren
	In Verbindung mit DR-Route bzw. vermehrtem Schrott-Einsatz	🟥	Elektrolichtbogenofen (EBO)	Stahlerzeugung in Verbindung mit Schrotteinsatz und Eisen aus Direktreduktion
CO_2-neutrales Gas	***Prozessbedingte Emissionen***	🟥	Direktreduktion von Eisenerz mit CO_2-neutralen, grünen Gasen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen
	Energiebedingte Emissionen	🟩	H_2 (aus Elektrolyse oder Methanpyrolyse)	Raumheizung und Klimaanlagen Prozesswärme </> 200 °C
	Energiebedingte Emissionen	🟩	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen Prozesswärme </> 200 °C
	Energiebedingte Emissionen	🟩	Bio-CH_4	Raumheizung und Klimaanlagen Prozesswärme </> 200 °C
Carbon Capture	⬛	⬛	⬛	⬛
Kreislaufwirtschaft	***Prozessbedingte Emissionen***	🟥	mittels Elektrolichtbogenofen	Vermehrter Einsatz von Schrott im EBO zur Stahlherstellung

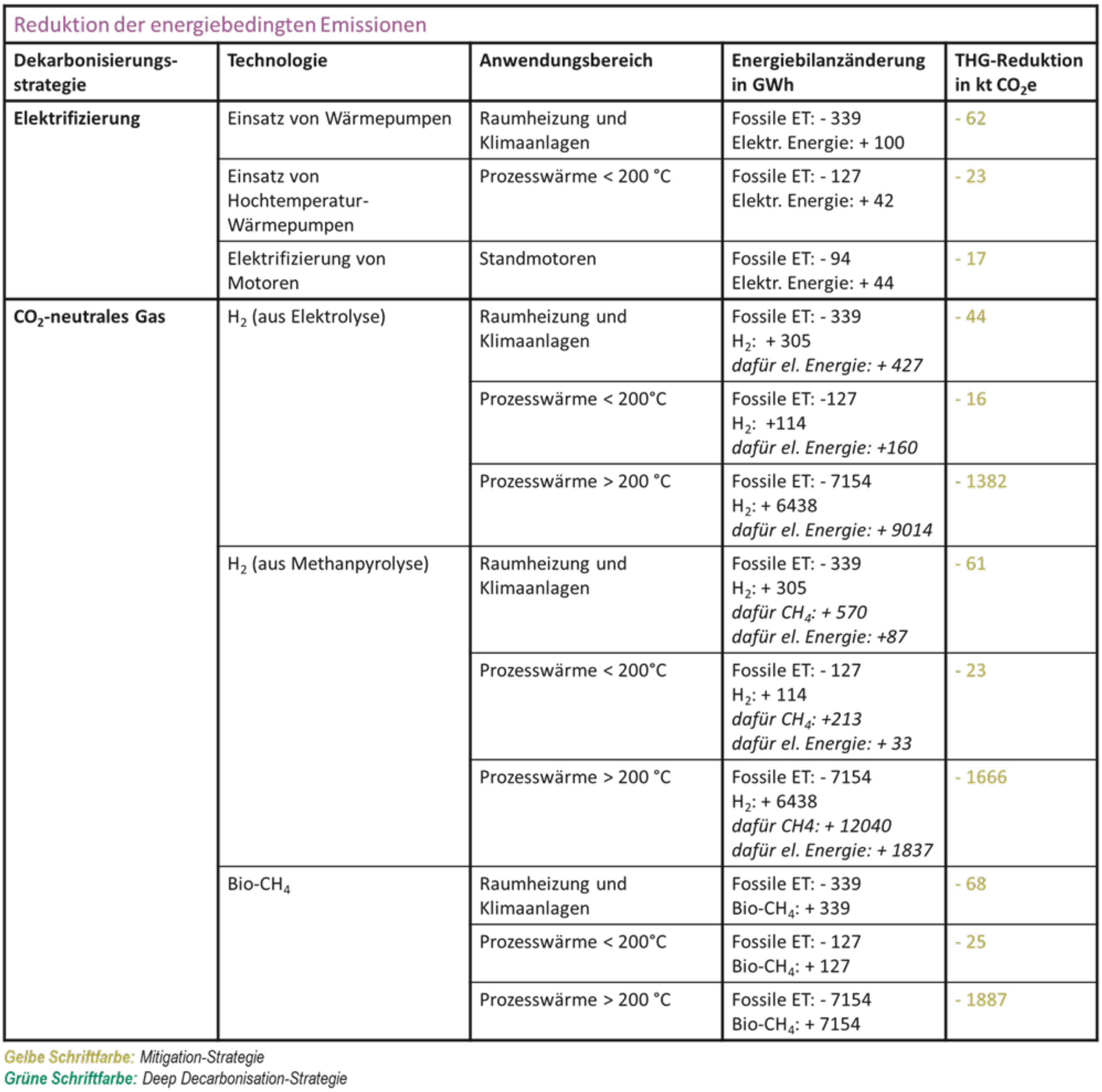
🟩 *Niedriger Umstellungsaufwand* 🟨 *Mittlerer Umstellungsaufwand* 🟥 *Großer Umstellungsaufwand* ⬛ *Keine Option*

Figure 18: Overview of the decarbonisation strategies in the iron and steel production sector

Decarbonising the useful energy processes of room climate and hot water as well as process heat <200°C through the use of heat pumps can reduce energy-related GHG emissions by up to 85 kt CO_2e. Process temperatures >200°C require the use of carbon-neutral gases. Covering all temperature levels as well as stationary motors with carbon-neutral gases would enable energy-related emissions to be reduced by up to 1,989 kt CO_2e.

If the upstream chains in the manufacture of hydrogen via electrolysis or pyrolysis were to be included, this would reduce the savings potential by up to 500 kt CO_2e, as Figure 19 shows. Although they are based on electrical energy, the use of electric arc furnaces is being considered together with direct reduction in the iron and steel production sector and thus appears in Figure 20 alongside the discussion of process-related emissions rather than in Figure 19.

Besides avoiding energy-related emissions as explained above, electrification and using carbon-neutral gases play an especially important role in avoiding process emissions (Figure 20) in particular. Replacing traditional blast furnaces with LD converters using H_2- or CH_4-based direct reduction in combination with electric arc furnaces would thus enable up to 10 Mt CO_2e to be saved if they were run on carbon-neutral gases, although it would be important here too to take account of the upstream chain for generating any hydrogen that is used. After all, if it were assumed that the hydrogen required for the abovementioned EU electricity mix with a CO_2 intensity of 56 g CO_2/kWh of electricity was generated via electrolysis, this would reduce the stated value by as much as 1,430 kt CO_2e. If the H_2 were generated using methane pyrolysis, this figure would still be almost 300 kt CO_2e.

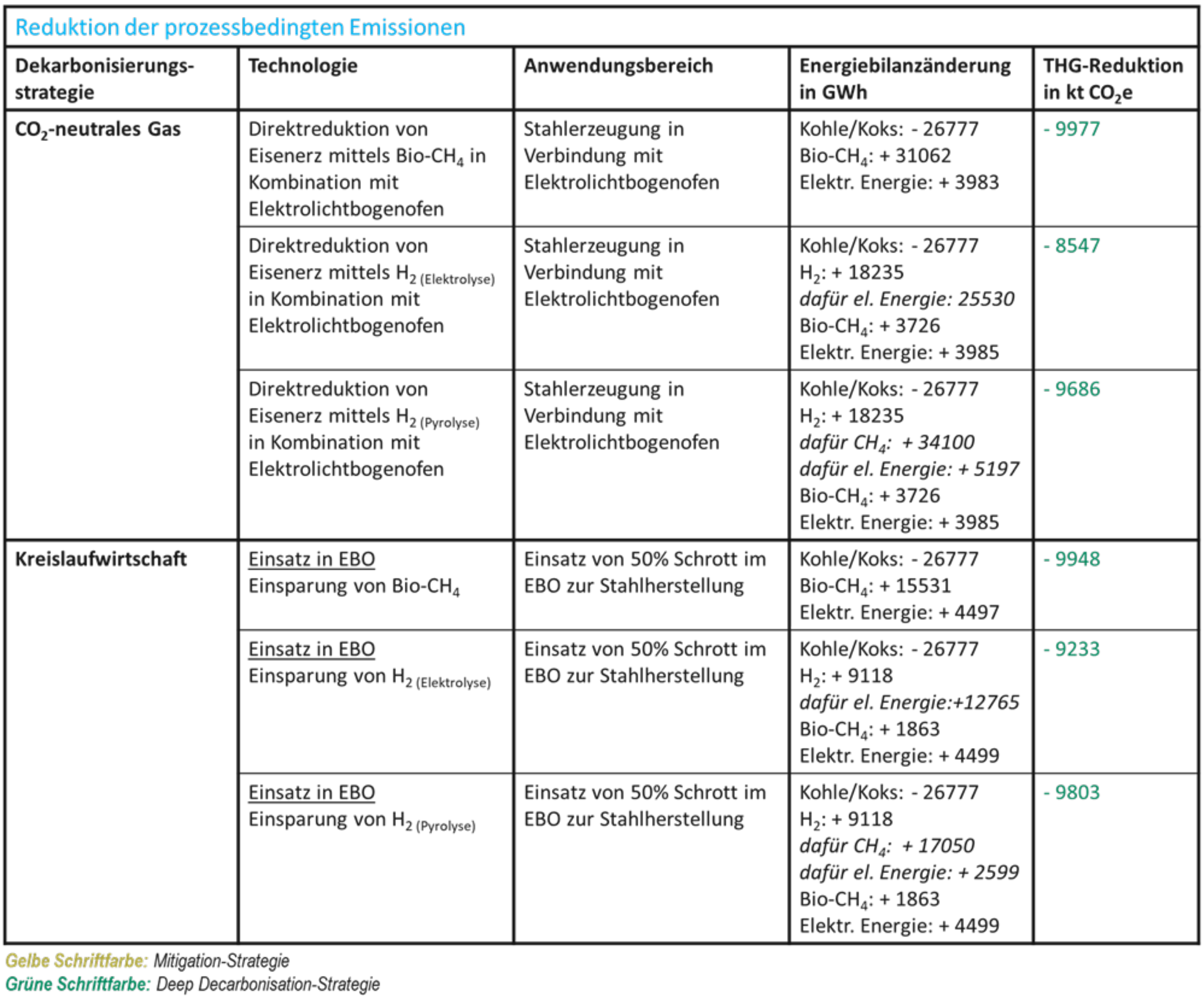


Reduktion der energiebedingten Emissionen				
Dekarbonisierungs-strategie	**Technologie**	**Anwendungsbereich**	**Energiebilanzänderung in GWh**	**THG-Reduktion in kt CO_2e**
Elektrifizierung	Einsatz von Wärmepumpen	Raumheizung und Klimaanlagen	Fossile ET: - 339 Elektr. Energie: + 100	- 62
	Einsatz von Hochtemperatur-Wärmepumpen	Prozesswärme < 200 °C	Fossile ET: - 127 Elektr. Energie: + 42	- 23
	Elektrifizierung von Motoren	Standmotoren	Fossile ET: - 94 Elektr. Energie: + 44	- 17
CO_2-neutrales Gas	H_2 (aus Elektrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 339 H_2: + 305 *dafür el. Energie: + 427*	- 44
		Prozesswärme < 200°C	Fossile ET: -127 H_2: +114 *dafür el. Energie: +160*	- 16
		Prozesswärme > 200 °C	Fossile ET: - 7154 H_2: + 6438 *dafür el. Energie: + 9014*	- 1382
	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 339 H_2: + 305 *dafür CH_4: + 570* *dafür el. Energie: +87*	- 61
		Prozesswärme < 200°C	Fossile ET: - 127 H_2: + 114 *dafür CH_4: +213* *dafür el. Energie: + 33*	- 23
		Prozesswärme > 200 °C	Fossile ET: - 7154 H_2: + 6438 *dafür CH4: + 12040* *dafür el. Energie: + 1837*	- 1666
	Bio-CH_4	Raumheizung und Klimaanlagen	Fossile ET: - 339 Bio-CH_4: + 339	- 68
		Prozesswärme < 200°C	Fossile ET: - 127 Bio-CH_4: + 127	- 25
		Prozesswärme > 200 °C	Fossile ET: - 7154 Bio-CH_4: + 7154	- 1887

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

Figure 19: Technical potential for reducing energy-related emissions in the iron and steel production sector

With regard to the increased use of circular economy measures, Figure 20 shows that the direct reduction process remains largely carbon-neutral when run on 100% carbon-neutral gas and only the energy footprint changes. The minimal increase in GHG emissions indicated is due to more electricity being required at the secondary metallurgy stage. However, this slight deterioration has to be seen in the context of the energy and resources saved by using more recycled scrap. For instance, increasing the amount of scrap used by 50% along the DRI/EAF route would result in primary energy savings of between 15 and 30 TWh per year. The amount of the savings depends on the upstream chain involved in generating the hydrogen.



