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NEW ENERGY FOR INDUSTRY

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PATHWAY TO INDUSTRIAL DECARBONISATION

SCENARIOS FOR THE DEVELOPMENT OF THE INDUSTRIAL SECTOR IN AUSTRIA

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Executive summary

At the 2015 Paris Climate Conference (COP21), more than 196 countries committed to the goal of limiting global warming to well below 2°C compared to pre-industrial levels. The European Union intends to lead these global ambitions with its European Green Deal, and its goal is to achieve climate neutrality by the year 2050. As a member state, Austria supports this goal, and has set even more ambitious targets in many areas. In its current legislative programme, the Austrian federal government is pursuing the ambitious target of making its economic system completely climate neutral by 2040.

Austrian manufacturing industries need to play a key role in achieving these goals as they are responsible for 34% (25 Mt CO_2e) of Austria's total greenhouse gas emissions (GHG) (2019). Combined, industrial processes at all industrial locations in Austria account for approximately 27% (110 TWh/a) of gross domestic energy consumption. Industry also plays an important role in ensuring the welfare and socio-economic development of the Austrian economy. At EUR 93 billion, in 2019 industry generated 24.8% of national GDP. Historically, industry has driven Austria's prosperity through research and development, creating global leaders in a variety of sectors. The most energy intensive sectors are iron and steel, non-metallic minerals, chemical and petrochemical industries, and pulp and paper. Together, they account for 61% (82 TWh in 2019) of total energy demand and 79% (21 Mt in 2019) of GHG emissions from industry. As communicated by the European Commission, the majority of production processes currently employed in these sectors correspond to the best-available technologies.

The New Energy for Industry (NEFI) innovation network is the primary contact point for industrial efforts to achieve climate neutrality in Austria. Within NEFI, stakeholders from a variety of subsectors team up with researchers and engineers to develop novel green technologies that will help industry to become climate neutral, simultaneously advancing Austria as an industrial location and securing its global technology leadership.

Aim of this study

NEFI has developed the industry demand scenarios outlined here as a visionary guideline for stakeholders in manufacturing industry, for policy makers, and for technology providers. This study presents the results of the three NEFI scenarios conducted for the timeframe 2017 to 2050:

(I) Business as usual (BAU)
(II) Pathway of industry (POI)
(III) Zero emission (ZEM)

Comparing the scenario results indicates the bandwidth of different pathways towards industrial climate neutrality and allows the most important fields of action to be identified. This study elaborates the demand scenarios for Austrian industry, while only including the supply of energy carriers to a limited extent, and where relevant. Therefore, assumptions are made about the development of the electricity sector's CO_2 intensity and the gas grid composition.

Methodology

The study was initiated in 2018 and considers the EU climate goals for 2050. The period 2017 to 2019 was taken as the basis for scenario projections. Although the government's current programme goal is to achieve climate neutrality by 2040, the target year 2050 was kept to allow for international comparisons and to increase the visibility of the project results. Having three scenarios provides a bandwidth of development possibilities, taking into account development uncertainties and providing a solid basis for comparison.

Key levers of action for Austrian industry to achieve climate neutrality

This work follows previous studies in identifying the following four key levers for industrial climate neutrality.

- Significant improvement of the energy efficiency of all industrial processes, and low-emission electrification of thermal and motive energy demands (heat pumps and motors)
- Fuel switching to carbon-neutral gases (hydrogen, bio- and synthetic CH_4)
- Carbon capture technologies
- Circular economy aspects[1]

The effects of implementing these levers are studied and shown in the three demand scenarios. Comparison of the scenarios allows identification of technological gaps in relation to the target pathway.

Business as usual (BAU): This scenario serves as a reference scenario, allowing the effectiveness of innovative technologies in the two transition scenarios below to be evaluated. It is obtained by extrapolating historic trends and economic development forecasts. This contrasts with a “with existing measures” scenario which would include forecasts based on current boundary conditions.

Pathway of industry (POI): This scenario is the result of close dialogue with representatives from leading industrial stakeholders who have assessed the technology deployments in their respective sectors under current and foreseeable boundary conditions through to 2030. Development through to 2050 is extrapolated on the basis of this assessment, and taking into account expected technology availability. This scenario is a unique representation of current industrial transformation plans and is well equipped to identify important areas of policy action in efforts to achieve climate neutrality.

Zero emission (ZEM): This scenario represents the implementation of extensive and ambitious measures that could make Austria’s industrial energy system completely climate neutral by 2050. It applies breakthrough technologies which have been identified as the most promising solutions to the transformation challenge on a sector by sector basis. A backcasting approach is used to calculate a normative pathway. This means that, starting from the target state of climate neutrality in the year 2050, a reverse pathway is developed indicating the steps leading to the successful achievement of this goal.

Scenario results are calculated using a total energy demand approach, guaranteeing that all energy flows needed for industrial production are considered. This includes both final energy applications as well as energy input into industrial transformation units (e.g., blast furnaces or CHP plants). In addition, the energy sector’s supply of renewable energy plays an important role in reaching industrial climate neutrality and has been included in the modelling. To account for the interdependencies between the Austrian and European electricity system, the actual GHG intensity of the modelled industrial transformation was calculated using GHG development for electricity generation for the EU 27. Shares of renewable gases were calculated specifically for each scenario. These take into account the development of costs for electrolysis and CO_2 emission certificates, among other factors. In the POI and ZEM scenarios, hydrogen prices break-even with fossil CH_4 prices between 2035 and 2045, and therefore starts to gain market share in the gas grid and hence across all sectors.

Main results of the industry scenarios

Business as usual (BAU)

In the BAU scenario, the historic trend of efficiency increases and growing production activity cancelling one another out with respect to GHG intensity is continued (Figure 1). Due to growing production activity, energy demand rises by 29 TWh, to a total of 161 TWh by 2050, including electrolysis losses (156 TWh without electrolysis, as hydrogen deployment is limited). Austrian industry continues to rely on large quantities of fossil-based energy carriers (such as coal, naphtha and oil), both for energy and feedstock demands, resulting in a total of 23.1 Mt CO_2e in 2050.

[1] Circular economy aspects have been taken into account only in terms of using sequestrated CO_2 as a new feedstock for the production of chemical base materials. In all other sectors, the current production and value chains were maintained.

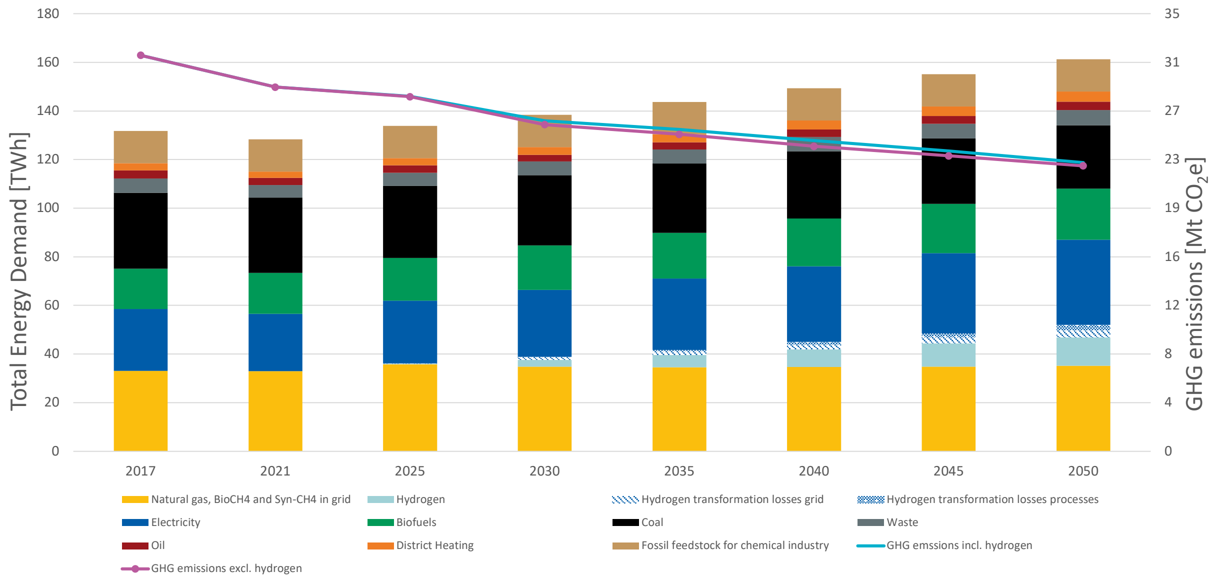

Figure 1: Total energy demand and GHG emissions of Austrian industry in the BAU scenario.

Pathway of industry (POI)

In this scenario, the total energy demand and GHG emissions follow the BAU scenario to 2025. From 2025 onwards, the POI (Figure 2) and ZEM (Figure 3) transition scenarios show clearly different patterns with respect to GHG emissions. This is due to the assumed technology changes, thereby induced fuel mix change and the introduction of an increasing quantity of low emission or carbon-neutral energy carriers in POI and ZEM. In both transition scenarios, by 2050 energy demand is characterised by three basic groups of energy carriers; electricity, gases, and biomass.

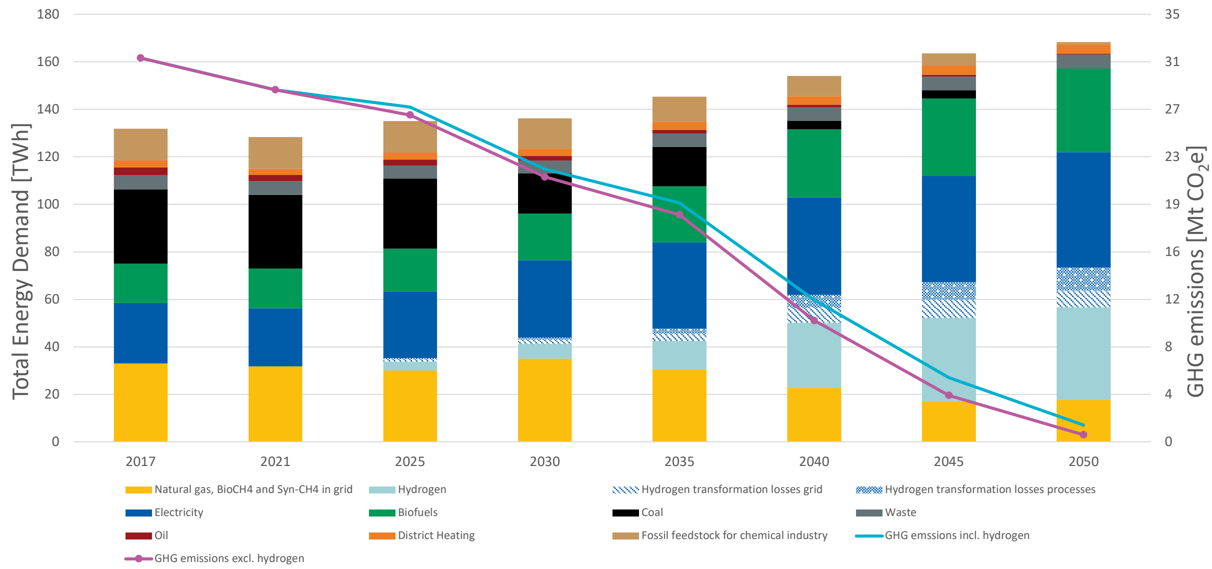

Figure 2: Total energy demand and GHG emissions of Austrian industry in the POI scenario.

POI follows industry's current transformation plans. The results show that Austrian manufacturing industry is capable of achieving significant progress towards climate neutrality by 2050. Total energy demand rises to 168 TWh when electrolysis losses are taken into account. Without electrolysis losses, the energy demand amounts to 152 TWh. Depending on the balance border considered, GHG emissions can be reduced by 30.8 Mt CO_2e to 0.6 Mt in 2050 when the emission intensity of electrolysis for hydrogen production is excluded.

Or, if included to 1.4 Mt CO_2e. In addition to wide-reaching fuel switches to sustainable energy carriers, the sequestration of geogenic emissions and the application of innovative process technologies for primary steel production are the main drivers for this development.

Zero emission (ZEM)

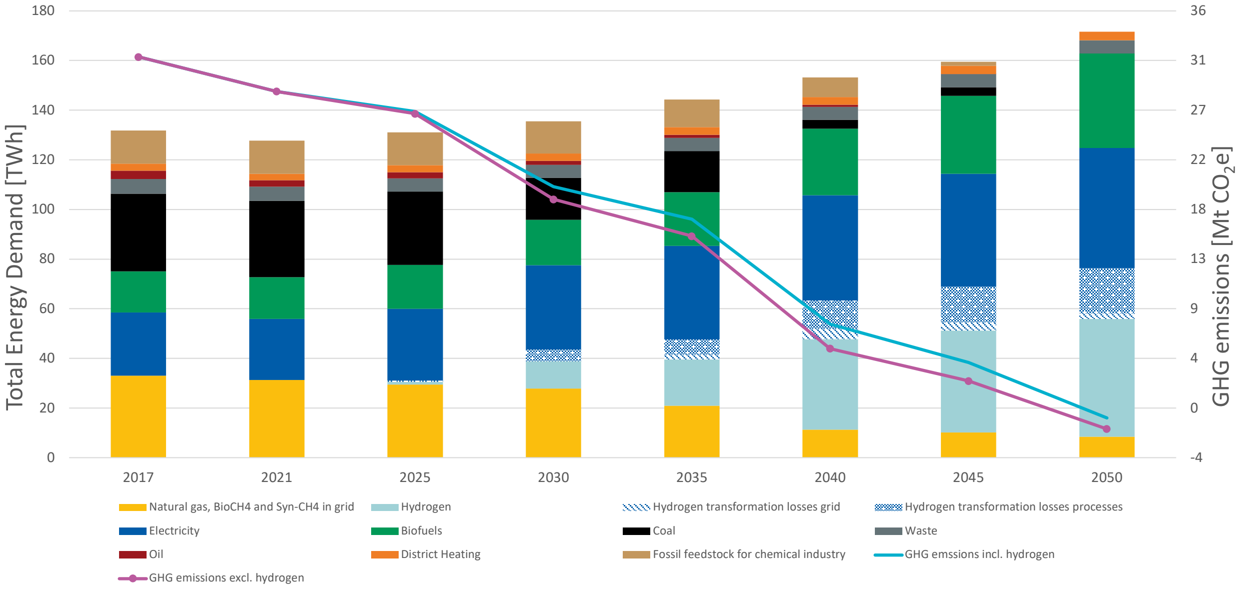

Figure 3: Total energy demand and GHG emissions of Austrian industry in the ZEM scenario.

ZEM is the most ambitious pathway towards industrial climate neutrality. In the ZEM scenario, total energy demand rises to 172 TWh by 2050. In comparison to POI, this is driven in particular by the focus on hydrogen-based production routes in the iron and steel and the chemical and petrochemical industries, which also increases losses from hydrogen production. Without considering losses for electrolysis, ZEM energy demand in 2050 nearly equals POI results, at 151 TWh per year.

General results

In both POI and ZEM scenarios, the chemical and petrochemical sector serves as the necessary CO_2 sink for counteracting remaining GHG emissions from other manufacturing industries. First and foremost, it provides a sink for sequestrated geogenic and therefore hard-to-abate CO_2 from the non-metallic minerals sector. Overall, a net total of 5 Mt CO_2 is absorbed by the chemical and petrochemical sector.

In both transition scenarios, a biomass demand of 35 (POI) to 38 (ZEM) TWh is projected, while extrapolating the trend in the BAU scenario results in 21 TWh in 2050.

49 TWh of electricity for final energy applications is needed to achieve industrial climate neutrality in both the POI and ZEM scenarios (excluding hydrogen production). In addition to general electrification efforts (e.g., heat pumps), electricity demand is driven in particular by the transformation of process emission-intensive sectors such as iron and steel and non-metallic minerals. In these sectors, the introduction of electric arc furnaces and carbon capture plants accounts for a significant demand in final electricity. If all hydrogen demand is met by electrolysis in Austria, total electricity demand for industrial production rises to 116 TWh/a in ZEM.

In the provision of gas, scenarios POI and ZEM involve different technological applications. In POI, industry relies more strongly on CH_4 and biomass-based technologies, while ZEM results focus on hydrogen-based technologies.

Conclusions and recommendations for action

Table 1 below outlines the main conclusions drawn from the scenario results and derived recommendations for action.

Table 1: Conclusions of the decarbonisation results and derived recommendations for action.

Conclusion	Recommendation for action
All four key levers are necessary for decarbonising the industrial energy system: • Energy efficiency improvement and low-emission electrification • Fuel switching to CO_2-neutral gases or biomass • Carbon capture technologies • Circular economy	Energy intensive industries need to quickly research, develop, demonstrate and rollout their specific technologies in order to remain on track to achieve their targets. The non-energy intensive sector must accelerate implementation of cross-sectoral technologies (e.g., heat pumps) to remain on track and to retain their competitive advantage: • Research & development AND demonstration are key to fast implementation of new technologies in industry. Efforts in both areas must be intensified and accelerated.
Three energy carriers will dominate in 2050: • CO_2-neutral gases • Electric energy • Biomass	• Supply of renewable energy carriers (gases, electricity) must be secured. • The utilisation of these energy carriers must be prioritised, based on technological requirements as well as temperature levels (e.g., CO_2-neutral gases for high-temperature processes and process demands, heating and cooling by heat pumps, etc.).
The switch to CO_2-neutral gases is a major lever with which Austrian industry can achieve climate neutrality, as: • They represent a sector-overarching mitigation of process-related and high-temperature heat-related GHG emissions.	• Infrastructure such as gas grids or storage need to be ready to cope with CO_2-neutral gases (e.g., hydrogen, bio-CH_4, Syn-CH_4) in a manner which includes infrastructures for H_2/CH_4-blends as well as dedicated H_2 infrastructures (this may include various H_2 carrier media such as ammonia). • Sourcing of renewable gases must include novel options and routes for import.
CO_2-neutral hydrogen also offers a means for using captured geogenic emissions from the non-metallic minerals sector in the novel hydrogen-based production processes applied in the chemical and petrochemical industry.	• Technological, logistical as well as policy related solutions for CO_2 as a feedstock need to be found.
Within the scope of this study, the current production and value chains are maintained. This leads to rising industrial energy demand in both transformation scenarios. However, ZEM and POI scenarios achieve similar results, indicating robustness.	If... • the circular economy in industrial production is enhanced (respecting the particularities of each sector), and/or • pre-products are imported (especially NH_3, methanol and renewable naphtha) …a decreased energy demand in industry may also be achieved.
Implications for the overall energy system:	
Climate neutrality in industry is part of Austria-wide efforts in all demand sectors (also buildings, transport) and in the energy industries. If Austria is to become climate neutral, the factors in the right-hand column must also be considered.	Domestic energy generation from renewable sources must be increased beyond the targets set for 2030. • Austrian gross domestic energy demand may exceed technical RES potentials. Import strategies, particularly for CO_2-neutral gases and its derivatives, need to be developed to ensure sustainable and secure energy supplies for the future. • The current energy infrastructure needs to adapt to reflect the developments noted above. This includes enhanced electricity grid capacities for both domestic and cross- border electricity transport, as well as infrastructure for hydrogen and its derivates.

1. Introduction

The goal of decarbonising the energy system to keep global warming below 2°C is one of the most significant challenges the world has ever faced. At the 2015 Paris Climate Conference, a commitment was made to limit global warming, and in 2019 the European Green Deal was signed, mandating the target of zero net emissions by 2050 and decoupling economic growth from resource use. To this end, the 'Fit for 55' package of legislation was proposed by the EU parliament and partially passed in 2022, introducing both the milestone of reducing GHG emissions by 55% to 2030 (compared to 1990) as well as several mechanisms to steer the economy in that direction. The package covers several economic aspects. For the manufacturing industry, this is most notably a carbon border adjustment mechanism (CBAM), an energy efficiency directive, and the extension of the Emissions Trading Scheme (ETS). In its current legislative programme, the Austrian federal government is pursuing the even more ambitious target of completely decarbonising its energy sector and its economic system by 2040 (UBA, 2021b).

Austrian industry is an essential pillar of the national economy and generated 24.8% of GDP in 2019. At the same time, manufacturing industry was responsible for approximately 34% of GHG emissions. Within the balance border drawn around all national industrial locations, more than 27% of annual gross domestic energy demand is consumed by industry (UBA, 2021a).

Due to its wide-ranging value chain, industrial activities involve several grades of processing. Their related inputs and outputs undergo numerous conversion processes, which in turn influence further economic activities and trigger a wide spectrum of innovation and technologies. This results in a magnified impact for the national economy, science, and technology development. Servicing consumer needs and the demand for cost-effective and competitive products are the foundations for industrial innovation. The legislative drivers noted above have significant implications for manufacturing industry: replacing fossil fuels as a primary energy source with renewables and, in many areas of basic materials production, using new processes and process chains. There are also many secondary implications, most notably a company's choice of technology. This is often strongly determined by dependencies and tertiary effects, especially in the energy sector, such as the need for additional and innovative energy transformation processes.

In many areas, Austrian industry is already effecting the transformation towards an efficient, sustainable and low carbon energy system, although these are early days. The New Energy for Industry (NEFI) innovation network was founded to support this process. NEFI is funded by the Austrian Climate and Energy Fund, and NEFI key technologies "Made in Austria" enable the decarbonisation of industrial energy systems and support Austria as an industrial location.

To assist decision-makers in their efforts to further increase European prosperity while decarbonising, the complexities of energy provision and use need to be considered and a clear pathway for each industrial sector identified. This report aims to provide such a guideline by assessing the current industrial production processes, projecting the future utilisation of different technologies, and summarising the resulting energy demands and technological pathways. Consequently, three distinct demand scenarios to 2050 have been developed. They represent a bandwidth of development possibilities which, by comparing the three scenarios, identify key fields of action towards industrial decarbonisation. The present report is structured as follows:

Chapter 2 investigates the status of Austrian manufacturing industry. This overview is supplemented by additional subsector-specific information in Appendix 1, Section 9. Chapter 3 explains the methodology of scenario development and modelling, while Chapter 4 outlines the results for each sector. The sector-based results are accompanied by a discussion of total results per scenario, as well as a comparison of the scenarios themselves and with respect to other high-level studies and reports (Section 5). Chapter 6 presents the key take-aways from the results of the studies and an outlook for decarbonising Austria's industry.

2. Austrian industry at a glance

Historically, manufacturing industry has played an important role in Austria's welfare and socio-economic development. At EUR 89.17 billion, it contributed 24.8% of Austria's GDP in 2019 (Statistics Austria, 2020a). From an economic viewpoint, the dominant industrial sectors are food, machinery and equipment (including electric and electronic), chemicals and petrochemicals, as well as the wood and paper industry.

The most energy intensive sectors of the thirteen industrial subsectors investigated are iron and steel, minerals, chemical and petrochemical industries, and pulp and paper (see Figure 4 below). Carbon emissions originating from energy including electricity and feedstock demand have been fairly stable at 32 Mt CO_2e/a over the last half decade. The impact of the pandemic can be seen in 2020, but is negligible compared to the efforts needed to decarbonise industry.

Industry's total energy demand (at the factory gate, including energy, non-energy and feedstock use) of approximately 27% of Austrian gross domestic energy consumption is a major factor in Austrian efforts to decarbonise. Therefore, scenario modelling is carried out within the defined balance border, as addressed in Section 3.

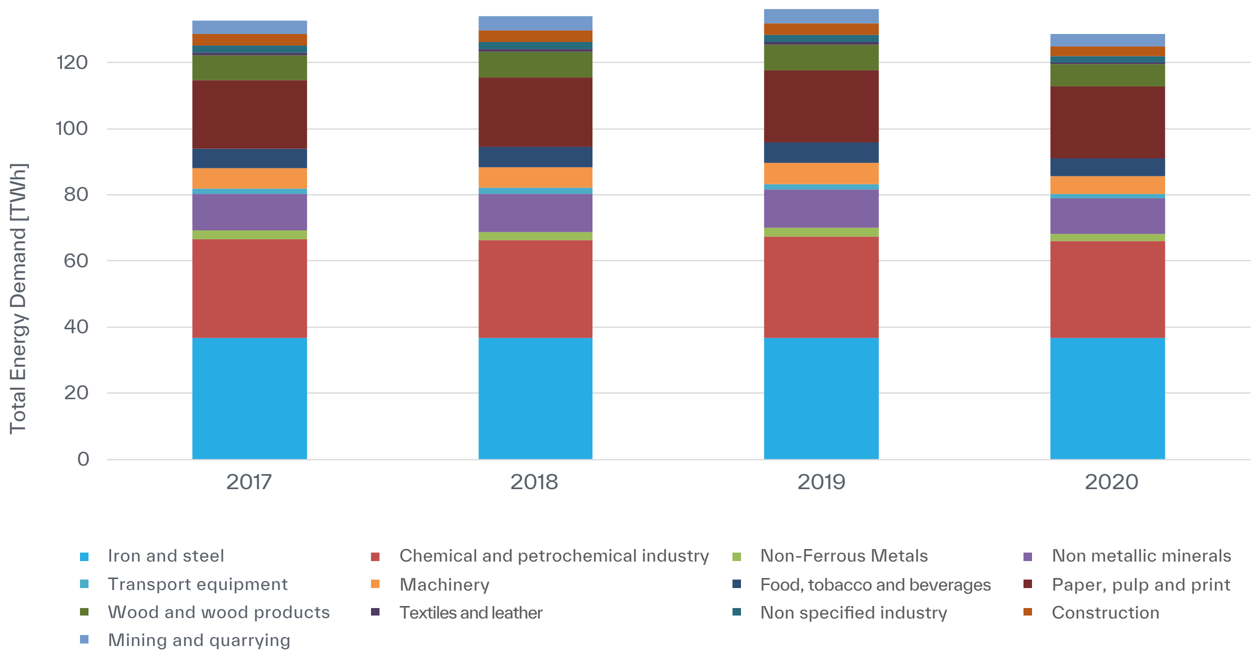

Figure 4: Energy consumption of Austrian industry by subsector (Statistics Austria, 2021a).

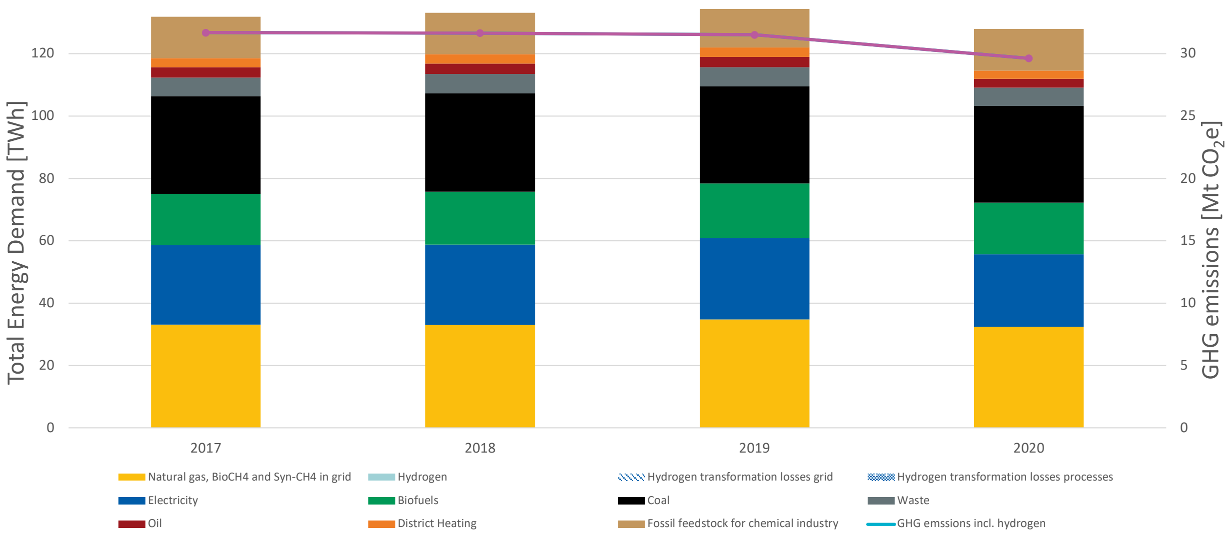

Figure 5: Total energy demand and GHG emissions of Austrian manufacturing industry by fuel type (Statistics Austria, 2021a).

Key levers of action for Austrian industry to achieve climate neutrality

The following action categories represent the main levers on the demand side for decarbonising manufacturing industries:

- Significant improvement in the energy efficiency of all industrial processes, and low-emission electrification of thermal and motive energy demands (heat pumps and motors)
- Fuel switching to carbon-neutral gases (hydrogen, bio- and synthetic CH_4)
- Carbon capture technologies
- Circular economy aspects

In combination with these industry-focused measures, decarbonising the supply side is essential to reach the intended goals. This includes, in particular, renewable electricity and gases as energy carriers. Section 3 addresses the applied methodology used for the specifics of the upstream energy sector.

3. Methodology

3.1 General approach

In this report the term ‘industry’ is used in the narrower sense of manufacturing industry, excluding commerce and tertiary services. Thirteen subsectors are defined in accordance with IEA classification. The industry scenarios presented are demand scenarios per subsector, and are driven by economic activity and scenario-specific technology deployment, but do not take into account the actual availability of energy carriers resulting from this demand. For this reason, a strict definition of the balance border under investigation, as well as necessary contact points with upstream energy provision by the gas and electricity grid, is needed, as presented in sections 3.1.2 and 3.1.3.

In order to project the long-term energy demand and formulate a decarbonisation strategy for Austrian industry, the methodology described involves the following key steps:

1. Collecting data on the current state and historical evolution of industrial products and related economic drivers, infrastructure and technologies, energy consumption, GHG emissions, etc.
2. Sector disaggregation: disaggregation of the industry sector into subsectors and groups of end-use categories, based on the type of processes and industrial activities following ISIC codes (OENACE, 2008). Thus Austrian industry is disaggregated into 13 subsectors, covering manufacturing activities and in addition to construction and mining. It also complies with the disaggregation scheme of IEA/UNECE/Eurostat for the economic activities of the producing branches as reflected in (OENACE, 2008).
3. Fuel allocation: the annual total energy consumption by fuel and useful energy category is specified for each subsector for the base year, based on official statistical data (STAT) and other complementary references for the industry branches.
4. Specifying the economic and technological determinants of Austrian industry’s current energy consumption by end-use category. This is the GDP value added (VA) by end-use activity, efficiency of energy conversion technologies, penetration rate of different fuel carriers, and related conversion technologies.
5. Reconstruction of the base year energy consumption to calibrate the model and establish the relationship between energy demand and the key techno-economic drivers.
6. Drafting the storyline and formulating the scenarios based on the five key levers of action for industrial decarbonisation:
    - Significant improvement of the energy efficiency of all industrial processes
    - Low-emission electrification of thermal and motive energy demands (heat pumps and motors)
    - Fuel switching to carbon-neutral gases (hydrogen, bio- and synthetic CH_4)
    - Carbon capture technologies
    - Circular economy aspects
7. Preparing the data for the quantitative scenario construction, using Austrian and international references on energy consumption of industry, results of stakeholder workshops and industry interviews.
8. Constructing consistent top-down and bottom-up scenario data, taking into account the results of an exhaustive participatory process with the industry key stakeholders to explore possible transformation pathways for national industry for the period 2017-2050.
9. Analysing the scenario results by subsector and fuel type, calculating the related GHG emissions in five-year steps over the study period, and tracking the transformation trajectories for each of the developed scenarios.

10. Plausibility check and sensitivity analysis of the developed strategy.
11. Extracting selected key indicators to track the evolution of the developed scenarios for energy and CO_2 emissions, share of electricity, share of renewables in energy demand.

Although it is a major lever, circular economy effects have been only taken into account at the level of recycling sequestrated CO_2 for the production of chemical base materials. Product design aspects and changes in material use were considered out of scope in order to provide a clear pathway from the current status quo.

3.1.1 Economic assumptions

The long-term evolution of national GDP and its structure is key to future energy demand in all sectors, particularly the industry sector. The approach taken here derives the energy demand for each economic subsector by the level of its economic activity expressed in terms of its GDP value added (VA) and the useful energy intensity. The GDP VA of all industry subsectors for the base period 2017 to 2019 and recent years has been obtained from the official national data on GDP and GDP structure issued by Statistics Austria (Statistics Austria, 2020b).

The forecasted development of Austrian GDP is determined by external references, historical trend developments, recent growth in 2019 that recorded an annual growth rate of 1.6%, and observed development for the short-term period 2020-2023 which was profoundly impacted by COVID-19. Assumptions about the expected long-term development for the period 2025-2050 are derived from historical development before 2020 and WIFO studies (Sommer et al., 2017).

The activity growth will follow the adopted GDP growth over the study period given in Figure 6. In Figure 6, the GDP is shown in 2019 price terms, and the applied average annual growth rates are given in real term values. Starting from a total value of EUR 360.14 billion in the base year 2017, GDP grew by a rate of 2.4% in 2018 and 1.6% in 2019 (Statistics Austria, 2020a), (World Bank, 2020). For the following years the growth rate fluctuates between -6.6% in 2020 and 1.6% in 2050, as noted above.

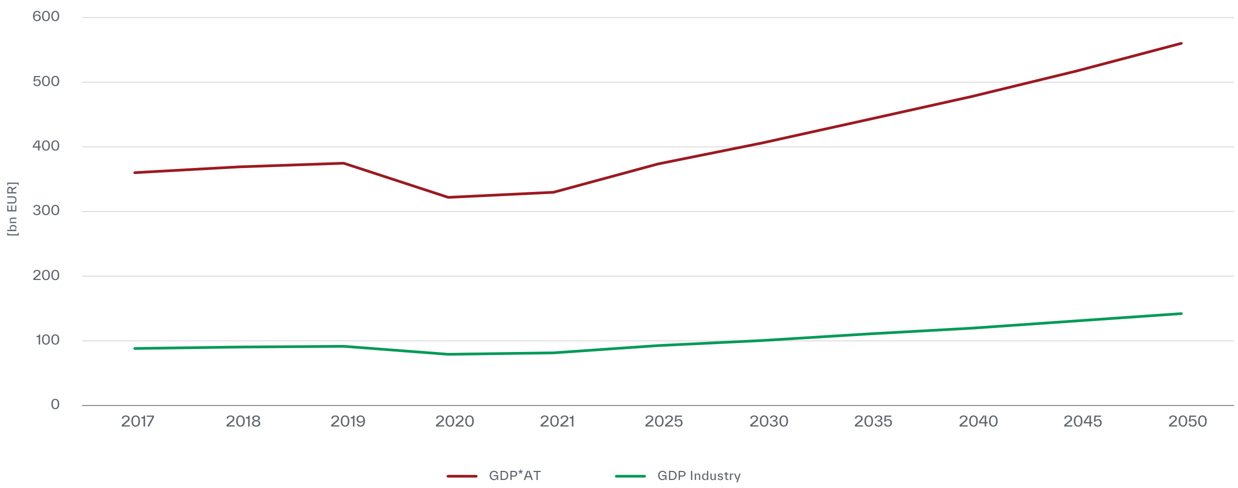

Figure 6: Underlying GDP of the Austrian economy and of the producing industry sector, including construction and mining.

3.1.2 Balance border

Scenario modelling is carried out within the defined balance border as shown in Figure 7. In contrast to international energy statistics, this balance border allows a holistic investigation and presentation of the total energy demand and GHG emissions for a given subsector, to provide the total industrial energy consumption.

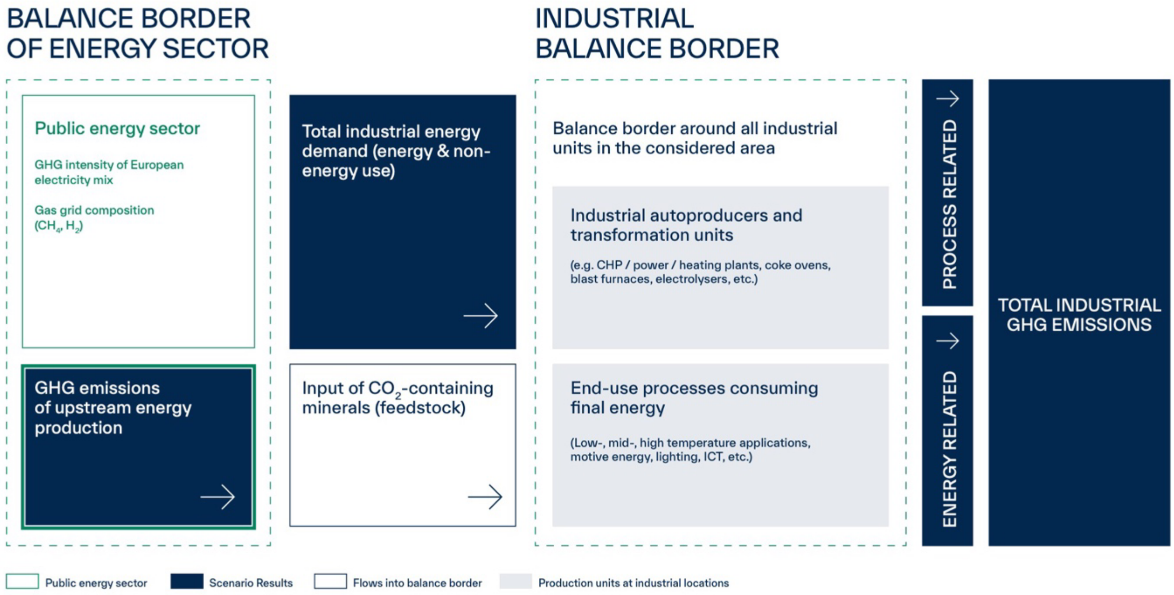

Figure 7: Balance border of industrial processes.

Total industrial energy demand is determined in situ by two general consumer categories located inside the balance border, covering all industrially-owned energy use and transformation units. On one side, energy is used by end-use devices consuming final energy, such as boilers, furnace, engines or lighting devices. On the other side, industries demand energy for their energy transformation units, e.g., CHP or power plants, blast furnaces, coke ovens, or electrolysers. In the future, many of these transformation units may be operated within or outside the presented industrial balance border. In cases where no definitive placement is possible in the scenarios, we have opted to show these instances separately and visibly.

The investigated GHG emissions comprise energy-related and process-related emissions. Energy-related emissions stem from the combustion of carbon-based energy carriers. Process-related emissions are caused by industrial transformation processes (e.g., blast furnaces) or through the introduction of carbonaceous minerals into the production processes (e.g., $CaCO_3$ for cement production). In addition, upstream production of energy carriers in the public energy sector, such as the combustion of gas for electricity generation, may add to the GHG intensity of industrial production. While not inside the industrial balance border, these emissions must also be included in the investigation of industrial transformation to avoid merely shifting the challenge of decarbonisation from one sector to another.

3.1.3 Scenario storylines

The preparation of a long-term strategy to reduce Austrian industry's CO_2 emissions to net decarbonisation by 2050 requires detailed analysis of the industry sector's energy demand. The developed scenarios follow the NEFI goals: **(I) Decarbonisation of the industry energy system, (II) Value Creation by technology made in Austria, (III) Securing production sites and jobs by user involvement.**

In this report, three scenarios have been prepared, based on three scientifically-documented scenario concepts. They open up a bandwidth of development possibilities which, when the scenarios are compared, allows important fields of action for industrial decarbonisation to be identified (see Figure 8).

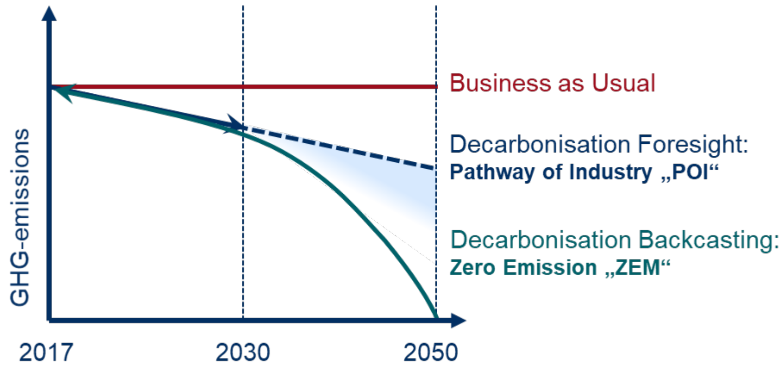

Figure 8: Stylised representation of the three investigated scenarios.

Business as usual (BAU)

BAU is a trend scenario extrapolating past and current trends in energy consumption and GHG emissions to 2050. It is used as a reference scenario and helps to assess the impact of innovative technologies used in the two transformation scenarios below.

Pathway of industry (POI)

POI is a foresight scenario prepared using an extensive stakeholder involvement process. Representatives from large companies in each industry subsector were contacted and interviewed to record their self-assessment of planned transformations until 2030 under current framework conditions. These assessments were then extrapolated based on the short- and midterm availabilities of best available technologies (BAT) and breakthrough technologies (BTT) to 2050. In line with the concept of foresight, the results of this scenario do not constitute deterministic forecasts. Rather, they are intended to paint a regularly updated picture of intentions, assessments and plans for Austrian industry. Comparison with the ideal pathway illustrated by the ZEM scenario below allows the identification of techno-economic and infrastructural gaps. Thus, it can inform the public discussion of necessary boundary conditions for successful decarbonisation.

Zero emission (ZEM)

ZEM is a backcasting scenario which represents one possible pathway towards decarbonisation using both technological as well as socio-economic parameters in its choice of technology. Starting from the goal of net zero emissions by 2050, strategies and BTT-based measures are developed that need to be deployed in the years leading up to this deadline.

3.2 Scenario modelling

3.2.1 Combination of top-down and bottom-up industry investigation

In order to increase the accuracy of scenario development, the chosen methodology combines a top-down approach for calculating industries' energy demand with the bottom-up assessment of technology rollouts of the subsectors. Both are contained in the model simulation, with the two directions of attack meeting at the level of a subsectors' employed technology share.

The basic principle of the top-down approach projects the useful energy demand where the specific **energy needs** for producing various goods and services are systematically **related to the socio-economic and technological** factors affecting the demand for each particular fuel. Energy demand is divided into a number of end-use categories, each corresponding to a given service (e.g., space heating) or the production of a certain good (e.g., primary steel, cement, equipment). A sector's value added and its energy intensity and useful energy demand are the basis for the cross-sectional technology changes (e.g., gas boilers to heat pumps) and fuel switches as calculated from the literature.

Bottom-up calculations are performed based on a selection of best-available (BAT) and breakthrough decarbonisation (BTT) technologies and their specific process parameters. This approach is especially useful in sectors where alternative production routes need to be deployed, as extensive GHG mitigation and energy transformation units are integrated into the production process. Scenario-specific development of deployment over time to 2050 is accomplished by the use of sector- and technology-specific penetration rates. These take into account detailed feedback from industry representatives about expected technology readiness development and applicability, publicly-accessible company reports, reference documents, scientific investigations and reports on reference plants. This first-hand information was gathered in several rounds of interviews, workshops and through the use of questionnaires. Essential guidelines for determining deployment rates per technology and scenario are discussed in 3.2.2.. An overview of all the subsectors investigated wholly or partly with a bottom-up-approach is given in Table 2.

Table 2: Overview of energy intensive industry sectors and processes considered bottom-up.

Industry sector	Considered processes
• Iron and steel	• Primary steelmaking
• Chemical and petrochemical	• Production of ammonia • Nitric acid, urea, fertiliser • Methanol • Olefines
• Non-metallic minerals	• Cement production • Magnesia production
• Pulp and paper	• Total pulp and paper production

3.2.2 Scenario-specific methodology

The overall target of radical GHG emission reduction entails the formulation of long-term sustainable energy consumption pathways with different decarbonisation measures. When modelling the scenarios, the bottom-up and top-down approaches meet at the technology level. The fundamentals of each scenario's development are presented below.

For top-down modelling, one global parameter is economic activity: it has been modelled equally in all three scenarios. In the sectors modelled bottom-up, subsector output development (by tonnage) is modelled based on industry feedback, but value added increases by quality improvements. Assumed output per subsector is given as part of the discussions of results in Chapter 4. In the non-energy intense sectors, growing value added and (contracting) energy intensity are the drivers of energy demand growth, held constant over all three scenarios and presented in the case of BAU.

Business as usual (BAU)

In bottom-up modelling, the technologies and process chains currently applied are continued. However, where applicable, fuel switches determined by the upstream energy sector (electricity and gas, see 3.3) are considered to include existing transformation projects for the overall energy system (e.g., domestically-produced hydrogen).

For the top-down modelling, the economic assumptions of the BAU scenario are the basis for all scenarios (the difference in the scenarios is the technological adaptation rates and grid mixes). The observed historical development trend of Austrian industry is applied to generate the key assumptions used to project the future energy demand in the BAU scenario, as follows:

- Structural change in terms of share of industry in total GDP as well as its disaggregation by subsector: it is assumed that industry subsectors will maintain their shares in gross value added close to present levels.
- Energy efficiency improvements are low in BAU and cannot compensate for the sectors' growth, see the results section for the respective assumptions. The improvement of useful energy intensity is assumed to improve by an average annual growth rate of -0.5% .
- End-use energy efficiency reflecting the efficiency improvement of conversion technologies used to convert final energy (fossil fuel, biofuel, electricity) to useful energy (motive power and heat): it is assumed that efficiency will improve at an average annual rate of 0.4% for thermal processes (distributed equally by temperature level and fuel type) and 0.1% for the provision of motive power.
- Technology adoption rate: no significant change in the penetration rate of fuel is assumed, except for the slight increase in the electrification rate that will show an improvement of around 3% over the whole study period.

Pathway of industry (POI)

Bottom-up, extensive dialogue sessions with industry representatives were used to screen and discuss the BAT and BTT. In accordance with the scenario storyline of POI, representatives then provided assumptions for applicable technologies and their deployment rates under the current economic and legislative framework. Generally, this outlook is based on the widespread adoption of best-available technologies in each of the investigated industrial sectors to 2050.

Top-down, the construction of POI relies on the development of the key techno-economic drivers of energy efficiency and technology adoption rates. In addition to feedback from the industry interviews, EU and national references are a valuable source of information, reflecting the expectations of Austrian industry and thus providing an important basis for estimating the potential for efficiency improvement, electrification and switching to alternative fuels and processes. The following techno-economic and structural changes are applied:

In contrast to BAU, **energy efficiency improvement** will be driven by the increased uptake of BAT which will replace existing machinery and equipment, by process optimisation, and structural change leading to a shift to higher value added and less energy intensive activity (as elaborated above). Several sources were consulted in order ensure consistent assumptions regarding energy efficiency developments (EU, 2016), (De Vita et al., 2018), (IIASA, 2012), (AEA, 2021), (Goodman et al., 2009), (Sommer et al., 2017).

- **Useful energy intensity** improvement: projected to reflect the improvement of process optimisation in addition to enhancing the modularity of industrial processes through digitalisation. The assumptions rely on international references and industry energy surveys, and have been developed in comparison to BAU.
- **Energy efficiency** improvements rely on unlocking existing energy efficiency potential supported with targeted policies and measures to lift/remove energy efficiency barriers (financial, structural, regulatory) and accelerate the penetration of BPT/BAT in all industry subsectors. In addition to the industry survey, international and national references have been consulted, including IEA estimations, IIASA study on energy efficiency potential, WIFO assessment of efficiency potential of energy intensive industry, and are used for estimating the technical improvement potential (Figure 1). The estimated potential varies between 10%-30% of current energy use.

- **Electrification** of formerly gas-powered units: consistent with the interviews, a target of up to 50% of useful thermal energy in the high and medium temperature zones has been assumed to 2050.
- **Fuel switching** is mainly driven by gas grid mix changes with increasing shares of hydrogen as illustrated in 3.3.2. Where applicable, solid biomass is also used to replace oil and gas, mostly after 2040.
- **Carbon capture and use (CCU)** is projected to be used in the non-metallic minerals industry only to mitigate geogenic emissions as no other technologies are available in this sector. The chemical and petrochemical sector presents an important sink for sequestrated CO_2.

Scenario zero emission (ZEM)

While the POI scenario can achieve significant mitigation (more than -80% GHG emissions) in decarbonising the Austrian industry, a backcasting approach is necessary in order to identify necessary additional measures that enable total decarbonisation of industry. Bottom-up, industry feedback on BTT was significantly expanded and complemented by desktop research on existing deep decarbonisation scenarios and employed technologies and processes, e.g., Material Economics, 2019a; Pee et al., 2018. Some industrial subsectors already have very precise, detailed decarbonisation plans. In these cases, the calculated pathways were substituted with first-hand strategies from industry representatives.

- **Energy efficiency improvement:** Most technologies, especially industrial boilers, are modelled to become more efficient, with the assumption that the efficiency potential of BAT will be exhausted by 2050. The uptake of heat pumps is modelled to increase and largely substitute boilers in the low temperature heat demand level, driven by wider availability, and in special applications such as construction machinery.
- **Fuel switching and electrification:** The net-zero backcasting methodology implies a shift in the industry sector towards low carbon fuels (biofuel, waste, H_2 and electricity) which, in many cases, is coupled with the shift to higher value added products that often rely on higher exergetic fuels, e.g., electricity. Therefore, closing the remaining gap to net zero is modelled by switching to biofuels with a small (<15% in all sectors) share in synthetic and bio fuels.
- **CCU:** Similar to POI, carbon capture of geogenic emissions in the non-metallic minerals sector and their use in the chemical and petrochemical industries is important in reducing geogenic emissions. As explained in detail in Section 4.2, POI and ZEM differ in terms of applied technology.

3.3 Modelling of the energy sector

The supply of renewable energy by the energy sector plays an important role in industrial decarbonisation and must be considered when investigating the industrial energy transformation. In order to maximise the information character of the scenario results, the following assumptions have been made.

3.3.1 Electricity grid

For electricity, the GHG emission intensity of upstream electricity generation is included. This serves to reflect the interdependencies between the Austrian and European electricity systems. To calculate the actual GHG intensity of industrial transformation, a decarbonisation path for the electricity system as formulated by the European Commission for the EU 27 in Scenario MIX is used as the basis (European Commission, 2020b). As the GHG intensity of the Austrian energy sector has historically been lower than that of the Union, we used the Austrian case as the starting point (European Environment Agency, 2021b). Thereafter, the European development as a percentage was applied from 2020 onwards. The derived GHG emissions development is illustrated in Figure 9.

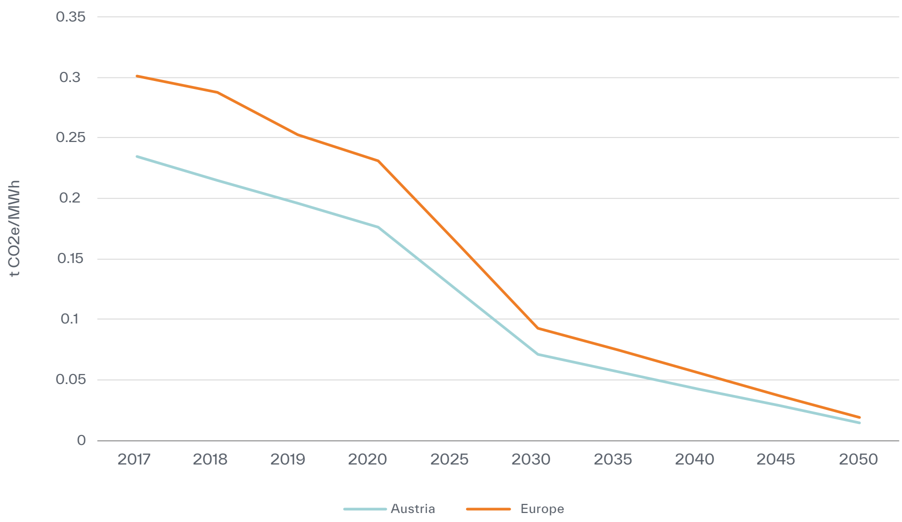

Figure 9: Assumed grid emission factor development for electricity based on UBA (2019b).

3.3.2 Gas grid

The evolution of the gas grid composition is driven by increasing CO_2 costs and decreasing costs for using electrolysis to produce hydrogen. To adequately model the available quantities of bio-CH_4, fossil CH_4 and hydrogen, a cost-based methodology was chosen to assess the composition of the Austrian gas grid in scenarios POI and ZEM. In BAU, growth rates of renewable gases are based on current government targets for 2030 and extrapolated to 2050. In scenarios POI and ZEM, renewable gases reach cost parity between 2035 and 2045 as illustrated in Figure 10. Underlying carbon price development is illustrated in

Table 3. The carbon prices for both scenarios take into account the price for carbon emissions which will be charged from July 2022 as part of the eco-social tax reform. The CO_2 tax is set to be 30 €$_{2017}$/CO_2 in 2022 and 55 €$_{2017}$/t CO_2 in 2025 (finanz.at, 2021). The further development of the CO_2 prices in the POI scenario corresponds to the growth of the prices in the WEM-scenario of the Environmental Agency Austria (EAA) (UBA, 2017). This path is also reported by Austria to the European Commission in its National Energy Climate Plan (NECP). In scenario ZEM, the developments of scenarios "Transition" and "WAM+" (With Additional Measures plus) of the EAA are followed (UBA, 2017).

Table 3: Assumed development of carbon prices in €2017/t CO_2 in scenarios POI and ZEM.

	2020	2025	2030	2035	2040	2045	2050
POI	24.70	55.00	76.30	94.30	112.20	154.90	197.60
ZEM	24.70	55.00	85.30	111.50	137.70	202.80	267.90

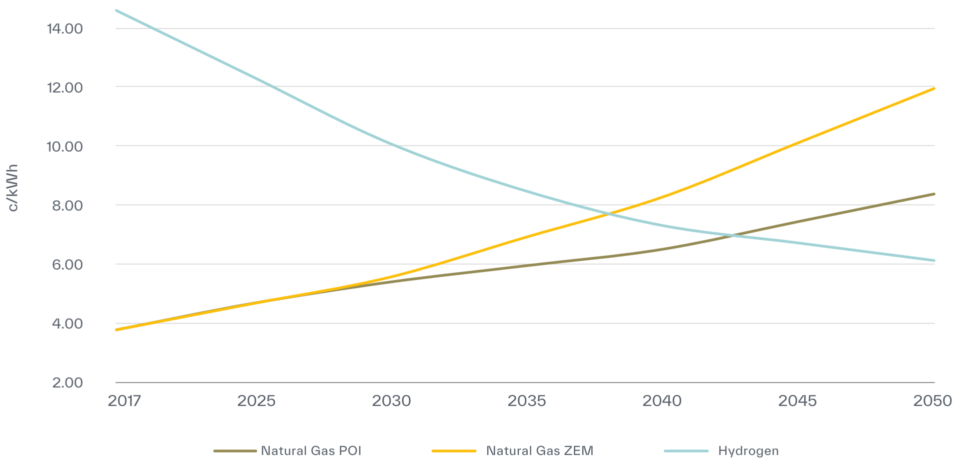

Figure 10: Cost development of fossil CH_4 and H_2 from electrolysis in c2017/kWh.

Total gas demand for Austria was modelled to calculate total available shares of each gas. For the industrial sector, preliminary industry scenario results were used, while all other sectors (e.g., buildings and transport) were covered using the above-mentioned WEM-scenario report prepared by the EAA under the EU Monitoring Mechanism. In order to merge the gas system modelling with bottom-up industry sector results (e.g., in the iron and steel and the chemical industry), defined gas types in these sectors were deducted form the overall gas system results. The process for calculating the remaining amounts per gas type is visualised by equation 1, with *t* representing each of the three distinct gas types, fossil CH_4, bio-CH_4 and H_2, respectively.

$$E_{t,Gas\ Grid,rem.} = T_{t,Total} - T_{t,Bottom-up}$$

The remaining gas comprises the gas grid available to all users connected to it. Its shares in each scenario are presented in Figure 11 (BAU), Figure 12 (POI) and Figure 13 (ZEM).

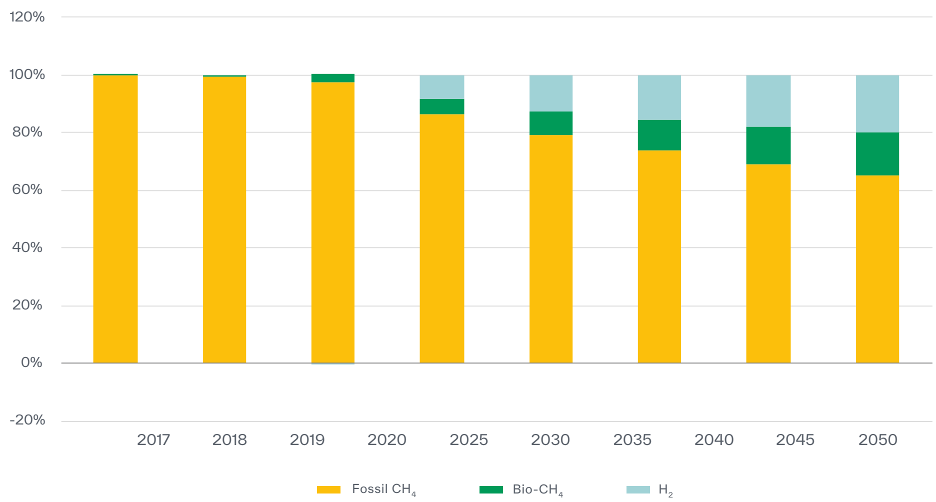

Figure 11: Calculated development of gas grid composition in BAU after subtraction of gas for iron and steel and the chemical and petrochemical industries.

In the BAU scenario, after subtraction of H_2 demand as modelled in the iron and steel industry, the extrapolation of government targets results in a 35% share of renewable gases by 2050, 20% of which are provided by hydrogen.

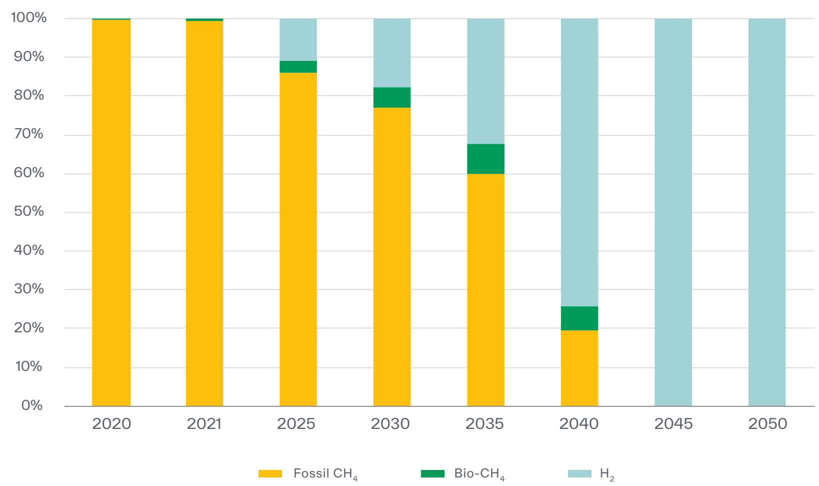

Figure 12: Calculated development of gas grid composition in POI after subtraction of gas for iron and steel and chemical and petrochemical industries.

In the POI scenario, as outlined in Section 4.1 below, the iron and steel industry and the chemical and petrochemical industry rely predominantly on CH_4-based production processes. Therefore, by 2045, only hydrogen remains for supply to conventional industrial customers connected to the gas grid.

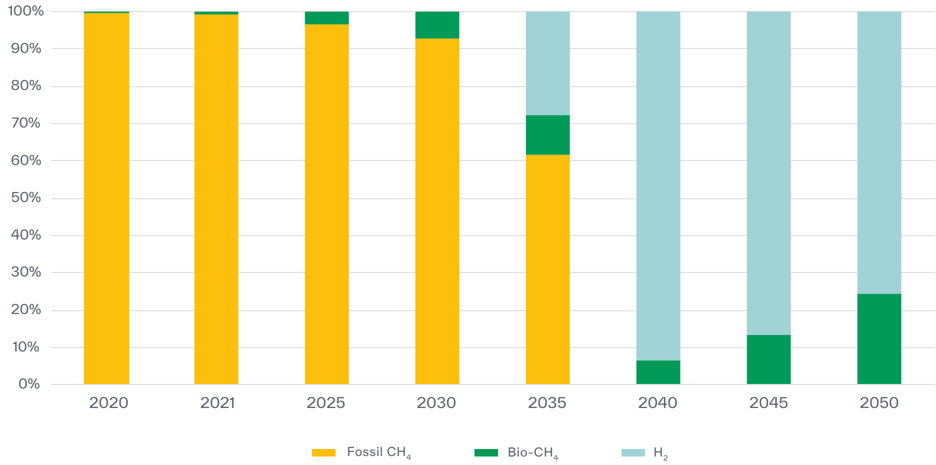

Figure 13: Calculated development of gas grid composition in ZEM after subtraction of gas for iron and steel and chemical and petrochemical industries.

In the ZEM scenario, processes modelled bottom-up for iron and steel and the chemical and petrochemical industry rely more strongly on H_2-based processes. Therefore, as bio-CH_4 production ramps up, more and more CH_4 becomes available as admixture in the predominantly H_2-based gas grid.

4. Results

This section presents the results of scenarios BAU, POI, and ZEM for each of the thirteen industrial subsectors considered. After presentation of the respective results, there is a scenario-based discussion of each sector. The sector-based results are followed by a discussion of the scenario results for all Austrian manufacturing industries.

4.1 Iron and steel

For the scenario development in the iron and steel subsector, an increase in economic activity was only considered for secondary metallurgy while, after feedback from industry representatives, primary steelmaking output was assumed to stay constant at approximately 7 Mt steel/year. As outlined in Appendix 1, Section 9.1, the largest challenge for decarbonising the iron and steel sector is posed by primary steelmaking. The main technology chosen to mitigate emissions from this process in scenarios POI and ZEM is the gas-based direct reduction route in combination with electric arc furnace (DR/EAF). The scenario parameters applied to the bottom-up investigation of this sector are based on results by Rechberger et al. (2020).

Results iron and steel – BAU scenario

In the BAU scenario, total energy demand by iron and steel increases to 40.5 TWh by 2050 (Figure 14). Approximately 2 TWh of hydrogen are deployed as an additive for the reduction process in the blast furnace/blast oxygen furnace route (BF/BOF). Additionally, ~3 TWh are supplied to secondary metallurgy operations through the gas grid. If H_2 production via electrolysis is taken into account, an additional ~2 TWh are expected, highlighted in Figure 14 by the hatched area in blue. In the scenario, emissions are reduced by merely 20% in comparison to the base year 2017. This amounts to approximately 10.8 Mt CO_2e. when taking into account GHG emissions in relation to electricity consumption for electrolysis (as illustrated by the blue line). As there is only minor electrolysis deployment, it does not deviate significantly from the second graph for GHG emissions which visualises GHG emissions when the upstream GHG intensity of electricity for H_2 generation is not considered (see purple line).

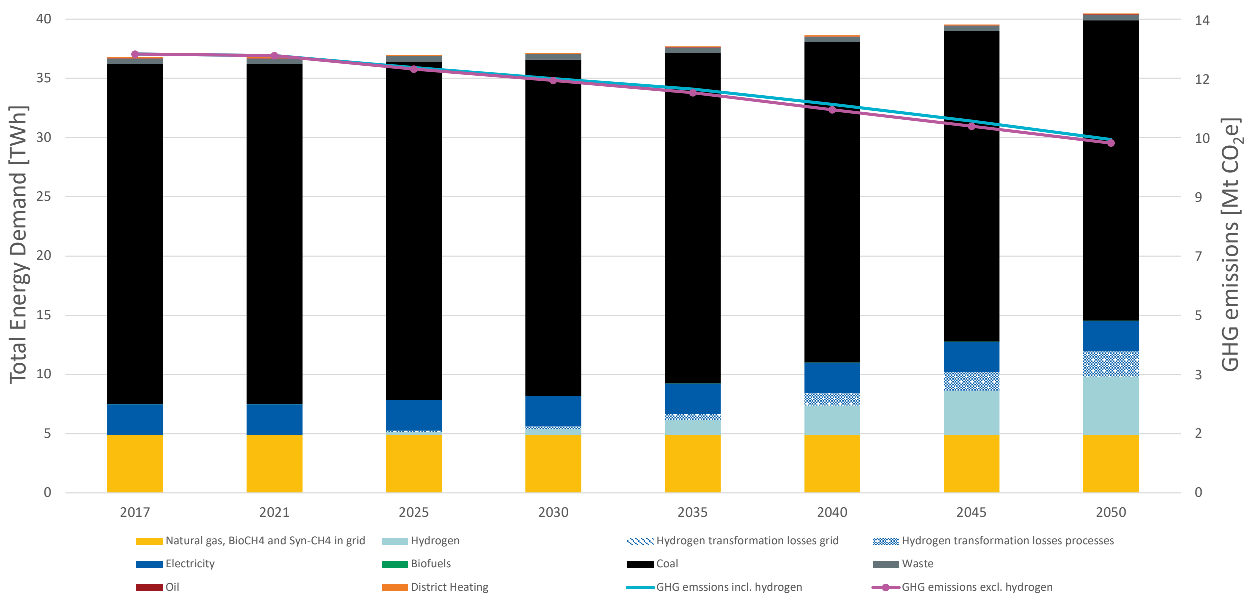

Figure 14: Total energy demand and GHG emissions in the iron and steel sector in BAU scenario.

Results iron and steel – POI scenario

In POI, the increasing substitution of the BF/BOF route by direct reduction (DR) and electric arc furnaces (EAF) for primary steelmaking reduces total energy demand by up to 9.3 TWh by 2050 (6.3 TWh if hatched area for electrolysis is also considered). Figure 15 illustrates the increasing use of CH_4-DR with a substantial share of hydrogen as reducing agent of up to 30% by 2050. Industry stakeholders envisage the substitution of traditional production routes beginning during the period 2025-2030 and reaching completion after 2045. By 2050, POI energy demand in primary steelmaking is exclusively characterised by three energy carriers; CH_4, H_2, and electricity. In secondary metallurgy, the increasing use of BAT in all aspects of production causes a slight decrease in energy demand while productivity rises. Due to the decarbonised nature of the gas grid in the POI scenario as described in Section 3.2. emissions can be reduced to at least 0.8 Mt CO_2e (see blue line below). Total emissions of 0.7 Mt CO_2e can be achieved if GHG emissions from electricity for electrolysis are not considered (see purple line).

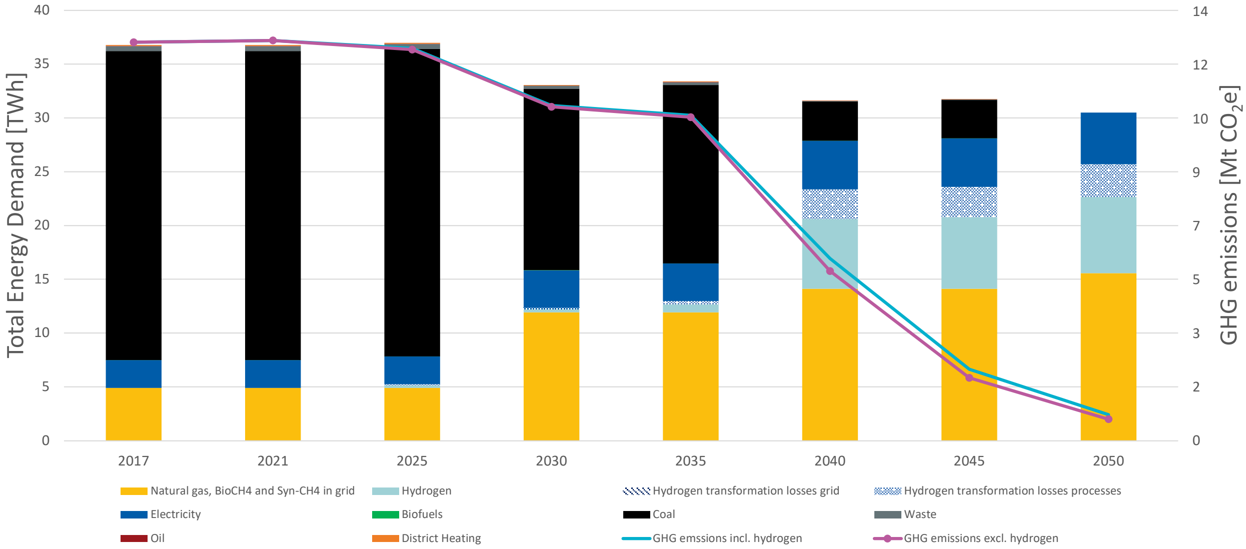

Figure 15: Total energy demand and GHG emissions by the iron and steel sector in the POI scenario.

Results iron and steel – ZEM scenario

The ZEM scenario uses BTT by way of H_2-DR/EAF to decarbonise the iron and steel sector (Figure 16). Following the same time path as POI for deployment of DR/EAF, hydrogen demand by the sector rises to almost 20 TWh annually, driven by primary steel production. The shift in energy system structure is further exemplified by an additional 8 TWh of electrical energy needed for electrolysis. Approximately 5 TWh of electricity are required for EAFs and production processes in secondary metallurgy. Similar to the POI results, GHG emissions are reduced by over 90% compared to the base year. If electricity-related GHG emissions for electrolysis are considered, 1.2 Mt CO_2e are emitted in 2050. This number is reduced to 0.8 Mt when the GHG emissions related to electricity needed for electrolysis are excluded.

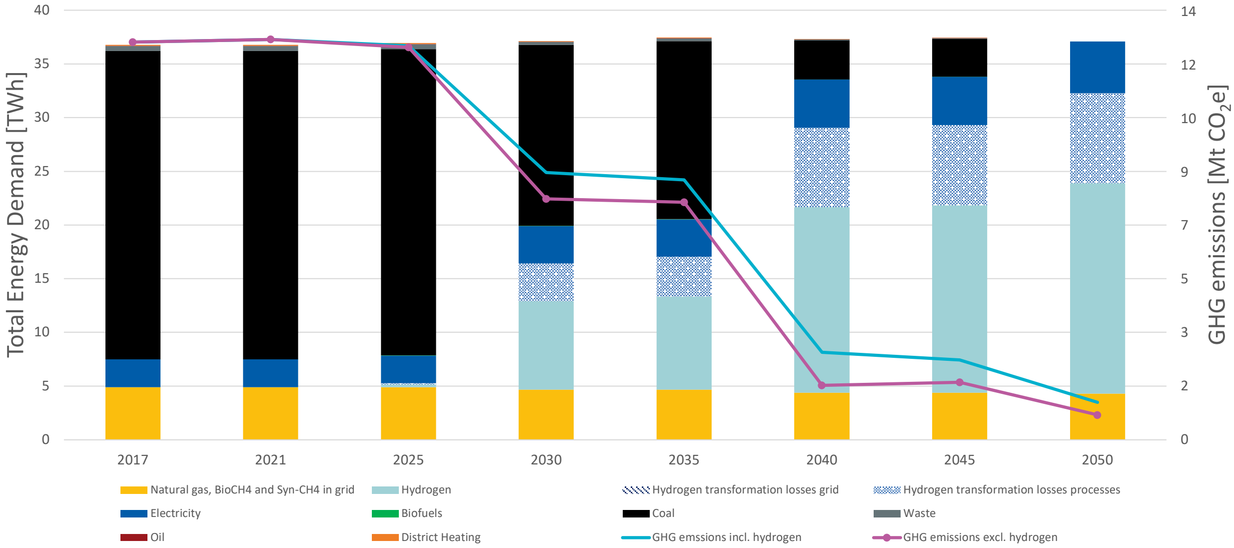

Figure 16: Total energy demand and GHG emissions by the iron and steel sector in the ZEM scenario.

Summary of results for iron and steel

GHG emissions in iron and steel are most strongly influenced by the scenario-specific production route chosen for primary steelmaking, as well as the upstream emission intensity of energy supply for electricity and gas. Figure 17 offers a comparison of the development of GHG emissions in the three scenarios when including the electricity-related GHG emissions from H_2 production through electrolysis. In BAU, where a maximum of 20 kg H_2 per ton of crude steel is added, the specific GHG emissions factor can only be reduced by approx. 20% in comparison with 2017. Minor efficiency measures in secondary metallurgy contribute to an overall emission reduction of 2.46 Mt CO_2e in iron and steel. In POI and ZEM, the deployment of direct reduction with gases enables more ambitious reductions of up to 12.0 Mt CO_2e. In these scenarios, the greatest rates of decrease from one 5-year period to the next are caused by additional capacities in primary steelmaking being moved from the BF/BOF to the DR/EAF-route. Generally, their decarbonisation success is dependent on the availability of gases (CH_4 or H_2) with a low emission profile. In secondary steelmaking, increasing electrification and the increasing supply of renewable gases in the gas grid enable additional CO_2 reductions.

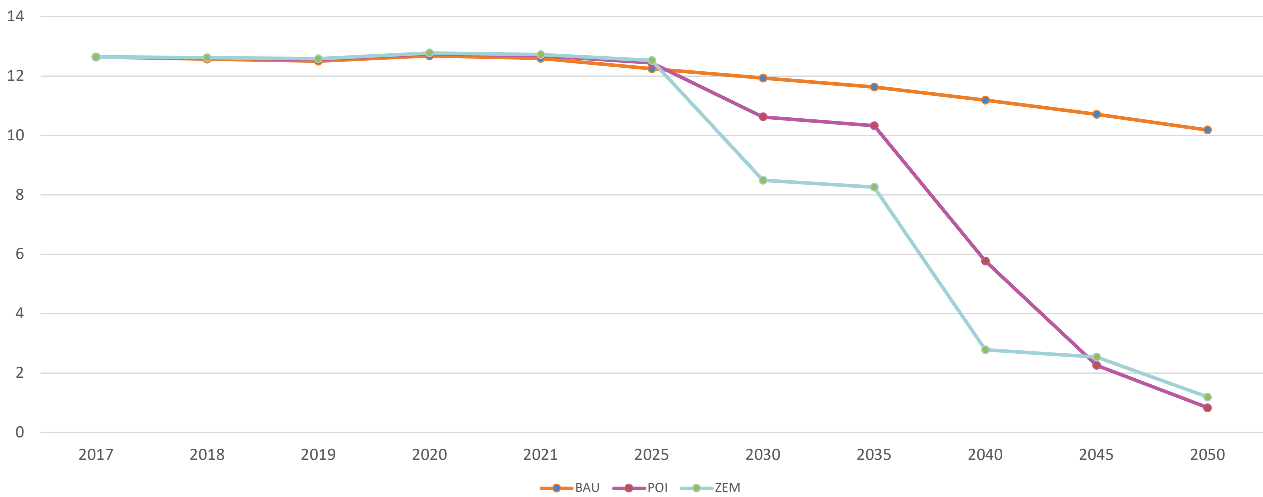

Figure 17: Comparison of GHG emissions in the iron and steel sector in the BAU, POI, ZEM scenarios when including H_2 generation for emission intensity.

4.2 Non-metallic minerals

The non-metallic minerals sector features several subsectors as described in Appendix 1, Section 9.4. The two largest and most emission-intensive subsectors, cement and magnesia, were modelled bottom-up based on specific process parameters. Their production output was set constant at base year production rates after consultation with sector representatives. For the remaining subsectors, production output increases by 1.5% annually. In the POI and ZEM scenarios, carbon capture technologies are incorporated across the sector to mitigate otherwise unavoidable geogenic emissions. Applied process parameters are based on CEMCAP (2019). However, no subsequent use or storage of sequestrated CO_2 has been modelled inside this sector. Instead, use of sequestrated CO_2 in cooperation with the chemical and petrochemical industry is discussed in 5 as part of the overall industry results.

Results non-metallic minerals – BAU scenario

In BAU, the basic trends of energy carrier deployment are prolonged. Due to the modelled production increase in some subsectors, energy demand increases for each of the energy carriers through to the end of the investigated period. Regarding the use of gas-based technologies, hydrogen and bio-CH_4 increase their share as modelled in accordance with the explanations for the gas grid in 3.3. As no carbon capture technologies are implemented in BAU, after a decrease due to rising shares of renewable gases in 2030, GHG emissions stagnate afterwards due to the offset caused by increasing production activity.

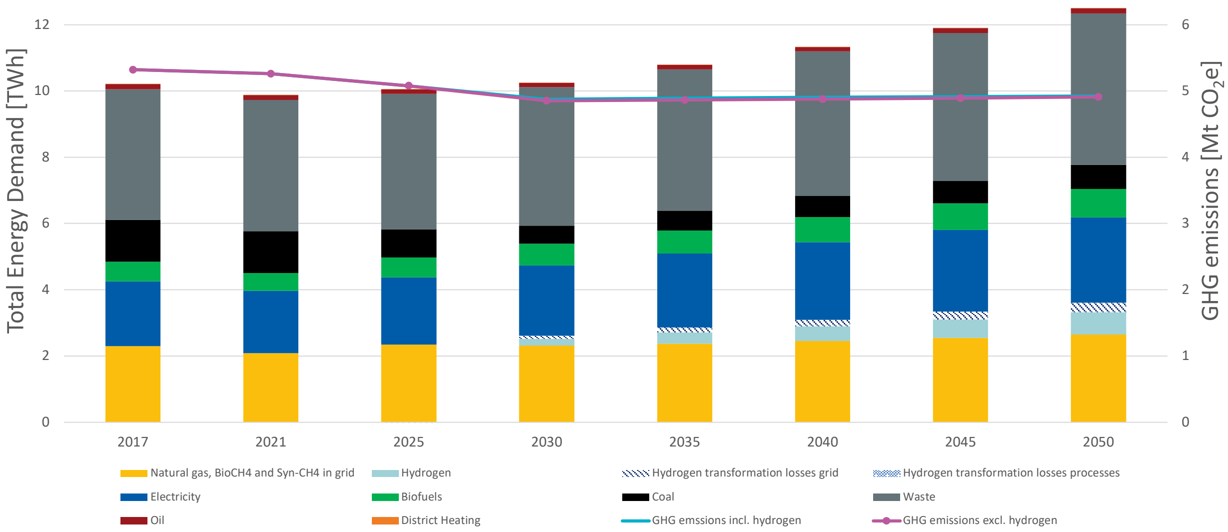

Figure 18: Total energy demand and GHG emissions by non-metallic minerals in the BAU scenario.

Results non-metallic minerals – POI scenario

For POI, industry representatives predict the introduction of carbon capture through the use of amine scrubbing technology, incrementally starting in 2025. This allows the sector to reduce emissions by up to 65% in comparison with the base year. Heat demand of the amine scrubber is supplied by the use of heat pumps, which adds significantly to the electricity column in Figure 19 (total of 7.2 TWh in 2050). Due to the high-temperature demands prevalent in the sector, gas demand is calculated to stay at current levels. However, as per underlying gas grid methodology, starting in 2045 it consists completely of hydrogen instead of CH_4. In cases where hydrogen is not suitable due to flame specifications, H_2 derivatives must be produced on-site from this gas grid supply.

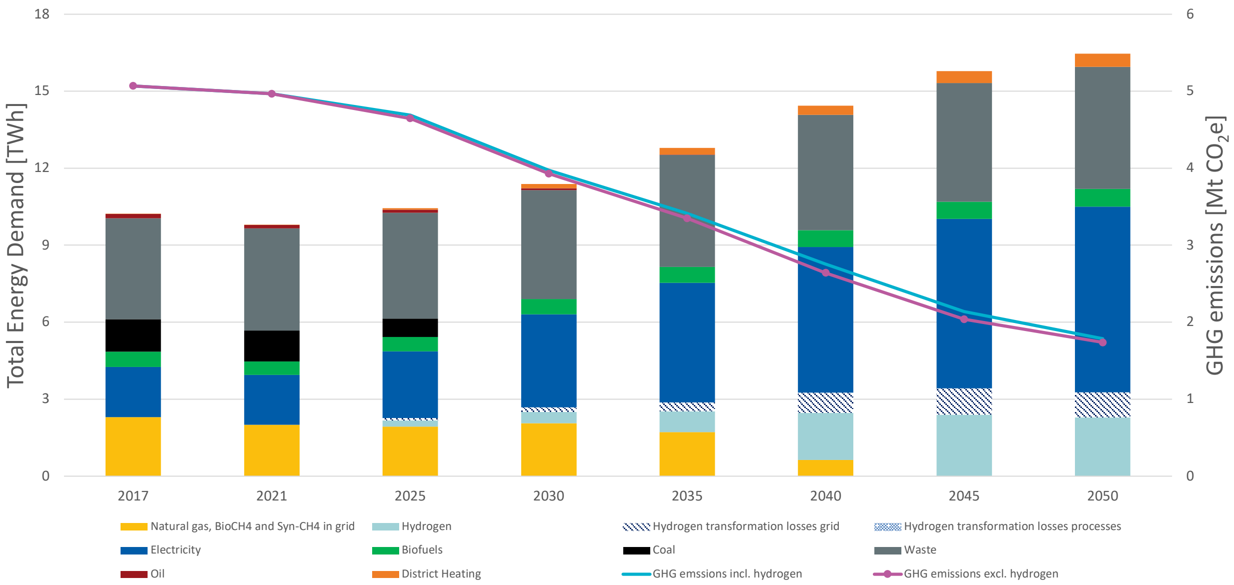

Figure 19: Total energy demand and GHG emissions by non-metallic minerals in the POI scenario.

Results non-metallic minerals – ZEM scenario

For the non-metallic minerals sector, the ZEM scenario sets itself apart not necessarily by more substantial GHG reductions (approx. -70%), but by its reduced energy demand. In comparison to POI, in 2050 total energy demand in ZEM amounts to just 70% of the base year level. This significant gap is attained through the deployment of oxyfuel technology for carbon capture instead of amine scrubbing. In comparison to the base year, total energy consumption rises by approximately 2 TWh (18%). This is primarily due to an increase in electricity demand by the carbon capture-associated processes (e.g., air separator).

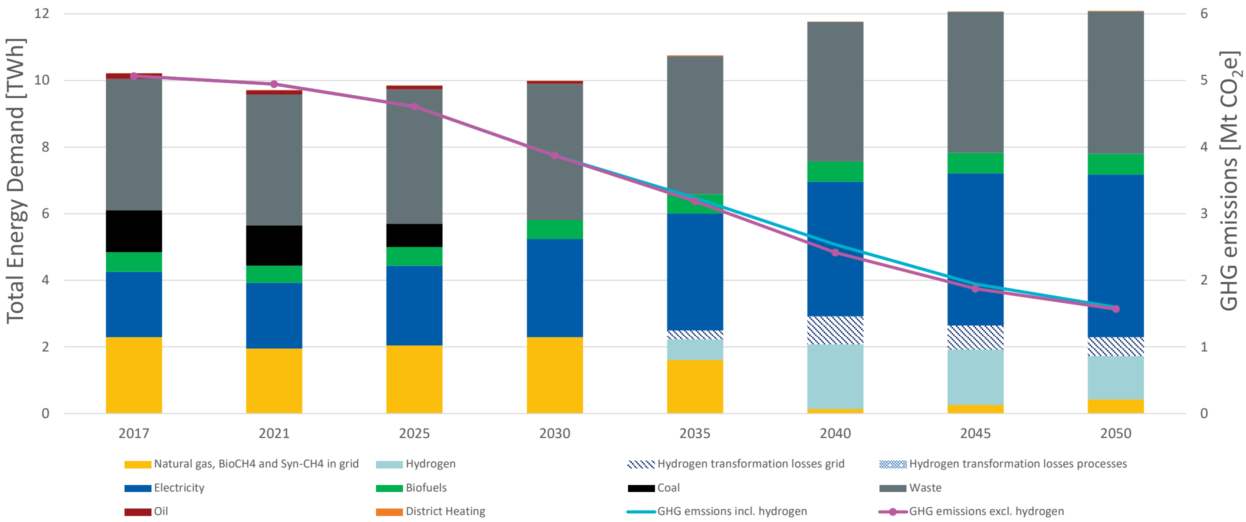

Figure 20: Total energy demand and GHG emissions by non-metallic minerals in the ZEM scenario.