Reduktion der prozessbedingten Emissionen

Dekarbonisierungs-strategie	Technologie	Anwendungsbereich	Energiebilanzänderung in GWh	THG-Reduktion in kt CO_2e
CO_2-neutrales Gas	Direktreduktion von Eisenerz mittels Bio-CH_4 in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 Bio-CH_4: + 31062 Elektr. Energie: + 3983	- 9977
	Direktreduktion von Eisenerz mittels $H_{2\,(Elektrolyse)}$ in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 H_2: + 18235 *dafür el. Energie: 25530* Bio-CH_4: + 3726 Elektr. Energie: + 3985	- 8547
	Direktreduktion von Eisenerz mittels $H_{2\,(Pyrolyse)}$ in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 H_2: + 18235 *dafür CH_4: + 34100* *dafür el. Energie: + 5197* Bio-CH_4: + 3726 Elektr. Energie: + 3985	- 9686
Kreislaufwirtschaft	Einsatz in EBO Einsparung von Bio-CH_4	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 Bio-CH_4: + 15531 Elektr. Energie: + 4497	- 9948
	Einsatz in EBO Einsparung von $H_{2\,(Elektrolyse)}$	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 H_2: + 9118 *dafür el. Energie:+12765* Bio-CH_4: + 1863 Elektr. Energie: + 4499	- 9233
	Einsatz in EBO Einsparung von $H_{2\,(Pyrolyse)}$	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 H_2: + 9118 *dafür CH_4: + 17050* *dafür el. Energie: + 2599* Bio-CH_4: + 1863 Elektr. Energie: + 4499	- 9803

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

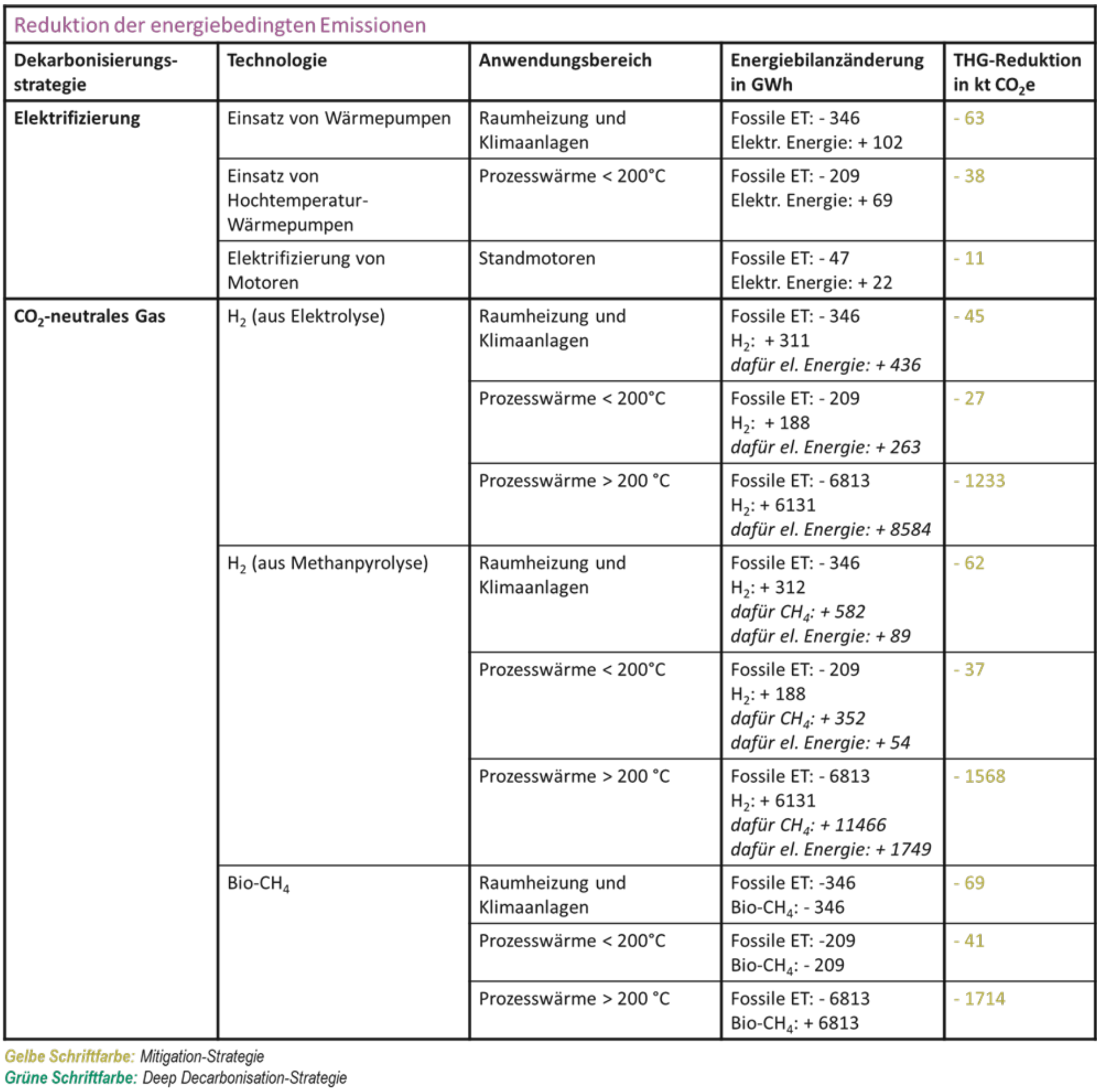
Figure 20: Technical potential for reducing process-related emissions in the iron and steel production sector

The calculations above indicate that the decarbonisation of iron and steel production can be achieved by using carbon-neutral gases in particular (approximately 9 to 11 Mt CO_2e in total). However, the need for these gases can be reduced significantly by using electrification measures at lower temperatures as well as an increased percentage of recyclate. It must be pointed out that, compared with the sponge iron obtained through direct reduction, the increased use of scrap in electric arc furnaces mainly has an impact on the energy intensity of the steelmaking, while climate neutrality is already achieved by using carbon-neutral gases in the direct reduction process.

4.1.2 Stone, earth and glass

In the stone, earth and glass sector, the need to feed CO_2-generating minerals into the production process means that avoiding process-related emissions through carbon capture is particularly important. As well as considering the other decarbonisation strategies, this report also investigates two of the most promising carbon capture technologies.

As Figure 21 shows, decarbonising the useful energy processes of room heating and air-conditioning systems as well as process heat <200°C can reduce energy-related GHG emissions by 100–110 kt CO_2e. The savings potential that can be achieved by electrifying industrial stationary motors in the stone, earth and glass sector amounts to a mere 11 kt CO_2e. Decarbonising process temperatures >200°C requires the use of carbon-neutral gases on account of the processes shown in Figure 13. This would enable energy-related emissions to be reduced by between 1,714 and 1,233 kt CO_2e depending on the technology used.

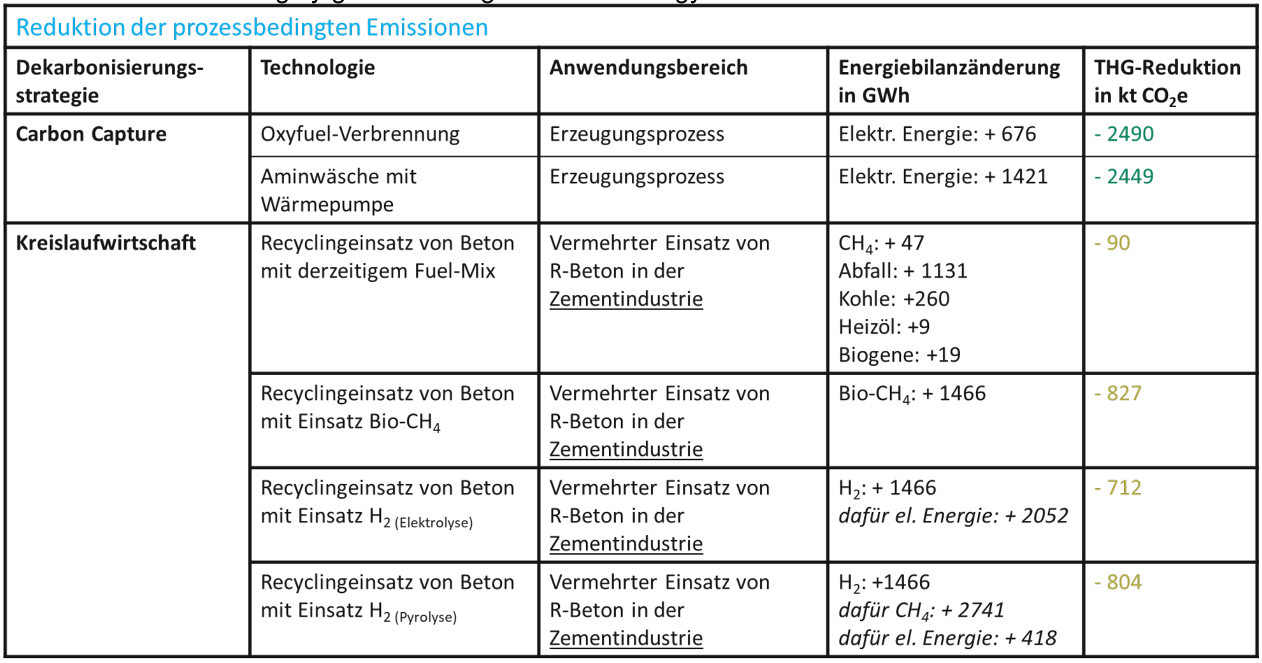


Reduktion der energiebedingten Emissionen				
Dekarbonisierungs-strategie	**Technologie**	**Anwendungsbereich**	**Energiebilanzänderung in GWh**	**THG-Reduktion in kt CO_2e**
Elektrifizierung	Einsatz von Wärmepumpen	Raumheizung und Klimaanlagen	Fossile ET: - 346 Elektr. Energie: + 102	- 63
	Einsatz von Hochtemperatur-Wärmepumpen	Prozesswärme < 200°C	Fossile ET: - 209 Elektr. Energie: + 69	- 38
	Elektrifizierung von Motoren	Standmotoren	Fossile ET: - 47 Elektr. Energie: + 22	- 11
CO_2-neutrales Gas	H_2 (aus Elektrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 346 H_2: + 311 *dafür el. Energie: + 436*	- 45
		Prozesswärme < 200°C	Fossile ET: - 209 H_2: + 188 *dafür el. Energie: + 263*	- 27
		Prozesswärme > 200 °C	Fossile ET: - 6813 H_2: + 6131 *dafür el. Energie: + 8584*	- 1233
	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 346 H_2: + 312 *dafür CH_4: + 582* *dafür el. Energie: + 89*	- 62
		Prozesswärme < 200°C	Fossile ET: - 209 H_2: + 188 *dafür CH_4: + 352* *dafür el. Energie: + 54*	- 37
		Prozesswärme > 200 °C	Fossile ET: - 6813 H_2: + 6131 *dafür CH_4: + 11466* *dafür el. Energie: + 1749*	- 1568
	Bio-CH_4	Raumheizung und Klimaanlagen	Fossile ET: -346 Bio-CH_4: - 346	- 69
		Prozesswärme < 200°C	Fossile ET: -209 Bio-CH_4: - 209	- 41
		Prozesswärme > 200 °C	Fossile ET: - 6813 Bio-CH_4: + 6813	- 1714

Gelbe Schriftfarbe: Mitigation-Strategie
Grüne Schriftfarbe: Deep Decarbonisation-Strategie

Figure 21: Technical potential for reducing energy-related emissions in the stone, earth and glass sector

Emission reduction through carbon capture is the only option in this sector for achieving as complete a decarbonisation as possible (Figure 22). Most of the technologies that are currently viable options can achieve CO_2 capture rates of 90–95%, and energy-related CO_2 emissions generated in supplying the temperatures required for the stripping process could also be captured (Anantharaman, et al., 2018). However, there are also significant differences in their respective energy intensities besides how they are essentially integrated into the system (integrated, with the possibility of improving system efficiencies, or positioned downstream of the process (“end-of-pipe”)) and the conversion outlay required for this. For instance, amine scrubbing, which takes place downstream of the traditional calcination process in a rotary kiln, requires more than twice as much electrical energy as oxyfuel technology, which offers additional potential for optimising the system in terms of producing and using oxygen during operation. This results in a lower CO_2 reduction potential of some 40 kt based on the EU electricity mix from (European Commission, 2020). When considering the decarbonisation potential offered by carbon capture, it is important to stress that the utilisation of the greenhouse gas that is captured further along in the process has not been investigated in the present study. This may potentially give rise to energy needs and GHG emissions in other economic sectors or countries and generate additional costs. Process-related GHG emissions can also be reduced in the cement production subsector by using more recycled concrete. When calculating the technical recycling potential, it was assumed based on (Müller, 2006) that there will be enough concrete reaching the end of its useful life in 2040 to enable the amount of primary cement required to be reduced by around 28% (Nusselder, et al., 2015). Taking the current energy mix as a basis (shown in Figure 13) for the recyclate drying required in accordance with (Sousa & Bogas, 2021), only up to 90 kt CO_2e can be saved. However, modifying this mix by using pure bio-CH_4 for the drying process instead would increase the savings potential to up to 804 kt CO_2e. Unlike in the iron and steel production sector, the increased use of recyclate in the cement sector would undoubtedly reduce process-related emissions as some of the calcium carbonate that would normally be required in the production process could be left out in favour of the recyclate. Without carbon capture technologies, this process generates emissions in this sector even if largely greenhouse-gas-neutral energy sources are used.



Reduktion der prozessbedingten Emissionen

Dekarbonisierungs-strategie	Technologie	Anwendungsbereich	Energiebilanzänderung in GWh	THG-Reduktion in kt CO_2e
Carbon Capture	Oxyfuel-Verbrennung	Erzeugungsprozess	Elektr. Energie: + 676	- 2490
	Aminwäsche mit Wärmepumpe	Erzeugungsprozess	Elektr. Energie: + 1421	- 2449
Kreislaufwirtschaft	Recyclingeinsatz von Beton mit derzeitigem Fuel-Mix	Vermehrter Einsatz von R-Beton in der Zementindustrie	CH_4: + 47 Abfall: + 1131 Kohle: +260 Heizöl: +9 Biogene: +19	- 90
	Recyclingeinsatz von Beton mit Einsatz Bio-CH_4	Vermehrter Einsatz von R-Beton in der Zementindustrie	Bio-CH_4: + 1466	- 827
	Recyclingeinsatz von Beton mit Einsatz $H_{2\ (Elektrolyse)}$	Vermehrter Einsatz von R-Beton in der Zementindustrie	H_2: + 1466 *dafür el. Energie: + 2052*	- 712
	Recyclingeinsatz von Beton mit Einsatz $H_{2\ (Pyrolyse)}$	Vermehrter Einsatz von R-Beton in der Zementindustrie	H_2: +1466 *dafür CH_4: + 2741* *dafür el. Energie: + 418*	- 804

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

Figure 22: Technical potential for reducing process-related emissions in the stone, earth and glass sector

As illustrated, besides reducing energy-related emissions, decarbonising the production process and its process-related emissions will also be particularly key to success in the stone, earth and glass sector.
As already explained, therefore, decarbonisation should be based predominantly on using a technology that forms part of the carbon capture strategy such as oxyfuels or amine scrubbing, although the potential offered by material cycles that can be closed is also to be regarded as highly significant due to the overall contribution to conserving resources that it could be expected to make.

4.1.3 Chemicals and petrochemicals

In the chemicals and petrochemicals sector too, all decarbonisation strategies studied are based on avoiding energy-related GHG emissions to a greater or lesser extent. The various areas of decarbonisation potential have been estimated from the analysis of useful energy using the top-down approach described and are listed in Figure 23.
As illustrated in Section 3.4.3, emissions in this sector are primarily generated through supplying process heat, with the provision of high-temperature process heat already converted to electricity in many cases. Converting it to carbon-neutral gases would unlock savings potential amounting to 204–237 kt CO_2e. Using high-temperature heat pumps to supply low-temperature process heat would enable GHG emissions to be reduced by 323 kt CO_2e, while the use of renewable gases could save up to 354 kt CO_2e. The fact that many stationary motors are already electrified means that there is virtually no scope for any further reductions in this category of useful energy.

Reduktion der energiebedingten Emissionen				
Dekarbonisierungs-strategie	**Technologie**	**Anwendungsbereich**	**Energiebilanzänderung in GWh**	**THG-Reduktion in kt CO_2e**
Elektrifizierung	Einsatz von Wärmepumpen	Raumheizung und Klimaanlagen	Fossile ET: - 705 Elektr. Energie: 208	- 130
	Einsatz von Hochtemperatur-Wärmepumpen	Prozesswärme < 200 °C	Fossile ET: - 1666 Elektr. Energie: + 553	- 323
	Elektrifizierung von Motoren	Standmotoren	Fossile ET: - 0,4 Elektr. Energie: + 0,2	- 0,1
CO_2-neutrales Gas	H_2 (aus Elektrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 705 H_2: + 634 *dafür el. Energie: + 94*	- 92
		Prozesswärme < 200°C	Fossile ET: - 1666 H_2: + 1499 *dafür el. Energie: + 2099*	- 181
		Prozesswärme > 200 °C	Fossile ET: - 1523 H_2: + 1371 *dafür el. Energie: + 1919*	- 237
	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 705 H_2: + 634 *dafür CH_4: + 1186* *dafür el. Energie: + 181*	- 126
		Prozesswärme < 200°C	Fossile ET: - 1666 H_2: + 1499 *dafür CH_4: + 2804* *dafür el. Energie: + 428*	- 319
		Prozesswärme > 200 °C	Fossile ET: - 1523 H_2: + 1371 *dafür CH4: + 2564* *dafür el. Energie: + 391*	- 271
	Bio-CH_4	Raumheizung und Klimaanlagen	Fossile ET: - 705 Bio-CH_4: + 705	- 141
		Prozesswärme < 200°C	Fossile ET: - 1666 Bio-CH_4: + 1666	- 354
		Prozesswärme > 200 °C	Fossile ET: - 1523 Bio-CH_4: + 1523	- 304

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

Figure 23: Technical potential for reducing energy-related emissions in the chemicals and petrochemicals sector

The chemicals sector currently uses substantial volumes of fossil raw materials to make chemical products. This generates process-related emissions directly from the manufacturing processes, while the subsequent disposal and burning of chemical products made from fossil raw materials generates fossil – and thus climate-relevant – CO_2. As these GHG emissions are not generated until the products undergo thermal recovery, these emissions are allocated to the sector that actually does the burning (e.g. waste management).

If one now assumes that these climate-relevant emissions are also to be avoided, this has a significant impact on the production processes in the chemicals industry. For this reason, the influence of alternative production processes in the chemicals industry on the most important chemical raw materials is analysed below. See (Andreas Windsperger, 2018) for a detailed and comprehensive analysis concerning decarbonising the chemicals industry.

4.1.3.1 Methanol from green hydrogen

Austria currently produces 28.7 kt of methane (Andreas Windsperger, 2018), which results in GHG emissions of some 15 kt CO_2e.[9] Natural gas with an equivalent energy content of 80 GWh is used as the raw material to make the methanol. This is mainly done in steam reformers, which generate hydrogen and CO as well as CO_2 from natural gas.

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[9] Own calculation based on the production processes used in Austri

DECHEMA (DECHEMA, 2019) has analysed a production route for decarbonising methanol production for Germany that uses green hydrogen. Scaling this analysis to fit Austria's production volumes suggests that 5.4 kt of hydrogen with an energy content of 180 GWh would be needed to make climate-neutral methanol. Using electrolysis to produce this hydrogen would require 252 GWh of energy.

4.1.3.2 Olefins from green methanol (methanol-to-olefins)

Olefins are needed as a raw material for plastics production, amongst other things. At present, they are obtained from crude oil in refineries. Austria currently produces 1,290 kt of olefins a year (Umweltbundesamt, 2021). Alternatively, olefins can be made from methanol, which itself can be made from green hydrogen, amongst other things. DECHEMA (DECHEMA, 2019) has analysed this so-called methanol-to-olefins route for Germany. Scaling this analysis to fit Austria's production volumes suggests that around 29 TWh of electrical energy would be needed to both produce the necessary hydrogen via electrolysis and run the production process.

4.1.3.3 Ammonia from green hydrogen

Ammonia is used as a raw material in the production of fertiliser, nitric acid, melamine and other nitrogen compounds and is a major source of GHGs in the chemicals industry. Much of the high level of GHG emissions attributable to the manufacture of ammonia is due to the production of hydrogen from natural gas, where the natural gas (generally CH_4) splits into hydrogen (H_2) and CO_2.

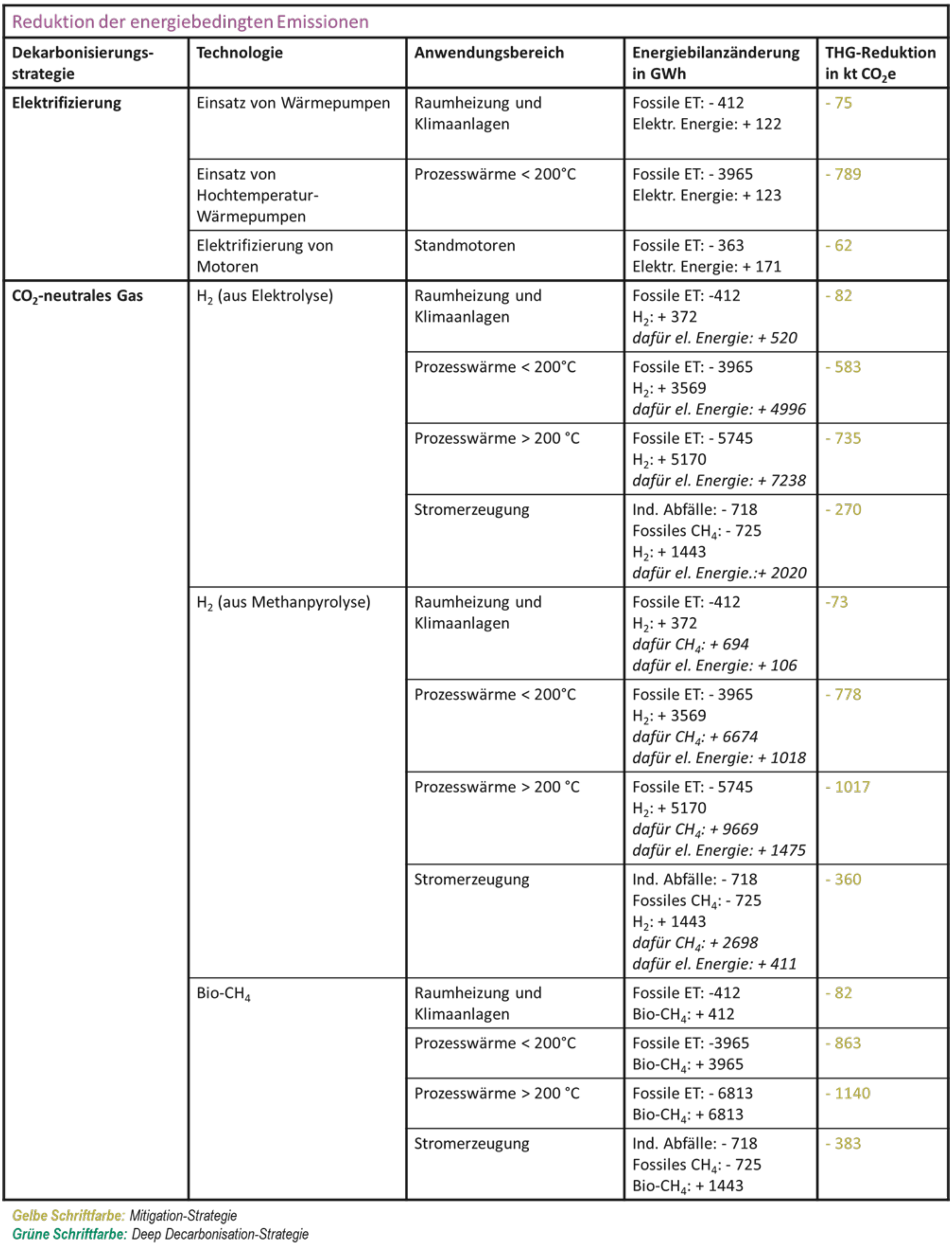
Austria currently manufactures 553 kt of ammonia. Producing this volume in a climate-neutral way would require 98.2 kt of hydrogen,[9] which equates to an energy content of 3.3 TWh. Factoring in the losses sustained in electrolysis, 4.6 TWh of electrical energy would be needed.