Summary of results for non-metallic minerals

Currently, GHG emissions in the non-metallic minerals industry are mainly due to geogenic emissions from the raw materials used, e.g., $CaCO_3$. In order to mitigate these emissions, carbon sequestration technologies constitute an important lever of action. Under current boundary conditions, Austrian industry representatives are planning on using amine scrubbing technology as it is technologically ready for implementation (POI scenario). As evident from Figure 21, GHG emissions of just 1.8 Mt CO_2e by 2050 can be reached, although electricity demand rises significantly in order to supply sufficient heat via heat pumps. At the same time, the deployment of this end-of-pipe solution does not allow for a reduction of gas demand. However, the oxyfuel technology supplied in the ZEM scenario allows net reduction of gas demand in spite of economic growth in some subsectors. Due to lower electricity demand, total GHG emissions caused by the transformation efforts are also reduced. As hydrogen production through electrolysis and associated GHG intensity of electricity is included, Figure 21 points to a difference in GHG emissions between the POI and ZEM scenarios of approximately 200 kt CO_2e. In both scenarios, emissions in the range of 10-15% must remain because of technology-specific leakage rates.

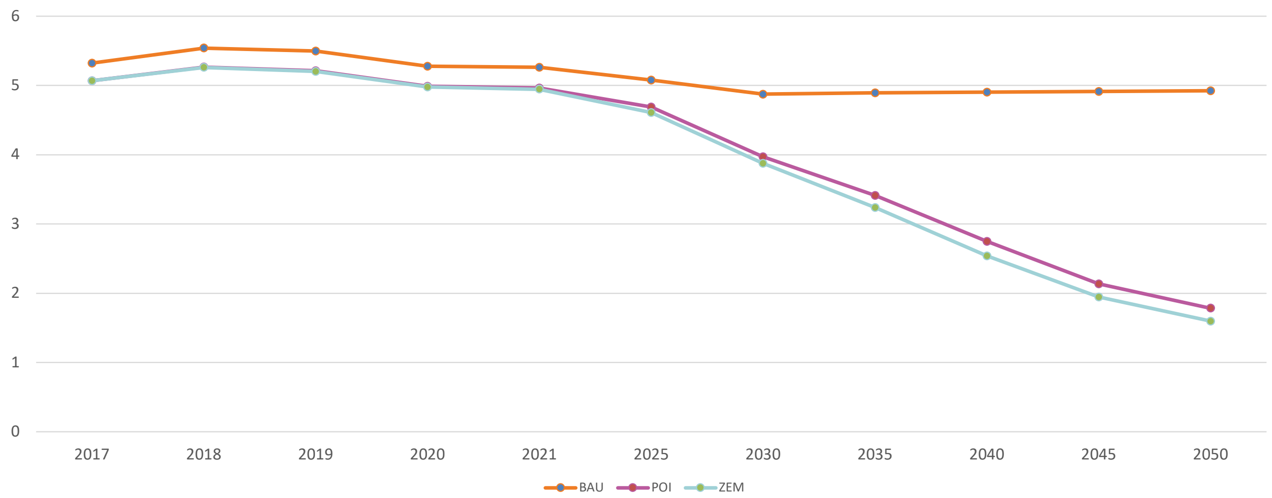

Figure 21: Comparison of GHG emissions in non-metallic minerals in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.3 Pulp and paper

As summarised in Appendix 1, Section 9.2, although large quantities of renewable energies are used, the energy intensity of the pulp and paper sector is an important reason to investigate the industry bottom-up. In agreement with industry representatives, the production capacity and structure of Austrian pulp and paper production has been maintained in the modelling. This includes pulping, the average yearly share of recycling paper, and the product qualities. An annual paper production growth rate of 0.2% was assumed.

Results pulp and paper – BAU scenario

In the BAU scenario, the already relatively high share of biofuels is maintained. Coal, oil and non-renewable industrial waste are replaced by the use of gas by 2025. Approximately 220 GWh of district heat is bought by companies in the pulp and paper sector as indicated in Figure 22. However, overall, the sector remains a significant supplier of district heat due to the unchanged employment of CHP plants. In 2018, the subsector provided approximately 1.2 TWh of district heat to networks all over Austria (see also 9).

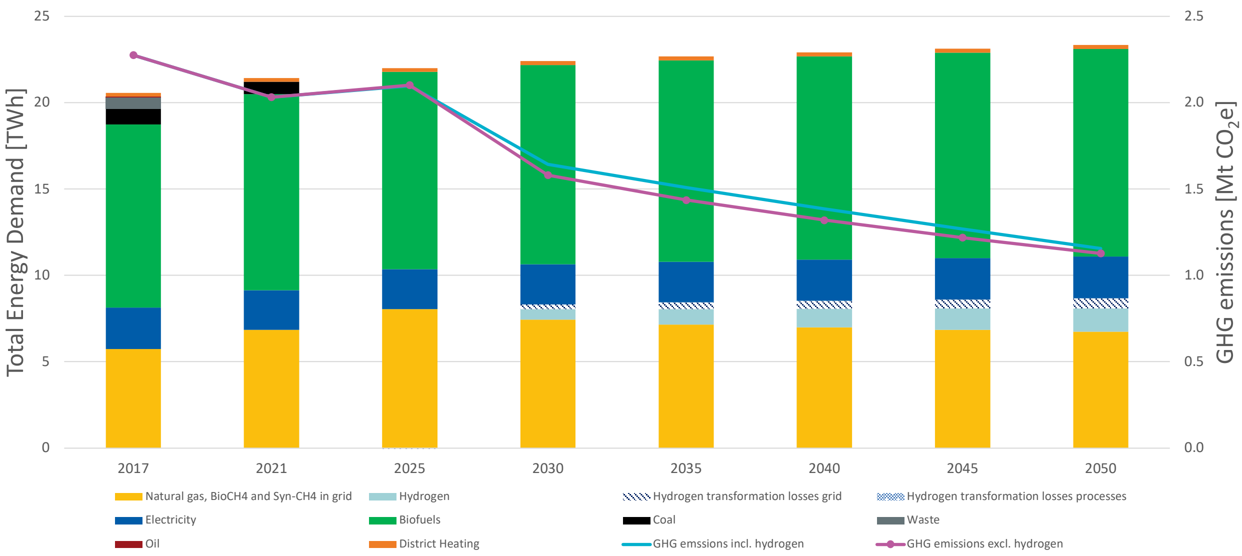

Figure 22: Total energy demand and GHG emissions by pulp and paper in the BAU scenario.

Results pulp and paper – POI scenario

In POI, the phase-out of fossil infrastructure for coal, oil and non-renewable waste from BAU is reproduced (Figure 23). Additionally, industry is seen to experience a gradual shift to increasing use of existing biomass routes for the production of process steam. By 2050, 50% of all gas boilers are switched to solid biomass (approx. 3.8 TWh). Furthermore, space heating and warm water are supplied exclusively by internal waste heat. This efficiency process is modelled to be completed by 2025 and amounts to energy savings of approximately 350 GWh/a.

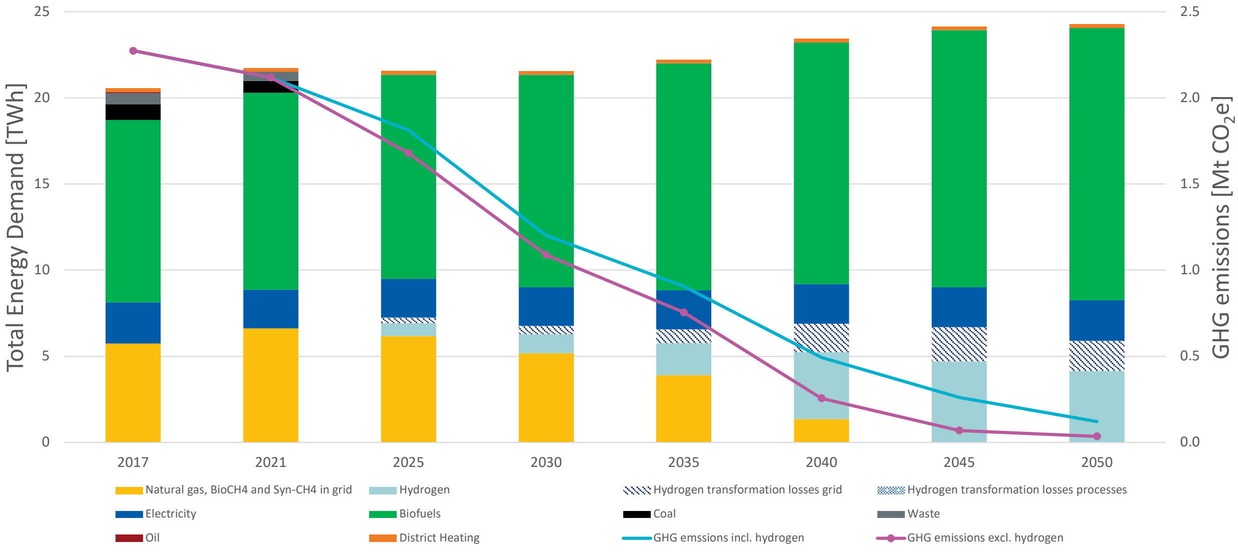

Figure 23: Total energy demand and GHG emissions by pulp and paper in the POI scenario.

Results pulp and paper – ZEM scenario

In the ZEM scenario, high-temperature heat pumps are used extensively to use the waste heat potential most effectively. BAU and POI measures are maintained where applicable. By 2050, approximately 2.7 TWh of electricity is used to provide a total of 5.6 TWh of process steam. While autogeneration capabilities are reduced, the overall energy balance of the subsector can also be reduced by approximately 1 TWh in 2050 compared to 2017. Small amounts of necessary high-temperature heat are provided through biofuels derived from inside the production process (black liquor and biogas).

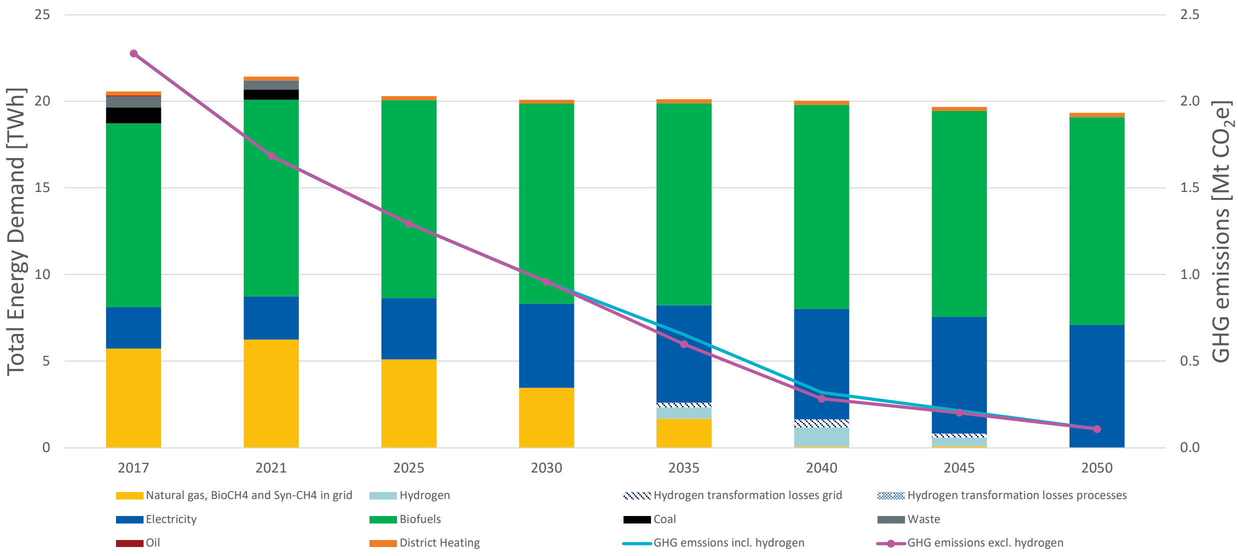

Figure 24: Total energy demand and GHG emissions by pulp and paper in ZEM scenario.

Summary of results for pulp and paper

The comparison of resulting GHG emissions in Figure 25 shows the strong impact of a substantial shift between scenarios POI and ZEM in the supply of process heat by electric high-temperature heat pumps. In scenario POI, emissions remain mainly due to the GHG intensity of electricity in H_2 production. Because 4.1 TWh of gas deployment remains in POI 2050, the provision of sufficient CO_2-neutral gases is still important in this scenario. If the gas is provided through electrolysis, the primary emissions from the electricity grid for hydrogen production remain. In that case, emission levels in scenarios POI and ZEM are almost identical, though reached by means of two different technological approaches. If GHG emission intensity of electrolysis is not considered in POI, emission levels in the POI scenario can undercut those of ZEM, due to widespread electrification in ZEM. The phase-out of coal and oil in the BAU scenario does not have any significant impact on GHG emission reduction. The observed reduction in GHG emissions of 1.1 Mt CO_2e by 2050 has its root mainly in the increasing supply of renewable gases from the gas grid.

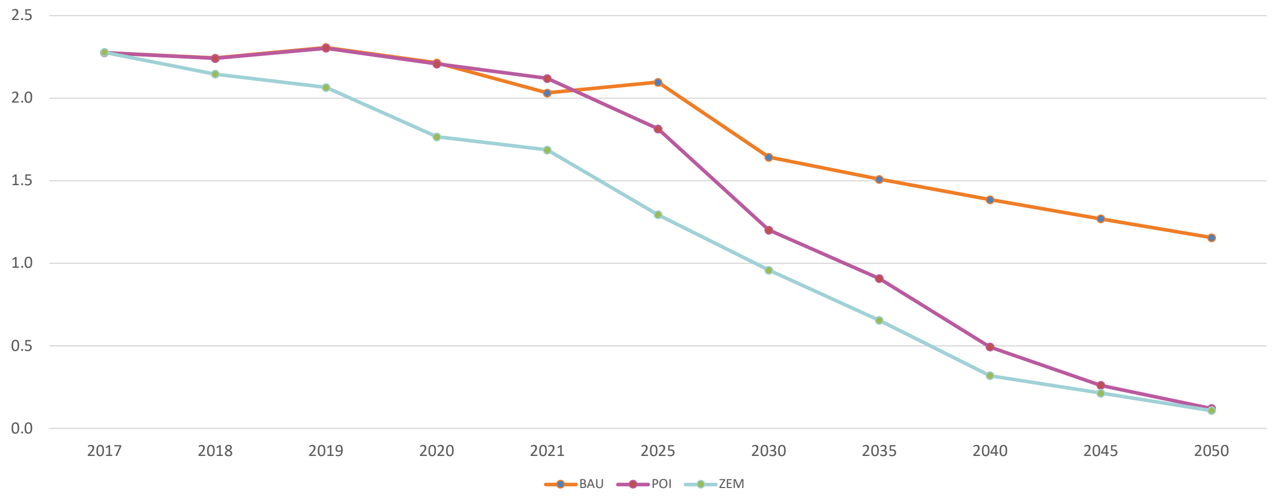

Figure 25: Comparison of GHG emissions in pulp and paper in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.4 Chemical and petrochemical industry

The chemical and petrochemical sector features several subsectors, in Austria primarily for the production of ammonia, urea, fertiliser, nitric acid, methanol and olefins, as noted in Section 9.5. The production output of the chemical industry from 2017 until 2050 was set to slightly increase, in line with the average production output of the chemicals from 2010 until 2017. In the POI and ZEM scenarios, a higher increase in methanol production was assumed than in the BAU scenario, because methanol represents a CO_2 sink and can be used for olefin production (see Section 9.5). As the production of urea and methanol in the low carbon route represents a CO_2 sink in the chemical and petrochemical industry, no subsequent use or storage of sequestrated CO_2 (CCU or CCS) was modelled.

Results chemical and petrochemical – BAU scenario

In the BAU scenario, the total energy demand of the chemical industries increases from 29.9 TWh by 2017 to 34.1 TWh by 2050 (Figure 26). In this scenario the fossil resources and the gas mix of natural gas, bio-CH_4 and synthetic-CH_4 makes up the highest share of fuels in the energy demand from 2017-2050. The reason for the high share of fossil resources in the chemical and petrochemical industry is the extensive use of naphtha in the olefin production process. Coal and oil are completely replaced by gas by 2030. In this scenario, electrical energy has the highest average increase of all fuels, at around 4.7% per year to 2050.

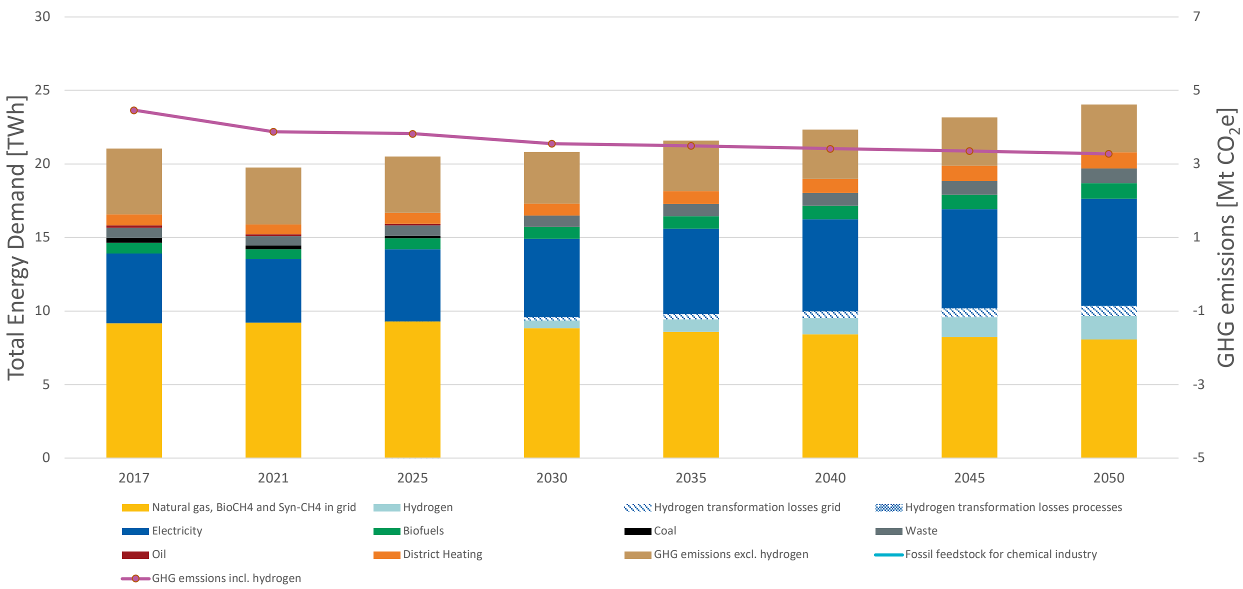

Figure 26: Total energy demand and GHG emissions by chemical and petrochemical industry in the BAU scenario.

Results chemical and petrochemical – POI scenario

In the POI scenario, the chemical industry is identified by the fuel switch from fossil resources and fossil fuels to hydrogen, biofuel including solid biomass, and electricity, with a small amount of the gas mix of natural gas, bio-CH_4 and synthetic-CH_4 (see Figure 27). On this occasion, the emission reduction technology options (see Table 19) from Section 9.5 are used. Because of the challenging transformation of all processes (e.g., production of ammonia, methanol and olefins) in the chemical industries to a low carbon route, a small amount of chemicals (production rate between 10-20%) will be produced in the POI scenario by the status quo production process. This means that the gas mix of natural gas, bio-CH_4 and synthetic CH_4 from carbon-neutral sources (Syn-CH_4) will cover 10% of the total energy demand by 2050, and that fossil resources (e.g., naphtha) will play a minor role at about 1 TWh (2% of the total energy demand) by 2050. The phase-out of fossil infrastructure for coal, oil and non-renewable waste by 2030 is also part of the POI scenario. Figure 27 also shows that biofuel substitutes a high amount of natural gas, especially in methanol and olefin production. Moreover, hydrogen will be one of the key fuels for decarbonising chemical processes in 2050, especially for ammonia, methanol and olefin production. Because of the low carbon MTO (methanol to olefin) process, the methanol production rate increases sharply in line with the olefin production rate. The MTO process has a higher energy intensity as the status quo production process, but also represents a high CO_2 sink. However, this sink is present only within the balance border of the industry sector, as the carbon absorbed here is emitted in thermal recycling in the energy sector (outside this report's balance border). Therefore, the sector emissions are presented in three lines in the graph in Figure 27 where in the lower lines (purple and blue) this sink is included, but not in the upper line. The difference of 4 Mt of emissions corresponds roughly to the sector's current emissions, or to the non-metallic minerals sector emissions (including cement production) where CCU is the main abatement technology. Transportation of the captured emissions from cement kilns to chemical plants represents one possible solution for both sectors. It should be noted however, that methanol production from biomass is much more efficient than sequestration of carbon dioxide, hydrogen production and methanol production of these two synthetic feedstocks. Furthermore, the increase of electrical energy in the POI scenario is explained by the use of electrical compressors in nitric acid production by 2030, and the use of electrical heating systems in urea synthesis by 2025, among others. The total energy demand of the chemical industries in the POI scenario increases from 29.9 TWh in 2017 to 53.1 TWh by 2050, due to losses in the synthetic production of feedstocks (naphtha is replaced by methanol, partly from biofuels and captured CO_2 with hydrogen).

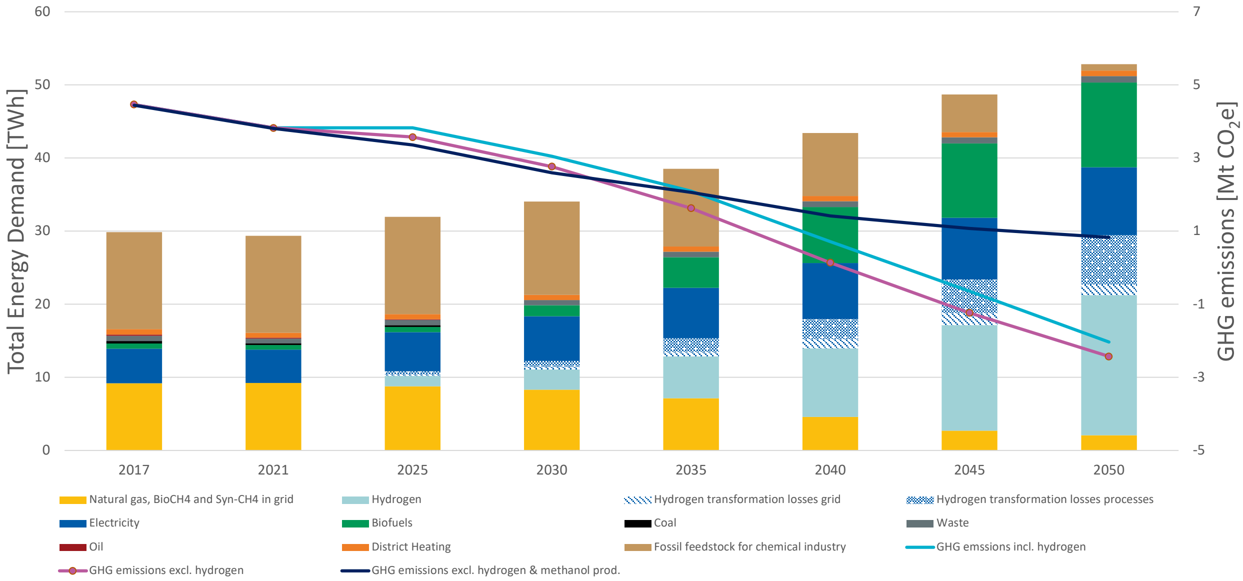

Figure 27: Total energy demand and GHG emissions by chemical and petrochemical industry in the POI scenario.

Results chemical and petrochemical – ZEM scenario

Even though the decarbonisation of the chemical and petrochemical sector was reached in the POI scenario and the industry has negative GHG emissions (see Figure 27), the aim of the ZEM scenario was the complete transformation of all processes in the chemical industries to a low carbon route and the total phase-out of all fossil fuels and fossil resources (e.g., naphtha). Figure 28 shows that 4% (2.6 TWh) of the total energy demand in 2050 is covered by the gas mix of natural gas, bio-CH_4 and syn-CH_4. In the ZEM scenario, natural gas in the gas mix will be substituted by hydrogen and bio-CH_4 by 2050. However, less hydrogen is needed as more methanol is produced from biomass, allowing for a higher overall efficiency (see Figure 27).

As described in the POI scenario, the key fuels in the ZEM scenario are also hydrogen, biofuel and electrical energy. In 2050, the olefins will be completely produced by the low carbon MTO process and the status quo process with the use of fossil resources in case of naphtha will end by 2050 (see Figure 28). In 2050, methanol will be completely produced by biomass and hydrogen and captured CO_2, with biomass having a higher share (as its efficiency is higher), and ammonia will be completely synthesised by hydrogen, produced by water electrolysis. Nitric acid, urea and fertiliser synthesis will also be transformed to a low carbon route by 2050 due to increased electrification. The total electricity demand will increase from 4.7 TWh in 2017 to 8.4 TWh by 2050. If hydrogen production is included, the electricity demand will increase to 42 TWh by 2050 and will cover 66% of the total energy demand in the chemical and petrochemical industry. The total energy demand of the chemical industries in the ZEM scenario increases from 29.9 TWh in 2017 to 63.7 TWh by 2050.

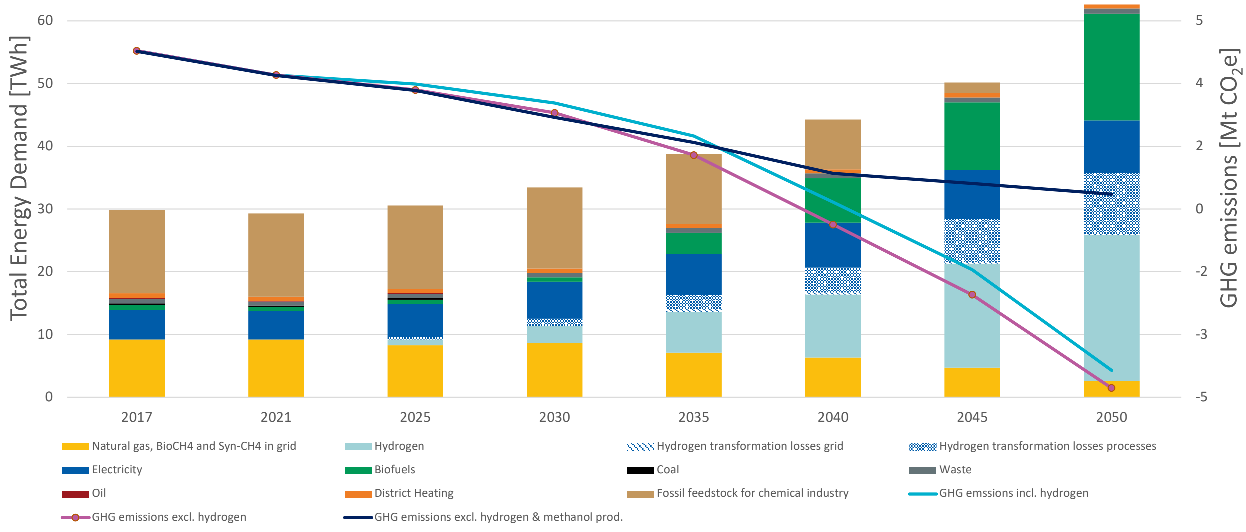

Figure 28: Total energy demand and GHG emissions by chemical and petrochemical industry in the ZEM scenario.

Summary of chemical and petrochemical industry

The comparison of resulting GHG emissions in Figure 29 clearly shows the significant impact of switching processes in the chemical and petrochemical industry. The POI and ZEM scenarios illustrate that the chemical and petrochemical sector can have negative GHG emissions by 2050 resulting from increased use of captured carbon from other sectors (mostly cement production). The difference of about 2.1 Mt CO_2e between the GHG emissions in the POI and the ZEM scenarios is caused by the complete change of the processes to a low carbon route and the non-use of fossil fuels, even in the gas mix, and fossil resources (e.g., naphtha) in the ZEM scenario. Moreover, Figure 26 shows that the production of methanol from biomass (mostly wood in this case) uses less energy (10 TWh in total) than the route via hydrogen and captured carbon monoxide.

The fact that by 2050 the chemical and petrochemical industry in the POI and ZEM scenarios has negative GHG emissions shows that this sector can play an important role in decarbonising the industrial sector. However, the balance border should be noted here: at a national level the negative emissions are not a sink but neutral, as at the end of their life cycle, plastics are mostly incinerated.

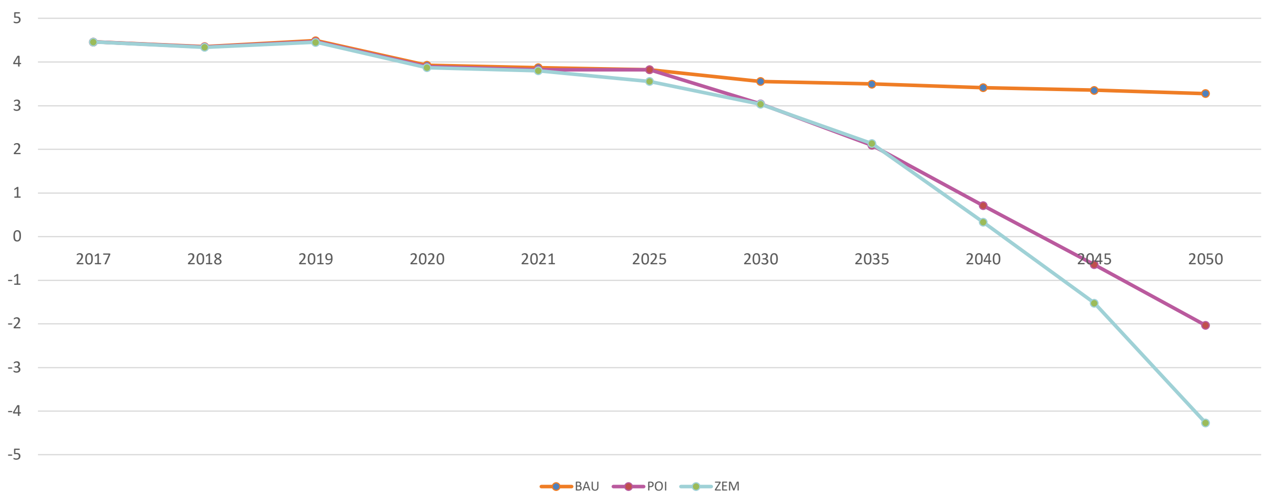

Figure 29: Comparison of GHG emissions in the chemical and petrochemical industry in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.5 Machinery

The machinery sector consists of a large number of small and medium sized firms and production sites. At an annual growth rate of 1.6%, the sector is projected to expand more than others. At the same time, efficiency gains of -0.25% p.a. for motive power, and -0.5% for thermal uses are in the same range as in other sectors. Hence the overall energy demand rises in all scenarios. As a non-energy intensive sector, space heating together with low temperature steam (up to 150°C) represents the major energy demand together with motive power. The low temperature heat demand including steam up to 150°C is modelled to be supplied by heat pumps with low diffusion rate in BAU starting in 2040, and an accelerated roll out in POI and ZEM serving nearly all technical possible demand in 2045. This trend is the main driver of the strong rise in electricity demand apart from general growth. In the motive power sector, only minor efficiency improvements are expected due to the already high efficiency of electric motors and relatively small threshold between the average appliance in the field and the state-of-the-art of under 10%.

Results machinery – BAU scenario

The main driver of carbon emissions reduction is the supply of less carbon-intense electricity, both from the grid and local generation, the latter included in the balance and representing a substantial potential due to the relatively low average energy intensity per site acreage. Apart from heat pumps for space heating, hydrogen is projected to be used in high-temperature applications from 2035 onwards, and supplied via the gas grid. Still, due to declining grid emission factors, GHG emissions are projected to decline by over 50% compared to 2017 (see Figure 30).

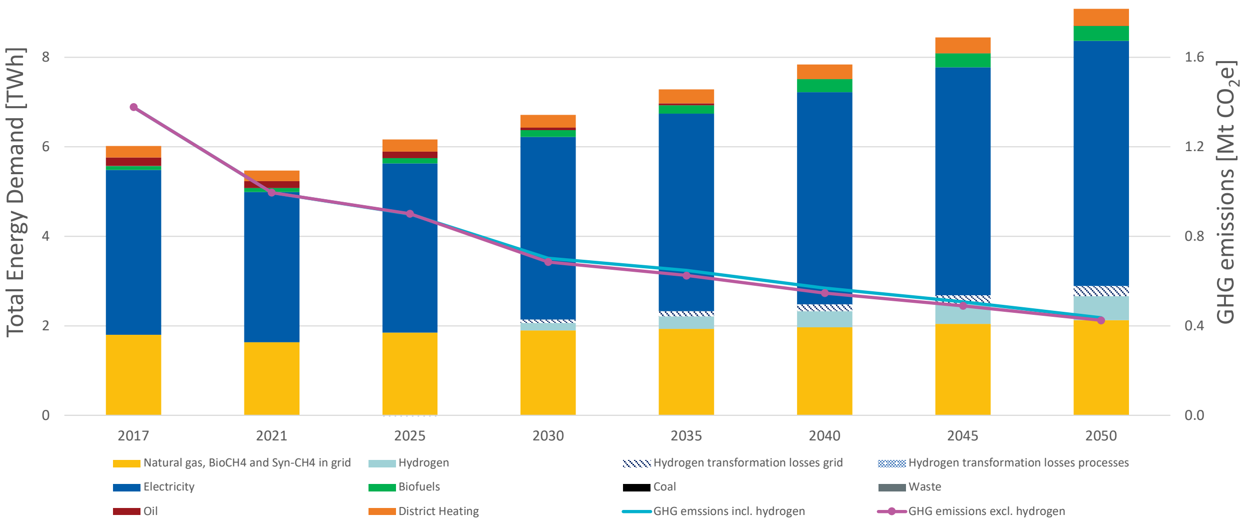

Figure 30: Total energy demand and GHG emissions by machinery in the BAU scenario.

Results machinery – POI scenario

According to the industry interviews, intense electrification is expected, mostly driven by heat pump rollout and a switch to hydrogen for heat uses. Direct electrification plays only a minor role in niches. The current emissions are projected to be almost fully abated by 2050, the main driver being the declining emissions from the electric grid, as shown in Figure 31.

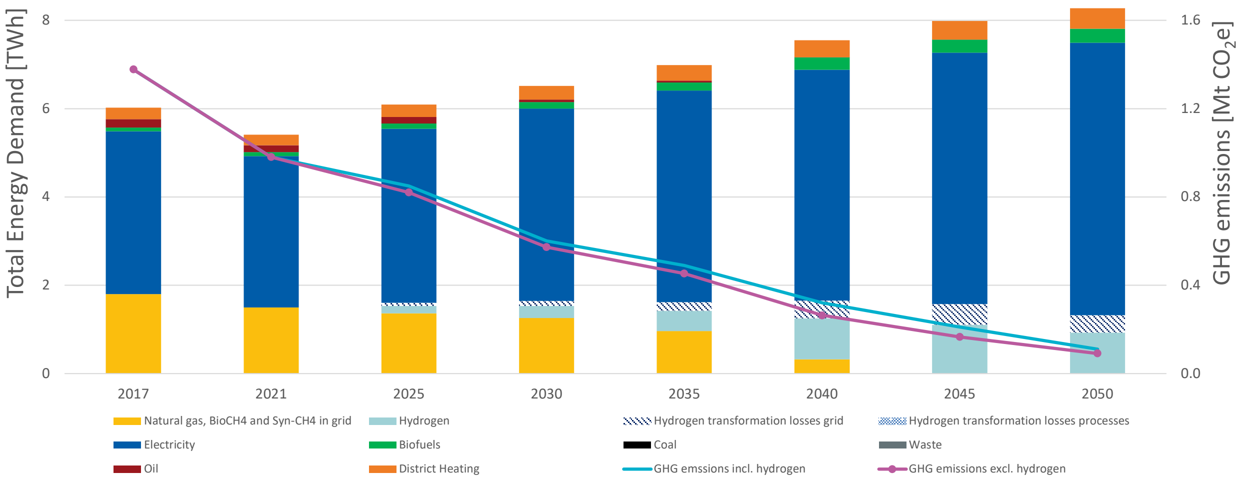

Figure 31: Total energy demand and GHG emissions by machinery in the POI scenario.

Results machinery – ZEM scenario

As the machinery industry is already on its way to being almost emission free by 2050, on the path stated in the interviews, the significant difference here is that at the higher end of the low temperature level more heat pumps are used earlier and instead of hydrogen. This entails the widespread use of high temperature heat pumps (up to 150°C) as early as 2035, reducing GHG emissions earlier (see Figure 32).

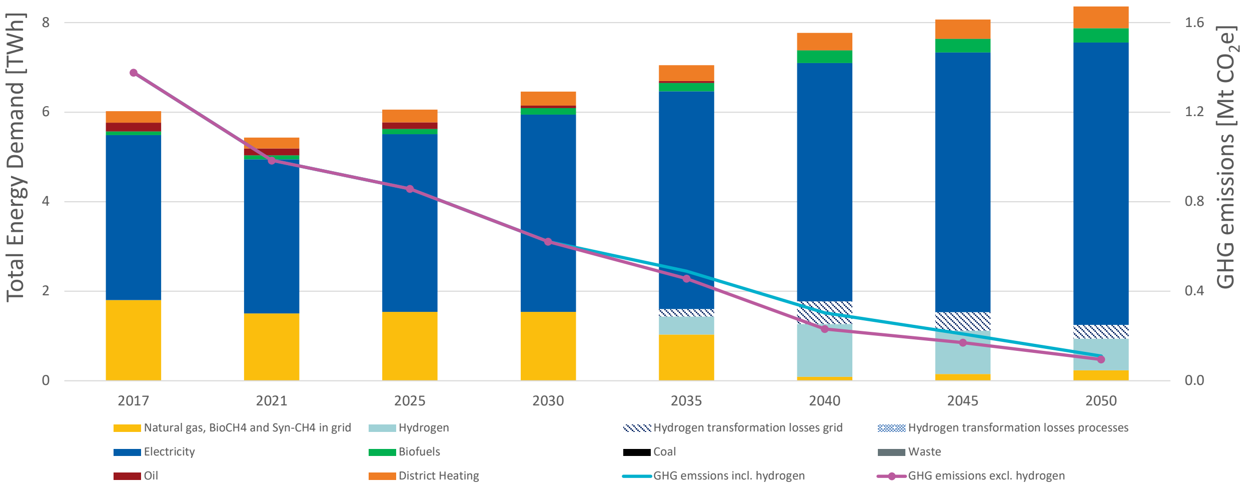

Figure 32: Total energy demand and GHG emissions by machinery in the ZEM scenario.

Summary of machinery

From the pathway stated in the interviews, the machinery sector is on course for widespread decarbonisation, already in the POI scenario. This is driven mainly by the electricity grid (more renewables), and substitution of gas with heat pumps and hydrogen as a heat source. The remaining emissions in 2050 originate from the electricity grid factor. The difference in the three paths depicted in Figure 33 originates from heat pumps substituting heat demands and different gas grid emission factors. Implementing heat recovery and heat pumps in space heating and heat demanding processes represents the single largest contribution and challenge to decarbonising this sector.

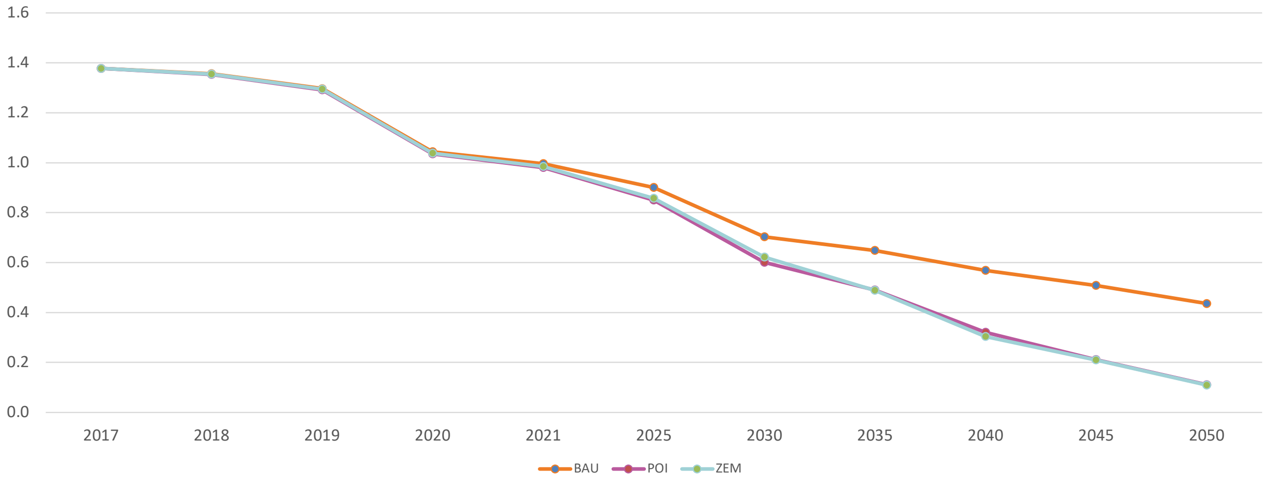

Figure 33: Comparison of GHG emissions in the machinery sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.6 Non-ferrous metals

This sector's projected value added growth of 1.3% per year is lower than that of other sectors due to assumed competition from regions abroad. Apart from space heating, the major energy consumers are tempering and melting furnaces. These offer the potential for electrification, however, in most cases the temperature levels do not allow for the high efficiency gains provided by heat pumps. Still, direct electrification does provide efficiency gains in the range of 12% to 18% on average, mainly due to reductions in exhaust losses. This process heat demand does provide for potential heat recovery, albeit only a fraction can be harnessed as most intermediate products are air cooled.