4.1.4 Paper and printing

The technical decarbonisation potential in the paper and printing sector is based on avoiding the energy-related emissions generated in this sector. The fact that alternative technologies already exist means that the use of carbon capture technologies is to be considered only in the background in this study as far as this sector is concerned. No quantitative statements can currently be made about the increased use of waste paper in the Austrian paper industry due to the complex interrelationships between product ranges and the life cycles of fibres over multiple production cycles.

Figure 24 shows that decarbonising two useful energy processes – room heating and air-conditioning systems – and converting stationary motors to electricity could each save around 70 kt CO_2e. However, the potential savings are far higher in the case of the need for process heat up to 200°C, where reductions of almost 800 kt CO_2e could be achieved depending on the energy source and the requisite upstream chain. Above 200°C, the savings potential is between 1,140 and 735 kt CO_2e thanks to the carbon-neutral gases bio-CH_4 and H_2. As regards replacing the more energy-intensive energy sources required for electricity generation that have been used in companies' own CHP plants up until now, the technical decarbonisation potential ranges from 270 to 383 kt CO_2e due to the same differences in the upstream production chain.

Decarbonisation in the paper and printing sector is to be achieved by reducing energy-related emissions, which can be done via electrification or carbon-neutral gases for a wide range of applications. Only carbon-neutral gases could be used for processes at temperatures above 200°C. Here too, it must be borne in mind for all alternative energy sources that the upstream chains required in order to supply them would need to be investigated and factored into the calculations.



Reduktion der energiebedingten Emissionen

Dekarbonisierungs-strategie	Technologie	Anwendungsbereich	Energiebilanzänderung in GWh	THG-Reduktion in kt CO_2e
Elektrifizierung	Einsatz von Wärmepumpen	Raumheizung und Klimaanlagen	Fossile ET: - 412 Elektr. Energie: + 122	- 75
	Einsatz von Hochtemperatur-Wärmepumpen	Prozesswärme < 200°C	Fossile ET: - 3965 Elektr. Energie: + 123	- 789
	Elektrifizierung von Motoren	Standmotoren	Fossile ET: - 363 Elektr. Energie: + 171	- 62
CO_2-neutrales Gas	H_2 (aus Elektrolyse)	Raumheizung und Klimaanlagen	Fossile ET: -412 H_2: + 372 *dafür el. Energie: + 520*	- 82
		Prozesswärme < 200°C	Fossile ET: - 3965 H_2: + 3569 *dafür el. Energie: + 4996*	- 583
		Prozesswärme > 200 °C	Fossile ET: - 5745 H_2: + 5170 *dafür el. Energie: + 7238*	- 735
		Stromerzeugung	Ind. Abfälle: - 718 Fossiles CH_4: - 725 H_2: + 1443 *dafür el. Energie.:+ 2020*	- 270
	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen	Fossile ET: -412 H_2: + 372 *dafür CH_4: + 694* *dafür el. Energie: + 106*	-73
		Prozesswärme < 200°C	Fossile ET: - 3965 H_2: + 3569 *dafür CH_4: + 6674* *dafür el. Energie: + 1018*	- 778
		Prozesswärme > 200 °C	Fossile ET: - 5745 H_2: + 5170 *dafür CH_4: + 9669* *dafür el. Energie: + 1475*	- 1017
		Stromerzeugung	Ind. Abfälle: - 718 Fossiles CH_4: - 725 H_2: + 1443 *dafür CH_4: + 2698* *dafür el. Energie: + 411*	- 360
	Bio-CH_4	Raumheizung und Klimaanlagen	Fossile ET: -412 Bio-CH_4: + 412	- 82
		Prozesswärme < 200°C	Fossile ET: -3965 Bio-CH_4: + 3965	- 863
		Prozesswärme > 200 °C	Fossile ET: - 6813 Bio-CH_4: + 6813	- 1140
		Stromerzeugung	Ind. Abfälle: - 718 Fossiles CH_4: - 725 Bio-CH_4: + 1443	- 383

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

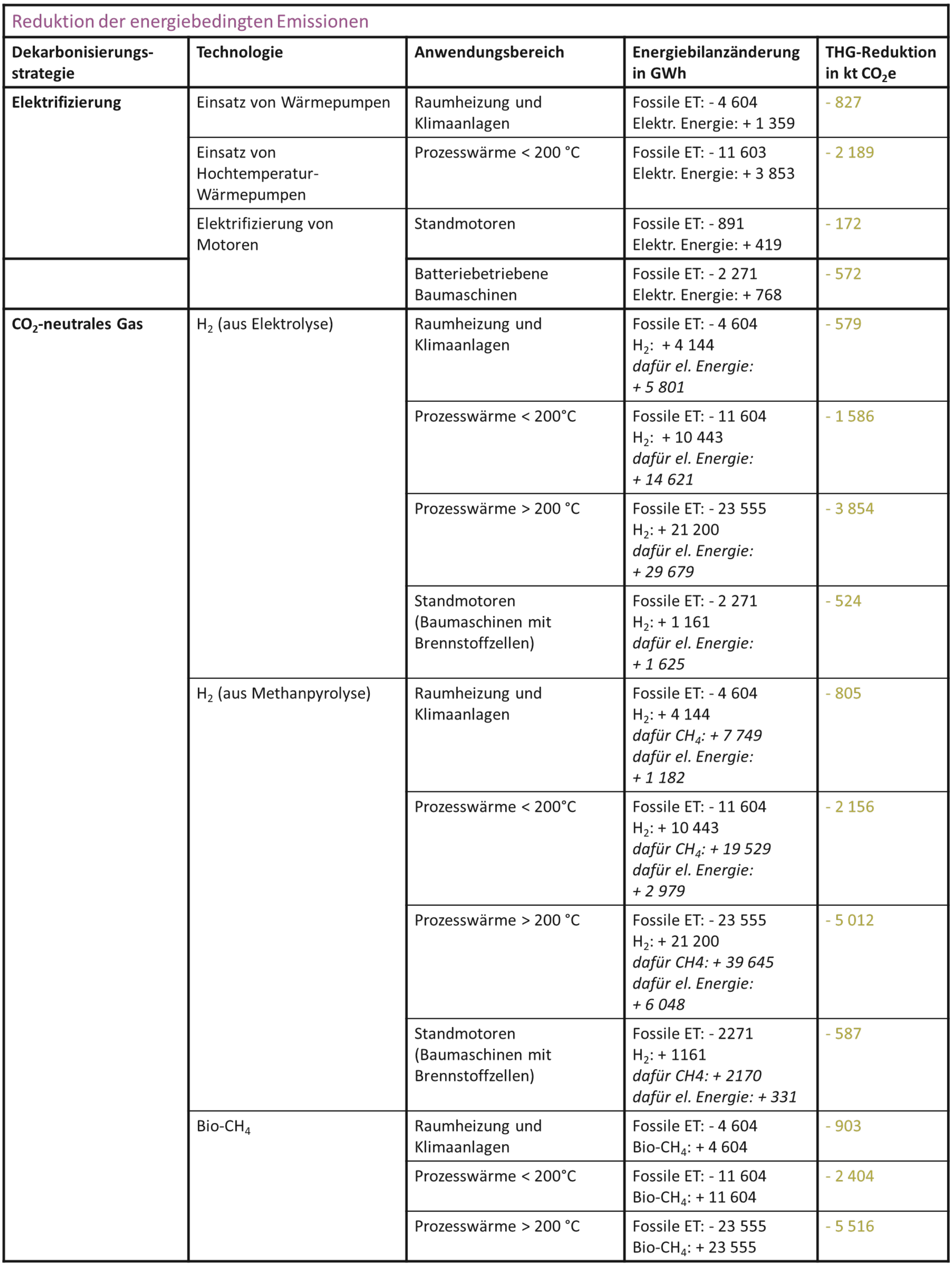
Figure 24: Technical potential for reducing energy-related emissions in the paper and printing sector

4.2 Summary of technical decarbonisation potential

Combining all the various areas of decarbonisation potential for Austrian industry produces the figures shown in Figure 25 (energy-related emissions) and Figure 26 (process-related emissions).

By far the greatest potential for decarbonisation lies in converting blast furnaces to run on carbon-neutral gases. This could save nearly 10 Mt CO_2e of GHG emissions, or roughly 37% of total industrial emissions in Austria. Using carbon capture technologies in the stone, earth and glass sector offers decarbonisation potential amounting to some 2.5 Mt CO_2e. It must be pointed out here that this reduction potential can be achieved in a single sector.

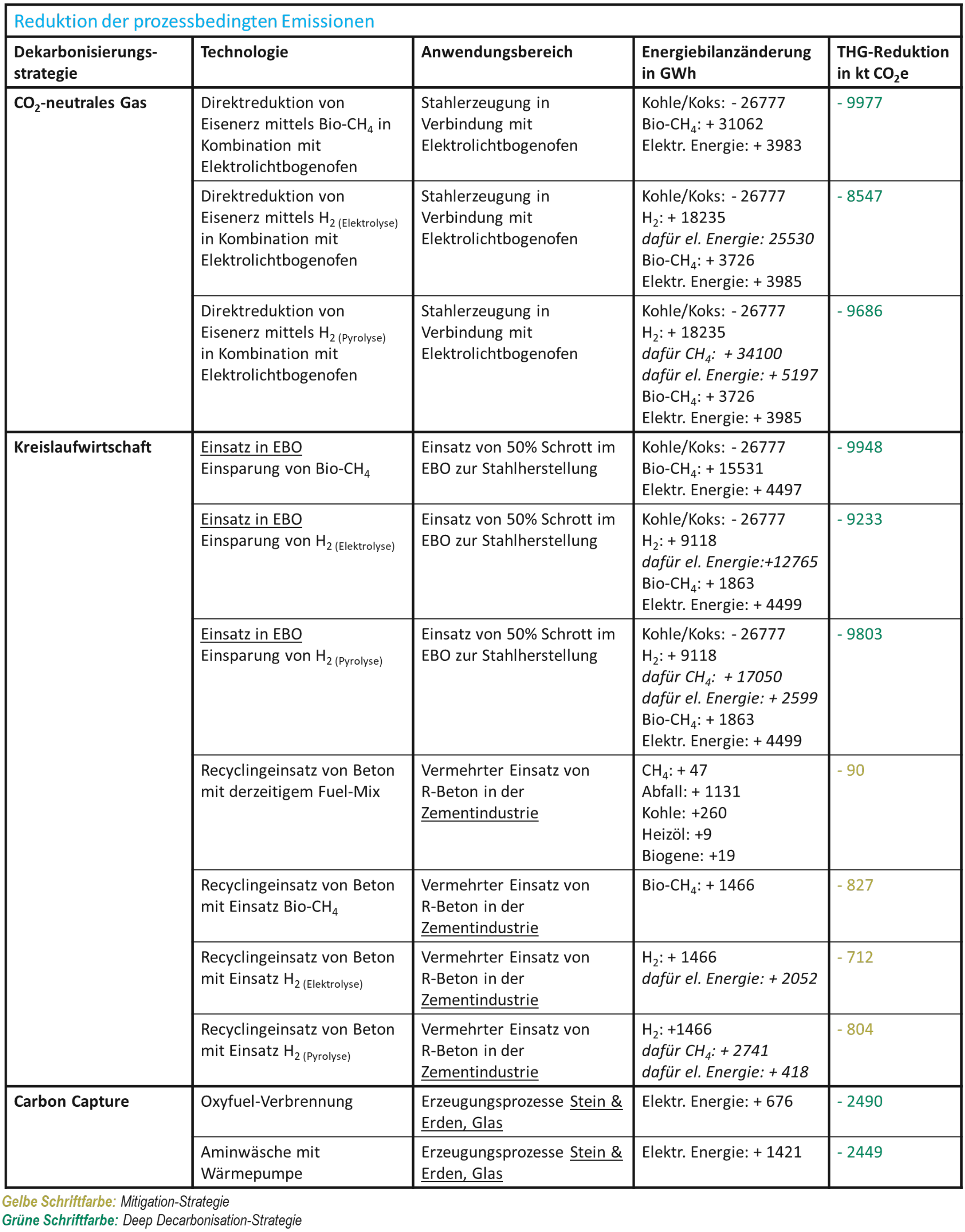
Decarbonising the supply of high-temperature process heat could reduce Austria's GHG emissions by between 3.8 and 5.5 Mt CO_2e. Unlike the two areas of decarbonisation potential mentioned above, however, this one covers all sectors and thus calls for relatively small-scale measures. Decarbonising the supply of low-temperature process heat could reduce Austria's GHG emissions by between 1.6 and 2.4 Mt CO_2e depending on the technology used. The potential for reducing emissions in room heating and cooling systems lies between 0.6 and 0.9 Mt CO_2e. Converting stationary motors to electricity could reduce industrial GHG emissions by around 0.2 Mt CO_2e, while decarbonising the mobile construction machinery used in the construction sector would cut them by some 0.5 Mt CO_2e.



Reduktion der energiebedingten Emissionen				
Dekarbonisierungsstrategie	**Technologie**	**Anwendungsbereich**	**Energiebilanzänderung in GWh**	**THG-Reduktion in kt CO_2e**
Elektrifizierung	Einsatz von Wärmepumpen	Raumheizung und Klimaanlagen	Fossile ET: - 4 604 Elektr. Energie: + 1 359	- 827
	Einsatz von Hochtemperatur-Wärmepumpen	Prozesswärme < 200 °C	Fossile ET: - 11 603 Elektr. Energie: + 3 853	- 2 189
	Elektrifizierung von Motoren	Standmotoren	Fossile ET: - 891 Elektr. Energie: + 419	- 172
		Batteriebetriebene Baumaschinen	Fossile ET: - 2 271 Elektr. Energie: + 768	- 572
CO_2-neutrales Gas	H_2 (aus Elektrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 4 604 H_2: + 4 144 *dafür el. Energie: + 5 801*	- 579
		Prozesswärme < 200°C	Fossile ET: - 11 604 H_2: + 10 443 *dafür el. Energie: + 14 621*	- 1 586
		Prozesswärme > 200 °C	Fossile ET: - 23 555 H_2: + 21 200 *dafür el. Energie: + 29 679*	- 3 854
		Standmotoren (Baumaschinen mit Brennstoffzellen)	Fossile ET: - 2 271 H_2: + 1 161 *dafür el. Energie: + 1 625*	- 524
	H_2 (aus Methanpyrolyse)	Raumheizung und Klimaanlagen	Fossile ET: - 4 604 H_2: + 4 144 *dafür CH_4: + 7 749* *dafür el. Energie: + 1 182*	- 805
		Prozesswärme < 200°C	Fossile ET: - 11 604 H_2: + 10 443 *dafür CH_4: + 19 529* *dafür el. Energie: + 2 979*	- 2 156
		Prozesswärme > 200 °C	Fossile ET: - 23 555 H_2: + 21 200 *dafür CH4: + 39 645* *dafür el. Energie: + 6 048*	- 5 012
		Standmotoren (Baumaschinen mit Brennstoffzellen)	Fossile ET: - 2271 H_2: + 1161 *dafür CH4: + 2170* *dafür el. Energie: + 331*	- 587
	Bio-CH_4	Raumheizung und Klimaanlagen	Fossile ET: - 4 604 Bio-CH_4: + 4 604	- 903
		Prozesswärme < 200°C	Fossile ET: - 11 604 Bio-CH_4: + 11 604	- 2 404
		Prozesswärme > 200 °C	Fossile ET: - 23 555 Bio-CH_4: + 23 555	- 5 516

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

Figure 25: Technical potential for reducing energy-related emissions in Austrian industry



Reduktion der prozessbedingten Emissionen

Dekarbonisierungs-strategie	Technologie	Anwendungsbereich	Energiebilanzänderung in GWh	THG-Reduktion in kt CO_2e
CO_2-neutrales Gas	Direktreduktion von Eisenerz mittels Bio-CH_4 in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 Bio-CH_4: + 31062 Elektr. Energie: + 3983	- 9977
	Direktreduktion von Eisenerz mittels $H_{2\,(Elektrolyse)}$ in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 H_2: + 18235 *dafür el. Energie: 25530* Bio-CH_4: + 3726 Elektr. Energie: + 3985	- 8547
	Direktreduktion von Eisenerz mittels $H_{2\,(Pyrolyse)}$ in Kombination mit Elektrolichtbogenofen	Stahlerzeugung in Verbindung mit Elektrolichtbogenofen	Kohle/Koks: - 26777 H_2: + 18235 *dafür CH_4: + 34100* *dafür el. Energie: + 5197* Bio-CH_4: + 3726 Elektr. Energie: + 3985	- 9686
Kreislaufwirtschaft	Einsatz in EBO Einsparung von Bio-CH_4	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 Bio-CH_4: + 15531 Elektr. Energie: + 4497	- 9948
	Einsatz in EBO Einsparung von $H_{2\,(Elektrolyse)}$	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 H_2: + 9118 *dafür el. Energie:+12765* Bio-CH_4: + 1863 Elektr. Energie: + 4499	- 9233
	Einsatz in EBO Einsparung von $H_{2\,(Pyrolyse)}$	Einsatz von 50% Schrott im EBO zur Stahlherstellung	Kohle/Koks: - 26777 H_2: + 9118 *dafür CH_4: + 17050* *dafür el. Energie: + 2599* Bio-CH_4: + 1863 Elektr. Energie: + 4499	- 9803
	Recyclingeinsatz von Beton mit derzeitigem Fuel-Mix	Vermehrter Einsatz von R-Beton in der Zementindustrie	CH_4: + 47 Abfall: + 1131 Kohle: +260 Heizöl: +9 Biogene: +19	- 90
	Recyclingeinsatz von Beton mit Einsatz Bio-CH_4	Vermehrter Einsatz von R-Beton in der Zementindustrie	Bio-CH_4: + 1466	- 827
	Recyclingeinsatz von Beton mit Einsatz $H_{2\,(Elektrolyse)}$	Vermehrter Einsatz von R-Beton in der Zementindustrie	H_2: + 1466 *dafür el. Energie: + 2052*	- 712
	Recyclingeinsatz von Beton mit Einsatz $H_{2\,(Pyrolyse)}$	Vermehrter Einsatz von R-Beton in der Zementindustrie	H_2: +1466 *dafür CH_4: + 2741* *dafür el. Energie: + 418*	- 804
Carbon Capture	Oxyfuel-Verbrennung	Erzeugungsprozesse Stein & Erden, Glas	Elektr. Energie: + 676	- 2490
	Aminwäsche mit Wärmepumpe	Erzeugungsprozesse Stein & Erden, Glas	Elektr. Energie: + 1421	- 2449

Gelbe Schriftfarbe: *Mitigation-Strategie*
Grüne Schriftfarbe: *Deep Decarbonisation-Strategie*

Figure 26: Technical potential for reducing process-related emissions in Austrian industry

4.3 Impact on the Austrian energy system

As already indicated in the technical potential tables (see Section 4.1), decarbonising Austrian industry will have a significant impact on the energy system. in the case of hydrogen electrolysis, for instance, switching to carbon-neutral gases and their production will increase demand for electrical energy. As well as the natural gas as the hydrogen source, the use of methane pyrolysis to supply carbon-neutral hydrogen from natural gas also requires electrical energy to run the pyrolysis systems (DECHEMA, 2019).

The figures below present the theoretical ramifications of the individual measures from the decarbonisation strategy studied, based on the assumption that every measure is implemented in full. When devising potential scenarios for the future, care must be taken to ensure that none of the GHG emissions that would be avoided are counted twice if several measures are combined. Note that the degree of implementation of the individual measures in each category of useful energy will be less than or equal to 100%. For instance, the electrification of room heating systems using heat pumps could be chosen with a degree of implementation of 60% plus the option of using biogas for room heating at 40%, thus utilising a total of 100% of the decarbonisation potential. However, setting both measures to 60% would not be possible as this would exceed the maximum possible decarbonisation potential.

Figure 27 shows the impact on the energy system of the measures from the "Carbon-neutral gases" decarbonisation strategy. The maximum possible decarbonisation potential is also shown above the bar that corresponds to each measure. Comparing the impact of using electrolysis and pyrolysis to supply hydrogen reveals that, overall, the latter would require much more energy than the former in order to produce the necessary quantities of hydrogen. However, pyrolysis needs less electrical energy than electrolysis because natural gas rather than water is used as the hydrogen source, meaning that much less energy is required to capture the hydrogen.

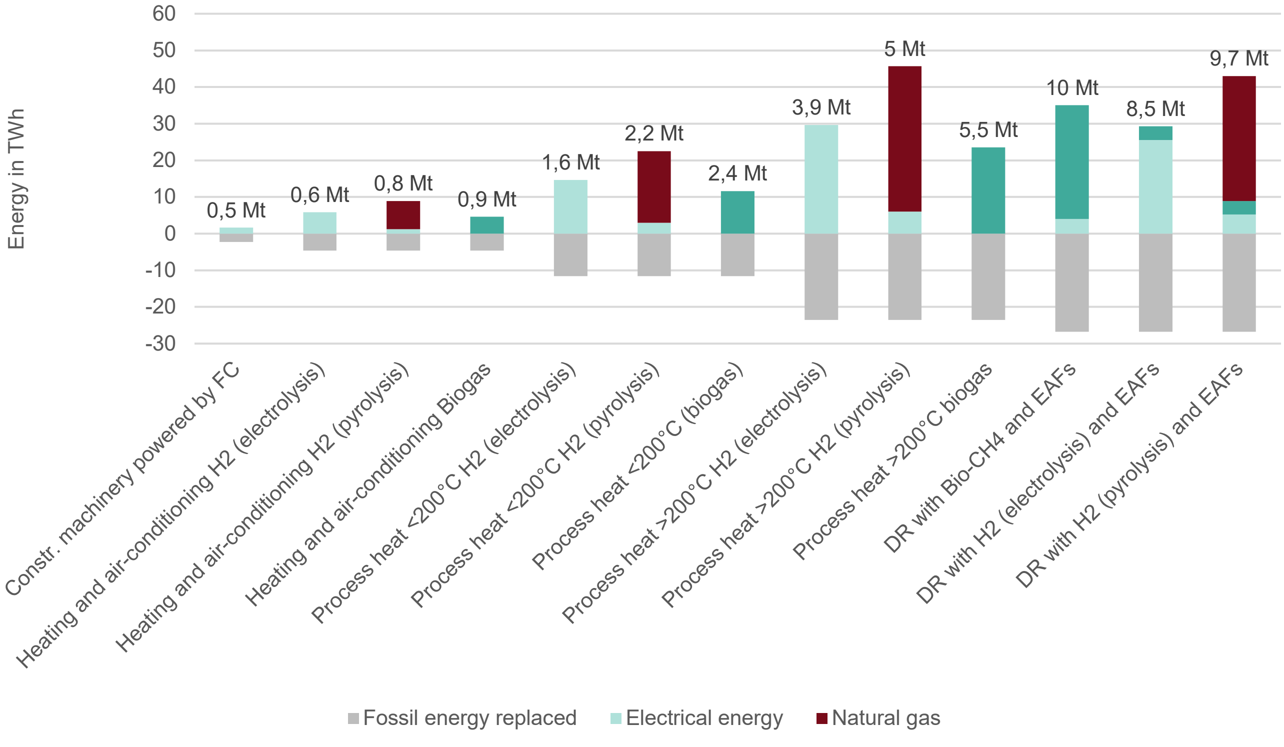


Figure 27: Impact of the "Carbon-neutral gases" decarbonisation strategy on the energy system assuming that all measures are implemented in full. The maximum possible decarbonisation potential in Mt CO2e is shown above the corresponding bar.