Results non-ferrous metals – BAU scenario

To contextualise the rise in energy demand in this sector (and most others), the assumptions made in Section 3 should be noted: annual value-added growth of 1.3% in this sector corresponds to 9.7% over a five-year period. Countering this growth is a 2.1% reduction of energy intensity and a 1.2% energy efficiency increase per five-year period. Including fuel switching effects and hydrogen generation losses (broken bars), the resulting energy demand increases on average by 8.3% per five-year period from 2020 onwards. The initial emission abatement from grid emission factor reduction is countered by the sector's growth and therefore flattening from 2030 onwards, as shown in Figure 34.

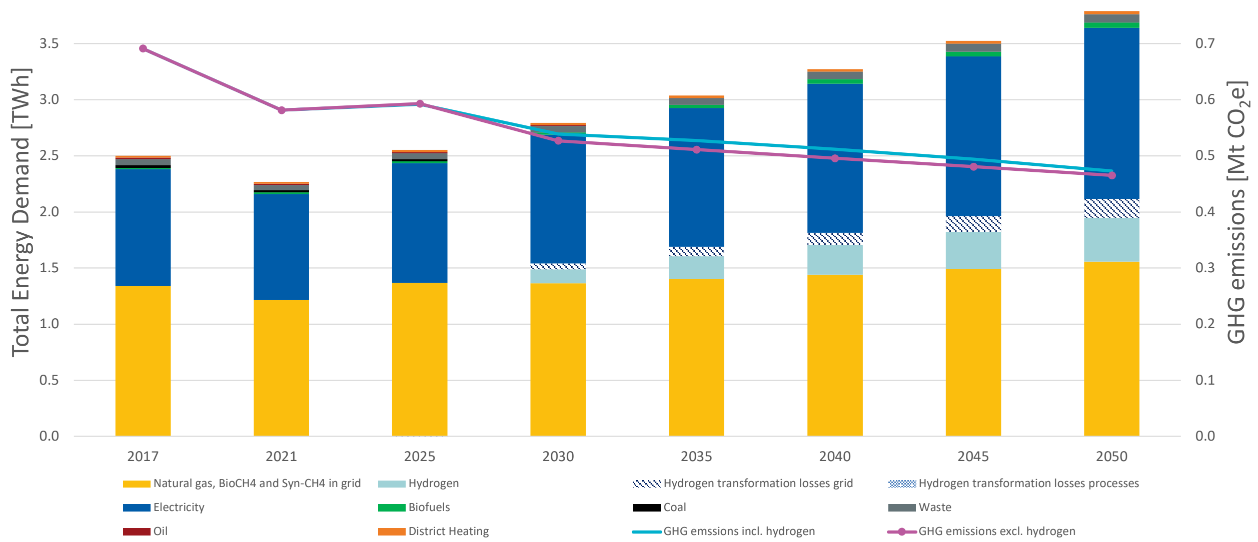

Figure 34: Total energy demand and GHG emissions by non-ferrous metals in the BAU scenario.

Results non-ferrous metals – POI scenario

Interviews with industry representatives led to the modelling of substantial electrification, both in the domain of space heating with heat pumps and furnaces, its share rising from 12% to 50% in the high and low temperature level. However, the most significant effect on carbon emissions comes from the projected gas and electricity grid emission factor decrease. Industry representatives do not expect direct hydrogen use on a widespread basis in the near future, and therefore this is modelled to play a role only from 2040 onwards, rising from 5% to 10% of heat supply. See Figure 35 for the respective fuel shares. Most importantly, the sector can nearly fully abate its emissions by 2050 through its expected pathway of technology rollout and fuel composition in the grid.

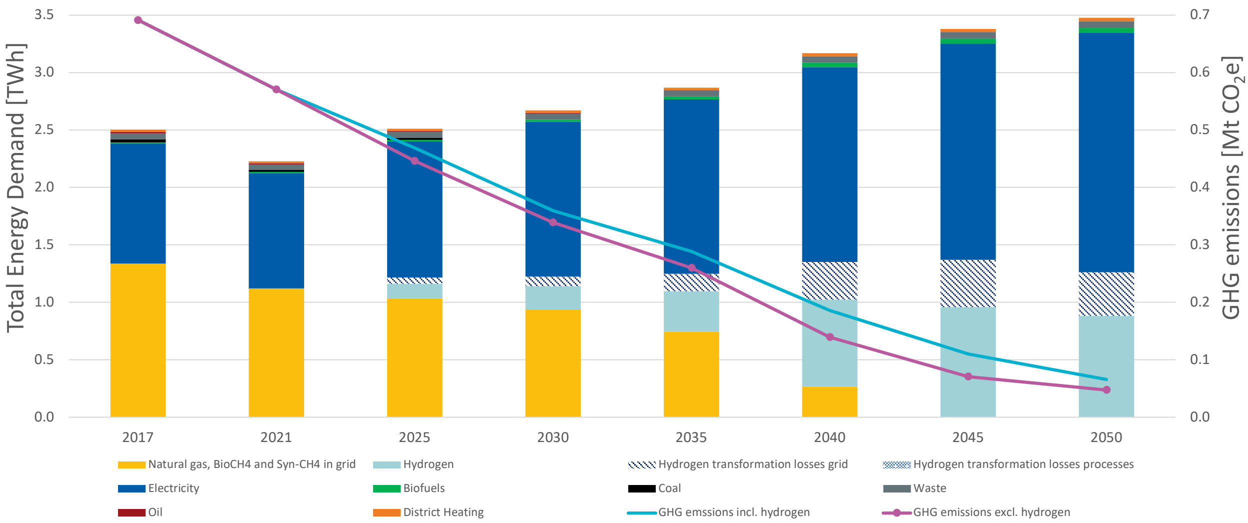

Figure 35: Total energy demand and GHG emissions by non-ferrous metals in the POI scenario.

Results non-ferrous metals – ZEM scenario

In comparison to POI, electrification efforts are projected to be intensified, resulting in less gas demand. This takes full effect only after 2040, hence the peak in that year. Since the methane share falls from 2040 onwards, hydrogen demand also sinks and with it the conversion losses (shaded bars), resulting in an overall decrease in energy demand. The remaining gas demand in the years 2040 to 2050 in Figure 36 originates from a higher share of biogas and a larger reliance on the grid in ZEM compared to the POI scenario.

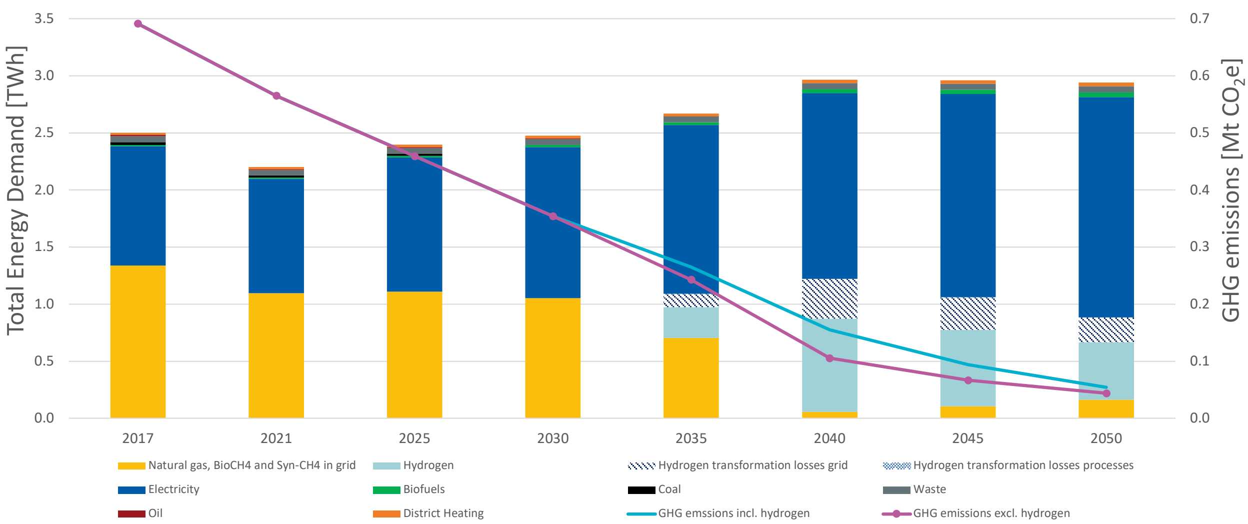

Figure 36: Total energy demand and GHG emissions by non-ferrous metals in the ZEM scenario.

Summary of non-ferrous metals

Electrification plays the major role in this sector's projected decarbonisation pathway. More than in other sectors, energy efficiency gains (-0.3% p.a.) together with the reduction in general energy intensity (-0.4% p.a.) compensates for the rise in value added (+1.3% p.a.). Hence, total energy demand rises less here. The major technological potential for abatement is heat pumps, both on low temperature levels (up to 150°C) for space heating and direct electrification for tempering and smelting furnaces. Additionally, hydrogen replaces methane in these processes in high-temperature applications from 2035 onwards, rising from 6% to 18%. In total, the largest effect originates from decreasing electricity grid emission factors. The rising emissions from 2030 onwards in BAU originate from output growth together with the high-temperature heat demands, served by natural gas. In POI and ZEM, these grid emissions decline and are the major driver of GHG emission abatement. The divergence of the two curves in Figure 37 reflects the increased diffusion of high-temperature hydrogen applications in the years between 2035 and 2040. Most notable here is that in ZEM, sunk costs arise from this quicker rollout from switching technologies twice, first from methane to hydrogen technologies in 2025 to 2035, and in the years following to direct electrification. The switch to electric furnaces and electrifying tempering processes is the largest contributor to decarbonising this sector.

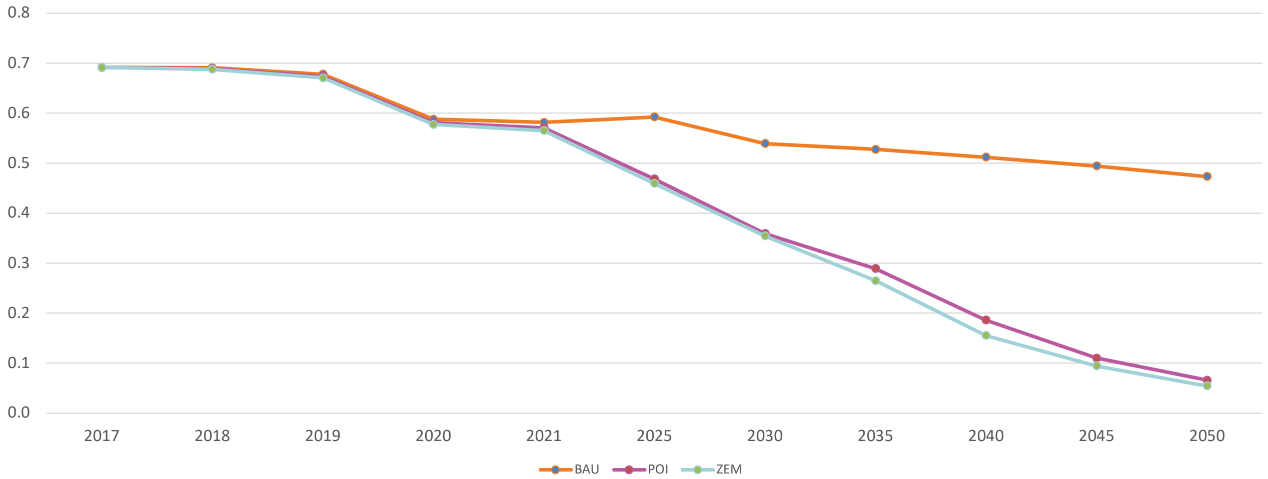

Figure 37: Comparison of GHG emissions in the non-ferrous metal sector in BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.7 Transport equipment

This sector is projected to grow by 1.6% per year on average until 2050. Decreasing energy intensities of -0.36 % p.a. and rising energy efficiency of + 0.26% p.a. lower the total energy demand growth to 1% per year. The sector features a relatively high district heating share covering 11% of total demand. This heat source is projected to increase further by approximately half across all three scenarios (47% in BAU). Space heating and low temperature heat demand comprise 87% of total heat demand in this sector, so that heat pumps represent the major emission abatement technology together with the decreasing grid emission factors (see Section 3.3).

Results transport equipment – BAU scenario

From the growth rates and efficiency gains noted above for this sector, after an initial decline, in BAU emissions stagnate at one third of the 2017 level. This scenario depicts the projection for an industry experiencing mainly exogenous changes in the energy domain: rising value creation increases energy demand but electricity grid emission factors scale back quicker in the beginning, resulting in flat lining emissions from the year 2030 onwards, as shown in Figure 38.

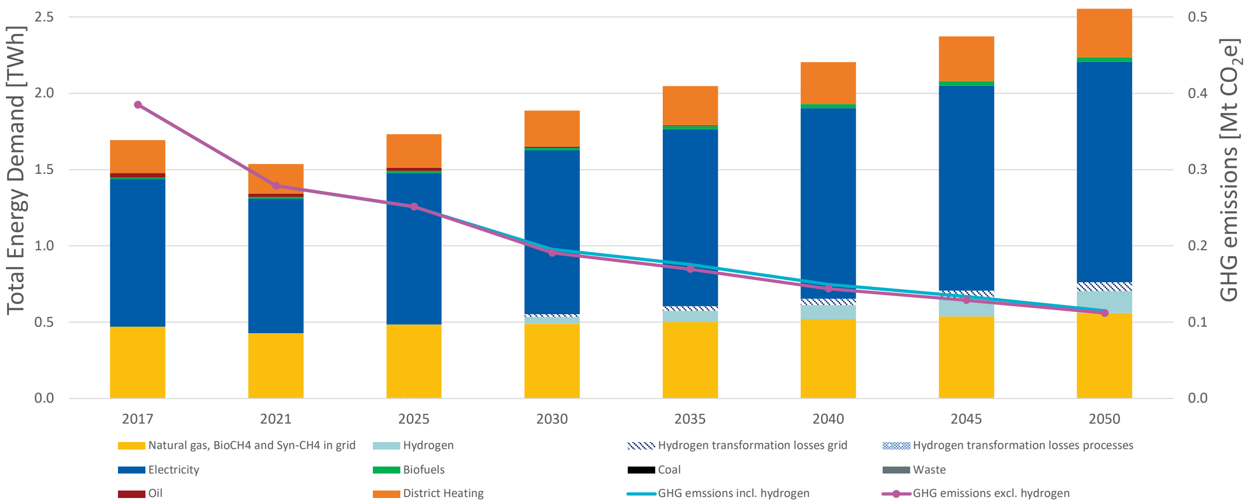

Figure 38: Total energy demand and GHG emissions by transport equipment in the BAU scenario.

Results transport equipment – POI scenario

Strong electrification, especially heat pumps for low temperatures and space heating, reduces the projected total energy demand compared to BAU. District heating demand expands by just one third. Starting as early as 2025, heat demands above 200°C are supplied by hydrogen. From 2035 on, most of the depicted hydrogen demand is supplied via the gas grid mix. The overall decarbonisation effect is mainly driven by the following factors: electrification and lower grid emissions. The remaining emissions result from the electric grid emission factor (see Section 3.3).

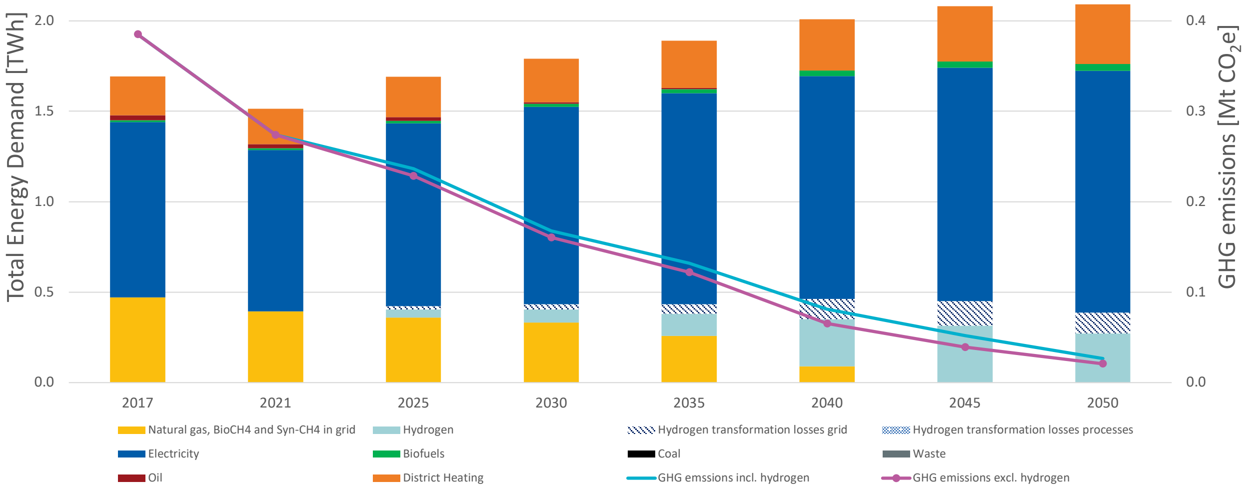

Figure 39: Total energy demand and GHG emissions by transport equipment in the POI scenario.

Results transport equipment – ZEM scenario

A higher heat pump utilisation rate than in POI, especially in the temperature range above 100°C, increases efficiency and reduces gas demand. This change is projected to start rather late, from 2035 onwards, and continues until 2050 with an accelerated diffusion rate. The result is the fall in energy demand, especially in gas demand from 2045 onwards, as depicted in Figure 40. With the electricity grid emission factor nearly reaching zero (see Section 3.3), emissions are abated in this sector as early as 2040.

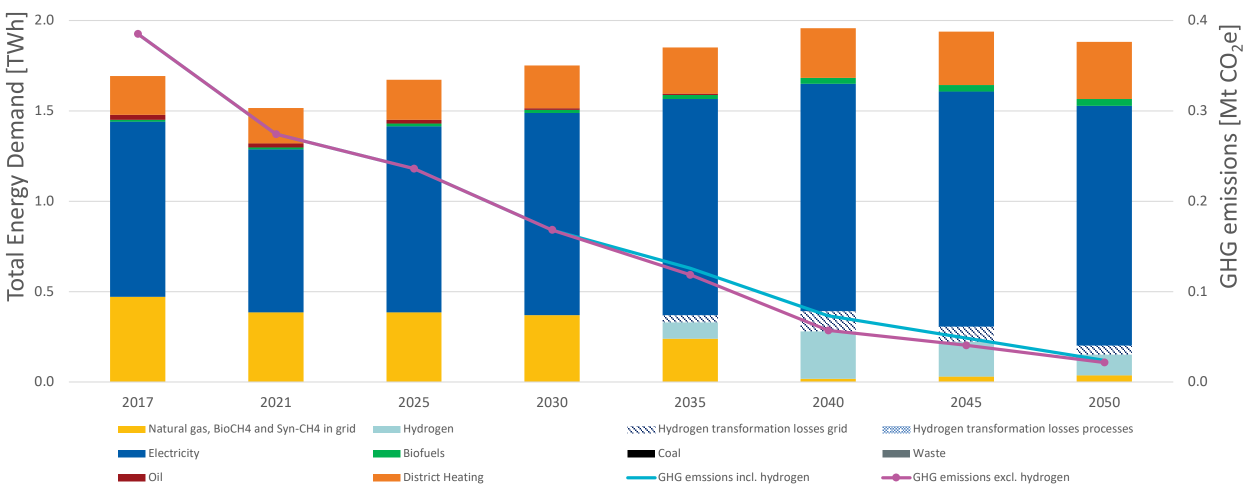

Figure 40: Total energy demand and GHG emissions by transport equipment in the ZEM scenario.

Summary of transport equipment

The already high proportion of electricity use, together with temperature demand at low levels (mostly below 150°C), electrification is the main driver of carbon emission abatement.

By using heat pumps, the efficiency gains can counter the sector's growth. This technology contributes one third of the overall energy demand reduction by 2050. The diverging emission pathways in the three scenarios are derived for this same trend in different technology uptake rates. Integrating heat pumps into space heating and thermal processes poses the largest challenge in decarbonising this sector.

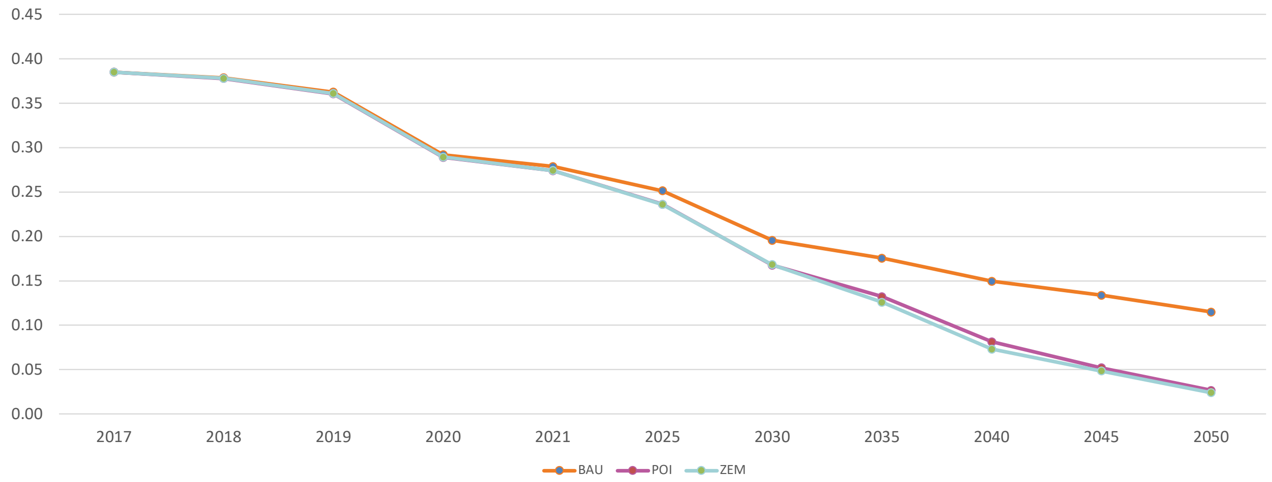

Figure 41: Comparison of GHG emissions in the transport equipment sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.8 Food and beverages, tobacco

This sector is projected to grow by 1.6% p.a. on average to 2050. Decreasing energy intensities (-0.42% p.a.) and rising energy efficiency (0.28% p.a.) lower the total energy growth to 0.9 % per year. The sector's high thermal energy demand presents a particular challenge as production is split into batch processes and covers a wide field of different technologies. Additionally, hygienic standards demand short cleaning periods.

Results food and beverages, tobacco – BAU scenario

Sector growth of 1.6% p.a. together with efficiency increases of 0.28% annually and -0.42% p.a. energy intensity reduction constitute a compound growth of value added of 0.9% p.a. The sectors' relatively high thermal energy demand in the mid-temperature level represents a challenge to decarbonisation, as many integrated appliances are currently steam powered. In BAU this technological state is not altered, and heat is mainly provided by gas from the grid, as can be seen in Figure 42. Therefore, GHG emissions decrease slowly due to grid emission factor reduction. Energy growth rises because of conversion losses in hydrogen production.

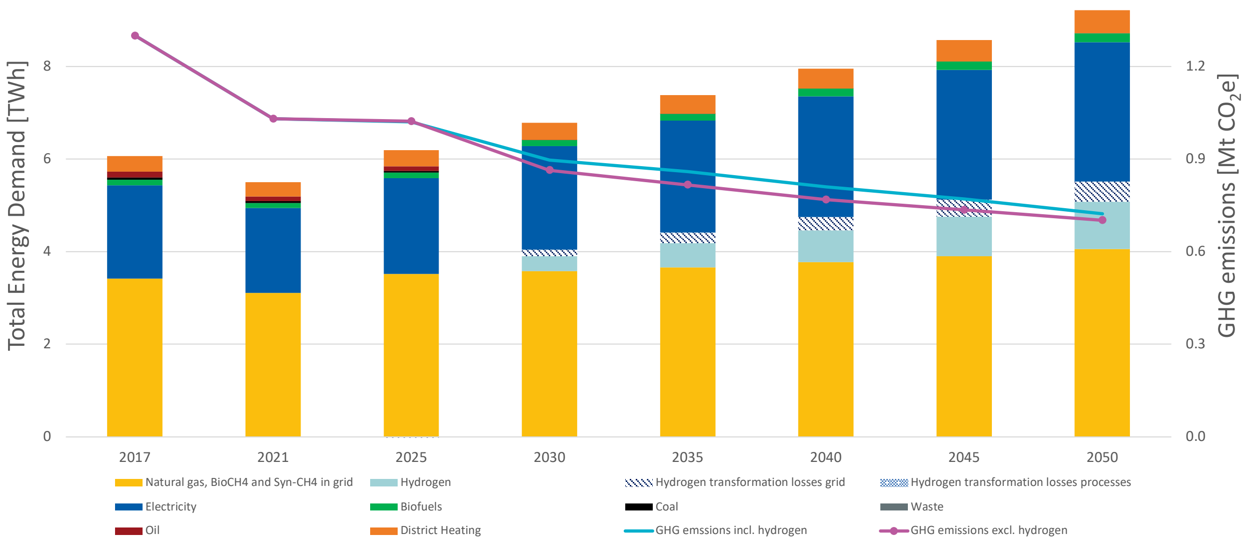

Figure 42: Total energy demand and GHG emissions by food and beverages in the BAU scenario.

Results food and beverages, tobacco – POI scenario

Interviewed industry representatives stated that, from 2035 onwards, around a quarter of the thermal demand can be substituted by heat pumps or direct electrification. The remaining heat demand is modelled to be supplied by the gas grid where the share of hydrogen significantly rises from 2040 (see Figure 43). As more and more hydrogen is supplied as via the gas grid, conversion losses in hydrogen generation represent half the total energy demand growth. Grid emission factors are the largest contributor to emission abatement. However, the increasing share of hydrogen in the gas grid necessitates infrastructure changes in the companies, mainly in burners but also in appliances.

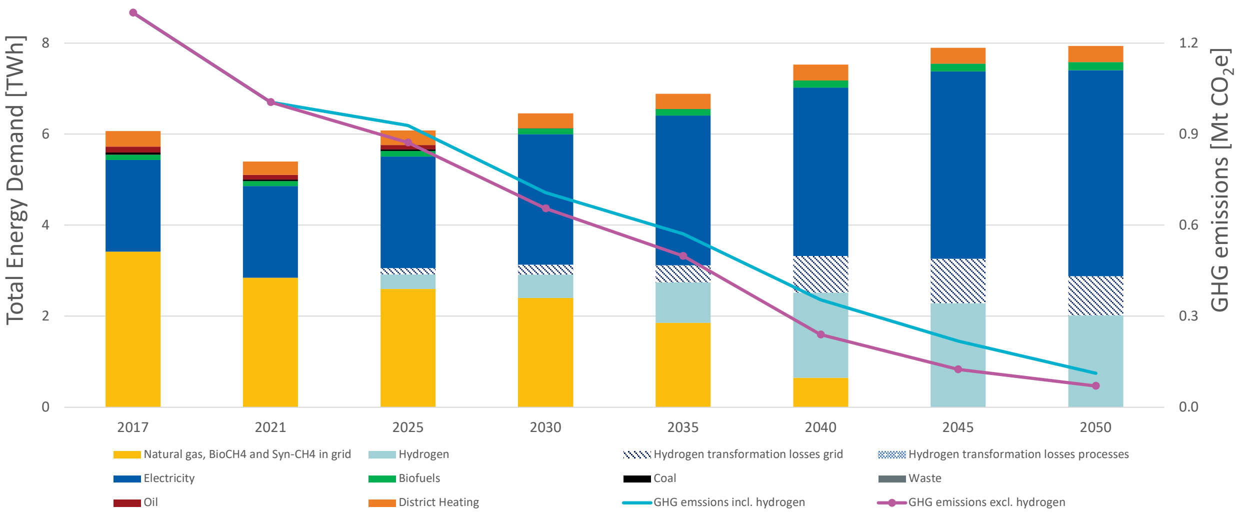

Figure 43: Total energy demand and GHG emissions by food and beverages in the POI scenario.

Results food and beverages, tobacco – ZEM scenario

Abating emissions further than the already low level projected in POI can be achieved by substituting gas with biomass for medium temperature level applications, and further efficiency gains from heat recovery in the processes (heat pumps). Biomass is in high demand in several sectors and competition for it is to be expected. However, unused products or withdrawals represent a source of biomass that can produce biogas as a substitute for methane. Local use cuts out the otherwise necessary gas cleaning and can represent a competitive advantage. Alternatively, biogas can be purchased externally. The higher reduction in thermal demand in ZEM compared to POI is driven by direct electrification and the increased and earlier implementation of high-temperature heat pumps reducing hydrogen demand from 2040 onwards (Figure 44).

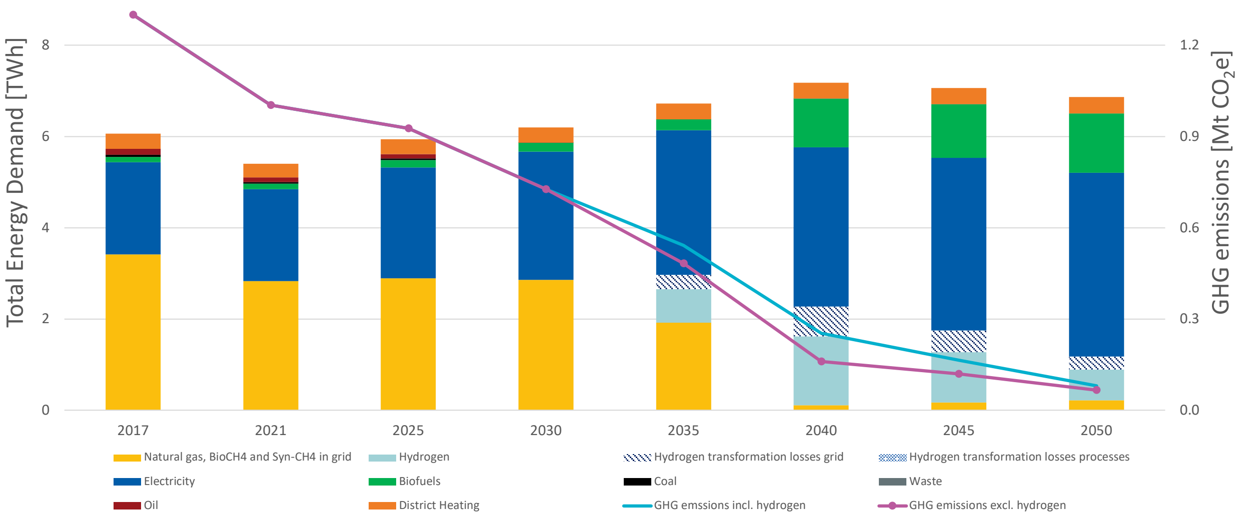

Figure 44: Total energy demand and GHG emissions by food and beverages in the ZEM scenario.

Summary of food and beverages, tobacco

The relatively high thermal energy demand at medium temperature level can only be partly substituted by high efficiency means. If not electrified directly, the sector is reliant on the gas grid or biogas production. This factor represents the main difference in the paths of POI and ZEM (Figure 45): in POI, most heat demand is covered by hydrogen, increasing total energy demand to 2050 by twice the sector's growth rate; in ZEM, this heat demand is projected to be provided via biogas, partly generated on site. This gain in autonomy can reduce the sector's energy demand from 2040 onwards. The model presents compound energy demands, the graph should not be interpreted as the sector sinking investments by switching technologies twice. Direct electrification provides for large efficiency gains as local conversion and transmission losses are reduced. A substantial emissions reduction by over half the 2017 value is possible by 2035 using available technologies (heat recovery and heat pumps) and relatively low hydrogen use. The implementation of this represents the main challenge for the sector. Further abatement will necessitate infrastructure extension such as bioreactors or local energy cooperations for biogas.

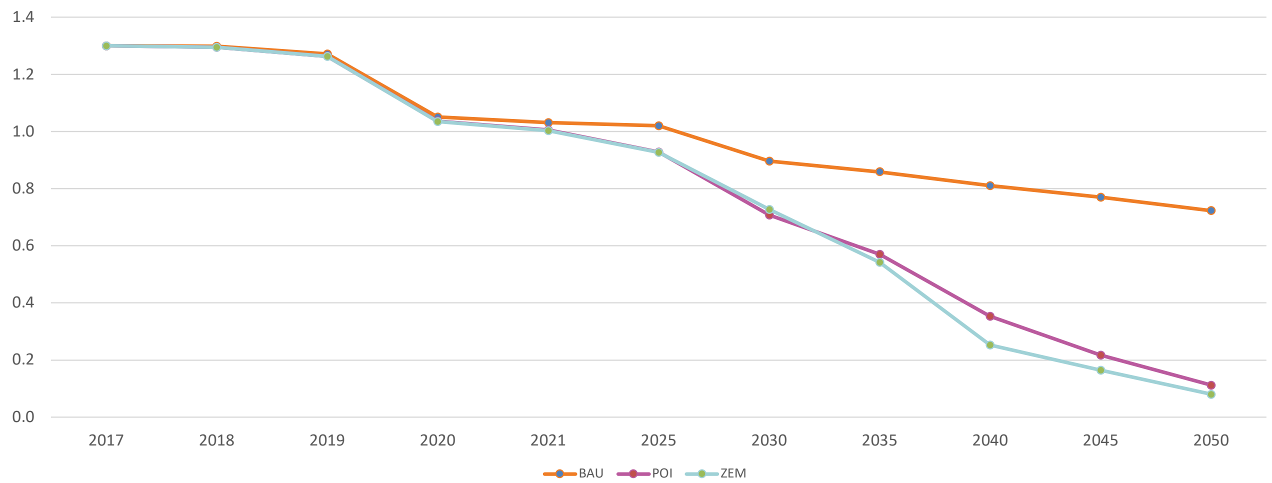

Figure 45: Comparison of GHG emissions in the food and beverages sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.9 Wood and wood products

By local availability, the sector's main fuel is biomass. The sector is projected to grow 1.6% annually, with general energy efficiency increasing by 0.5% p.a., and compound energy intensity falling by 0.4% p.a. mainly driven by thermal processes. The sector's heat demand is made up of two thirds at the high-temperature level, and one third at the low-temperature level. The large share of district heating together with biomass use stands out compared to the other sectors.

Results wood and wood products – BAU scenario

Initial emission reductions originate from district heating and the decreasing electricity grid emission factor – i.e., external drivers (see Section 3.3). Starting from a low carbon intensity, these emission reductions reach 74% in 2050 compared to 2017. After 2040, these factors can not compensate for growth and emissions stay flat.

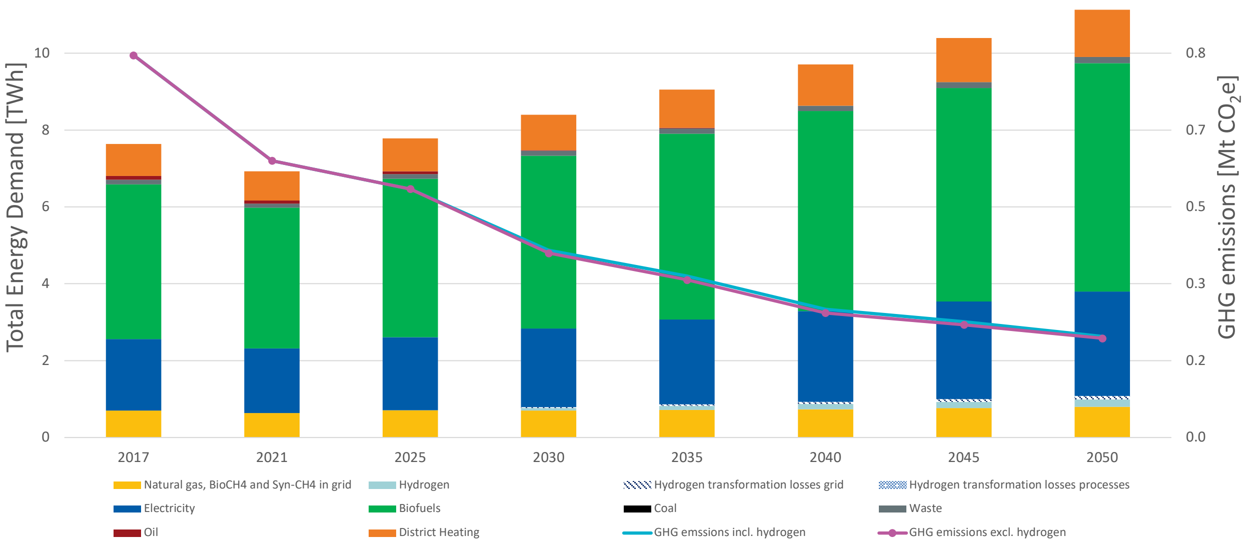

Figure 46: Total energy demand and GHG emissions by wood and wood products in the BAU scenario.

Results wood and wood products – POI scenario

District heating demand is projected to increase from 0.8 TWh in 2019 to 1.1 TWh in 2050 as local availability is projected to increase with an expected heat grid expansion. One third of heat demand is in the low temperature domain (<150°C) which is increasingly provided via heat pumps until 2030. The high-temperature heat demand not provided by biomass remains supplied via the gas grid. A reduction in the share of biomass is not expected by the industry. Residual emissions originate from district heating, gas and electricity grid emission factors. Altogether, the sector manages nearly full decarbonisation in the POI scenario according to current expectations and the industry's investment plans (see Figure 47).

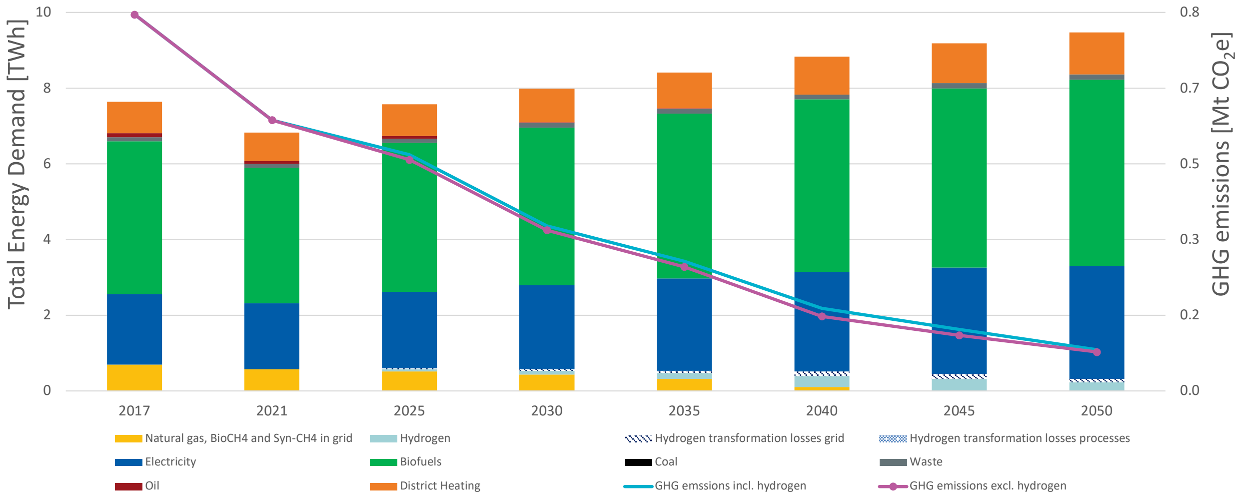

Figure 47: Total energy demand and GHG emissions by wood and wood products in the POI scenario.

Results wood and wood products – ZEM scenario

The intense competition expected for wood residues may represent an incentive for greater heat pump technology implementation in drying processes. ZEM projects a higher heat pump implementation rate, substituting both gas from the grid and biomass for low temperature heat demands. The biomass this makes available is modelled to replace gas in higher temperature applications in the sector. As a result, overall energy demand decreases slightly compared to POI (see Figure 48). However, wood transportation may increase.