Figure 28 shows the impact on the energy system of the measures from the "Electrification" decarbonisation strategy. Using efficient heat pumps and electric drives for construction machinery would mean that much less energy would be required to generate the necessary useful energy than is the case with the current systems, which run on fossil fuels.

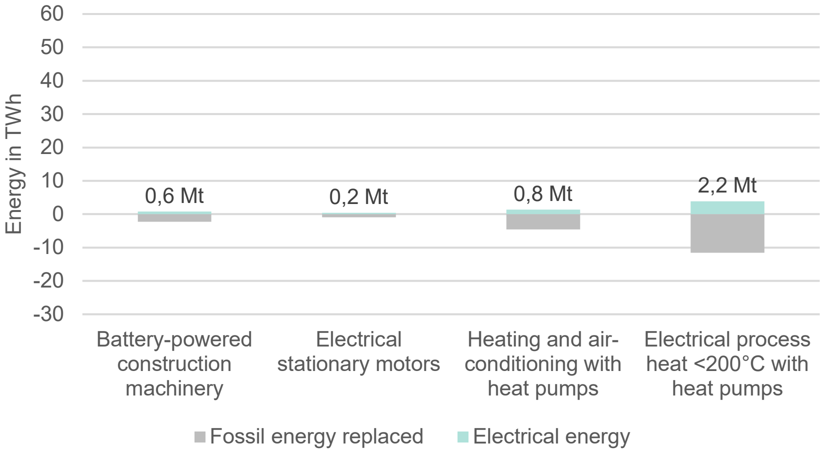


Figure 28: Impact of the "Electrification" decarbonisation strategy on the energy system assuming that all measures are implemented in full. The maximum possible decarbonisation potential is shown above the corresponding bar.

Figure 29 shows the impact on the energy system of the measures from the "Circular economy" decarbonisation strategy. Here, for instance, comparing the impact of using direct reduction with hydrogen from electrolysis shows that using 50% scrap would reduce the amount of electricity required and thus the impact on the power grid by around one third. This is due to the reduced need for electrolysis, as using more scrap means less iron ore has to be reduced in the direct reduction plant.

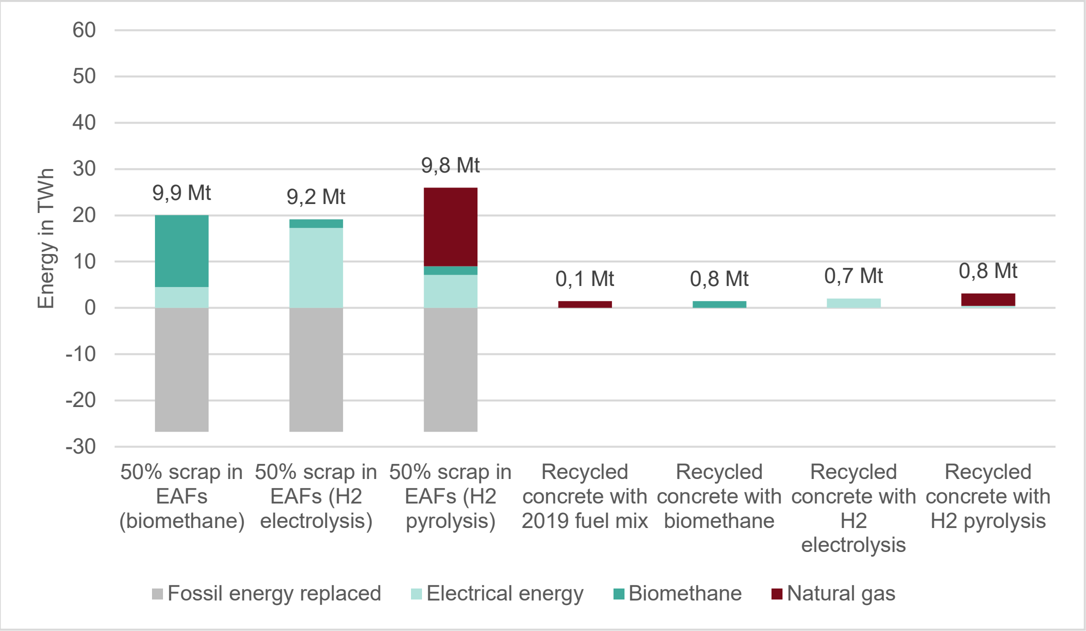


Figure 29: Impact of the "Circular economy" decarbonisation strategy on the energy system assuming that all measures are implemented in full. The maximum possible decarbonisation potential for each measure is shown above the corresponding bar.

5 Costs of the transformation

This part of the report contains estimates of the investment costs and, where available, the specific CO_2 reduction costs involved in decarbonising Austrian industry. These estimates have been made based on the literature on the cost of various decarbonisation options.

According to the European Commission, 2% of EU GDP is currently being invested in the energy system and its associate infrastructure. To achieve a GHG-neutral economy, it is assumed that this percentage will have to increase to 2.8% a year, i.e. to some EUR 520–575 billion (Europäische Kommission, 2019). (McKinsey & Company, 2020) believes that the investments required in technologies and processes in order to achieve EU-wide decarbonisation by 2050 will cost much more – EUR 28 trillion in total. Between 1% and 2% of this figure will be attributable to the various sectors of industry, equating to around EUR 410 billion in all. The

likely investment costs facing Austrian industry as a result of the decarbonisation strategies studied are analysed below using the same approach.
To maintain consistency with the statements in the previous section, the investment costs for the individual decarbonisation options shown in the figures below cannot simply be added together to obtain the total costs. Instead, the figures are intended to give a general idea of the investment costs that the individual options would incur in the various sectors.

Whilst the present study considers direct investment costs for the respective measures identified for decarbonising industry, operating costs must also be factored in if a holistic techno-economic assessment is to be produced and a choice made between various alternative options.

Such a holistic evaluation of investment and operating costs over the entire life cycle of the technologies concerned would require separate detailed analyses that included macroeconomic calculations in various scenarios as well as the involvement of the relevant stakeholders (e.g. to identify typical investment cycles).

5.1 Costs of cross-cutting technologies

As described in Section 4, the technologies for reducing energy-related CO_2 emissions are used in several sectors, some indeed in all sectors. The subsections below present the costs associated with these measures in each individual sector. These costs are estimates of actual costs for 2040 based on currently available information.
It must be borne in mind that, unlike switching to heat pumps, using carbon-neutral gases will not necessarily result in a modification to the technology itself. In the case of carbon-neutral gases, the investment costs include the costs for producing the gases. The technology required to supply the heat is not considered. This results in higher investment costs for heat pumps in relative terms in the following sections, amongst other things.
It must also be pointed out that the cost estimate is not based on any in-depth analysis of the building stock involved, meaning that no detailed statement can be made about actual feasibility or the total outlay required either.

5.2 Investment costs of decarbonisation in the individual industrial sectors

5.2.1 Iron and steel production

Table 4 shows the total investments required between now and 2040 for the cross-cutting technologies to be applied in the *Iron and steel production* sector based on the specific technology costs detailed in Section 5.
In addition, process-related emissions play a particularly significant role in the iron and steel production sector. The costs of the various decarbonisation strategies for avoiding process-related emissions are shown in Table 5.

Table 4: Investment costs for cross-cutting technologies in the “Iron and steel production” sector[10]

Costs of decarbonisation – energy-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Electrification	Using heat pumps	Room heating and air-conditioning systems	136
	Using high-temperature heat pumps	Process heat <200°C	9
Carbon-neutral gas	H_2 (from electrolysis)	Room heating and air-conditioning systems	42
		Process heat <200°C	16
		Process heat >200°C	881
	H_2 (from methane pyrolysis)	Room heating and air-conditioning systems	32
		Process heat <200°C	12
		Process heat >200°C	677
	Bio-CH_4	Room heating and air-conditioning systems	28
		Process heat <200°C	10
		Process heat >200°C	513

Table 5: Investment costs for reducing process-related emissions in the iron and steel production sector

Costs of decarbonisation – process-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Carbon-neutral gas	Direct reduction of iron ore using bio-CH_4 in combination with electric arc furnaces	Steel production in combination with electric arc furnaces	2,226 DRI-CS 2,524 Bio-CH_4
	Direct reduction of iron ore using H_2 (electrolysis) in combination with electric arc furnaces	Steel production in combination with electric arc furnaces	2,226 DRI-CS 2,523 H_2 (electrolysis)
	Direct reduction of iron ore using H_2 (pyrolysis) in combination with electric arc furnaces	Steel production in combination with electric arc furnaces	2,226 DRI-CS 1,917 H_2 (pyrolysis)
Circular economy	Use in EAFs Saving bio-CH_4	Using 50% scrap in EAFs for steelmaking	1,607 DRI-CS 1,262 Bio-CH_4
	Use in EAFs Saving H_2 (electrolysis)	Using 50% scrap in EAFs for steelmaking	1,607 DRI-CS 1,248 H_2 (electrolysis)
	Use in EAFs Saving H_2 (pyrolysis)	Using 50% scrap in EAFs for steelmaking	1,607 DRI-CS 958

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[10] The investment costs shown for the “Room heating and air-conditioning systems” scope of application are not directly comparable with one another due to the assumptions described in Section 5.1

			Pyrolysis

The following two figures combine the information on the potential areas for reducing CO2 in iron and steel production and on the investment costs of the individual measures, separated into energy- and process-related emissions. The figures below make it clear that using scrap can significantly reduce investment costs while achieving virtually the same reduction in CO2.

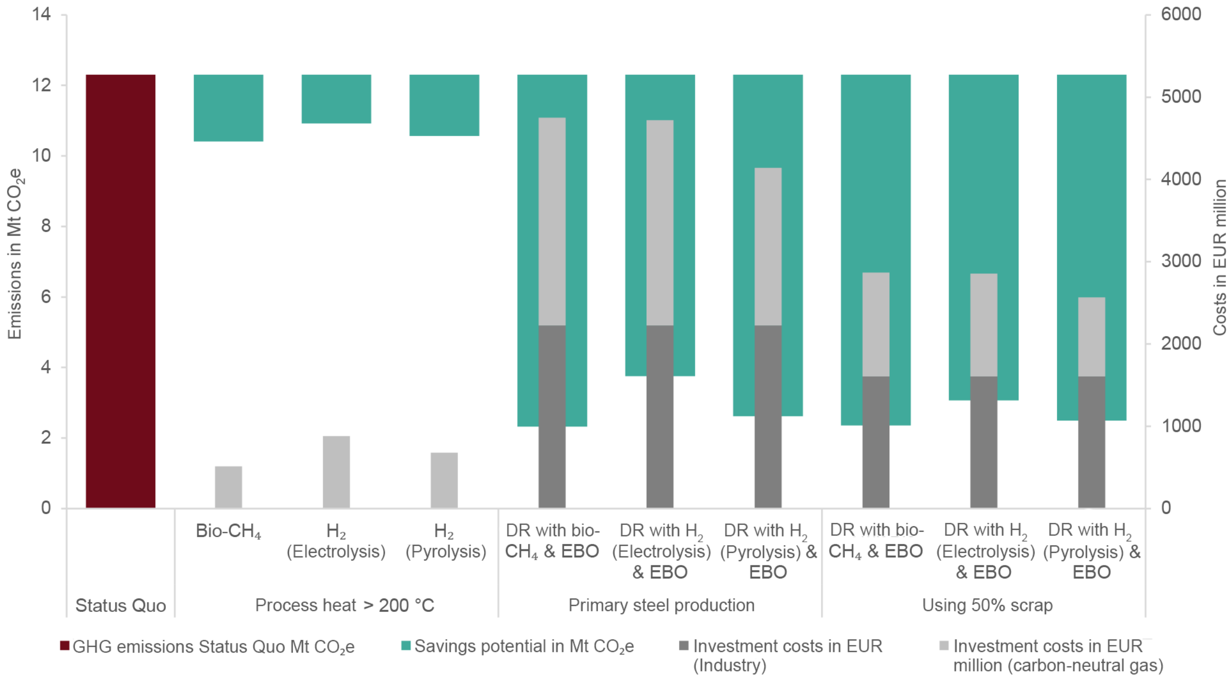

Figure 30: Summary of CO2 reduction potential and investment costs in the iron and steel production sector for the “Process heat >200°C” and “Steel production” scopes of application

5.2.2 Stone, earth and glass

Table 6 shows the total investments required between now and 2040 for the cross-cutting technologies to be applied in the *Stone, earth and glass* sector.

Table 6: Investment costs for cross-cutting technologies in the “Stone, earth and glass” sector[11]

Costs of decarbonisation – energy-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Electrification	Using heat pumps	Room heating and air-conditioning systems	139
	Using high-temperature heat pumps	Process heat <200°C	14
Carbon-neutral gas	H_2 (from electrolysis)	Room heating and air-conditioning systems	43
		Process heat <200°C	26
		Process heat >200°C	839
	H_2 (from methane pyrolysis)	Room heating and air-conditioning systems	33
		Process heat <200°C	20
		Process heat >200°C	644
	Bio-CH_4	Room heating and air-conditioning systems	28
		Process heat <200°C	17
		Process heat >200°C	488

The costs required to avoid process-related emissions are shown in Table 7.

Table 7: Investment costs for technologies to reduce process-related emissions in the “Stone, earth and glass” sector

Costs of decarbonisation – process-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Carbon capture	Burning oxyfuels	Production process	619
	Amine scrubbing via heat pump	Production process	369
Circular economy	Using recycled concrete with current fuel mix	Using more recycled concrete in the cement industry	35

Converting process heat above 200°C would generate the highest investment costs in this sector, provided that the costs for producing the energy sources are allocated to the industry sector. The two carbon capture measures appear relatively cost-efficient. (Andreas Windsperger, 2018)

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[11] The investment costs shown for the “Room heating and air-conditioning systems” scope of application are not directly comparable with one another due to the assumptions described in Section 5.1

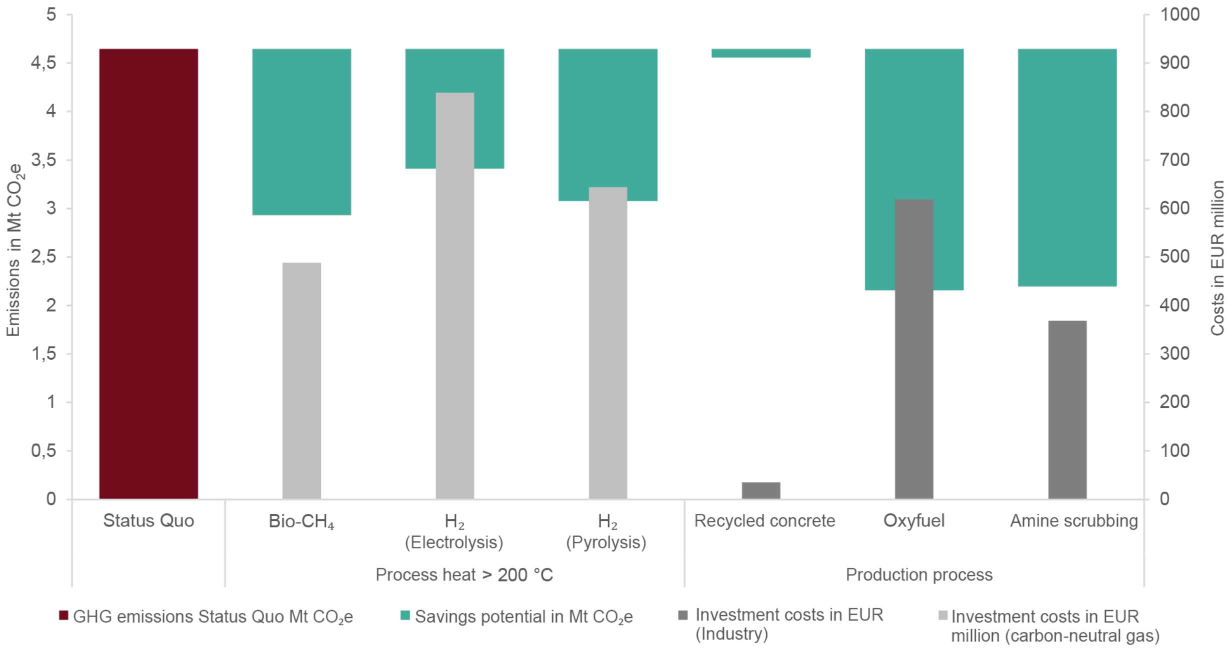

Figure 31: Summary of CO[2] reduction potential and investment costs in the stone, earth and glass sector for the “Process heat >200°C” and “Production process” scopes of application

5.2.3 Chemicals and petrochemicals

Table 8 shows the total investments required between now and 2040 for the cross-cutting technologies to be applied in the Chemicals and petrochemicals sector.

Table 8: Investment costs for cross-cutting technologies in the "Chemicals and petrochemicals" sector[12]

Costs of decarbonisation – energy-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Electrification	Using heat pumps	Room heating and air-conditioning systems	284
	Using high-temperature heat pumps	Process heat <200°C	112
Carbon-neutral gas	H_2 (from electrolysis)	Room heating and air-conditioning systems	87
		Process heat <200°C	205
		Process heat >200°C	188
	H_2 (from methane pyrolysis)	Room heating and air-conditioning systems	67
		Process heat <200°C	158
		Process heat >200°C	144
	Bio-CH_4	Room heating and air-conditioning systems	57
		Process heat <200°C	135
		Process heat >200°C	109

The method for deriving the costs for the specific options in the chemicals and petrochemicals sector described in the previous section is described below. The costs for supplying the carbon in the form of CO_2 that is required to produce the synthetic hydrocarbons (methanol, olefins) is not included in these calculations. As the potential sources for the CO_2 used can be extremely diverse as a basic principle, it is virtually impossible to allocate them to a single industry sector or even to industry in general. Potential facilities for stripping CO_2 could be built specifically for the purpose, such as direct air capture (DAC), could already be part of measures in other sectors, e.g. biomethane production or carbon capture, or could arise as a byproduct of processes not considered here, such as the production of bioethanol. An overview of different CO_2 and associated capture rates and costs can be found in the relevant literature (Rodin, Lindorfer, Böhm, & Vieira, 2020).

5.2.3.1 Methanol from green hydrogen

Both DECHEMA (DECHEMA, 2019) and the IEA (IEA, 2020) indicate corresponding investment costs for producing methanol (MeOH) from green hydrogen. Both of these estimates are based on electrolysis taking place at the industrial site and thus include the costs for a corresponding electrolysis system. However, there are significant differences between the two sources, although similar reductions in costs are anticipated over the long term (bottom cost threshold). The IEA data has been used to estimate total investment costs, due not

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[12] The investment costs shown for the "Room heating and air-conditioning systems" scope of application are not directly comparable with one another due to the assumptions described in Section 5.1.

least to comparability with the other hydrogen-based applications. Assuming an annual methanol production volume of 28.7 kt, investment costs amounting to **EUR 11.9 million** are to be anticipated between now and 2040.

5.2.3.2 Olefins from green methanol (methanol-to-olefins)

The investments required for the methanol-to-olefins route have been estimated based on the underlying costs for producing the renewable methanol that were discussed in Section 5.2.3.1 above. The methanol-to-olefins plant will also incur costs. This results in total specific investment costs of some EUR 1,130 per tonne of olefins. Assuming an annual olefin production volume of 1,290 kt, investment costs amounting to EUR 1,458 million are to be anticipated between now and 2040.

5.2.3.3 Ammonia from green hydrogen

DECHEMA (DECHEMA, 2019) and IEA (IEA, 2020) studies detail corresponding costs for producing ammonia (NH_3) from renewable hydrogen. Although both studies are based on electrolysis taking place at the industrial site and thus include the costs for a corresponding electrolysis system, they do not make any other statements about the scope of the system and are thus only comparable to a very limited extent. Here too, the cost forecasts in the IEA report have been used to estimate total investment costs. Assuming an annual ammonia production volume of 553 kt, investment costs amounting to **EUR 343 million** are to be anticipated between now and 2040.

5.2.4 Paper and printing

Table 9 shows the total investments required between now and 2040 for the cross-cutting technologies to be applied in the *Paper and printing* sector based on the specific technology costs detailed in Section 5.

Table 9: Investment costs for cross-cutting technologies in the “Paper and printing” sector[13]

Costs of decarbonisation – energy-related emissions			
Decarbonisation strategy	**Technology**	**Scope of application**	**Investment costs (EUR million)**
Electrification	Using heat pumps	Room heating and air-conditioning systems	166
	Using high-temperature heat pumps	Process heat <200°C	267
Carbon-neutral gas	H_2 (from electrolysis)	Room heating and air-conditioning systems	51
		Process heat <200°C	488
		Process heat >200°C	708
		Electricity generation	197
	H_2 (from methane pyrolysis)	Room heating and air-conditioning systems	39
		Process heat <200°C	375
		Process heat >200°C	543
		Electricity generation	152
	Bio-CH_4	Room heating and air-conditioning systems	34
		Process heat <200°C	322
		Process heat >200°C	412
		Electricity generation	117

Converting process heat above 200°C would generate the highest investment costs in this sector, provided that the costs for producing the energy sources are allocated to the industry sector.

Converting the industry’s own CHP plants to carbon-neutral gases would require investment of EUR 117–197 million.

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[13] The investment costs shown for the “Room heating and air-conditioning systems” scope of application are not directly comparable with one another due to the assumptions described in Section 5.1

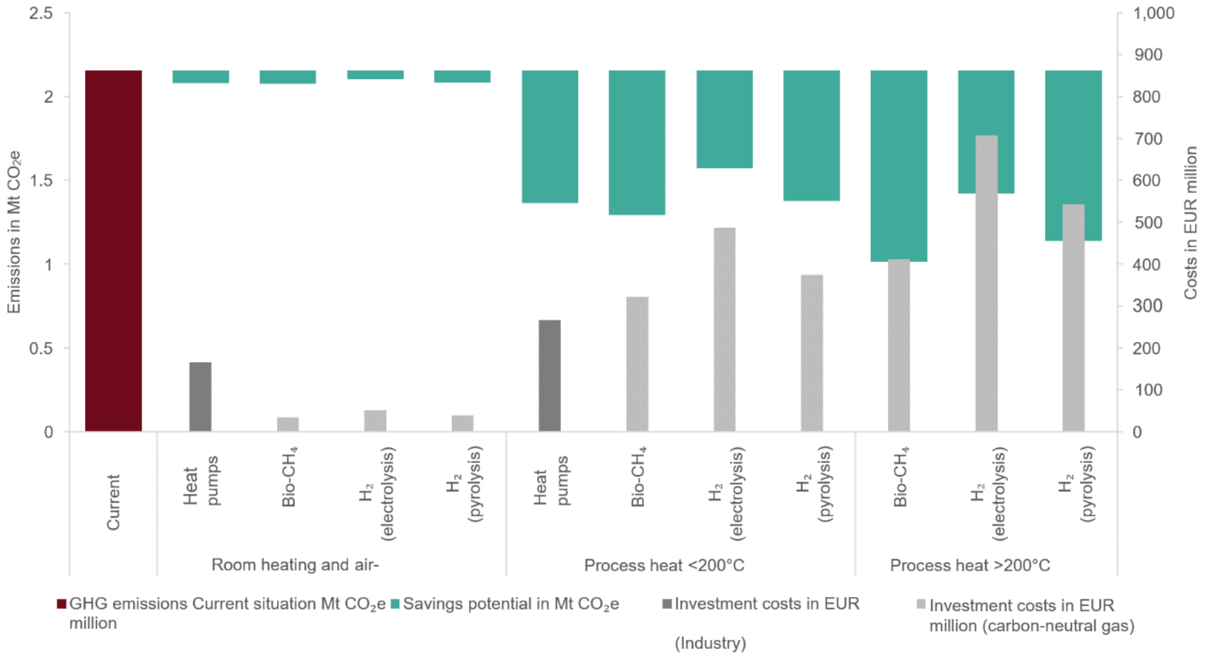

Figure 32: Summary of CO2 reduction potential and investment costs in the paper and printing sector[14]

5.3 Summary of investment costs

Looking at the energy-related GHG emissions, which play a crucial role in the non-energy-intensive sectors in particular, it is clear that converting room heating and air-conditioning systems and process heat <200°C would require significant investment. Whilst the use of carbon-neutral gases would appear to be the lowest-cost option for room heating and air-conditioning systems, it must be reiterated here that other factors aside from simple cost efficiency need to be factored into the choice of decarbonisation strategy, such as resource efficiency, associated upstream chains and available resource potential. With regard to the use of high-temperature heat pumps for process heat <200°C, the anticipated cost efficiency of large-scale industrial plants (in contrast to small-scale installations for room heating) puts this cost benefit into perspective.