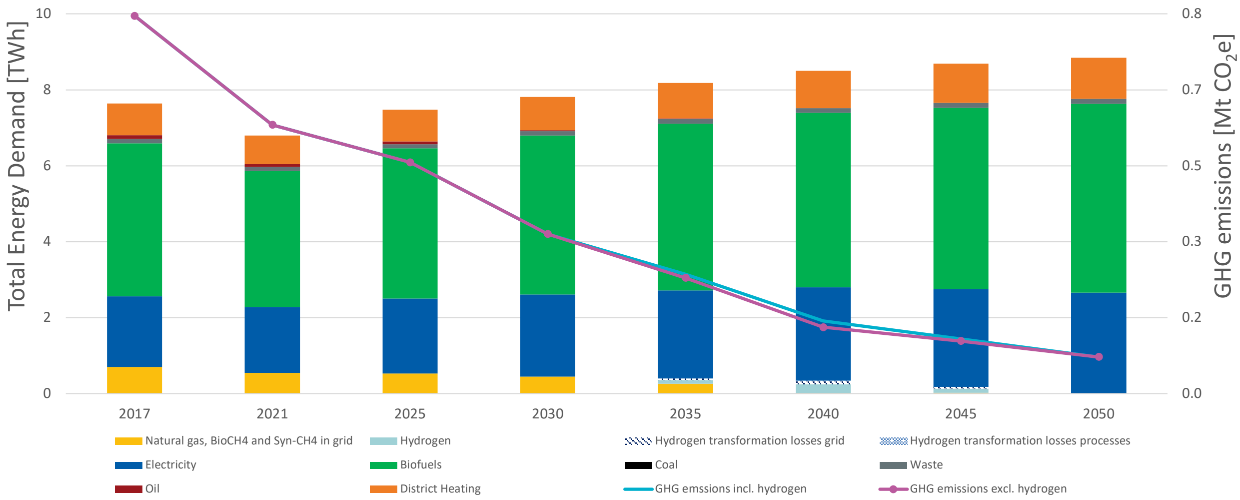

Figure 48: Total energy demand and GHG emissions by wood and wood products in the ZEM scenario.

Summary of wood and wood products

The already very high share of renewables in the sector sets a low basis of emissions. Heat pumps for drying are the main driver of emission abatement, together with electrification. A complete exit from gas is projected to be possible in ZEM in nearly all processes by 2045, resulting in nearly full abatement as early as 2040 (see Figure 49). The potential for higher efficiency gains exists and opens the door to biomass export to other sectors. This potential poses both a challenge in adapting to heat pump dryers and an opportunity for the sector to increase added value.

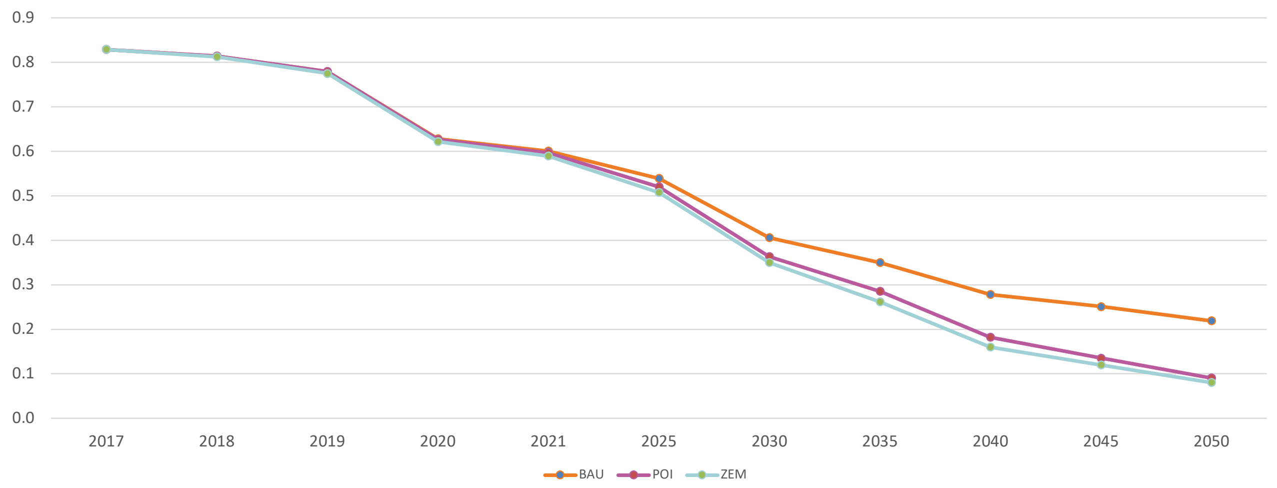

Figure 49: Comparison of GHG emissions in the wood and wood products sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.10 Textiles and leather

The sector is projected to grow by 1.4% annually, with general energy efficiency increases of 0.3%, and energy intensity falling by -0.4% annually, especially in thermal demands. Heat demand is distributed at one quarter low (<150°C) and mid-level (<400°C) respectively, and half at the high-temperature level above 400°C. Due to this relatively high share of high-temperature heat demand, hydrogen substituting natural gas is projected to be the main technical option for emission abatement.

Results textiles and leather – BAU scenario

The high-temperature heat demand is projected to be partially met by biogas to replace oil and natural gas. However, availability has been considered here, and is expected to restrict biogas share to 20% of total heat demand. Direct electrification plays an ancillary role in BAU. Gas consumption is projected to stay high due to the high share of high-temperature heat demand. Only with the gas grid mix increasing share of hydrogen is heat consumption partly decarbonised from 2035 onwards (see Figure 50).

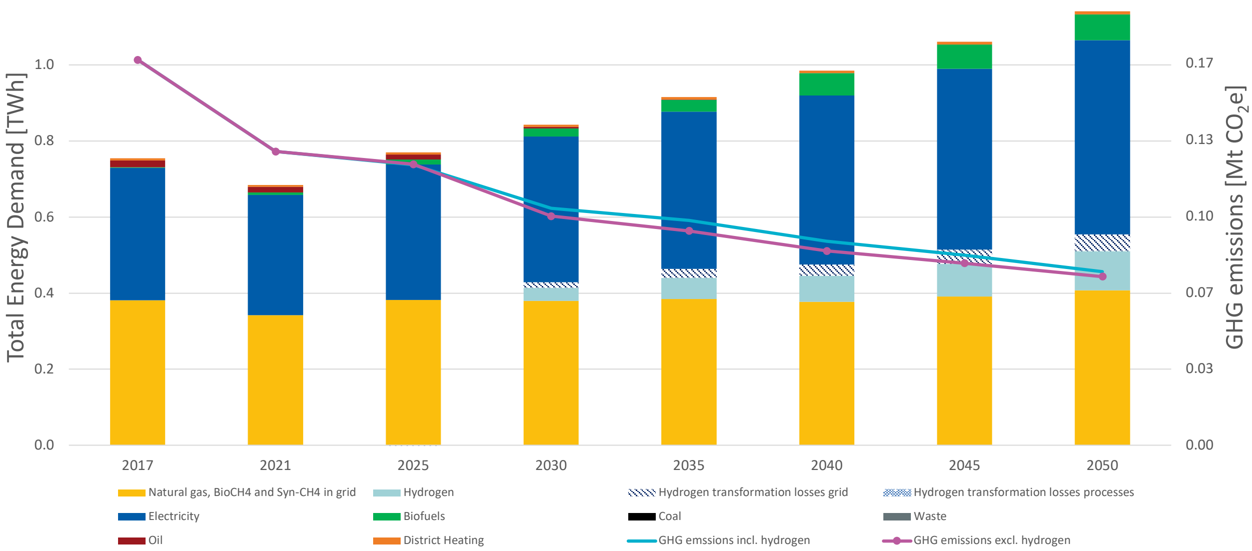

Figure 50: Total energy demand and GHG emissions by textiles and leather in the BAU scenario.

Results textiles and leather – POI scenario

Industry representatives expect low temperature heat to be provided by heat pumps from 2030 onwards. Supplying parts of the high-temperature heat demand by biofuels (locally sourced) starts as early as 2025. Remaining heat demands are met by the gas grid with its rising share of hydrogen. These three factors contribute equally to a steep fall in emissions and nearly full abatement in 2050 (see Figure 51). The overall projected energy demand rises from 2035 onwards, caused by hydrogen conversion losses. Assuming these losses are incurred not by the sector but by energy suppliers, energy demand stays nearly constant, i.e., efficiency gains can balance growth of added value.

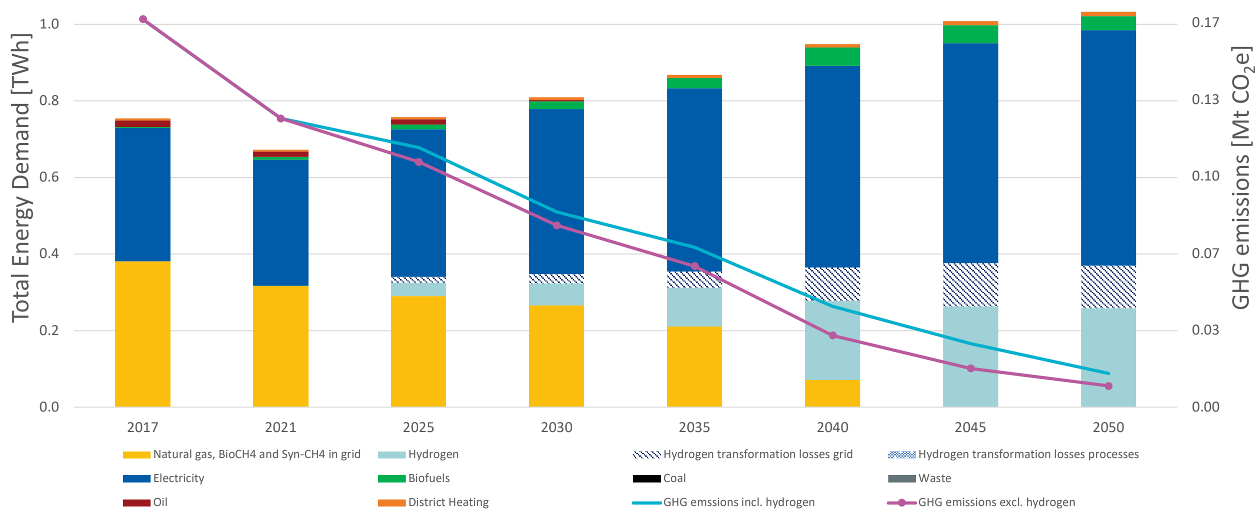

Figure 51: Total energy demand and GHG emissions by textiles and leather in the POI scenario.

Results textiles and leather – ZEM scenario

In ZEM, total energy demand falls from 2040 onwards, even including hydrogen conversation losses. Without these, the sector is projected to achieve a total energy demand reduction (at the growth rates stated above). This strong decoupling of productivity from energy demand is largely driven by electrifying low and medium level heat demand, the former by heat pumps, leading to 30% energy demand reduction, the latter by direct electrification with 10% efficiency gains. The remaining gas grid demand is provided by renewable gases. Direct electrification is the main challenge of this sector, and is projected to really take off only from 2040, hence the slowing in abatement progress from 2040 onwards (see Figure 52).

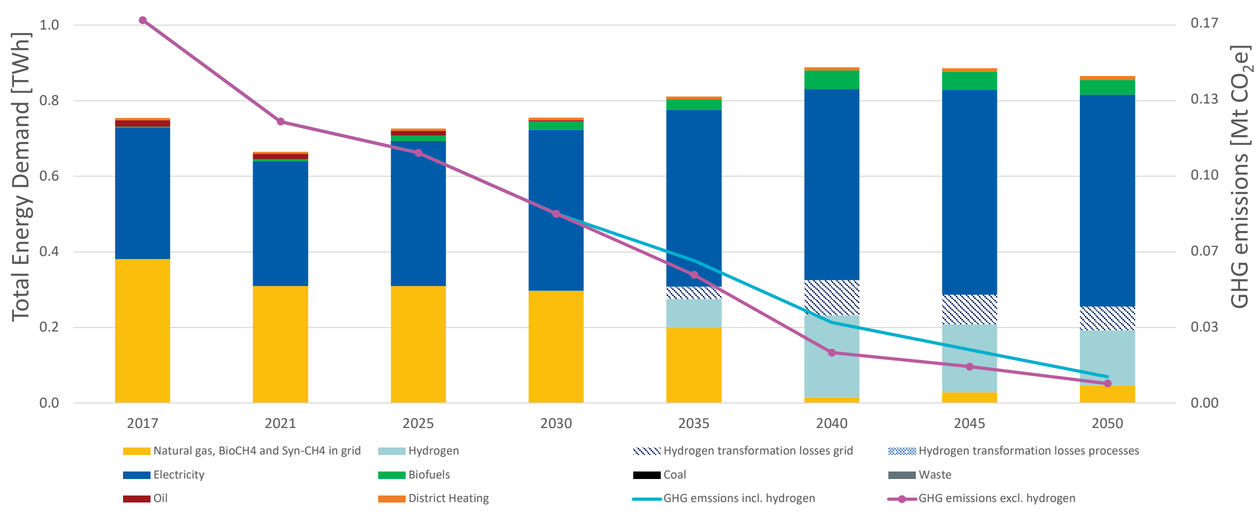

Figure 52: Total energy demand and GHG emissions by textiles and leather in the ZEM scenario.

Summary of textiles and leather

The relatively small size of plants and high specialisation of the sector in Austria provides for a diverse technological base. Efficiency gains from low temperature heat supply by heat pumps contribute most to the projected abatement in the years to 2040. Decarbonisation efforts strongly rely on the electricity grid or local generation with direct electrification of medium temperature appliances. Reaching net zero emissions becomes harder and costlier on the last mile. Even so, according to stakeholder expectations, the industry will reach a 90% emission reduction in POI by 2050, and by applying the additional measures as described above, can increase to 95%, as shown in Figure 53.

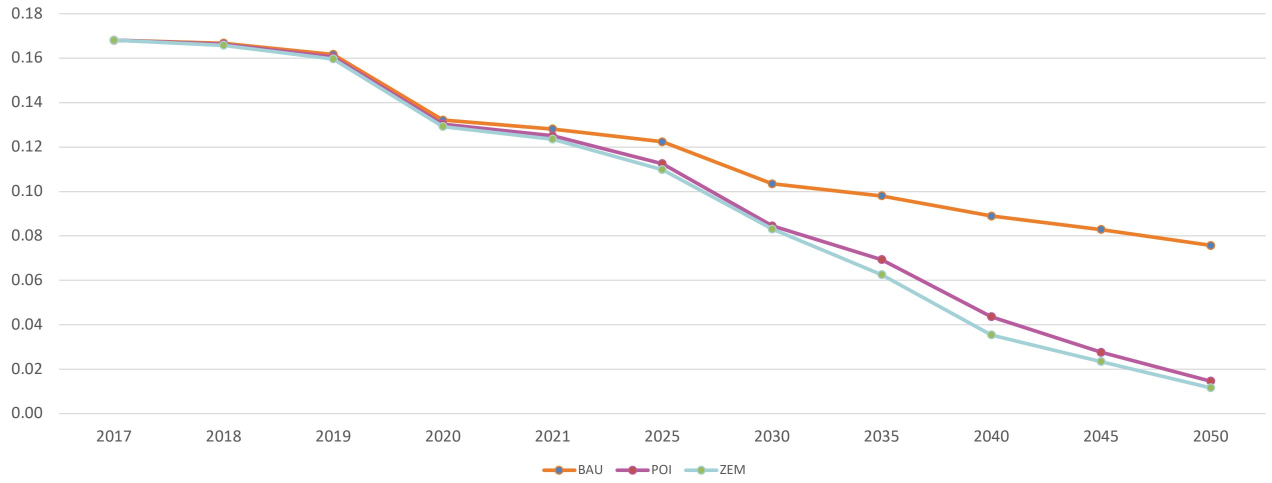

Figure 53: Comparison of GHG emissions in the leather and textiles sector in the BAU, POI and ZEM scenarios when including H2 generation for emission intensity.

4.11 Construction

In the construction sector, diesel-powered mobile applications constitute the bulk of energy demand. These provide the largest potentials for emission abatement. The sector is projected to grow by 1.4% annually with efficiency gains reducing the growth in energy demand to 0.8% per year.

Results construction – BAU scenario

For the highly specific machinery used in this sector, the BAU scenario does not assume any technological changes. Therefore, sector growth directly leads to energy demand and emissions growth, apart from the small efficiency gains noted above.

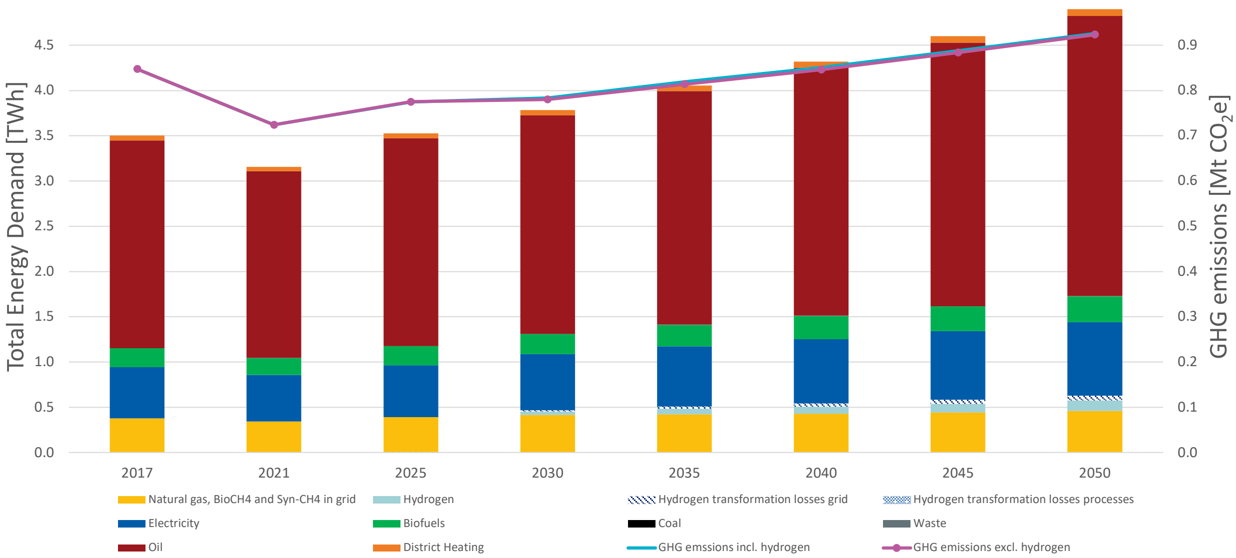

Figure 54: Total energy demand and GHG emissions by construction in the BAU scenario.

Results construction – POI scenario

Oil demand in the form of diesel for motive power of construction vehicles, largely not self-propulsion, is projected to be either electrified or substituted by synthetic or biofuels starting from 2025. Hydrogen, due to its elaborate handling, demands plays a minor role here. Biofuels are used as a substitute for diesel in applications where high-energy density is necessary. Slow turning, torque-heavy drives of construction machinery are predestined for electrification. Therefore, electrification is projected to take place at a consistently high diffusion rate, as manufacturers offer more of these solutions. The one technology contributing most to abatement efforts in the sector is electric batteries, their effect even exceeding the described fuel switching. The results of these technology changes are shown in Figure 55.

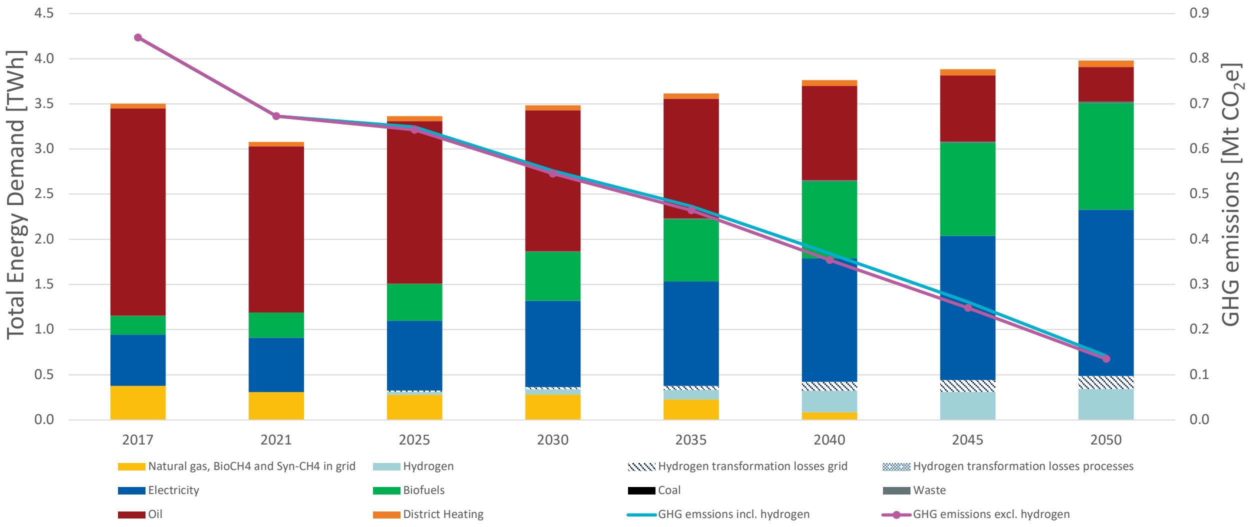

Figure 55: Total energy demand and GHG emissions by construction in the POI scenario.

Results construction – ZEM scenario

As many applications are principally well suited for electrification, but market availability is expected to only develop from 2030 onward, its diffusion into the market can be accelerated by higher demand or legislative drivers. These drivers are assumed to be present in ZEM. With electrification, efficiency gains increase, allowing for compensation of the sector’s growth in added value, and holding energy demand constant. A slightly higher use of hydrogen applications in larger on-site vehicles is assumed here compared to POI (see Figure 56).

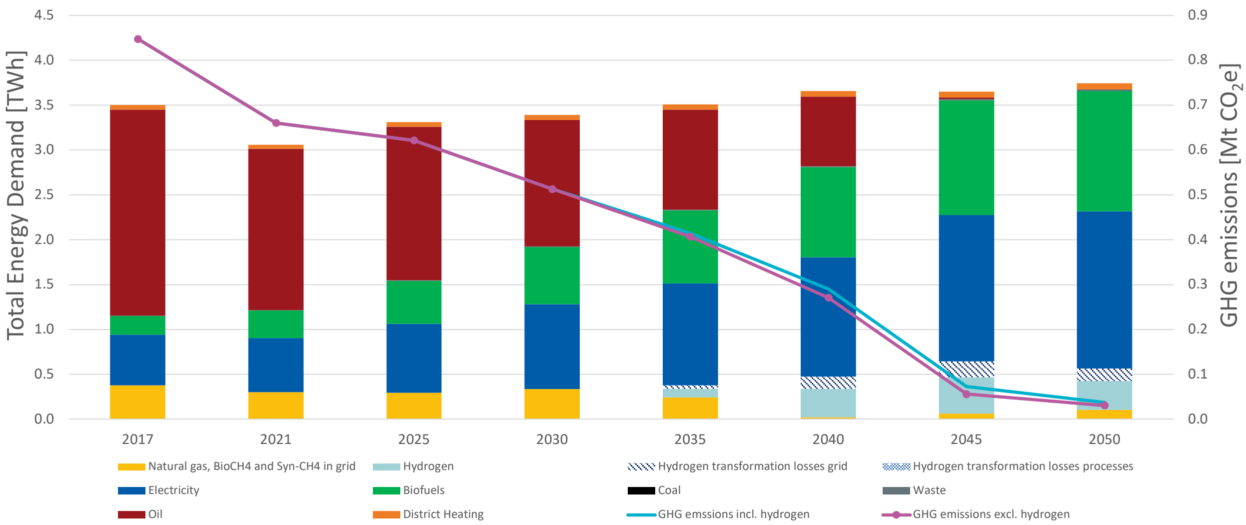

Figure 56: Total energy demand and GHG emissions by construction in the ZEM scenario.

Summary of construction

Electrification and substitution of diesel with biofuels for mobile machinery are mainly driving the abatement efforts. The rate of emission decrease depends on market availability and the sector’s demand pressure on manufacturers of these machines. The basic technologies already exist but are not widely available in the specialised machinery employed in this sector. Hence, the typical development cycles of machinery manufacturers allow for a full decarbonisation of the sector only as early as 2045. Therefore, POI and ZEM show similar abatement results (see Figure 57). The kink in 2045 for ZEM originates from full diesel substitution only being implemented at this point, following our backcasting method.

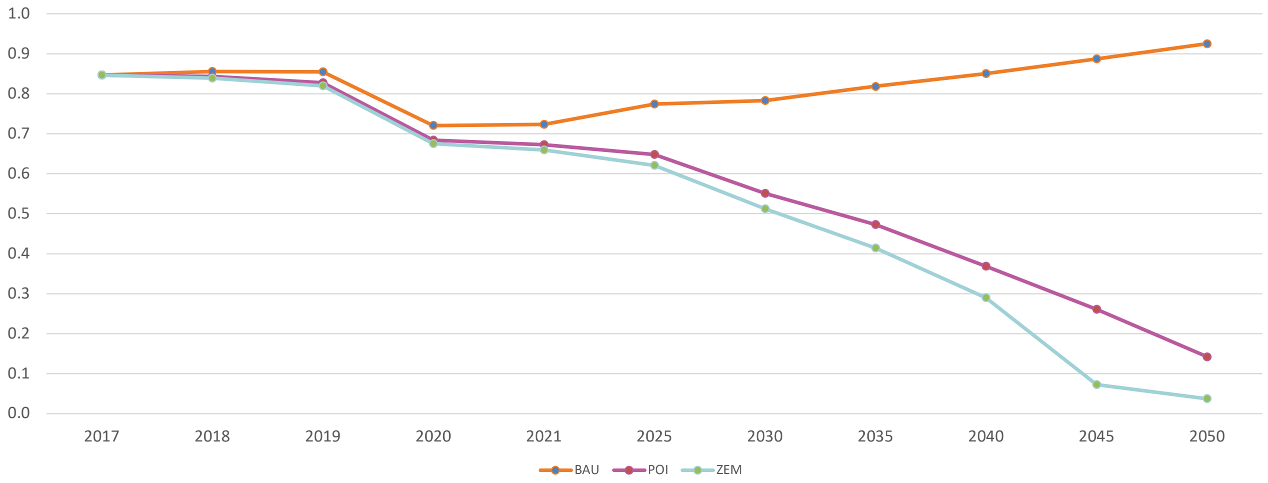

Figure 57: Comparison of GHG emissions in the construction sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.12 Mining

With the conflicting macro trends of shifting resource demands and the possible stark increase in circular use, growth of the mining sector is hard to predict. Additionally, the threat exists that sustainability efforts and competition push the sector to low wage countries with lower environmental standards. Recent efforts to reshore the mining of crucial minerals may increase the sector's output. These potentially stark nonlinearities have not been incorporated into the model. A growth in value added of 1.4% p.a. results in energy demand growth of 0.7% per year after efficiency gains are taken into account. In Austria most mines are connected to the electricity grid, therefore diesel-powered generation plays a minor role. The sector's relatively high heat demand lies in the medium temperature range of 150°C – 400°C. Therefore, only direct electrification is feasible, and is the single most important technology for decarbonising this sector.

Results mining – BAU scenario

Following the BAU scenario narrative of just extrapolating historic trends, there are no changes in fuel shares in this sector. Energy demand grows with the projected increase in added value. The depicted (Figure 58) reduction in emissions is caused by contraction of the grid emission factors (see Section 3.3 for the methodology of grid modelling).

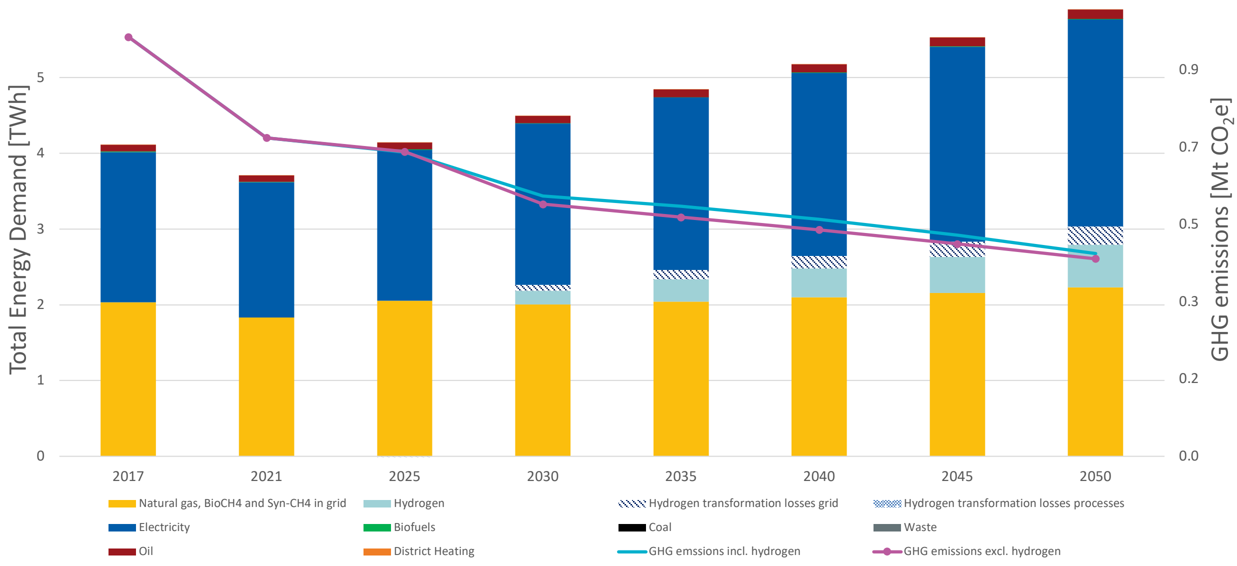

Figure 58: Total energy demand and GHG emissions by mining in the BAU scenario.

Results mining – POI scenario

Thermal energy demand in the mining sector is mainly in the mid-level of 150°C – 400°C. Therefore, its decarbonisation by hydrogen use really starts to make an impact as late as 2035. However, the sector's growth can be largely driven by electric applications, formerly gas powered. This trend leads to a reduction of total energy demand compared to BAU where conversion losses are assumed to be incurred by the energy providers. The driver is efficiency gains in motive power and low temperature heat supply. Hydrogen use in specific applications is projected to account for only 5% of mid and high-temperature heat demand (and zero in the low temperature domain). Its use is mainly driven by the increasing share in the gas grid mix from 2040 onwards (see Figure 59).

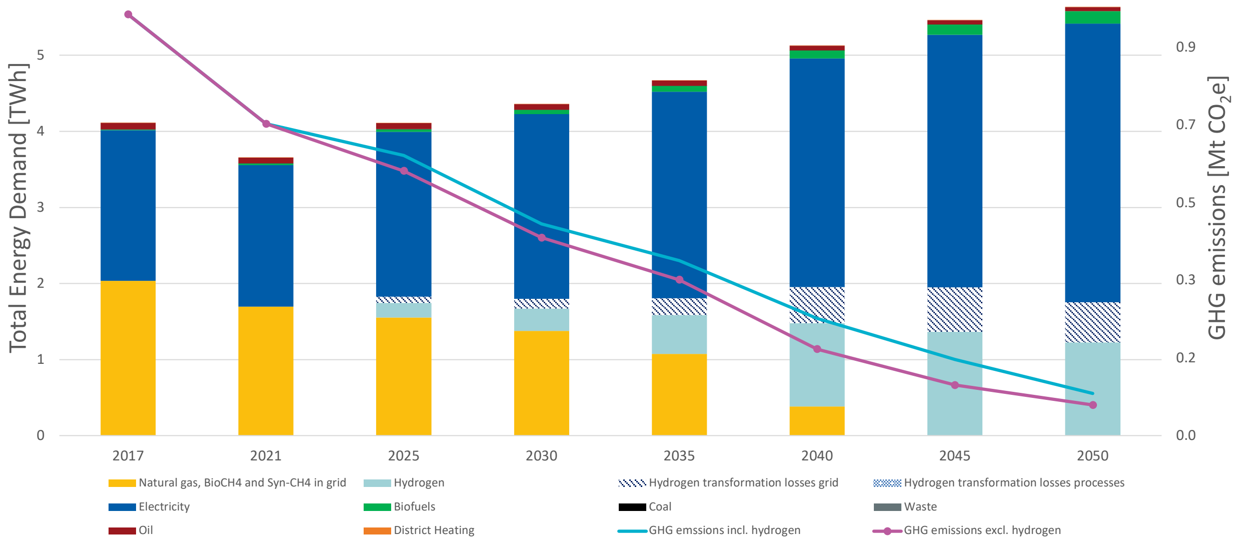

Figure 59: Total energy demand and GHG emissions by mining in the POI scenario.

Results mining – ZEM scenario

Extended electrification efforts in the mid-temperature level reduce gas demand and allow for efficiency gains in the ZEM scenario. These efficiency gains even outweigh the growth and lead to a decrease in total energy demand from 2040 onwards where hydrogen generation losses are excluded. All diesel-powered applications are projected to be powered by synthetic- and biofuels. With the late uptake of direct electrification, hydrogen applications become electrified, leading to a fall in hydrogen demand from 2040 onwards, and increasing overall efficiency of fuel supply.

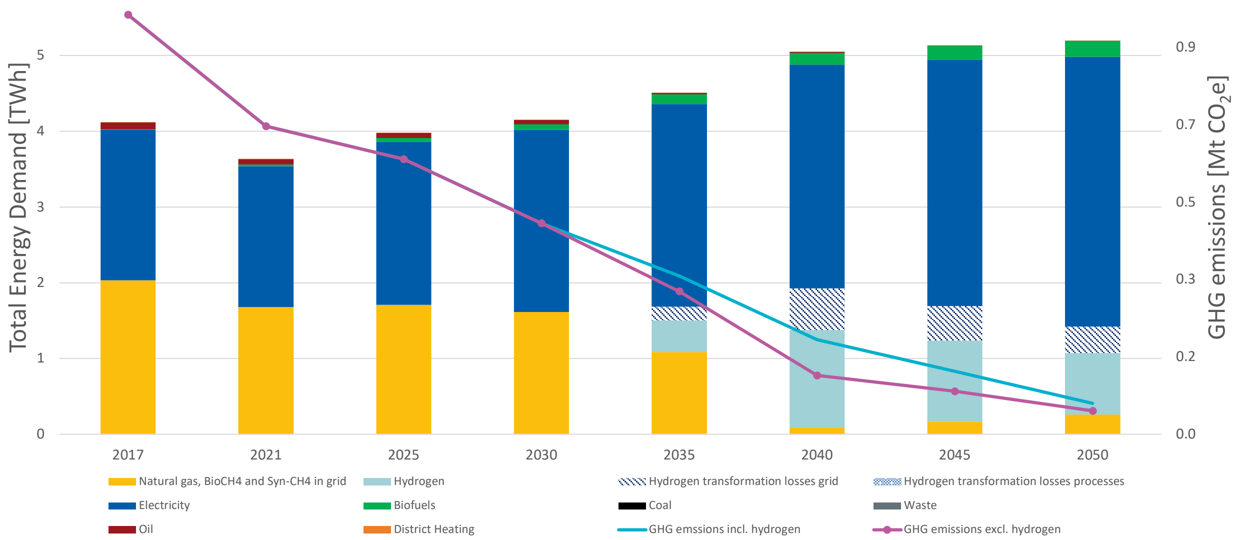

Figure 60: Total energy demand and GHG emissions by mining in the ZEM scenario.

Summary of mining

The initial strong fall in emissions between 2017 and 2020 is not assumed to be sustainable. Further efforts will have a lesser impact, until the supply side (in terms of reducing grid emission factors) steps in from 2025 onwards. With the increasing share of renewable gases contained in the grid mix, emission abatement can be sped up substantially, reaching a 93% decrease in 2040 in the ZEM scenario, compared with 90% in POI. Remaining grid emission factors prohibit a complete decarbonisation in 2050.

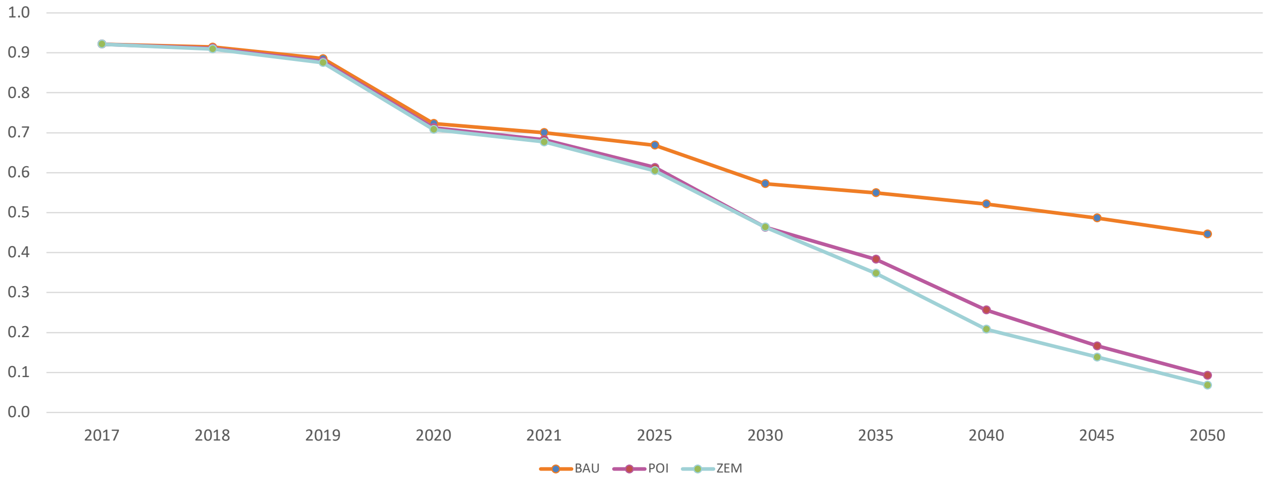

Figure 61: Comparison of GHG emissions in the mining sector in the BAU, POI and ZEM scenarios when including H_2 generation for emission intensity.

4.13 Non-specified industry

Enterprises not allocated to one of the 12 industries above make up 1.3% of total Austrian industry energy demand and 9% of production industry's value added. These enterprises mostly operate in the production of rubber and plastic goods as well as furniture. The inhomogeneity of this subsector did not allow for technology-specific modelling, hence cross sectional technology efficiency gains have been considered. With 1.1% annual growth, the sector is projected to grow less rapidly than any other.

Results non-specified industry – BAU scenario

Following the BAU scenario narrative of simply extrapolating historic trends, no changes in fuel shares result in this sector. Energy demand grows with the projected increase in added value. The depicted (Figure 58) reduction in emissions is caused by the grid emission factors contracting (see Section 3.3 for the methodology of grid modelling).

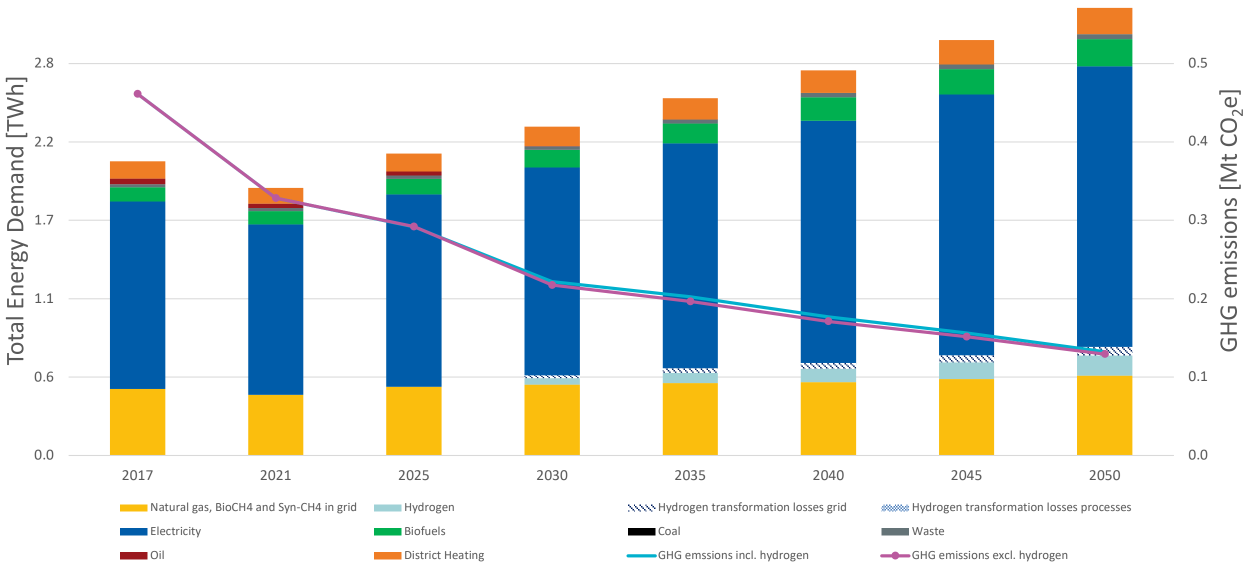

Figure 62: Total energy demand and GHG emissions by non-specified industry in the BAU scenario.

Results non-specified industry – POI scenario

Industry interviews were not conducted for this sector, therefore projections are based on other sectors' pathways in the five useful energy categories. Slightly lower growth of 1.1% p.a. with higher overall efficiency gains of 0.6% due to large low-temperature level demand provide for a subdued energy demand growth compared to other sectors. Additional demand falls mainly on electric devices, but thermal demand also rises slightly (see Figure 66).