The figure below shows the minimum and maximum costs of the individual decarbonisation strategy for industry as a whole. In each case, it illustrates the total costs of implementing the respective decarbonisation strategy in full. As a result, some areas of application and the associated costs are included in more than one strategy, meaning that the individual categories cannot simply be added together. It must also be pointed out that the future investment costs are subject to an element of uncertainty. The figures shown in this report can therefore merely give a general idea of the investments required between now and 2040.

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[14] The investment costs shown for the “Room heating and air-conditioning systems” scope of application are not directly comparable with one another due to the assumptions described in Section 5.1.

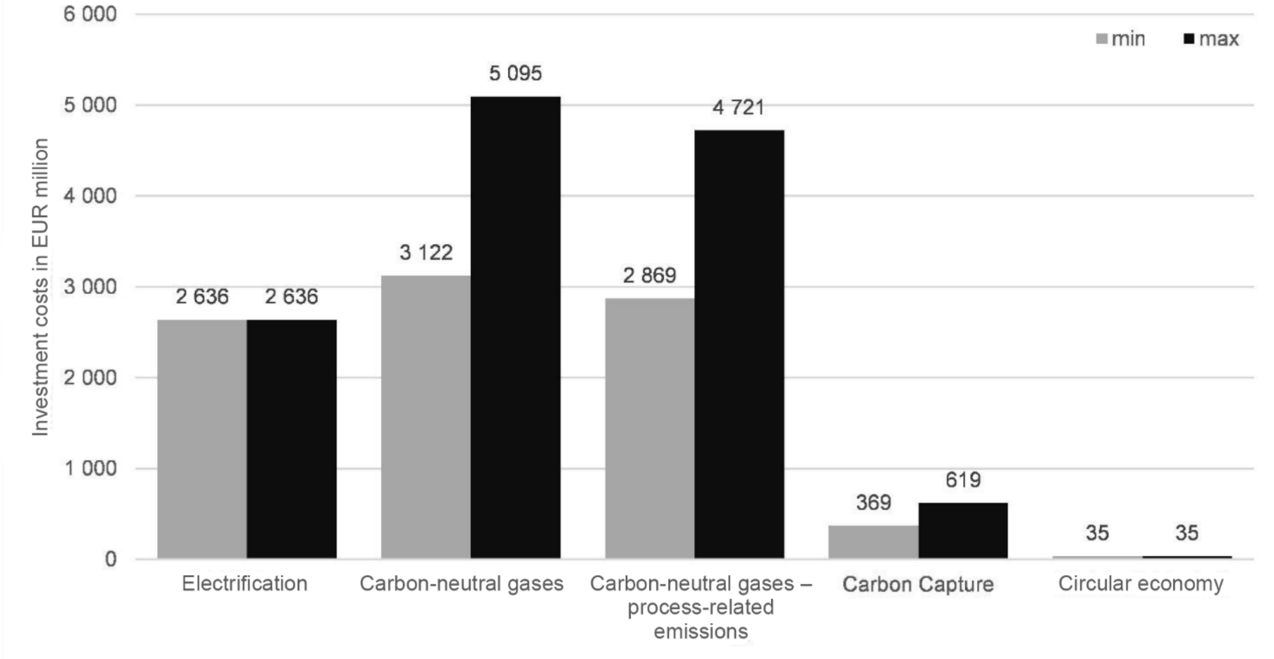

Figure 33: Value ranges for investment costs for each decarbonisation strategy

Converting room heating and air-conditioning systems to electricity would incur investment costs of EUR 1,853 million, while converting process heat under 200°C would cost EUR 783 million. As no rival technologies are being considered within the *Electrification* strategy, the corresponding minimum and maximum costs are identical. The same applies to the *Circular economy* category, whose sole area of application is the use of recycled concrete. For the *carbon-neutral gases* decarbonisation strategies, the minimum costs indicated were calculated using the option based on bio-CH_4 and the maximum costs using that based on H_2 from electrolysis. In the *Carbon capture* decarbonisation strategy, meanwhile, amine scrubbing technology represents the minimum value and burning oxyfuels the maximum value.

In the “Carbon-neutral gas – process-related emissions” category, the wide variation in values can be explained by the options that involve using 50% scrap in the steel industry, which would significantly reduce investment costs.

The investment costs for carbon-neutral gas and for reducing process-related emissions are also subject to a wide fluctuation margin depending on the technology adopted. The investment costs for carbon-neutral gas are depicted in lower resolution in the figure below.

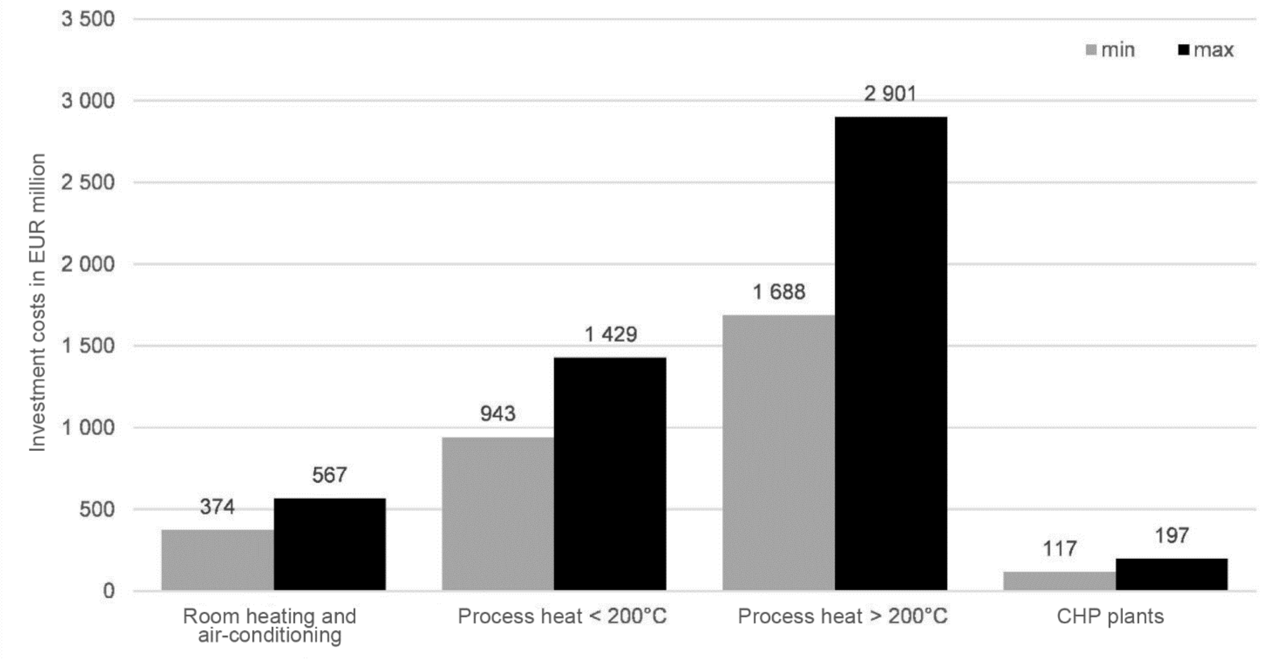

Figure 34: Value ranges for investment costs for the “Carbon-neutral gases” decarbonisation strategy

The total investment costs between now and 2040 for the decarbonisation options presented vary between EUR 6.2 billion and EUR 11.2 billion (excluding operating costs) depending on the technologies chosen. The differences are due to which options are selected for each specific application.

Just under half of the maximum total costs of EUR 11.2 billion are for investment in hydrogen production, which would take place either directly in the industry sector or in the energy sector. Much of the at most EUR 11.2 billion would be for the iron and steel production sector. This includes the investment costs required to produce hydrogen for own use.

The scope of the present study is restricted to estimating the costs of the transformation based on the available literature. A complete estimate of total costs – including operating costs – and of the optimum combination of individual measures did not form part of this study and would require further investigation.

5.4 Instruments

What percentage of the investment costs presented in the previous sections would require additional funding cannot be estimated reliably within the scope of this study. The cost-effectiveness of the decarbonisation measures depends on the corresponding operating costs (particularly for energy) and on other framework conditions (e.g. taxes, CO2 price). The lower the costs for CO2-free electricity, biogas and CO2-free hydrogen, the more cost-effective the options.

This section thus provides an overview of potential instruments for accelerating the transformation within industry.

The OECD (OECD, IEA, NEA, & ITF, 2015) has identified four policy pillars for a greenhouse-gas-neutral future, with the greatest degree of effectiveness to be achieved primarily by combining various different instruments from all the pillars (see Table 10).

a) Price signals for CO_2
b) Regulatory measures
c) RTI policies for new technologies
d) Information-sharing and awareness-raising

Table 10: Policy pillars for a greenhouse-gas-neutral future

	Price signals for CO_2	**Regulatory measures**	**RTI policies for new technologies**	**Information-sharing and awareness-raising**
Scope of application	Essentially global, EU-wide (generally with exceptions)	Wherever price and market signals are ineffective due to market barriers and transaction costs	Innovation, research and development, breakthrough technologies	Focus on consumers (target-group-oriented)
Examples	• EU-ETS and other trading systems • Direct CO_2 taxes • Indirect CO_2 taxes (e.g. on fuels or other energy sources) • Subsidies for cutting emissions • Carbon border adjustments • Carbon contracts for difference	• Reporting obligations • Fleet standards • Technology standards • Bans • Land use planning • Market design	• Direct and indirect support for R&D • Innovation-oriented public procurement • Green certificates • Subsidies (e.g. feed-in tariffs) • Investment promotion • Spaces for regulatory experimentation (“sandboxes”)	• Information campaigns • Labelling as part of life cycle analyses • Education and training • Certification and awards schemes
Challenge	• Distribution effects • Acceptance If countries or Europe go it alone: • Carbon leakage • Effect on competitiveness	• Securing the binding character required to enable all stakeholders to plan for the long term • Acceptance	• Ensuring that support/promotion works • Turning technological developments into marketable innovations • Technology choice, lock-in	• Effectiveness/measurability of the impact of measures • Rebound effects, e.g. shifting monetary savings to more CO_2-intensive consumption

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AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH
Giefinggasse 2 | 1210 Vienna | Austria

www.ait.ac.at
Fax +43 50550-6679

Dr. Christian Diendorfer
Research Engineer
Integrated Energy Systems
Center for Energy

Dr. Bernhard Gahleitner
Business Manager
Center for Energy
+43 50550-3614
bernhard.gahleitner@ait.ac.at

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