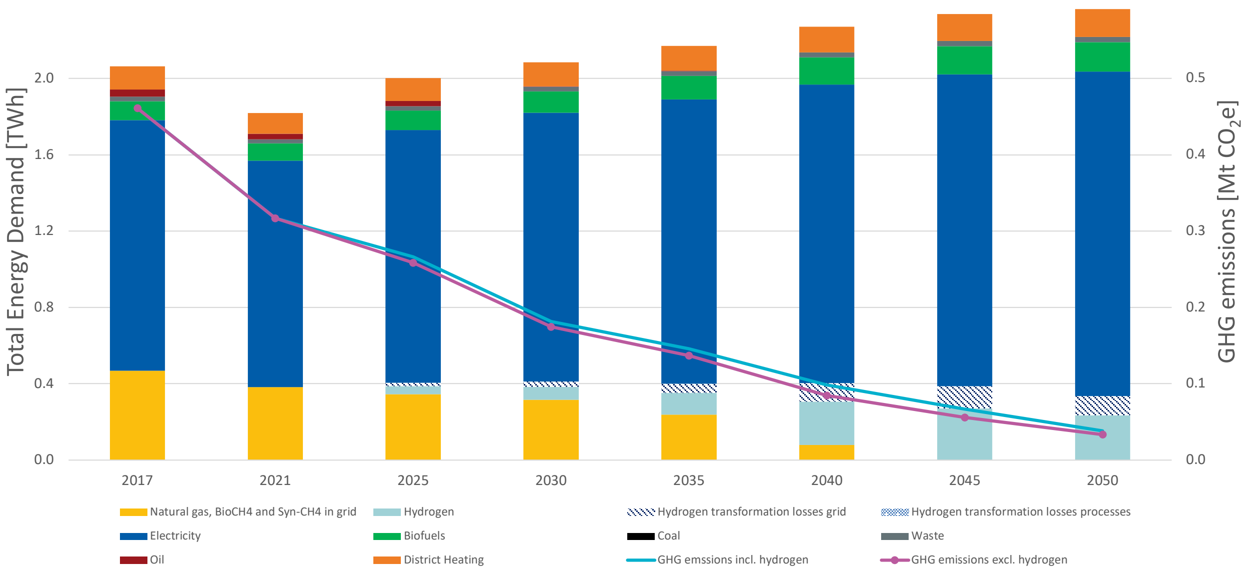

Figure 63: Total energy demand and GHG emissions by non-specified industry in the POI scenario.

Results non-specified industry – ZEM scenario

With the projected increase in renewable gas shares in the grid and the falling electricity grid emission factor, the abatement of emissions accelerates in ZEM. With a faster diffusion of highly efficient equipment and high-temperature heat pumps, energy efficiency increases allow for stagnating energy demand until the year 2040 and a fall thereafter (see Figure 68).

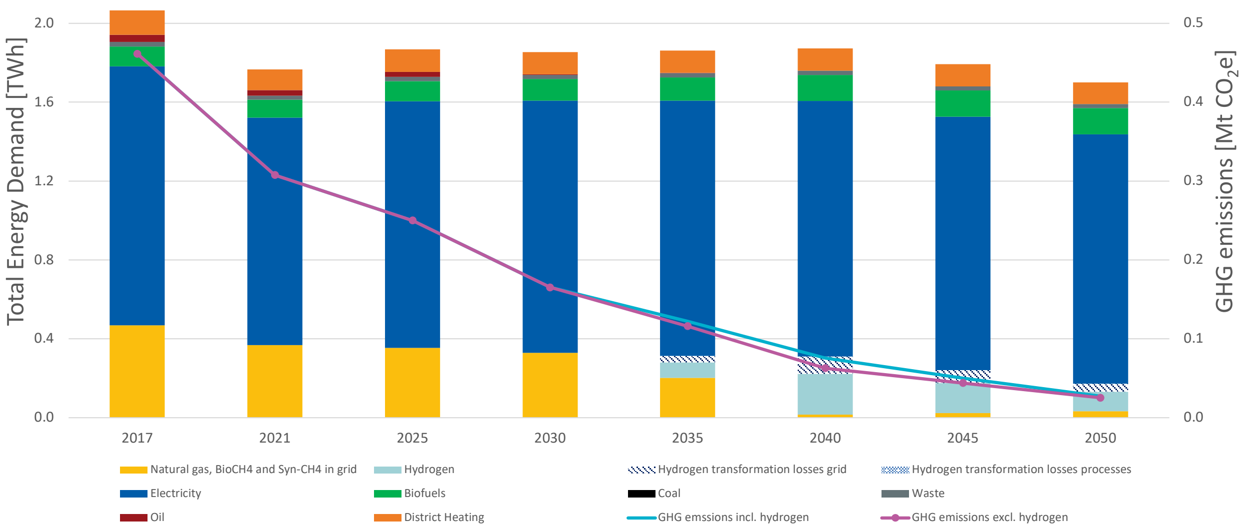

Figure 64: Total energy demand and GHG emissions by non-specified industry in the ZEM scenario.

Summary of non-specified industry

The depicted (Figure 69) differences in total energy demand arise from increased heat pump acceptance and efficiency gains. Diverging emission pathways between the scenarios from the year 2030 onwards reflect different grid emission factors, both for electricity and gas.

Figure 65: Comparison of GHG emissions in the non-specified industry in the BAU, POI and ZEM scenarios when including H2 generation for emission intensity.

5. Discussion of Austrian industry scenarios

In this section, the results of the three scenarios BAU, POI and ZEM are discussed separately at a cross-sectoral level. In Section 5.4, a comparative analysis between the scenarios is provided, as well as a discussion of how results relate to other high-level studies and documents.

5.1 Business as usual (BAU) scenario

As outlined above, the BAU scenario serves as a trend scenario in which the technology mix of the historic trend is prolonged. Only the energy supply by the energy system is changed, as outlined in Section 3.3. Thus, a rather small share of renewable gases and lower CO_2-emission intensities in the electricity system are provided to industry. In this baseline scenario, the historic trend of general efficiency measures and increasing productivity neutralising each other with respect to GHG intensity is continued, while energy demand rises by up to 29 TWh. In BAU, Austrian industry still relies on large shares of fossil-based energy carriers, both for energy and process demand. In combination with efficiency improvements, this leads to a slight decrease in yearly emissions to approximately 23 Mt CO_2e (GHG intensity of electricity production included). The introduction of up to 12 TWh of hydrogen until 2050 contributes to this trend as well as the decreasing emissions from electricity. In BAU, chemical production still relies on fossil feedstock. Therefore, the chemical and petrochemical industry cannot act as a GHG sink.

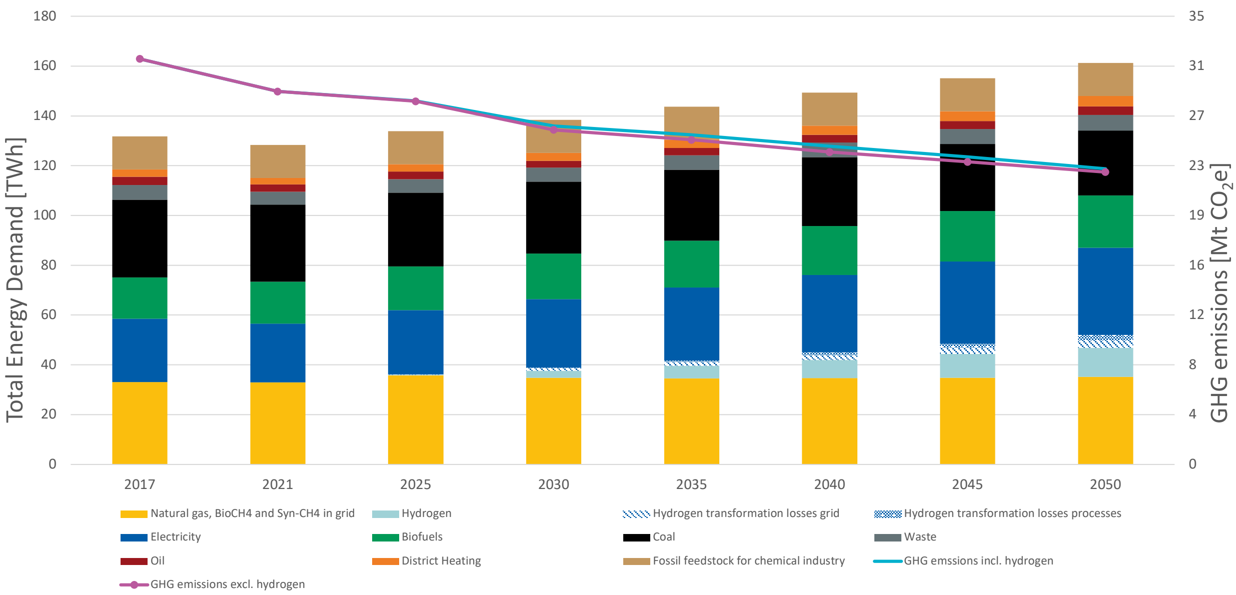

Figure 66: Total energy demand and GHG emissions of Austrian industry in the BAU scenario.

5.2 Pathway of industry (POI) scenario

Total results in the POI scenario indicate that, based on a technological approach, far-reaching decarbonisation of Austrian manufacturing industry until 2050 is possible when the current transformation plans of industry representatives are taken into account. The methodology underlying the scenario is explained in Section 3.2.2. Compared to BAU, total energy demand rises to 168 TWh when electrolysis losses are considered. At its core, the industrial energy system as modelled in POI according to feedback from industry representatives relies on four main energy carriers; solid biomass, electricity, hydrogen, and methane from synthetic and biogenic sources.

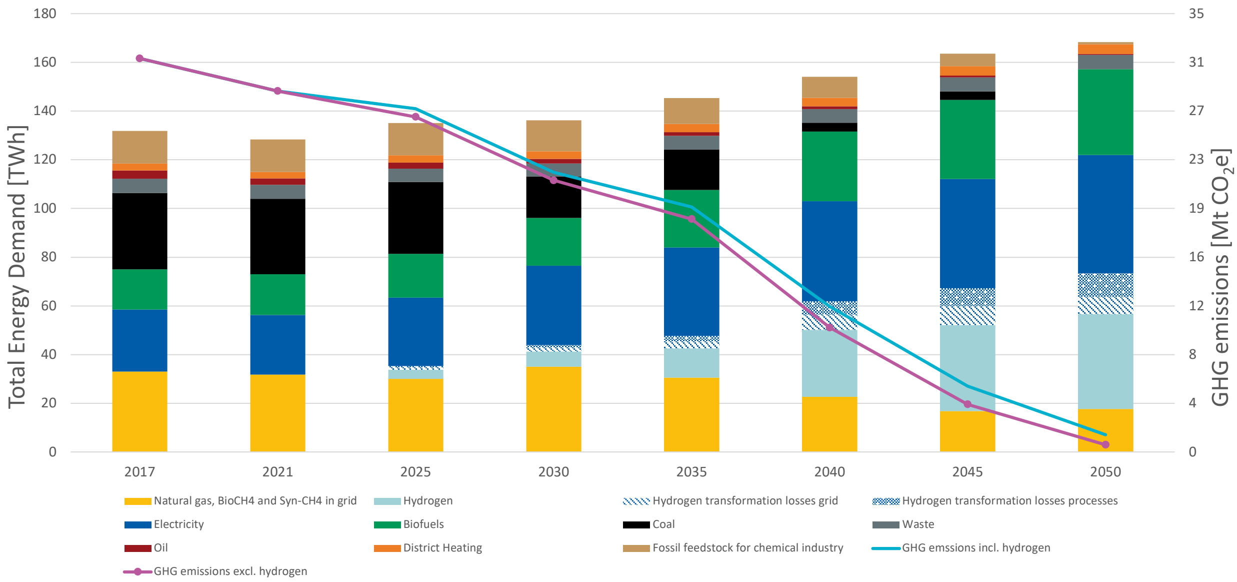

Figure 67: Total energy demand and GHG emissions of Austrian industry in the POI scenario.

Solid biomass demand increases by almost 19 TWh to 35.1 TWh by 2050. The POI scenario also relies on an additional 23.1 TWh of electricity when compared to 2017, reaching close to 50 TWh in 2050. Due to the envisioned break-even point in production costs of hydrogen and fossil CH_4, the gas grid features large shares of hydrogen in the POI scenario. Assuming hydrogen production is exclusively in Austria, an additional 61.3 TWh of electricity is required to produce 39.1 TWh of hydrogen. In Figure 67, losses from electrolysis for the hydrogen demand of the iron and steel and the chemical and petrochemical industries, and losses for the hydrogen demand for the general gas grid are illustrated in slightly different colour patterns. Total gas demand rises despite electrification efforts for final energy applications. This is due to large amounts of renewable gases being needed to decarbonise feedstocks in the iron and steel and the chemical and petrochemical industries, assuming that all necessary chemical intermediate products are synthesised in Austria.

Overall, GHG emissions can be reduced by up to 30.8 Mt CO_2e to just 1.4 Mt in 2050, depending on the considered balance border (purple line without losses for electrolysis considered). One important factor in this achievement is the use of sequestrated CO_2 from non-metallic minerals industries in the chemical and petrochemical industry. While high in energy demand, the chemical and petrochemical sector also represents an important emissions sink for approximately 2.8 Mt CO_2e. Most notably, leaving regional separation between industrial plants aside, the non-metallic minerals sector can be used as a source of highly concentrated CO_2 for efficient sequestration.

5.3 Zero emission (ZEM) scenario

In the ZEM scenario, total energy demand (172 TWh) reaches net GHG neutrality in the industrial sector by 2050 (Figure 68). Similar to POI, the structure of necessary energy carriers is simplified in this scenario when compared to the current energy mix. Only solid biomass, electricity and sustainable gases, mostly hydrogen, remain. The yet again increasing share of CH_4 in the period 2040 to 2050 can be explained by the modelled increase in sustainable CH_4, most notably bio-CH_4. In ZEM, net neutrality is achieved through the even more extensive use of low carbon, energy intensive production routes for basic chemical production (mostly based on H_2). When all necessary chemical intermediate products are synthesised in Austria, the sector serves as the necessary CO_2 sink to counteract all remaining GHG emissions of the Austrian manufacturing industries, and constitutes an efficient purpose for already sequestrated CO_2 from the non-metallic minerals sector. Overall, a net total of 5.1 Mt CO_2 is used in the chemical and petrochemical sector in scenario ZEM as hydrogen-based production routes are favoured over biomass-based routes. Low emissions only remain when considering upstream GHG emissions in the electricity sector due to electrolysis demand. To take account of the possibility of producing hydrogen domestically or abroad, the blue and purple lines show the difference in resulting emissions in Austria. Whereas total hydrogen demand is fairly constant in the years from 2040 onwards, its consumption shifts away from the gas grid to processes (iron & steel and chemicals), originating from the switch to other heat sources.

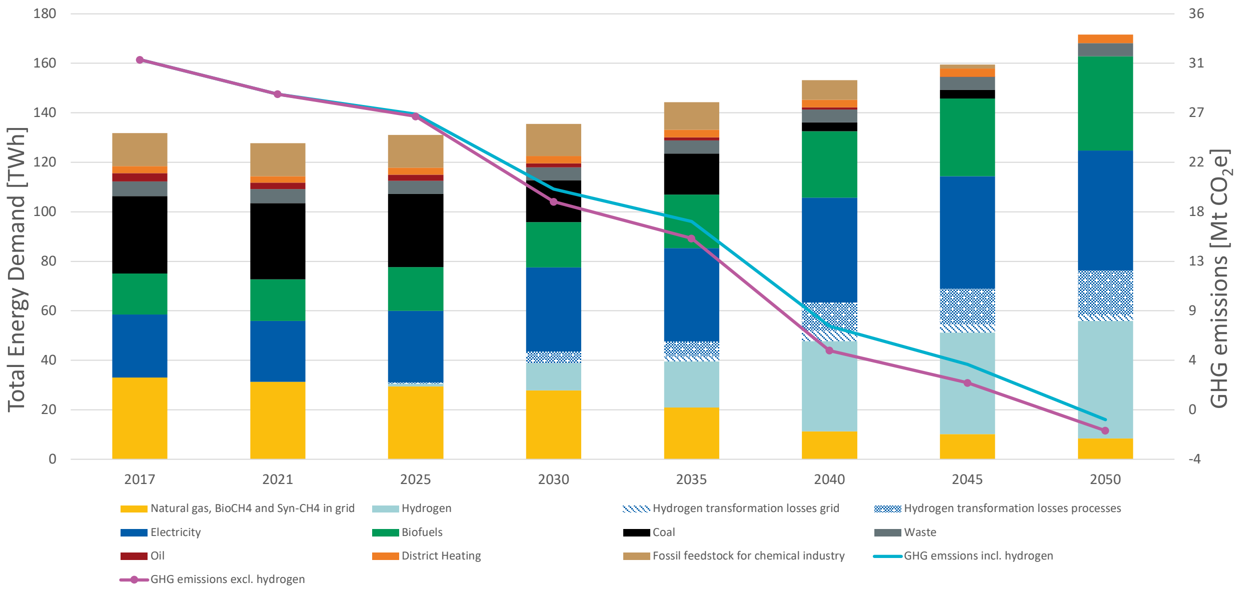

Figure 68: Total energy demand and GHG emissions of Austrian industry in the ZEM scenario.

5.4 Comparative assessment and development trends

In the baseline BAU scenario, total energy demand as well as industrial emissions are projected to increase slightly although the counteracting effects of energy efficiency improvements can be observed. Starting in the period between 2025 and 2030, the POI and ZEM transition scenarios are starting to create a development gap compared to BAU. Fossil fuels with high emission intensities, most notably coal, oil and fossil waste, are phased out and replaced by less GHG-intensive alternatives. Considering H_2 generation, as illustrated in Figure 69 below, scenarios POI and ZEM decrease emissions by more than 25% in the period between 2025 and 2035. The backcasting approach of scenario ZEM illustrates that the envisioned time frame for acting is vital for successfully finding the pathway towards industry decarbonisation. As evident from comparing the POI and ZEM graphs, industry representatives in a wide variety of subsectors already envision a low carbon pathway. While relying on different technologies than those in ZEM, GHG emission development in the two transition scenarios is very comparable.

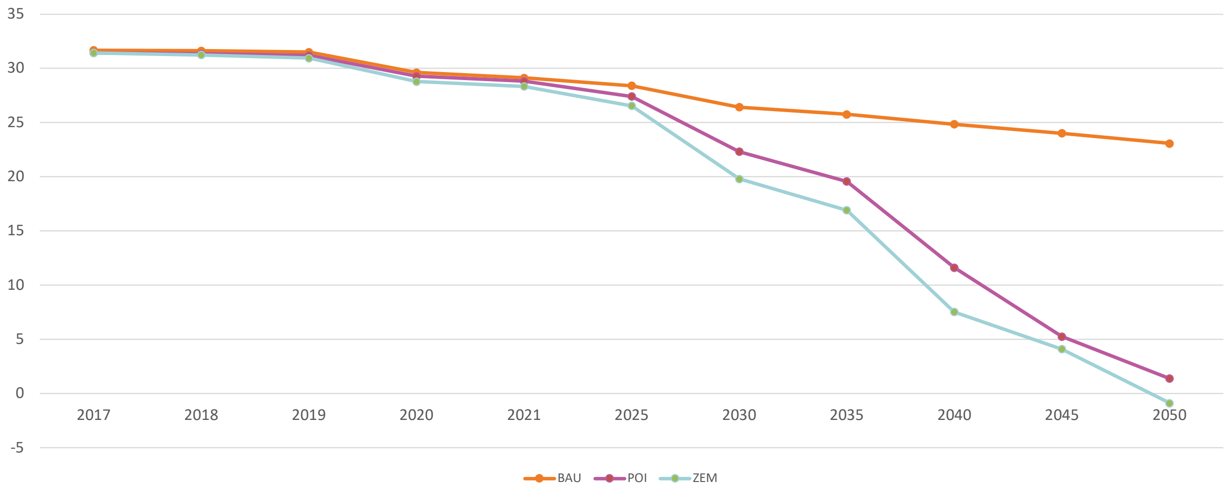

Figure 69: Comparison of GHG emissions from Austrian industry including H_2 generation in BAU, POI and ZEM.

With respect to total industrial energy demand, visualised in Figure 70, both in POI and ZEM, energy demand is characterised by three basic forms of energy carriers; electricity, gases and biomass, while in BAU the energy mix is significantly more diverse because of the use of several forms of fossil energy carriers and feedstock material (e.g., coal, naphtha, oil). In order to substitute these energy sources, extended production chains are necessary which exhibit greater transformation losses (e.g., hydrogen from electrolysis for the methanol-to-olefine route). Therefore, slightly larger total energy demands can be seen for the POI and ZEM transformation scenarios than for the BAU reference scenario. The difference in necessary upstream production chains is also the reason for slightly higher ZEM results for total energy demand (172 TWh) than can be observed for POI (168 TWh). As ZEM requires greater amounts of hydrogen, more transformation losses for electrolysis have to be taken into account. However, if the hatched area of electrolysis losses that may be situated inside the upstream energy industries is disregarded, the ZEM scenario results are slightly lower than POI, exhibiting the efficiency potential in the ZEM scenario realised directly inside the manufacturing industries.

In the POI and ZEM transition scenarios, 2050 biomass demand of approximately 35 TWh (POI) to 38 TWh (ZEM) is calculated, while trend extrapolation forecasts approximately 21 TWh/a. The deviation from the trend scenario amounts to +66% or +86%, respectively. In comparison, the yearly addition of unused wood in Austrian forests since 2008 amounts to a maximum of approximately 9.6 TWh/a (Höher, 2019).

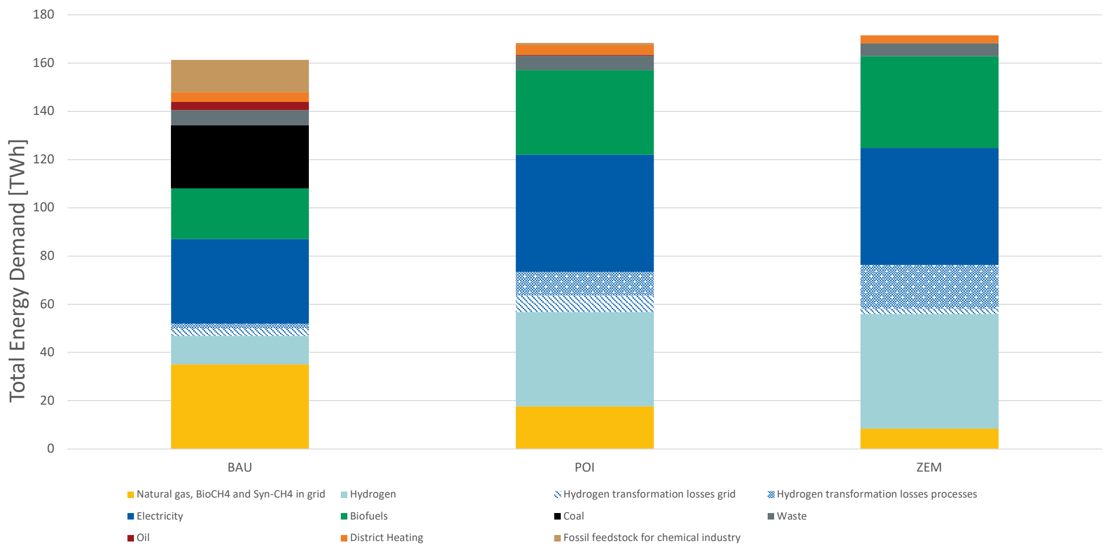

Figure 70: Comparison of 2050 results in the BAU, POI and ZEM scenarios.

Around 50 TWh of electricity for final energy applications is necessary in both POI and ZEM, an increase of 24 TWh. This almost equals the amount Austria has set out to install in renewable electricity generation between 2020 and 2030 (27 TWh) (Bundeskanzleramt Österreich, 2020). If this electricity generation goal is linearly extrapolated to 2050, approximately 72 TWh of additional sustainably generated electricity would be available for Austria annually. Of these, according to scenario results in both POI and ZEM, at least 70% (~50 TWh) would be needed directly in the industrial sector for final energy demands. Taking into account economic development and efficiency improvements over time, these scenario results converge with previous studies of final electricity demand in Austrian industry (Geyer et al., 2019). In addition to general electrification efforts, e.g., heat pumps, electricity demand is especially driven by the decarbonisation of process-emission intensive sectors such as iron and steel and non-metallic minerals. In these sectors, the introduction of electric arc furnaces and carbon capture plants signifies a significant demand in final electricity.

Taking into account the possible additional electricity demand for hydrogen production via electrolysis, total electricity demand for industrial production in Austria rises to approximately 104 TWh in POI and 116 TWh in ZEM. On the other hand, analyses of technical potentials indicate a maximum electricity generation capacity from PV, wind and hydro of approximately 180 TWh (Sejkora et al., 2020).

In the gas sector, a difference in application technologies can be observed between the POI and ZEM scenarios. In POI, industry representatives rely more heavily on CH_4-based technologies for direct reduction, especially in the iron and steel industry, using close to 18 TWh of CH_4 derived from biogenic and synthetic sources. In comparison, by 2050, CH_4 demand in ZEM amounts to only ~8 TWh, while total hydrogen demand surpasses demand in POI by 8 TWh (~48 TWh H_2 total). Hydrogen exhibits higher shares in the ZEM gas grid when compared to the POI scenario because of the widespread deployment of breakthrough technologies, also in energy intensive industries other than the chemical sector. For example, in primary steelmaking hydrogen direct reduction is deployed in combination with electric arc furnaces to transform the sector towards climate neutrality. Because of this, electricity losses for hydrogen generation in iron and steel and in the chemical and petrochemical industries are approximately 10 TWh greater than in POI (8.5 TWh). Overall, approximately 56 TWh (ZEM) to 57 TWh (POI) of gases are needed.

6. Conclusion and outlook

This report presents the results of the three NEFI industry scenarios

(I) Business as usual (BAU)
(II) Pathway of industry (POI)
(III) Zero emission (ZEM)

for the timeframe 2017 to 2050. BAU serves as a reference scenario while POI and ZEM are considered transition scenarios. The key finding of this study is that the industrial energy system of the future can operate at net zero emissions with the widespread use of four dominating key levers:

- Significant improvement of the energy efficiency of all industrial processes, and low-emission electrification of thermal and motive energy demands (heat pumps and motors)
- Fuel switching to carbon-neutral gases and biomass
- Carbon capture technologies
- Circular economy aspects[2]

Other technology solutions, such as solar thermal, high-temperature electrical direct heat, alternative binders for cement production or the deployment of complex bio refinery structures do not have a significant impact.

Comparison of scenarios

Until 2025, the total energy demand and GHG emissions in POI and ZEM follow the BAU scenario. However, from 2025 onwards, the POI and ZEM transition scenarios show clearly different patterns regarding the GHG emissions. Assuming unchanged production and value chains as well as widely constant production volumes (especially in the chemical and petrochemical and the iron and steel industries) compared to BAU, total energy demand rises significantly in both transition scenarios. In POI and ZEM, energy is largely provided by three types of energy carriers: renewable gases, electric energy and biomass. While the technologies deployed differ, the absolute values for energy demand per energy carrier follow the same trends. By 2050, POI indicates 35 TWh of solid biomass demand in comparison to 38 TWh per year in scenario ZEM. Bio-CH_4, synthetic CH_4 and H_2 together amount to 57 TWh in POI, just 2% more than that demand in the backcasting scenario ZEM.

For final electricity demand, the difference is even smaller (48.6 TWh in POI versus 48.5 TWh in ZEM). In contrast to total energy demand, GHG emissions decrease significantly in POI and ZEM starting in the period between 2025 and 2030, while BAU results stay more or less constant due to rising economic activity, counteracting general efficiency gains.

Both POI and ZEM can reach net emissions neutrality by 2050 when GHG intensity of upstream electricity production for H_2 generation is ignored. In both scenarios, the use of electricity and gases with low emission intensities is one of the key factors for decarbonisation, replacing fossil fuels with high emission intensities, most notably coal, oil and fossil waste.

The strong trends and overlaps in total energy demand found in both transition scenarios underlines the robustness of the NEFI industry scenario and confirms Austrian industry's international leadership ambitions towards climate neutrality.

Cross-sectoral outcomes

In 2050, three energy carriers will dominate: carbon-neutral gases, electric energy and biomass. Strategies for the most efficient application and utilisation of these energy carriers in the different subsectors are fundamental in this study. Therefore, carbon-neutral gases and biomass are used predominantly for high-temperature heat provision and as a feedstock for basic materials production. Electrification by means of heat pumps is

[2] Circular economy aspects have been taken into account only on the level of using sequestrated CO_2 as a new feedstock for the production of chemical base materials. In all other sectors, the current production and value chains were maintained.

especially important for the decarbonisation of temperature levels up to 200°C, apart from general energy efficiency improvements such as heat recovery or more efficient state-of-the-art processes and plants.

Climate-neutral gases are particularly important for mitigating process-related GHG emissions across sectors. Minimising these process-related emissions constitutes a main lever for the decarbonisation of Austrian manufacturing industry. Most notably, this entails the decarbonisation of primary steel production by use of the DR/EAF route as well as the use of captured geogenic emissions from the non-metallic minerals sector for carbon-based products in the chemical and petrochemical industry. Such symbiosis can play a vital part in securing Austria's reputation as an attractive industry location. Suitable framework conditions must be developed to foster such intersectoral cooperations for industrial decarbonisation.

Together with decarbonisation efforts in the remaining economic sectors (e.g., buildings and transport), the expansion of (renewable) energy sources is necessary on an unprecedented scale, both at home and abroad. For Austria, this provides not only domestic added value, but also increases resilience to crises on the international energy markets. However, as the results above indicate and past studies confirm, a 100% self-sufficient and sustainable supply of energy in Austria is not attainable at the current economic output. Therefore, the existing practice of energy imports must be adapted to provide sustainable and secure energy supplies (Baumann et al., 2021; Diendorfer et al., 2021; Sejkora et al., 2022).

In future, climate-neutral industrial energy systems, cross-sector energy and material exchange will be crucial. However, today's framework conditions in terms of policies (no CO_2 storage, no incentives for intercompany or intersectoral energy and material exchange), infrastructure (e.g., non-existence of clustered industrial parks) and logistics still hinder the development of the industrial structures needed to achieve this optimal state.

Infrastructure and energy market development

The development of infrastructure and import plans must be aligned with the necessary energy carriers. Therefore, most notably, import options for the supply of carbon-neutral hydrogen, its derivates (e.g., ammonia) and other green gases must be found, gas infrastructure adapted accordingly, and electricity import capacities increased. In addition to providing electricity for a wide range of energy transformation and final consumption technologies, these electricity import capacities, in combination with existing gas storage in Austria, may help diversify the sourcing portfolio of green gases through domestic electrolysers (preferably at times of low electricity costs). The development of more resilient energy infrastructure is vital, due to the increase in volatile renewable electricity generation. Therefore, the investigation of infrastructural demands for the realisation of the NEFI decarbonisation scenario results must extend beyond the above-mentioned import capacities to include domestic transmission and distribution grids in electricity, gas and heat grids, as well as their interconnectivity. NEFI currently analyses future energy grid and infrastructure demands by extending the investigation scope beyond energy quantities obtained in the scenarios described above, by integrating a novel method for the development of sector- and process-specific industrial load profiles. The temporal resolution obtained is supplemented with a spatial resolution based on statistical indicators of economic activity as well as first-hand company reports on deployed on-site processes.

In order to better assess the magnitude of the import capacities needed and the domestic energy production required, all sectors of the Austrian economy must be considered. In many areas, industrial production is closely associated with the supply of electricity and heat to other sectors (e.g., district heating grids provided by steel or integrated paper production plants). In many categories of energy demand, the same levers of decarbonisation can be identified in other sectors (e.g., electrification of heat supply in buildings). Often, these parallel developments may increase the magnitude of the challenge and, consequently, the need for action. Therefore, a comprehensive decarbonisation scenario for all of Austria is needed, to provide an important guideline for decision makers in both industry and politics, and to guarantee implementation of decarbonisation technologies as described above. For Austria, the NEFI decarbonisation scenarios are designed to provide detailed information on the potential transformation of the thirteen subsectors of manufacturing industry. Both scenarios presenting significant decarbonisation advances underline the importance of fundamental changes in technology deployment in the time frame 2025-2030 in order to guarantee that the net zero emissions goal can be achieved by the middle of the century.

Conclusion: In order to reach the climate targets, the need to establish strong infrastructures and secure energy supplies is clear. While the former is already included in the political decision-making process, the latter is not. A climate-neutral energy system depends on the availability of a huge amount of renewable gases. To reduce energy imports to a minimum, demand should be limited to those applications for which there are no domestic alternatives. In this respect, industrial high-temperature and process energy demand are crucial factors.

7. Kurzfassung

Auf der Pariser Klimakonferenz (COP21) im Jahr 2015 verpflichteten sich mehr als 196 Länder auf das Ziel, die globale Erwärmung auf deutlich unter 2°C im Vergleich zum vorindustriellen Niveau zu begrenzen. Die Europäische Union will mit dem *European Green Deal* und dem Ziel der Klimaneutralität bis zum Jahr 2050 eine Vorreiterrolle einnehmen. Österreich als Mitgliedsstaat unterstützt dieses Ziel und hat sich in vielen Bereichen noch ambitioniertere Ziele gesetzt. Die österreichische Bundesregierung verfolgt in ihrem aktuellen Gesetzgebungsprogramm das ehrgeizige Ziel, ihr Wirtschaftssystem bereits bis 2040 vollständig klimaneutral zu stellen.

Die österreichische verarbeitende Industrie spielt für das Erreichen dieser Ziele eine wichtige Rolle, da ihr Anteil an den gesamten österreichischen Treibhausgasemissionen im Jahr 2019 34% (25 Mio. t CO_2e) betrug. Der Gesamtenergiebedarf zur direkten Versorgung aller Prozesse der Industriestandorte beträgt rund 27% (110 TWh/a) des nationalen Bruttoinlandsenergieverbrauchs. Die Industrie hat auch einen großen Einfluss auf das Allgemeinwohl und die sozioökonomische Entwicklung der österreichischen Wirtschaft. Mit insgesamt 93 Mrd. $€_{2019}$ betrug ihr Anteil am nationalen BIP im Jahr 2019 24,8%. Historisch gesehen ist die Industrie ein wichtiger Motor für den Wohlstand in Österreich, da sie durch Forschung und Entwicklung in einer Reihe von Sektoren eine weltweite Führungsposition einnimmt. Die energieintensivsten Sektoren sind Eisen und Stahl, nicht-metallische Mineralien, die chemische und petrochemische Industrie sowie die Papier- und Zellstoffindustrie. Zusammen machen sie einen kumulierten Anteil von 61% (82 TWh 2019) des gesamten Energiebedarfs und 79% (21 Mio. t 2019) der Treibhausgasemissionen des verarbeitenden Gewerbes aus. Die meisten der derzeit in diesen Sektoren eingesetzten Produktionsverfahren entsprechen den sogenannten Best-Available-Technologies der Europäischen Kommission.

Das Innovationsnetzwerk New Energy for Industry (NEFI) ist die zentrale Anlaufstelle für die Bestrebungen der Industrie, in Österreich Klimaneutralität zu erreichen. In NEFI arbeiten Stakeholder aus einer Vielzahl von Teilsektoren gemeinsam mit Forschern und Ingenieuren an der Entwicklung neuartiger und umweltfreundlicher Technologien, die dazu beitragen, die Klimaneutralität der Industrie zu erreichen, den Industriestandort Österreich zu fördern und die globale Technologieführerschaft zu sichern.

Ziel dieser Studie

NEFI hat innerhalb des oben genannten Rahmens die nachfolgend beschriebenen Nachfrageszenarien für die Industrie entwickelt, die eine wichtige visionäre Leitlinie für die Akteure der verarbeitenden Industrie, für politische Entscheidungsträger und Technologieanbieter darstellen. In dieser Studie werden die Ergebnisse der drei NEFI-Szenarien für den Zeitrahmen 2017 bis 2050 vorgestellt:

I. Business-as-usual (BAU)
II. Pathway-of-industry (POI)
III. Zero-Emission (ZEM)

Der Vergleich der Ergebnisse dieser Szenarien zeigt die Bandbreite der verschiedenen Pfade zur industriellen Klimaneutralität auf und ermöglicht es, die wichtigsten Handlungsfelder zu identifizieren. Diese Studie konzentriert sich auf die Erarbeitung von Nachfrageszenarien der österreichischen Industrie und bezieht die Bereitstellung von Energieträgern nur in geringem Ausmaß dort mit ein, wo dies relevant ist. Daher werden notwendige Annahmen über die Entwicklung der CO_2-Intensität des Stromsektors und die Zusammensetzung des Gasnetzes einbezogen.

Methodik

Die vorliegende Studie wurde 2018 mit Blick auf die EU-Klimaziele für 2050 initiiert und nutzt den Zeitraum von 2017 bis 2019 als Basis für die Szenarioprojektionen. Obwohl das aktuelle Regierungsprogramm Klimaneutralität bis 2040 anstrebt, wurde das Zieljahr 2050 beibehalten, um eine internationale Vergleichbarkeit zu ermöglichen und die Sichtbarkeit der Projektergebnisse zu erhöhen. Um Entwicklungsunsicherheiten zu berücksichtigen und eine solide Vergleichsbasis zu schaffen, decken drei Szenarien eine Bandbreite an Entwicklungsmöglichkeiten ab.

Zentrale Handlungshebel zur Erreichung der Klimaneutralität in der österreichischen Industrie

In Anlehnung an frühere Studien werden in dieser Arbeit die folgenden vier zentralen Hebel für die Klimaneutralität der Industrie identifiziert.

- Signifikante Verbesserung der Energieeffizienz aller industriellen Prozesse und emissionsarme Elektrifizierung des thermischen und motorischen Energiebedarfs (Wärmepumpen und Motoren)
- Brennstoffumstellung auf kohlenstoffneutrale Gase (Wasserstoff, Bio- und synthetisches CH_4)
- Technologien zur Kohlenstoffabscheidung (Carbon Capture)
- Aspekte der Kreislaufwirtschaft[1]

Die Auswirkungen der Umsetzung dieser Hebel werden untersucht und in den drei Nachfrageszenarien dargestellt. Der Vergleich der Szenarien ermöglicht die Ermittlung technologischer Lücken in Bezug auf den Zielpfad.

Das **Szenario Business-as-usual (BAU)** dient als Referenzszenario, das die Bewertung der Wirksamkeit innovativer Technologien in den beiden folgenden Übergangsszenarien ermöglicht. Es wird durch Extrapolation historischer Trends und Prognosen der wirtschaftlichen Entwicklung gewonnen. Dies steht im Gegensatz zu einem Szenario "mit bestehenden Maßnahmen", das eine Prognose auf der Grundlage aktueller Randbedingungen beinhalten würde.

Das **Szenario Pathway-of-industry (POI)** ist das Ergebnis eines engen Dialogs mit Vertretern führender industrieller Interessengruppen, die eine Bewertung des Technologieeinsatzes in ihren jeweiligen Sektoren unter den derzeitigen und absehbaren Randbedingungen bis 2030 angekündigt haben. Auf der Grundlage dieser Bewertung wird die Entwicklung bis 2050 hinsichtlich der erwarteten Technologieverfügbarkeit extrapoliert. Dieses Szenario ist eine einzigartige Darstellung aktueller industrieller Transformationspläne und kann sich dazu eignen, wichtige Bereiche für policy-Maßnahmen zur Erreichung der Klimaneutralität zu identifizieren.

Das **Szenario Zero-Emission (ZEM)** stellt die Umsetzung umfangreicher und ambitionierter Maßnahmen dar, die eine vollständige Klimaneutralität des industriellen Energiesystems in Österreich bis 2050 ermöglichen können. Es wendet sogenannte Breakthrough-Technologies an, die wissenschaftlich als die vielversprechendsten Lösungen identifiziert wurden, um die Transformationsherausforderung sektorspezifisch anzugehen. Ein Backcasting-Ansatz wird zur Berechnung eines normativen Pfades verwendet. Das bedeutet, dass der ideale Zielzustand der Klimaneutralität im Jahr 2050 festgelegt und ein Pfad von damals bis heute entwickelt wird, der die erfolgreiche Erreichung dieses Ziels ermöglicht.

Die Ergebnisse der Szenarien werden auf der Grundlage eines Gesamtenergiebedarfsansatzes berechnet, der die Berücksichtigung aller für die industrielle Produktion erforderlichen Energieströme gewährleistet. Dies umfasst sowohl die Endenergieanwendungen als auch den Energieeinsatz in industriellen Umwandlungseinheiten (z. B. Hochöfen oder KWK-Anlagen). Darüber hinaus spielt die Bereitstellung von erneuerbaren Energien durch den Energiesektor eine wichtige Rolle bei der Erreichung der industriellen Klimaneutralität und wurde in die Modellierung einbezogen. Um die Interdependenzen zwischen dem österreichischen und dem europäischen Stromsystem zu berücksichtigen, wurde die tatsächliche THG-Intensität der modellierten industriellen Transformation anhand der THG-Entwicklung der Stromerzeugung für die EU-27 berechnet. Die Anteile der erneuerbaren Gase wurden für jedes Szenario spezifisch berechnet. Diese berücksichtigen u.a. die Entwicklung der Kosten für Elektrolyse und CO_2-Emissionszertifikate. In den Szenarien POI und ZEM erreicht Wasserstoff zwischen 2035 und 2045 den wirtschaftlichen Break-Even zu fossilen CH_4-Preisen und beginnt damit, Marktanteile im Gasnetz und damit in allen Sektoren zu gewinnen.

Wichtigste Ergebnisse der Industrieszenarien

Szenario Business-as-usual (BAU): Im Szenario BAU setzt sich der historische Trend fort, dass sich Effizienzsteigerung und steigende Produktionstätigkeit im Hinblick auf die Treibhausgasintensität gegenseitig aufheben (Abbildung 1). Aufgrund der zunehmenden Produktionstätigkeit steigt der Energiebedarf bis 2050 um bis zu 29 TWh auf insgesamt 161 TWh, wenn die Elektrolyseverluste berücksichtigt werden (156 TWh ohne Elektrolyseverluste, wenn man von einem begrenzten Einsatz von Wasserstoff ausgeht). Die österreichische Industrie stützt sich weiterhin zu einem großen Teil auf fossile Energieträger (wie Kohle, Naphtha und Öl), sowohl was den Energie- als auch den Rohstoffbedarf betrifft, was zu einem Gesamtausstoß von 23,08 Mt CO_2e im Jahr 2050 führt.

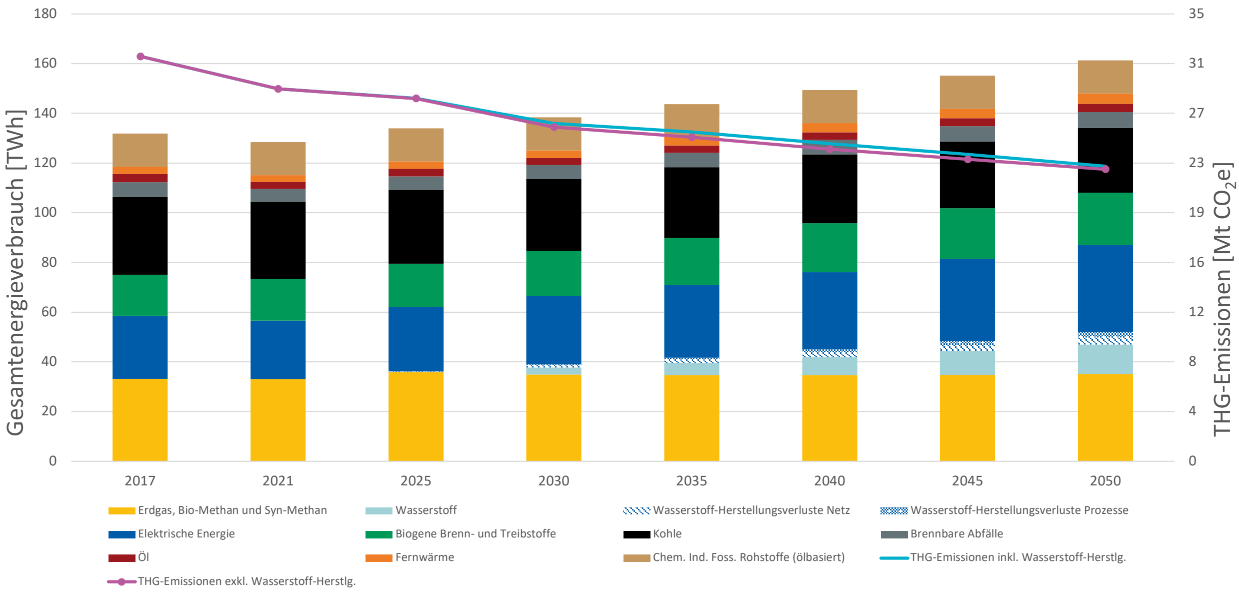

Abbildung 1: Gesamtenergiebedarf und Treibhausgasemissionen der österreichischen Industrie im Szenario BAU

Szenario Pathway-of-Industry (POI): Bis 2025 folgen die Gesamtenergienachfrage und die THG-Emissionen dem BAU-Szenario. Ab 2025 zeigen die Übergangsszenarien POI (Abbildung 2) und ZEM (Abbildung 3) jedoch deutlich abweichende Muster hinsichtlich der THG-Emissionen. Dies ist auf den angenommenen Ausstieg aus fossilen Brennstoffen und Rohstoffen und einen zunehmenden Anteil emissionsarmer oder kohlenstoffneutraler Energieträger in POI und ZEM zurückzuführen. In beiden Übergangsszenarien ist die Energienachfrage bis 2050 durch drei grundlegende Gruppen von Energieträgern gekennzeichnet: Strom, Gase und Biomasse.

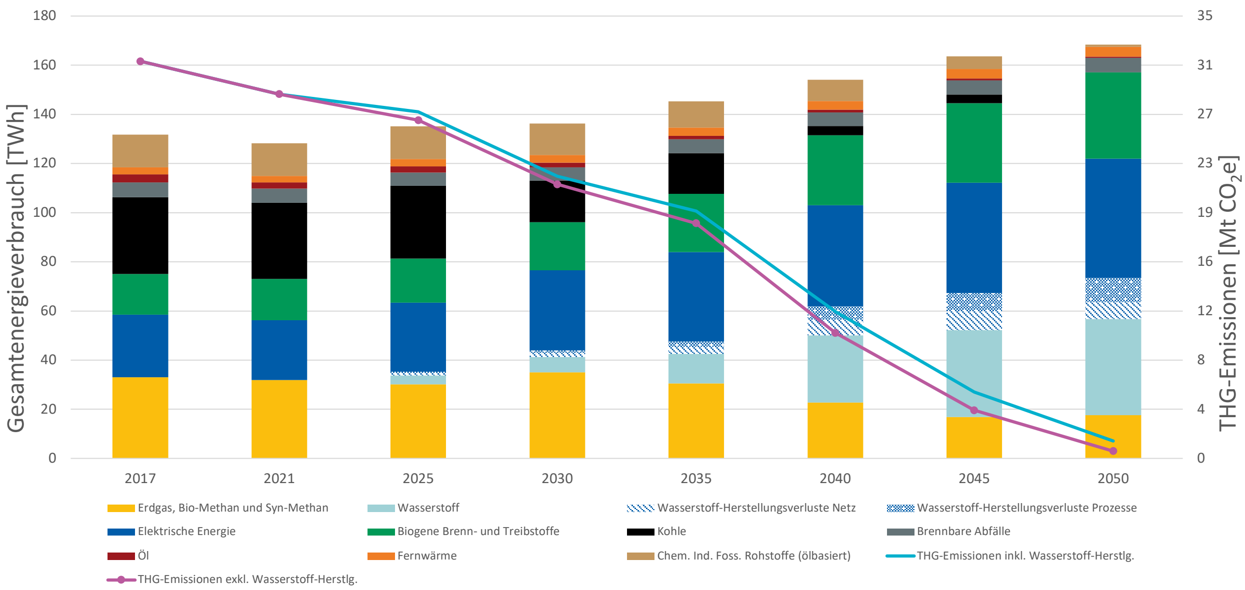

Abbildung 2: Gesamtenergiebedarf und Treibhausgasemissionen der österreichischen Industrie im Szenario POI

POI folgt den aktuellen Transformationsplänen der Industrie. Die Ergebnisse zeigen, dass weitreichende Fortschritte in Richtung Klimaneutralität der österreichischen verarbeitenden Industrie bis 2050 möglich sind. Der Gesamtenergiebedarf steigt auf 168,3 TWh, wenn die Elektrolyseverluste berücksichtigt werden. Ohne Elektrolyseverluste liegt der Energiebedarf bei 151 TWh. Je nach betrachteter Bilanzgrenze können die THG-Emissionen um bis zu 30,8 Mio. t CO_2e auf nur 0,58 Mio. t im Jahr 2050 reduziert werden, wenn die Emissionsintensität der Elektrolyse für die Wasserstofferzeugung nicht berücksichtigt wird. Neben einem weitreichenden Brennstoffwechsel zu nachhaltigen Energieträgern sind die Sequestrierung geogener

Emissionen und die Anwendung innovativer Prozesstechnologien für die Primärstahlerzeugung die wichtigsten Treiber für diese Entwicklung.

Szenario Null-Emissionen (ZEM)

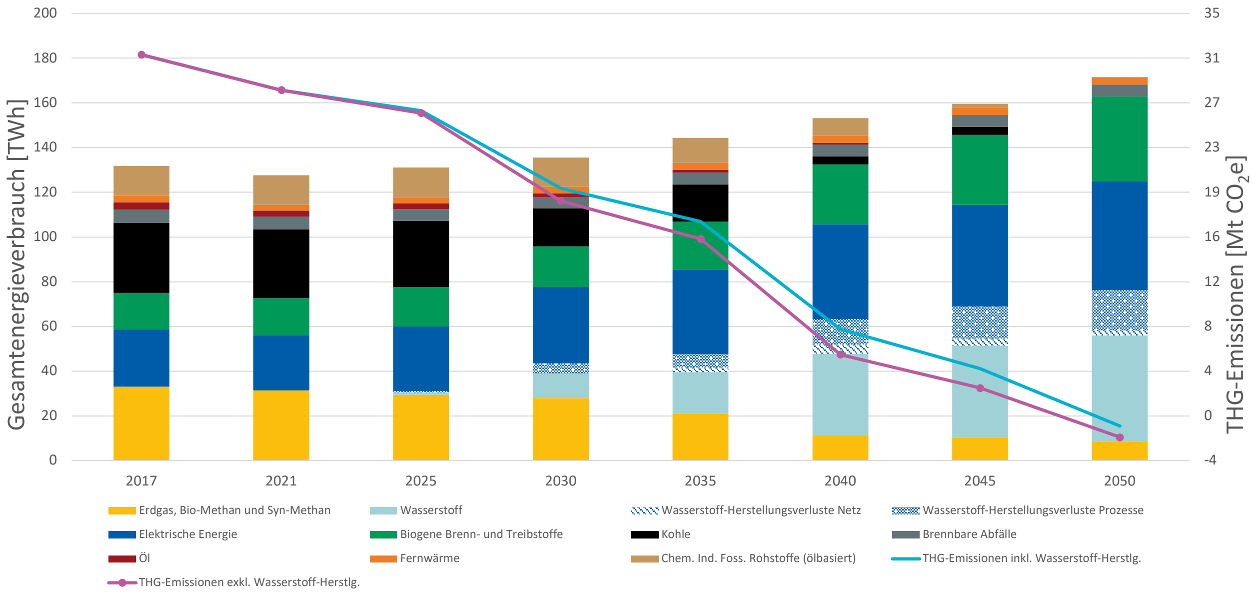

Abbildung 3: Gesamtenergiebedarf und Treibhausgasemissionen der österreichischen Industrie im Szenario ZEM

ZEM stellt den ehrgeizigsten Weg zur Klimaneutralität der Industrie dar. Im Szenario ZEM steigt der Gesamtenergiebedarf bis 2050 auf bis zu 171,5 TWh. Im Vergleich zum POI wird dies vor allem durch den verstärkten Einsatz von wasserstoffbasierten Produktionsrouten in der Eisen- und Stahlindustrie sowie in der chemischen und petrochemischen Industrie getrieben, was auch die Verluste aus der daraus resultierenden Wasserstoffproduktion erhöht. Ohne Berücksichtigung der Verluste bei der Elektrolyse entspricht der ZEM-Energiebedarf im Jahr 2050 mit 151 TWh pro Jahr den Ergebnissen des POI.

Allgemeine Ergebnisse

In beiden Szenarien, POI und ZEM, dient der chemische und petrochemische Sektor als notwendige CO_2-Senke, um die verbleibenden Treibhausgasemissionen der österreichischen verarbeitenden Industrie zu reduzieren. Dominierend ist hierbei die Senke für sequestriertes geogenes und daher schwer abbaubares CO_2 aus dem Sektor der nichtmetallischen Mineralien. Insgesamt werden im chemischen und petrochemischen Sektor netto bis zu 5 Mio. t CO_2 absorbiert.

In beiden Übergangsszenarien wird ein Biomassebedarf von etwa 35 bis 40 TWh berechnet, während die Trendextrapolation im Szenario BAU etwa 21 TWh/a erreicht.

Für die industrielle Klimaneutralität sind in beiden Szenarien, POI und ZEM, ca. 50 TWh Strom für Endenergieanwendungen notwendig. Neben allgemeinen Elektrifizierungsbestrebungen, z.B. Wärmepumpen, wird die Stromnachfrage vor allem durch die Umwandlung von prozessemissionsintensiven Sektoren wie Eisen und Stahl und nichtmetallische Mineralien getrieben. In diesen Sektoren ist die Einführung von elektrischen Lichtbogenöfen und Anlagen zur Kohlenstoffabscheidung für einen erheblichen Bedarf an elektrischer Endenergie verantwortlich. Berücksichtigt man den möglichen zusätzlichen Strombedarf für die Wasserstofferzeugung durch Elektrolyse, so steigt der Gesamtstrombedarf für die industrielle Produktion in Österreich auf etwa 116 TWh/a.

Im Gassektor ist ein unterschiedlicher Einsatz von Technologien zwischen den Szenarien POI und ZEM zu beobachten. Im POI setzen die Industrievertreter stärker auf CH_4- und biomassebasierte Technologien, während die ZEM-Ergebnisse wasserstoffbasierte Technologien betonen.

Schlussfolgerungen und Handlungsempfehlungen

Die folgende Tabelle 2 gibt einen Überblick über die wichtigsten Schlussfolgerungen aus den Ergebnissen der Szenarien und leitet daraus Handlungsempfehlungen ab.

Tabelle 2: Schlussfolgerungen aus den Dekarbonisierungsergebnissen und abgeleitete Handlungsempfehlungen.

Schlussfolgerung	Handlungsempfehlung
Für die Dekarbonisierung des industriellen Energiesystems sind alle vier zentralen Hebel notwendig: • Verbesserung der Energieeffizienz und emissionsarme Elektrifizierung • Brennstoffumstellung auf CO_2-neutrale Gase oder Biomasse • Technologien zur Kohlenstoffabscheidung • Kreislaufwirtschaft	*Energieintensive Industrien müssen ihre spezifischen Technologien schnell erforschen, entwickeln, demonstrieren und einführen, um auf dem Weg zu den Zielen zu bleiben.* *Der nicht energieintensive Sektor muss die Einführung sektorübergreifender Technologien (z. B. Wärmepumpen) beschleunigen, um auf dem Weg zur Erreichung der Ziele zu bleiben und seinen Wettbewerbsvorteil zu wahren;* • Forschung und Entwicklung UND Demonstration sind der Schlüssel zu einer schnellen Umsetzung neuer Technologien in der Industrie. Die Anstrengungen in beiden Bereichen müssen verstärkt und beschleunigt werden.
Im Jahr 2050 werden drei Energieträger dominieren: • CO_2-neutrale Gase • Elektrische Energie • Biomasse	• Die Versorgung mit erneuerbaren Energieträgern (Gase, Strom) muss gesichert werden • Die Nutzung der Energieträger muss nach technologischen Erfordernissen sowie nach Temperaturniveaus priorisiert werden (z.B. CO_2-neutrale Gase für Hochtemperaturprozesse, Heizen und Kühlen durch Wärmepumpen etc.)
Die Umstellung auf CO_2-neutrale Gase stellt einen wesentlichen Hebel zur Erreichung der Klimaneutralität in der österreichischen Industrie dar, denn: • Sie stellen eine sektorübergreifende Minderung der prozess- und hochtemperaturwärmebedingten Treibhausgasemissionen dar	• Infrastrukturen wie Gasnetze oder Gasspeicher müssen für den Umgang mit CO_2-neutralen Gasen (z.B. Wasserstoff, Bio-CH_4, Syn-CH_4) in geeigneter Weise vorbereitet sein, einschließlich einer Infrastruktur für H_2/CH_4-Gemische sowie einer speziellen H_2-Infrastruktur (diese kann verschiedene H_2-Trägermedien wie Ammoniak umfassen). • Die Beschaffung von erneuerbaren Gasen muss neue Optionen und Importwege umfassen.
CO_2-neutraler Wasserstoff bietet auch die Möglichkeit, abgeschiedene geogene Emissionen aus dem Sektor der nicht-metallischen Mineralien in neuartigen wasserstoffbasierten Produktionsprozessen der chemischen und petrochemischen Industrie zu nutzen.	• Technologische, logistische und politische Lösungen für CO_2 als Ausgangsstoff müssen gefunden werden
Im Rahmen dieser Studie werden die derzeitigen Produktions- und Wertschöpfungsketten beibehalten. Dies führt in beiden Transformationsszenarien zu einem steigenden industriellen Energiebedarf. ZEM und POI kommen jedoch zu ähnlichen Ergebnissen, was auf Robustheit schließen lässt.	Wenn ... • die Kreislaufwirtschaft in der industriellen Produktion verbessert wird (unter Berücksichtigung der Besonderheiten der einzelnen Sektoren), und/oder • Vorprodukte importiert werden (insbesondere erneuerbares NH_3, Methanol und Naphtha) ...kann auch ein geringerer Energiebedarf in der Industrie erreicht werden.
Implikationen für das gesamte Energiesystem:	
Klimaneutralität in der Industrie ist Teil der österreichweiten Bemühungen in allen Nachfragesektoren (auch Gebäude, Verkehr) und in der Energiewirtschaft. Um die Klimaneutralität in Österreich zu erreichen, können die auf	• Die heimische Energieerzeugung aus erneuerbaren Quellen muss über die für 2030 gesetzten Ziele hinaus gesteigert werden.

der rechten Seite aufgezählten Maßnahmen als "no regret"-Aktivitäten betrachtet werden.	• Der österreichweite Bruttoinlandsenergiebedarf kann die technischen EE-Potenziale übersteigen. Importstrategien, insbesondere für CO_2-neutrale Gase und deren Derivate, müssen entwickelt werden, um eine nachhaltige und sichere Energieversorgung für die Zukunft zu gewährleisten. • Die Energieinfrastruktur ist essentiell, um die oben genannten Entwicklungen zu ermöglichen. Dazu gehören erweiterte Stromnetzkapazitäten sowohl für den inländischen als auch für den grenzüberschreitenden Stromtransport. Dazu gehören auch die Infrastrukturen für Wasserstoff und/oder seine Derivate.

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9. Austrian Industry at a glance: industry sector fact sheets

9.1 Iron and steel

Austria's iron and steel industry is Europe's sixth-largest steel producer, accounting for 5% of total European steel production in 2019. In Austria, two different steel production technologies are now in use: primary steelmaking by blast furnace/basic oxygen furnace route (BF/BOF) and secondary steelmaking by electric arc furnaces (EAF). In 2019, 90% of total steel output was accounted for by BF/BOF and 10% by EAF (World Steel Association, 2020). The iron and steel production sector is concentrated in 52 companies employing a total of 24,642 people, and the sector gross value added to the Austrian economy amounts to approximately EUR 2.8 billion. (Diendorfer et al., 2021).

Table 4: Overview of the iron and steel industry (Diendorfer et al., 2021)

Number of companies	52
Employees	24 642
GDP-VA in€ million	2 757
GHG emissions in Mt CO_2	11.9
Share of GHG emissions in the sector industry	46.0%

In 2019, iron and steel manufacturing consumed approx. 35.1 TWh of total energy, accounting for 10% of Austria's total gross domestic energy consumption. As shown in the energy Sankey diagram in Figure , approximately 88% of this energy comes from fossil fuels including coal, coke, natural gas, and bituminous coke. Fossil fuel is mainly used for two purposes: 54% as a reducing agent and 46% as an energy source (Statistics Austria, 2021a). In order to extract the oxygen compounds-bound iron (Fe_xO_y) in the blast furnace, the carbon contained in the coal is used as a reducing agent. After all relevant reactions have been completed, the reaction of carbon together with the oxygen initially present in the iron ore generates the greenhouse gas CO_2. In addition to CO_2, the coking plant and the BF/BOF route also produce high energy waste gases, which are used in power and CHP plants to generate electricity and steam or heat.

In 2019, iron and steel manufacturing also utilised 10.5 TWh of final energy, as displayed in Figure 72. This amount corresponds to 12% of industrial final energy use and is consumed primarily to provide high-temperature process heat in furnaces (Statistics Austria, 2021b).

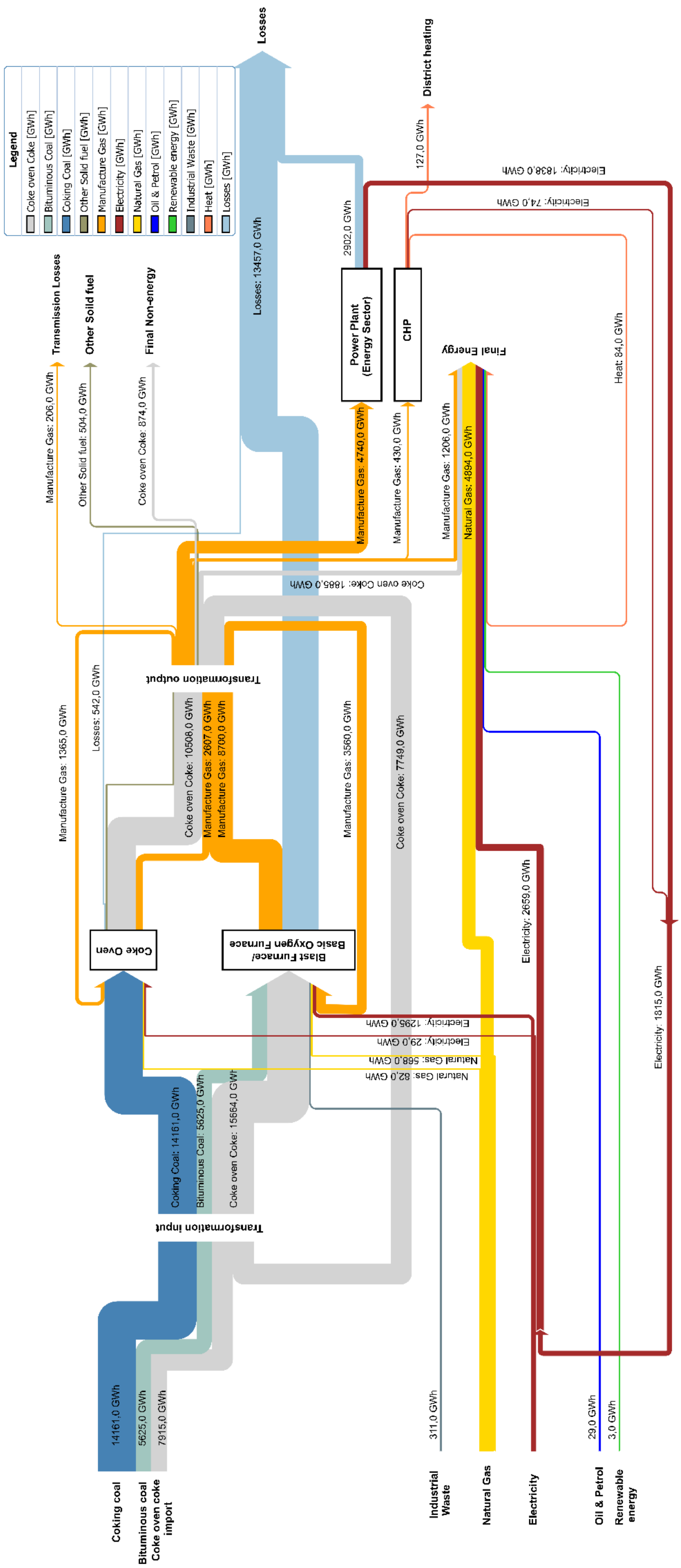

Figure 71: Energy Sankey diagram of the Austrian iron and steel industry. Own illustration based on Statistics Austria (2021b, 2021a).

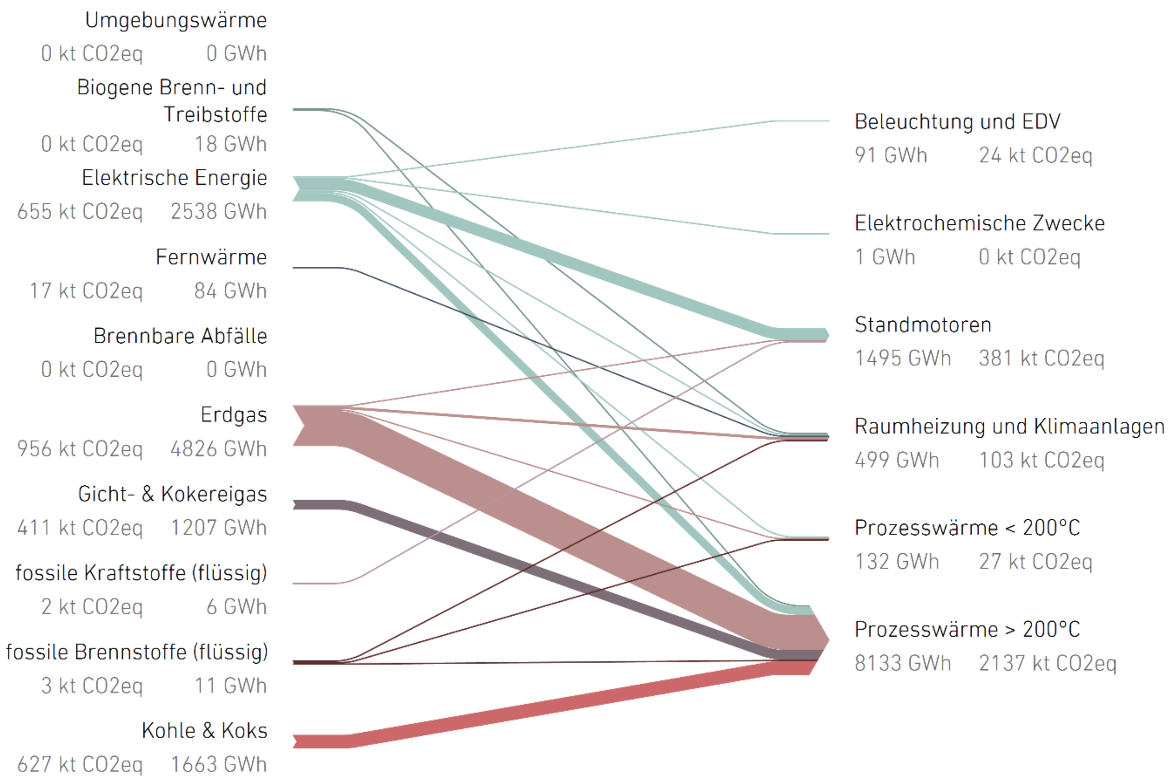

Figure 72: Final energy and GHG intensity of the supply of useful energy categories in the Austrian iron & steel industry 2019 (Diendorfer et al., 2021).

Austrian steel production contributed about 12.3 Mt CO_2e to the Austrian GHG balance in 2019, accounting for 12.9% of total national GHG emissions, mainly due to fossil fuel use as a reducing agent, with a share of 90% for process-related emissions (UBA, 2021a). Essentially, all emissions from the sector are included in the ETS. The emissions are caused by 3 companies, with voestalpine AG and its subsidiaries responsible for over 99% of the emissions (see Table 5).

Table 5: ETS-listed companies in the iron and steel production sector, including verified GHG emissions for 2019. Own representation based on European Commission, 2020a.

Company	Energy-related GHG emissions in t CO_2 e
Production of raw iron, steel and ferroalloys	**11 952 918**
voestalpine Stahl Linz	812 969
Sinteranl., Hochöfen, Stahlwerk Donawitz	2 846 643
Stahlproduktion Böhler Edelstahl Kapfenberg	129 297
voestalpine Schienen GmbH	48 666
voestalpine Wire Rod Austria GmbH	39 612
Stahlwerk Marienhütte GmbH	36 550
Breitenfelder Edelstahl Mitterdorf	26 777
voestalpine BÖHLER Bleche GmbH & Co KG	12 404
Production of steel pipes, pipe fittings, pipe plugs and pipe unions of steel	**62 610**

voestalpine Tubulars GmbH & Co KG	62 610
Total	**12 015 528**

In secondary steelmaking, electric arc furnaces and a few gas-fired melting furnaces are used to melt down around 1 Mt of steel scrap per year for secondary metallurgical processing. The energy requirements and CO_2 emissions created in this process are attributes that can only be allocated to the final energy categories presented in Figure 72. The final energy consumption and the resulting GHG emissions of secondary steelmaking are also included in the diagram in Figure 72.

In Austria, the iron and steel subsector has focused on increasing energy efficiency and process control in order to minimise emissions, particularly from the BF/BOF route. Because of these efforts, between 1990 and 2019, specific CO_2 emissions were reduced from 2.15 t CO_2 to 1.7 t CO_2 per ton of steel in BF/BOF production processing (UBA, 2021a).

The most promising and effective technologies that have been screened in the process of scenario modelling are summarised in Table 6.

Table 6: Emission reduction technology options for the iron and steel industry

Technology option	TRL	Description
Electrification	4-5	Use of electricity to reduce the iron ore in two ways: Electrolysis (ULCOLYSIS) and Electrowinning (ULCOWIN) (World Steel Association, 2021). Emission reduction potential (EUROFER, 2013): 30% with today's electricity generation mix 98% with CO_2-free electricity generation
Smelting reduction process (HIsarna)	7	Reduce directly injected iron ore at the top and coal powder at the bottom by using purified oxygen to replace the air in the smelting reduction process. The process will produce CO_2-rich waste gas and is suitable for combination with a CCS plant (Junjie, 2018). Emission reduction potential (EUROFER, 2013): 20% without CCS 80 % with CCS
Top gas recycling (TGR)	7	Recycle the CO and H_2-containing blast furnace exhaust gas (BFG) and utilise it as a reduction agent to replace coke or coal (Junjie, 2018; van der Stel et al., 2014). Emission reduction potential (EUROFER, 2013): 15% without CCS 60% with CCS
Direct reduction with natural gas	9	Use of natural gas as a reducing agent in direct reduced iron (DRI) replacing coke. To increase the emission reduction efficiency process can be integrated with CCS (EUROFER, 2013). Emission reduction potential: 40% without CCS (Material Economics, 2019b) 80% with CCS (EUROFER, 2013)
H_2 plasma direct reduction	4	Use of H_2 plasma to melt the pre-reduced fine or pelletised iron ore as reductant (IEA, 2020).
Direct reduction iron with hydrogen (DRI-H_2)	5	Use H_2 (renewable) instead of coal to reduce iron ore pellets in the shaft furnace or fine iron powder in the fluidised bed (IEA, 2020). Emission reduction potential: Up to 95% (Chan et al., 2019)
CCS/ CCUS	6-7	CO_2 separation of other produced gases (BF gas containing up to 60% CO_2) in the iron-making process and capture it. The captured CO_2 can be used in other industrial processes, such as the chemical industry (Material Economics, 2019b). Emission reduction potential: 50- 90%

9.2 Pulp and paper

In Austria, the pulp, paper and printing sector combines the production of paper, paperboard, and goods made from them, as well as the manufacture of printed products, producing around 5 Mt of paper, or 5.6% of EU paper production in 2019 (CEPI, 2020). The sector comprises 957 pulp, paper and paperboard and printing manufacturing companies with 27,458 employees and a gross value added of EUR 2.79 billion (Diendorfer et al., 2021). They produce around 48% of paper from raw wood (via 15% mechanical pulp, 63% kraft and sulphite pulp, and 22% textile pulp), and the rest from RCF pulp using recovered paper (with a paper recycling rate of 77.6% in 2019)(Austropapier, 2021). Paper production comprises 46% graphic paper, 48% packaging and board, and 6% special paper, such as sanitary and beverage labels (Austropapier, 2021).

Table 7: Overview of the pulp, paper and printing industry (Diendorfer et al., 2021)

Number of companies	957
Employees	27 458
GDP-VA in€ million	2 791
GHG emissions in Mt CO_2	1.98
Share of GHG emissions in the sector industry	7.7%

In 2019, the pulp, paper and printing sector consumed 22.5 TWh of total energy, accounting for more than 5% of Austrian gross domestic energy production (see Figure 73) (Statistics Austria, 2019, 2021a). Approximately 21.4 TWh were used as final energy, corresponding to 24.5% of industrial final energy consumption in 2019. Figure presents an overview of supplied final energy categories. As shown, energy is mainly used for generating steam which is used in the drying and separation process (73.6%) (Statistics Austria, 2021b). The Austrian pulp and paper sector is equipped with local heat and power generators, especially in integrated paper mills and chemical pulping mills. The biofuel obtained from chemical pulping, mainly black liquor, is used in the cogeneration plants (CHP) and, together with other internal bioenergy sources such as waste wood and biogas, generates the majority of the electricity demand, approximately 3 TWh, which corresponds to 69% of the sector's total electricity demand in 2019 (Austropapier, 2021). Subsequently, the steam output at low and medium pressure is applied to production processes, making the sector mostly self-sufficient in terms of steam generation. Excess heat and electricity are fed into the grid (Austropapier, 2021).

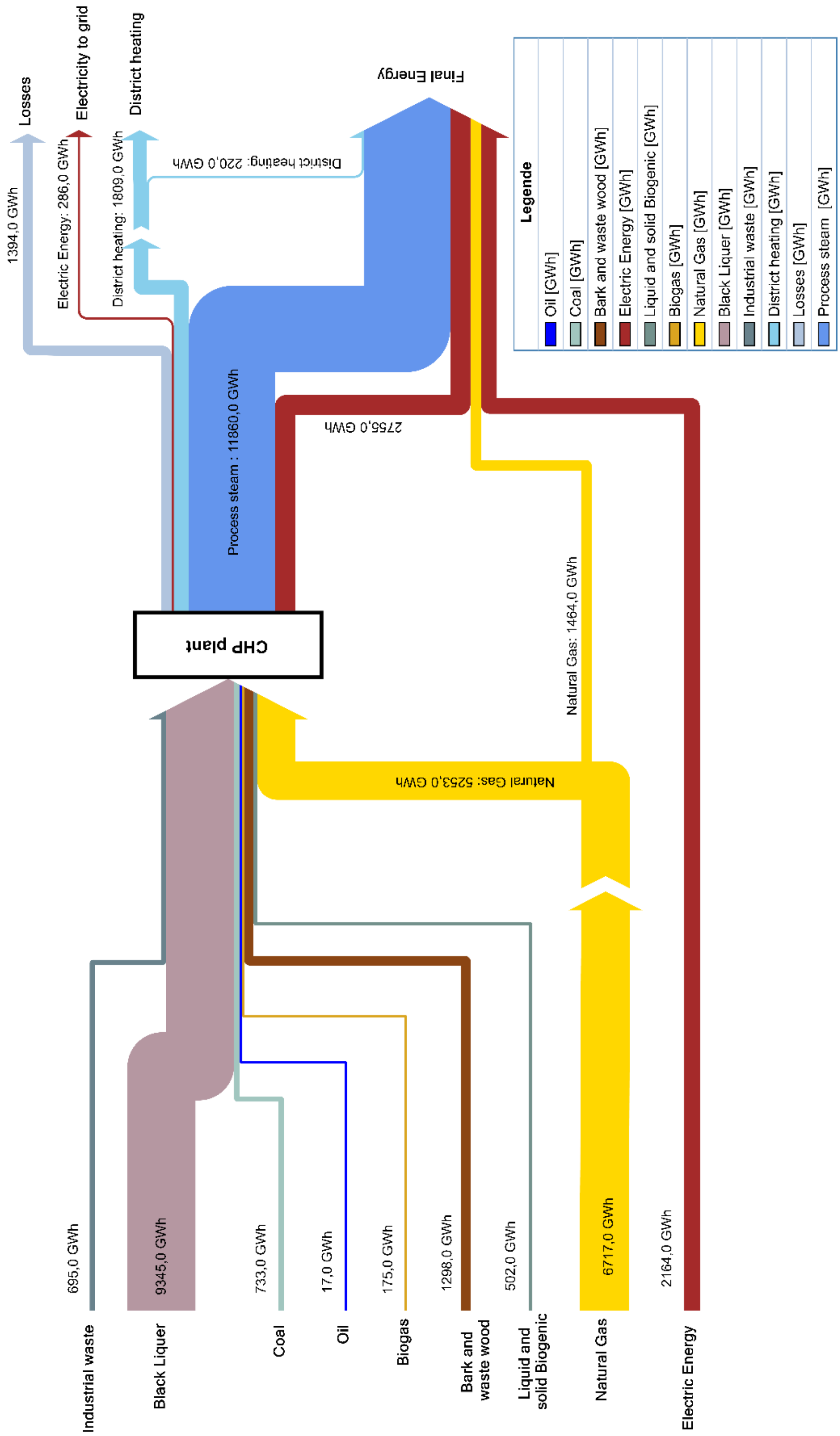

Figure 73: Energy flow diagram of the paper & printing sector. Own illustration based on Rahnama Mobarakeh et al. (2021); Statistics Austria (2021a).

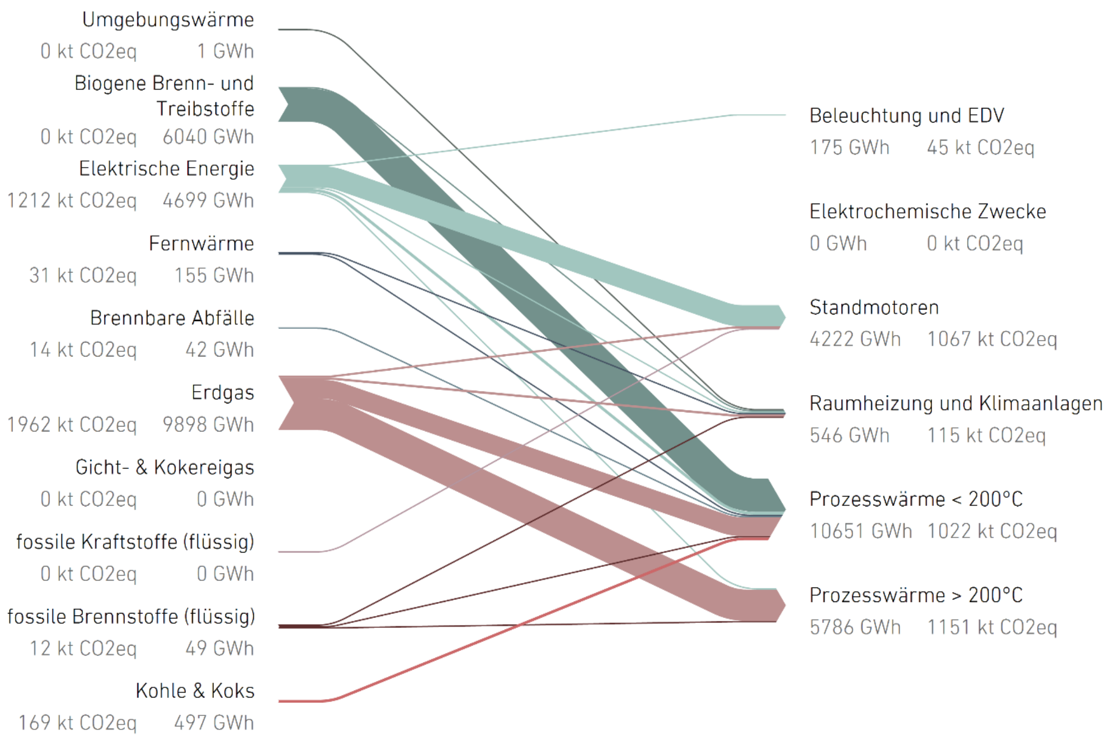

Figure 74: Final energy and GHG intensity of the supply of useful energy categories in the Austrian pulp, paper and printing sector in 2019 (Diendorfer et al., 2021)

As can be seen in the energy flow Sankey diagram in Figure 74, around 40% of fossil fuels (coal, oil, and natural gas) were consumed as energy sources. The fossil fuels used in the Austrian pulp and paper sector emitted approximately 2kt CO_2 as direct or fuel-related emissions in 2019 (including a small share of 3% process-related emissions from the lime kiln) (Austropapier, 2021; European Environment Agency, 2021a). Nineteen companies in the sector are listed in the ETS and together emit over 1.4 Mt CO_2e (see Table 8).

Table 8: ETS-listed companies in the pulp, paper & printing sector, including the verified GHG emissions in 2019. Own representation based on (European Commission, 2020).

Company	Energy-related GHG emissions in t CO_2 e
Production of cardboard and paper	**1 368 858**
Sappi Gratkorn	419 088
Norske Skog Bruck GmbH	199 666
Papierfabrik Hamburger Pitten	165 791
Mayr Melnhof Karton Frohnleiten	147 384
Neusiedler Hausmening	84 083
Essity Ortmann	73 393
Nettingsdorfer Ansfelden	56 979
Frantschach St. Gertraud	38 419
Feinpapier Feurstein Traun	36 744

Steyrermühl AG Steyrermühl	36 125
Mayr Melnhof Karton Hirschwang	27 836
Neusiedler Kematen	24 153
Rondo Ganahl Frastanz	23 921
Papierfabrik Wattens	21 151
Merckens Schwertberg	3 930
Profümed GmbH	3 467
Brigl & Bergmeister Niklasdorf	3 424
SCA Laakirchen	2 329
Lenzing Papier GmbH	975
Production of pulp	**63 537**
Zellstoff Pöls	53 294
Neusiedler Zellstoff Kematen	8 184
M-real Hallein	2 059
Total	**1 432 395**

In Austria, the pulp, paper and printing sector has improved its energy efficiency in recent decades. Over the last twenty years, by implementing the best available technologies, transitioning from fossil fuels to biofuel produced on-site (black liquor), and increasing recycling rates have allowed the industry to reduce absolute CO_2 emissions by roughly 20% and specific CO_2 emissions per ton of paper by 40% (Austropapier, 2021). Further emission reductions can be obtained using cutting-edge technological paths that have been included in the scenario modelling and are summarised in Table 9.

Table 9: Emission reduction technology options for the pulp, paper and printing industry.

Technology option	TRL	Description
Black liquor gasification (BLG)	8-9	BLG is a new technology capable of efficiently recovering energy from the black liquor's organic content using a recovery boiler and gasification process (Moya, J. A., Pavel, 2018). Emission reduction potential: Up to 10%
Electrification: direct electric heating with electric boiler	7-8	Fossil fuel emissions could be eliminated by replacing fossil fuels with electricity and using an electric boiler instead of a fossil fuel boiler (natural gas boiler) to generate heat (steam) demand. Net-zero emissions could be achieved if the electricity is supplied from renewable sources (Marsidi et al., 2019). Emission reduction potential: Depending on the power mix emission factor, 20% with the current power mix (CEPI, 2013)
Heat pump and waste heat recovery	6-7	The heat pump can convert low temperature waste heat from process to medium temperature by consuming electricity. Reusing the waste heat at an acceptable temperature would drastically reduce fossil fuel emissions and improve energy efficiency (Marsidi et al., 2019). Emission reduction potential: Between 40 and 90%, with an average of 75% (Wilk et al., 2019)
New drying techniques	3-7	Replacing the conventional drying system with new drying technologies such as superheated steam drying (CEPI, 2013), gas-fired dryers (CEPI, 2013; Kong et al., 2016), microwave drying (Kong et al., 2016), etc. to improve energy efficiency and reduce the energy consumption and CO_2 emissions.

Deep eutectic solvents (DES)	3	DES are produced naturally by plants and can break down wood and selectively extract cellulose fibres required in the papermaking process. DES has the potential for use in pulp production using wood and waste paper with minimised energy demand and CO_2 generation (CEPI, 2013). <u>Emission reduction potential:</u> Up to 20% (CEPI, 2013)
Flash condensing	3-5	The concept of this technology is to produce waterless paper using high turbulent steam combined with dry fibres. The technology can be applied to any pulp (chemical, TMP, RCF), reducing energy consumption and fossil fuel CO_2 emissions (CEPI, 2013). <u>Emission reduction potential:</u> Up to 50% (CEPI, 2013)
CCS with biomass	6	CO_2 emissions from combustion processing, the recovery boiler, and the lime kiln, particularly at the kraft pulp mill, can be captured and stored, allowing the industry to be a negative emissions site (Sagues et al., 2020). <u>Emission reduction potential:</u> Up to 98% (European Commission, 2018)

9.3 Non-ferrous metal

The Non-Ferrous Metal (NFM) sector is divided into several subsectors: base metals (aluminium, copper, lead, zinc, nickel and tin), precious metals (e.g., gold, silver) and so-called technology metals (e.g., molybdenum, cobalt, silicon, selenium, manganese) (Cusano et al., 2017; European Commission, 2018). In Austria, the NFM sector includes 85 companies with 13,480 employees and a gross value added of EUR 1.3 billion of which the aluminium sector accounts for 40% (Diendorfer et al., 2021).

Table 10: Overview of the non-ferrous metal industry (Diendorfer et al., 2021)

Number of companies	85
Employees	13 480
GDP-VA in€ million	1 328
GHG emissions in Mt CO_2	0.57
Share of GHG emissions in the sector industry	2.2%

Scrap and recycled materials are the main sources for the Austrian NFM sector, which require 90-95% less energy than primary manufacture. Secondary products, such as secondary aluminium and secondary lead, as well as foundries and other metal processing enterprises, utilise approximately 2.5 TWh of final energy for material processing, accounting for 3% of final industrial energy consumption in 2019 (Statistics Austria, 2021b). The main energy carriers are fossil fuels, mostly natural gas, which accounts for 57% of final energy and are primarily used for high-temperature heat demand in the furnaces, followed by electricity, which accounts for 42% and is predominantly operated in stationary engines (see Figure 75).

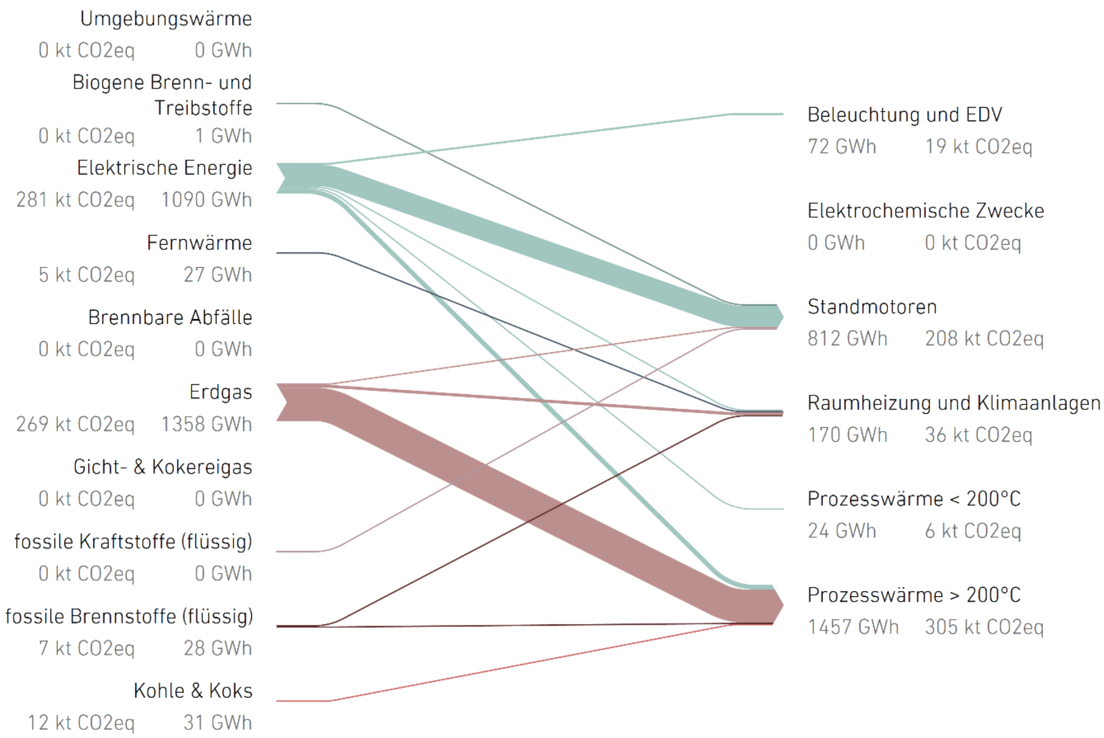

Figure 75: Final energy and GHG intensity of the supply of useful energy categories in the Austrian non-ferrous metal sector in 2019 (Diendorfer et al., 2021).

The NFM sector is responsible for around 295 kt CO_2e in terms of direct emissions due to fossil fuel consumption, especially natural gas (European Environment Agency, 2021a; UBA, 2021a). There is also a minor amount of 10 kt of process-related emissions in aluminium and lead production due to the anode consumption in the production process (UBA, 2021a). Aluminium manufacturing, whose largest producer (AMAG) is on the ETS list (see Table 11), is responsible for about half of the sector's emissions, with 142 Kt emissions (137 Kt of fuel-related emissions and 5 Kt of process emissions)(UBA, 2021a).

Table 11: ETS-listed companies in the non-ferrous metal sector, including the verified GHG emissions in 2019. Own representation based on (European Commission, 2020).

Company	Energy-related GHG emissions in t CO_2e
Production and first processing of aluminium	**96 163**
AMAG casting GmbH	73 385
AMAG rolling GmbH	22 778
Production and first processing of copper	**36 151**
Montanwerke Brixlegg AG	36 151
Total	**132 314**

As the NFM sector in Austria is characterised only by production via the secondary route and the main emission source is fossil emissions, the critical drivers of decarbonisation considered in the modelling of the Austrian NFM industry mainly relate to improved energy efficiency and fuel switching (see Table 12). Although the listed technologies are mostly associated with the aluminium industry, they can also be applied by other NFM manufacturers.

Table 12: Emission reduction technology options for the non-ferrous metal industry.

Technology option	TRL	Description
New de-coating equipment	8-9	De-coating technology removes the contaminated material and cleans the surface of recycled aluminium. This technology improves the process and reduces raw material loss (Chan et al., 2019; Moya et al., 2015). Emission reduction potential: Up to 10%
Electrification of furnaces		Carbon emissions could be eliminated by replacing fossil fuels with electricity and employing an electric furnace. Net-zero emissions may be possible if electricity is generated from renewable sources (International Aluminium Institute, 2022; World Economic Forum (WEC), 2020). Emission reduction potential: Depending on the power mix emission factor, 15-20% with the current power mix
Fuel switching to biofuel	8-9	Fuel-related emissions from fossil fuel consumption for high-temperature heat demand in the furnace are the main source of CO_2 emissions in the aluminium industry (as well as NFM), which can be replaced with biomethane or hydrogen to eliminate fuel-related emissions (International Aluminium Institute, 2022; World Economic Forum (WEC), 2020). Emission reduction potential: Up to 100%
Recuperative or regenerative burners	8-9	Upgraded furnace designs with recuperative and regenerative burners in secondary smelters can save up to 30-50% of energy use while also lowering investment costs (Chan et al., 2019; Moya et al., 2015).
Emerging technologies for aluminium sorting		Scrap aluminium comes in a multitude of grades and qualities (as well as impurities), which adds to the cost. Scrap collection and sorting must be cost-effective. Physical scrap metal sorting is more cost-effective than melt refining. The following are some examples of low-cost aluminium sorting techniques: • Fluidised bed sinks float technology (Chan et al., 2019) • Colour etching then sorting (Chan et al., 2019) • Laser-induced breakdown spectroscopy (LIBS) (Chan et al., 2019)

9.4 Non-metallic minerals

According to the Professional Association for Stone and Ceramics, the non-metallic mineral (NMM) sector is divided into several subsectors: clay products, refractory products, glass and glass products, cement, lime, concrete, ceramics, and gypsum. This production group processes mined or quarried natural raw materials such as sand, stone, clay, and refractory material (magnesia) into semi-finished or finished products such as lime, cement, and concrete (Chan, Yeen; Kantamaneni, 2015; Eurostat, 2008). In Austria, the NMM sector comprises 1,329 companies employing a total of 31,355 people. The gross value added amounts to approximately EUR 2.5 billion.

Table 13: Overview of the non-metallic mineral industry (Diendorfer et al., 2021).

Number of companies	1 329
Employees	31 355
GDP-VA in€ million	2 538
GHG emissions in Mt CO_2	5.27
Share of GHG emissions in the sector industry	20.4%

With a consumption of 10.1 TWh of final energy, the NMM sector is responsible for 12% of Austrian industry's final energy use in 2019 (Statistics Austria, 2021b). As shown in Figure , the primary energy carriers are fossil fuels (5.1 TWh) with 80% natural gas, which is mainly used in industrial furnaces for high-temperature heat demand, followed by electricity (24%) and alternative waste fuels (AWF, 22%). AWF, such as wood, waste paper, animal meal, used tyres, and waste oil, are currently utilised in cement production and contain fossil as well as biogenic substances (Mauschitz, 2021).

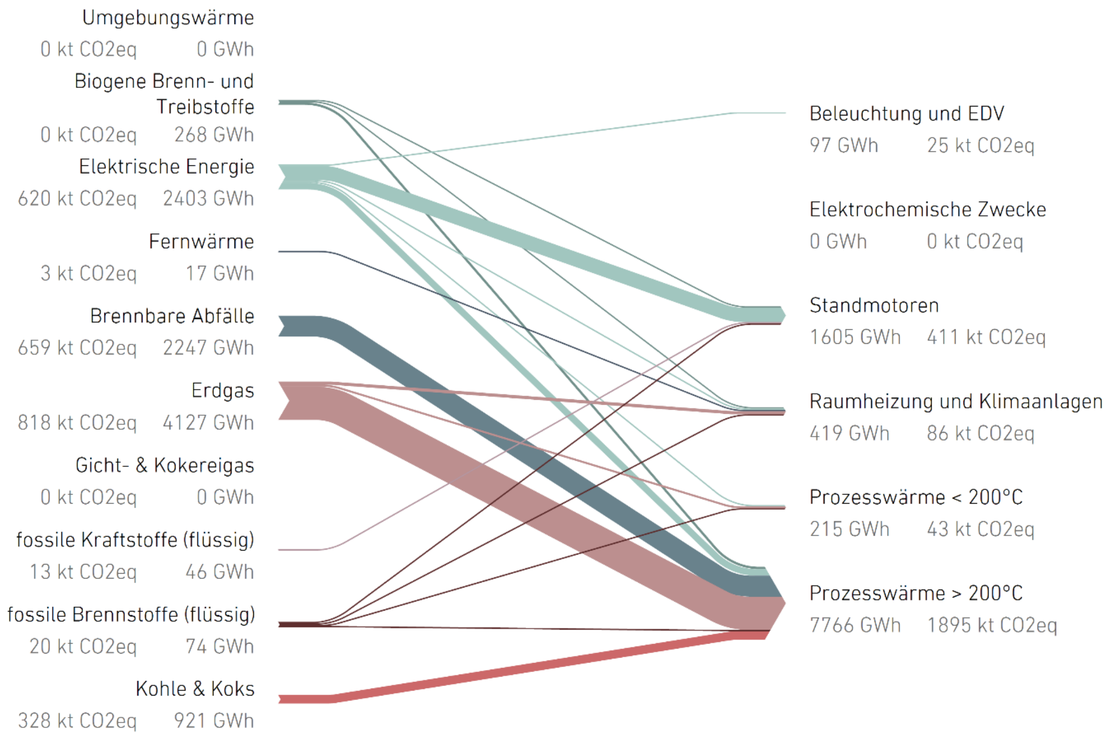

Figure 76: Final energy and GHG intensity of the supply of useful energy categories in the Austrian non-metallic minerals sector in 2019 (Diendorfer et al., 2021).

The NMM sector accounts for a total of 4.5 Mt CO_2e of climate-relevant greenhouse gas emissions. With a share of 20% of total industrial emissions in Austria, it has the second-highest sector emissions. In the sector, 33 companies are listed in the ETS, which together are responsible for emissions of 4.1 Mt CO_2e (see Table 14). Around 60% of the sector's emissions result from process-related emissions generated during the conversion of the mineral raw materials used (e.g., conversion of limestone $CaCO_3$ to CaO and CO_2). For this reason, the sector represents a particular challenge in decarbonising Austrian industry.

Table 14: ETS-listed companies in the non-metallic minerals sector, including the verified GHG emissions in 2019. Own representation based on (European Commission, 2020).

Company	Energy-related GHG emissions in t CO_2 e
Production of cement	**2 653 171**
Lafarge Perlmooser Mannersdorf	610 139
Wietersdorfer & Peggauer Zement Wietersdorf	468 704
Zementwerke Leube Gartenau	320 992
Lafarge Perlmooser Retznei	300 968
Zementwerk Wopfing	291 278
Gmundner Zement Gmunden	253 322
Zementwerk Hofmann Kirchdorf	233 084
Schretter & Cie (Zement) Vils	174 684
Production of chalk and plaster of Paris	**722 227**
VOEST-Alpine Stahl Linz (Kalk) Steyrling	303 621
Kalkwerk Wopfing	138 751
Wietersdorfer & Peggauer (Kalk) Peggau	91 459
Kalkwerk Tagger (Leube) Golling	83 498
Baumit Baustoffe Bad Ischl	46 415
Schretter & Cie (Kalk) Vils	35 934
Ernstbrunner Kalktechnik Ernstbrunn	22 549
Production of bricks and other structural ceramics	**258 055**
Wienerberger Hennersdorf	26 252
Wienerberger Krengelbach Haiding	26 050
Tondach Gleinstätten	23 827
Ziegelwerk Pichler Wels	20 309
Ziegelwerk Eder Peuerbach Bruck	18 202
Wienerberger Göllersdorf	17 084
Wienerberger Knittelfeld (Apfelberg)	15 831
Ziegelwerk Eder Weibern	14 906
Leitl Spannton Eferding	14 685
Ziegelwerk Martin Pichler Aschach	14 202
Ziegelwerk Frixeder Senftenbach	13 716
Ziegelwerk Brenner Wirth St. Andrä	13 256

Tondach Pinkafeld	9 678
Comelli Ziegel Kirchbach Maxendorf	9 358
Wienerberger Helpfau Uttendorf	7 803
Ziegelwerk Danreiter Ried im Innkreis	5 129
Ziegelwerk Rhomberg-Dornbirn	3 740
Ziegelwerk Obermair Neuhofen	2 150
Ziegelwerk Lizzi Erlach	1 877
Production of fireproof ceramic material and goods	**234 345**
Veitsch-Radex Hochfilzen	119 859
Veitsch-Radex Radenthein	76 311
Veitsch-Radex Trieben	17 959
Veitsch-Radex Veitsch	12 505
Rath GmbH Krummnußbaum	7 711
Production of hollow glass	**179 291**
Vetropack Kremsmünster	68 178
Vetropack Pöchlarn	59 982
Stölzle-Oberglas Köflach	51 131
Production of plaster material for construction	**52 425**
Knauf Werk Weißenbach	29 007
Saint-Gobian Rigips Austria GmbH, Werk Bad Aussee	23 418
Production, refinement and processing of other glass including technical glass products	**15 968**
Swarovski Wattens	8 605
Technoglas Voitsberg	7 363
Production of ceramic goods for other technical applications	**2 913**
Lias Fehring	2 913
Total	**4 118 395**

In the Austrian National Inventory Report, the NMM sector is subdivided into seven subsectors (shown in Table 15) of which the cement industry accounts for the majority of process-related emissions (63%)(UBA, 2021a). In the following description, it is therefore used as an example for the entire sector.

Table 15: Process-related GHG emissions in the non-metallic mineral sector and its subsectors (UBA, 2021a).

2019	Cement	Chalk	Magnesite	Glass	Bricks	Dolomite	Na_2CO_3	Sector total
Process emissions in kt CO_2e	1771	584	293	41	104	7	9	2809
% of sectoral process emissions	63 %	21%	10%	1%	4%	<1%	<0.5%	100%

The Austrian cement industry, with a production capacity of around 5.2 Mt, is a massive economic sector with a high degree of regionality that meets local cement demand (VÖZ, 2019). In 2019, the cement industry used about 4.4 TWh of total final energy, 86% for thermal and 14% for electrical applications (Mauschitz, 2021). In recent years, the Austrian cement subsector has substantially replaced fossil fuels with AWF and is one of the world's largest AWF users, with a share of 80% (VÖZ, 2019). The energy flow Sankey diagram of the Austrian cement subsector is shown in Figure .

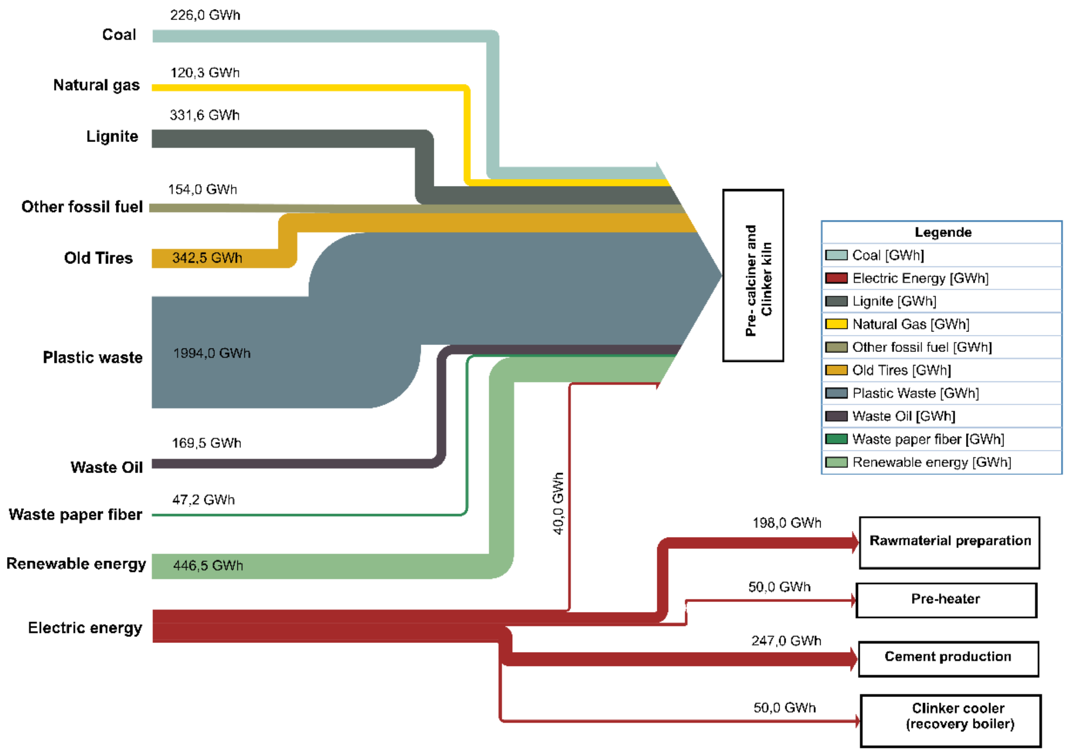

Figure 77: Energy flow diagram of the cement subsector. Own illustration based on Mauschitz (2021); VÖZ (2019).

The cement subsector is responsible for 2.7 Mt CO_2e of emissions, about 67% of which are caused by processes and 33% by fuels (Mauschitz, 2021; UBA, 2021a). Due to the use of energy-efficient plants, the high share of alternative fuels, and the reduction of the clinker-cement ratio to below 69% through the use of alternative raw materials such as fly ash (a by-product of coal-fired power plants) and BFS granulate (a by-product of the iron and steel industry) (Mauschitz, 2021; VÖZ, 2019), the Austrian cement industry has one of the lowest emission factors in Europe (European Environment Agency, 2021a).

Table 16 outlines the technological options for emission reduction in cement manufacturing reviewed for scenario modelling, which can also be applied to the other subsectors of the overall NMM sector.

Table 16: Emission reduction technology options for the non-metallic minerals industry.

Technology option	TRL	Description
Waste heat recovery	8-9	Recovery of waste heat from the kiln and clinker cooler and converted to electricity using available technologies such as organic Rankine cycle, single flash steam cycle, dual pressure steam cycle (Pardo et al., 2011). Emission reduction potential: Up to 10%

Electrification	4	Instead of fossil fuels, electricity can be used to meet the clinker kiln's high-temperature (1400 °C) heat demand. Electrification is achieved by adapting plasma technologies, microwave heating, and induction heating, which are not commercially available (IEA, 2020; Lechtenböhmer et al., 2016). Emission reduction potential: Up to 40% (Material Economics, 2019b)
New binder material	5-8	Conventional clinker, which uses limestone as the main raw material, can be replaced by alternative materials such as alkali-activated binders, carbonate-calcium silicate clinker, magnesium silicates, etc., which have the potential to reduce process-related emissions (Gartner & Sui, 2018; IEA, 2020). Emission reduction potential: Between 43 to 100% (Preston & Lehne, 2018)
CCS - Oxyfuel	6-7	Use of oxygen instead of air to produce CO_2-rich exhaust gas that can be easily captured after purification (CEMCAP, 2019). Emission reduction potential: Up to 90% (Material Economics, 2019b)
CCS - Calcium looping (CaL)	6-7	In CaL technology, part of the captured CO_2 from production processing is used in a reversible carbonation reaction to produce the CaO. The remaining CO_2 is stored. CaL can be implemented in tail-end or integration configuration (CEMCAP, 2019; De Lena et al., 2017). Emission reduction potential: Up to 95% (CEMCAP, 2019)

9.5 Chemical and petrochemical industry

In 2017, the energy consumption of the Austrian chemical and petrochemical industry reached 15.6% of the final energy demand of national manufacturing industry, making it one of the most energy intensive industry branches (Statistics Austria, 2021b). The chemical and petrochemical production subsector in Austria is concentrated in 520 companies employing a total of 35,051 people, and with a gross value added of around EUR 4.8 billion (Diendorfer et al., 2021). The chemical and petrochemical sector is characterised by a multitude of different products and heterogenic processes (S. Moser et al., 2018). At 36.3%, the production of plastic goods is the largest area, followed by pharmaceuticals at 14.4% and chemicals at 13.1%, as well as primary plastic production at 13% (FCIO, 2018).

Table 17: Overview of the chemical and petrochemical industry (Diendorfer et al., 2021).

Number of companies	520
Employees	35 051
GDP-VA in€ million	4 791
GHG emissions in Mt CO_2	2.17
Share of GHG emissions in the sector industry	8.4%

According to the study “Perspektiven der Decarbonisierung für die chemische Industrie in Österreich”, the relevant processes for decarbonising the Austrian chemical and petrochemical industry include:

- Chlorine with caustic soda as by-product
- Ammonia, urea, nitric acid and fertiliser production
- Methanol syntheses
- Olefins (ethylene, propylene) as starting materials for plastics and other products (Windsperger et al., 2018)

Chemical and petrochemical (C&P) is an energy intensive industry, with an energy consumption of around 12,621 GWh in 2019. Starting with 11,899 GWh in 2010, the historical development of energy demand recorded an average annual growth rate of 0.95% over the period 2010-2017 (Statistics Austria, 2021b).

It should be noted here that, according to the international definition, petroleum processing (e.g., the Schwechat refinery) is not part of the chemicals and petrochemicals sector, but instead part of the energy sector. As presented in Figure 78, the final energy and GHG intensity for supplying the various categories of useful energy shows a dominance of electrical energy at around 61.3%, followed by natural gas at 27.4%. Other fuels, such as district heating (6.6%), combustible waste (2.1%), biogenic fuels (1.8%), fossil fuels (liquid) for combustion (0.5%), and ambient heat (0.01%) make up a smaller proportion of the final energy demand in the chemical and petrochemical industry. Moreover, Figure 78 illustrates that the final energy in the chemical and petrochemical sector is mainly required for supplying process heat >200°C (46%) and process heat <200°C (16%). Furthermore, 28% of the final energy is consumed by stationary motors, which are mostly electrified (Diendorfer et al., 2021).

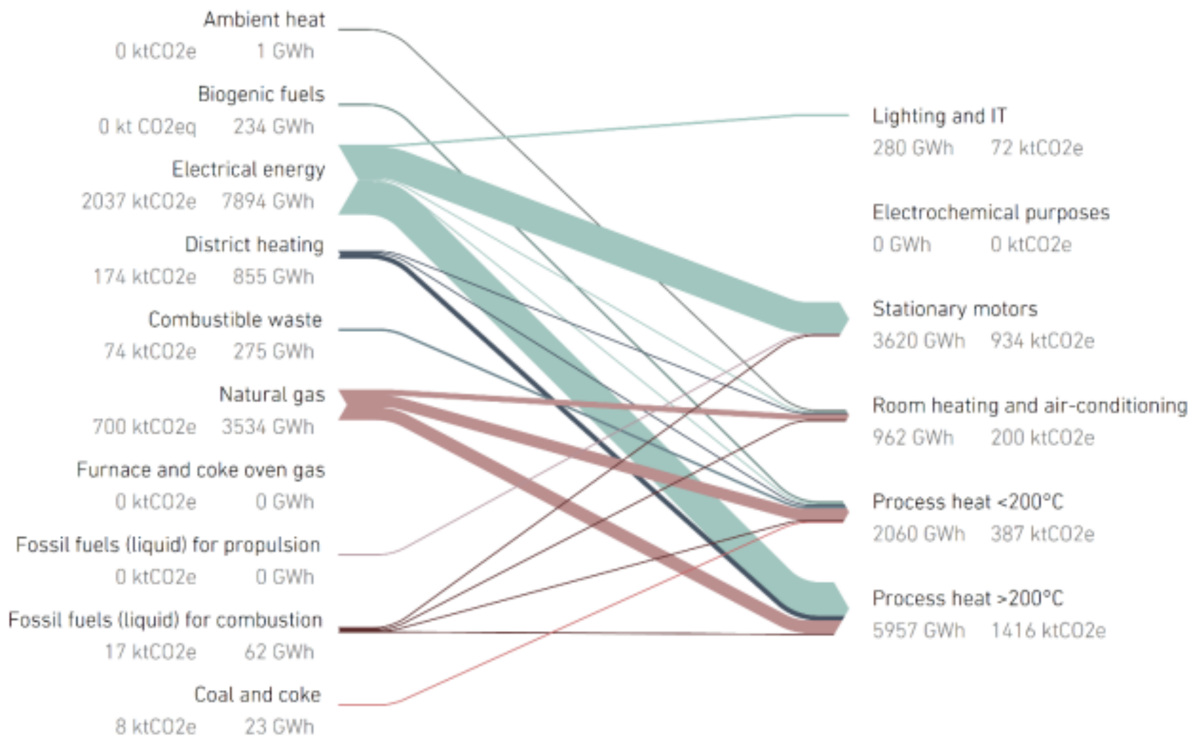

Figure 78: Final energy and GHG intensity for supplying the various categories of useful energy in the chemicals and petrochemicals sector. Whole of Austria 2019, (Diendorfer et al., 2021) without feedstocks natural gas and naphtha.

Around 0.6% of Austria's total GHG emissions originate from the chemical and petrochemical industry (UBA, 2021a). The total process-related emissions for the Austrian chemical and petrochemical industry in 2019 account for 851 ktCO_2e, where ammonia production with a share of 60% of the total emissions in this sector has the highest share in 2019. The amount of CO_2 emissions in the chemical industry sector fluctuates over time according to production levels. CO_2 is mainly emitted within the production process for ammonia, nitric acid, urea and fertilisers (UBA, 2021a). Austrian petrochemical and chemical industry emissions amount to 1,800 kt CO_2e and over 60% are related to the production of fertiliser and nitrogen compounds (Diendorfer et al., 2021).

According to the ETS, the emissions are created by 11 companies, with Borealis Agrolinz Melamine GmbH and its subsidiaries being responsible for over 58% of the emissions, see Table 18.

Table 18: ETS-listed companies in the petrochemical and chemical sector, including verified GHG emissions for 2019. Own representation based on (European Commission, 2020a)

Company	Energy-related GHG emissions in t CO_2 e
Production of fertiliser and nitrogen compounds	**1 104 501**
Borealis Agrolinz Melamine Ammoniakanlage	962 179
Borealis Agrolinz Melamine Salpetersäureanlage	81 598
AMI Agrolinz Melamine International Linz	60 724
Production of other organic raw materials and chemicals	**271 597**
Jungbunzlauer Wulzeshofen	234 709
ATMOSA Petrochemie GmbH	27 429

DSM Fine Chemicals Austria Linz	9 459
Production of chemical fibre	**262 481**
Lenzing AG Faser+Energie 1, Zellstoff, Papier	172 994
Energie- und Medienzentrale Heiligenkreuz	89 487
Production of other chemical products	**73 351**
Bioethanolanlage Pischelsdorf	73 351
Production of basic pharmaceutical products	**57 869**
Sandoz Werk Kundl	57 869
Production of plastics in primary forms	**31 911**
Dynea Krems	20 111
Borealis Schwechat	11 800
Production of plastics in primary forms	**2 126**
Solvay Ebensee	2 126
Total	**1 803 836**

The chemical and petrochemical sector accounts for 2.17 Mt CO_2e of climate-relevant greenhouse gas emissions. With a share of 8.4% of total industrial emissions in Austria, it has the third-highest sector emissions. Because of the significant environmental impact of the chemical and petrochemical industry in Austria, it will be a challenge to decarbonise this sector. The most promising and effective technologies that can help to reduce greenhouse gas emissions in the chemical and petrochemical industry are summarised in Table 19.

Table 19: Emission reduction technology options for the chemical and petrochemical industry.

Technology option	TRL	Description
Low-carbon hydrogen production of ammonia	7	Ammonia synthesis itself is carbon free, hence, a reduction in emissions and/or energy can only be achieved via low-carbon hydrogen production. For this process the hydrogen can be produced by water electrolysis and the nitrogen needed can be generated by an air separation unit. Furthermore, electrified compressors are also necessary to compress both hydrogen and nitrogen to the required pressure levels for ammonia synthesis, as well as for refrigeration within the air separation process. (Bazzanella & Ausfelder, 2017). <u>Emission reduction potential:</u> 90%-100% (related to the electricity mix)
Methane pyrolysis	4-5	Thermal decomposition of methane is a promising route for the production of hydrogen with a low carbon footprint, e.g., for ammonia synthesis. Methane or biogas, landfill gas or synthetic methane are decomposed in a high-temperature pyrolysis process, generating hydrogen and solid carbon (Bazzanella & Ausfelder, 2017). If the electricity mix is generated by renewable sources and biogas is used for the methane pyrolysis, hydrogen can be produced with a carbon free footprint. <u>Emission reduction potential:</u> 90%-100% (related to the electricity mix and the pyrolysis gas)
Electricity-based steam production	7	The chemical and petrochemical sector is characterised by high process energy demand for heat, including in the form of steam at different temperature and pressure levels. Steam is usually produced with natural gas-fired boilers. The switch to electricity-based heating is seen as promising. It has a fast response time and therefore a higher flexibility in the

Technology option	TRL	Description
		use of intermittent surplus supply of renewable electricity (e.g., effects on demand side management, benefit from low electricity prices) (Bazzanella & Ausfelder, 2017). Emission reduction potential: Up to 90%
Electrification and use of waste heat	-	Another way to decarbonise chemical processes is the increased use of waste heat and low carbon electricity. An example is the switch from fossil fuel-driven compressors to electrified compressors and the use of waste heat, e.g., from ammonia synthesis for nitric acid production. Emission reduction potential: Up to 80% (related to the electricity mix)
Urea from low-carbon ammonia and CO_2	-	The production of urea in Austria is coupled with ammonia synthesis and therefore depends on the CO_2 produced as a by-product in the conventional ammonia production process. In the low-carbon ammonia process no CO_2 is available, hence it needs to be recycled from fossil fired power plants or industrial processes in order to be fed into urea production (Bazzanella & Ausfelder, 2017). Where this is the case, the production of urea represents a CO_2 sink of about 0.73 t CO_2/t_{urea} (DECHEMA et al., 2019). Emission reduction potential: Up to 120% (related to the electricity mix)
Low-carbon hydrogen production of methanol	7	Similar to the low-carbon route for ammonia production, methanol production can also use hydrogen produced via electrolysis using renewable energy sources and hydrogenation of CO_2. Part of the CO_2 hydrogenation is water formation with a higher water share compared to the conventional process. It is generated from recycled gas and crude methanol and can be removed by distillation. Electrolysis probably needs an additional hydrogen purification step and compression (Bazzanella & Ausfelder, 2017). The production of methanol by the hydrogen route with a carbon free electricity mix represents a CO_2 sink of about 1.37 t $CO_2/t_{methanol}$.(DECHEMA et al., 2019). Emission reduction potential: Up to 120% (related to the electricity mix)
Biomass-based methanol	6-7	The production of methanol from biomass is carried out via synthesis gas production by gasification of the biomass followed by conventional methanol synthesis. The main types of biomass feedstock are organic waste as well as agricultural and forestry residues. In a first step the feedstock has to be pre-treated by shredding, dried to a water content of max. 15% and freed from foreign matter. Gasification can be operated both allothermally (external heat input) and autothermally (proportionate combustion of the raw material used). Limited oxygen supply favours the formation of synthesis gas and reduces CO_2 and water content. Gasification is followed by gas cleaning, where tar, dust and inorganic residues are separated. The final step after synthesising the gas is conventional methanol synthesis (Bazzanella & Ausfelder, 2017). As biomass is renewable, this methanol production process represents a CO_2 sink of about 1.37 t $CO_2/t_{methanol}$, depending on a carbon free electricity mix (DECHEMA et al., 2019). Emission reduction potential: Up to 120% (related to the electricity mix)
Lowcarbon production of ethylene and propylene via MTO	8-9	The production process can be compared with the methanol production process, with the further step of converting methanol to olefin (MTO). Two-step dehydration ensures the control of the heat of the exothermic reaction and the adiabatic temperature increase. The two steps include the dehydration of methanol to dimethyl ether and the conversion to olefins. The catalyst significantly affects the type of product (e.g., methanol-to-propylene) (Bazzanella & Ausfelder, 2017). The advantage of the MTO process is the high demand for methanol. This uses CO_2 which can originate from other industrial processes via carbon capture technologies. Thus, 1.89 tCO_2/t of ethylene or propylene can be avoided in total using this production pathway (Geyer et al., 2019). Emission reduction potential: Up to 45%

9.6 Transport equipment

The transport equipment industry's energy demand was 1,953 GWh in 2017. This corresponds to a share of 2.1% of the total energy of the industry sector, or 0.6% of Austria's energy consumption. Almost 54% of the energy demand is covered by electrical energy. Natural gas is used for another 31%, together totalling 85% of the transport equipment sector's energy demand. Including district heating, these three energy sources contribute 97% of the required energy. The most important end-use categories are space heating and air conditioning at 51%, as well as stationary engines at 33%. In 2017, 222 companies were manufacturing motor vehicles and motor vehicle components, and another 90 companies were manufacturing other vehicles in Austria. The process of transport equipment production is composed of pressing (which is often not directly in the vehicle production plant but at external locations because of the high-energy demand and mechanical vibrations (Sejkora et al., 2018)) as well as car body construction, varnishing and assembly (trim, wedding and final assembly, without subassembly). On the utilisation side, approximately half of the energy demand is used for space heating and air conditioning (of which 57.6% is provided by fossil sources). Approximately a third of the energy demand is required for stationary engines. Of that, 95% is already provided by electrical energy (Statistics Austria, 2021b).

Technology option	**TRL**	**Description**
Optimised handling of compressed air		Reviewing if and where compressed air has escaped and how these leakages could be eliminated; lowering the pressure level of the whole system with steady security standards and improvement of compressed air pipelines to reduce the total pressure losses (VDMA, 2014). Emission reduction potential: 13 t CO_2e reduction per year Energy reduction potential: 53% less compressed air
Modernisation of cooling tower and cooling water pump		Accurately dimensioned pumps (VDMA, 2014). Energy reduction potential: 25% reduced electricity demand compared to standard pump system
Space heating via heat pumps	9	As the demand share of space heating is high, and largely covered by fossil fuels, (air) heat pumps can provide large efficiency increases and decarbonisation (if electricity is sourced renewably).

9.7 Machinery

Energy demand in the machinery sector was 8,640 GWh in 2017 (C. Sejkora, 2020), accounting for 8.9% of the energy demand of the industry sector, or 2.7% of the energy demand in Austria. The share of renewable energy is 41%. More than half of the energy demand is covered by electricity. Natural gas is the second most used energy source, at 36% of energy demand. Together, these two energy carriers cover almost 90% of the energy demand of this sector. Other energy sources are only used to a limited extent. The end-uses of industrial furnaces, stationary engines, space heating and air conditioning each account for about 30%. The machinery sector is comparatively heterogeneous and contains the entire range of small to large companies. The manufactured products include pulp and paper machines, construction machines, robots, cranes, cable cars, tractors, engines, logistic systems and water treatment plants. The main processes are mechanical processing, such as turning, milling, pressing and welding a wide variety of materials (mostly metals). The bulk of fossil fuels is used for industrial furnaces, as well as space heating and air conditioning. None of these processes depend on a specific energy carrier. Therefore, substitution with renewable energies is not a substantial challenge from a technical point of view. Space heating and air conditioning can be electrified and operated efficiently with heat pumps. For the operation of industrial furnaces, biofuels, electricity and renewable fuels (e.g., hydrogen, ammonia) as well as high-temperature heat pumps can be used (Windsperger et al., 2018).

Technology option	**TRL**	**Description**
Combined heat and power	9	Conversion of the heat supply from steam to hot water with renewal of the heating infrastructure. Reduction of the flow temperature for certain processes and adapted temperature levels for heating networks (VDMA, 2014). Emission reduction potential: 16% primary energy demand
High-tech furnaces	9	Integrated process technology with optimised control depending on requirements, integration of exhaust gas heat (VDMA, 2014). Energy reduction potential: Up to 15% energy reduction
Hydrogen used for industrial furnaces		Partial heating of the melting or refining material using suitable storage materials (storage capacity: 400-2000 kJ/kg with sensitive storage, phase change material, thermocompact storage) (*SPIRE-CCNI 2050 Roadmap*, n.d.).
Use of thermal storage for melting and refining		Partial heating of the material to be melted or processed using suitable storage materials (storage capacity: 400-2000 kJ/kg with sensitive storage, phase change material, thermocompact storage) (Sejkora et al., 2018).
High-temperature heat pumps	3-4	Electrically-driven compression heat pumps with single or multi-stage cold vapour circuits (Rieberer, 2015).

9.8 Food, beverages and tobacco

In 2017, the food, beverages and tobacco industry used 8,872 GWh of primary energy (Sejkora et al., 2018). This corresponds to 8.6% of the energy used in the manufacturing sector or 2.6% in all of Austria. Almost half of the energy used is provided by natural gas. Electrical energy contributes another third to energy use. Together, these two energy sources provide 82% of the energy required. The most important consumers are steam generation at 38%, followed by stationary motors at 26% and industrial furnaces at 25%. Food and beverage production has the following characteristics:

- A large number of subsectors (e.g., dairy processing, bakery, beer production, meat processing, etc.)
- A large number of small processing companies, resulting in very different energy supply systems at the locations (over 90% SMEs)
- Comparatively low process temperatures (cf. data for Germany 2002: 60% below 100 °C).

Cooling requirements arise at two temperature levels: normal cooling up to 4°C and freezing (-6 to -20°C). Examples of process steps in the low-temperature range (<100°C) are the processes of providing space heating (up to 25°C), washing, cleaning, concentrating, heating and distilling (40°C to 110°C). Medium temperature heat is, in many cases, provided via steam, e.g., for pasteurisation (up to 120°C), cooking (up to 240°C), drying (up to 250°C) and baking (up to 260°C).

Because of these specifics, the use of heat pumps is not only suitable for generating hot water, space heating and cooling, but also for providing process heat. In future, heat can therefore be provided by means of renewable electricity, heat pumps and waste heat. For example, the integration of a heat pump for starch drying has been demonstrated (DryF, n.d.). Utilisation of ambient heat (e.g., solar or geothermal energy) and district heating is also possible in restricted amounts in accordance with local availability. Integration concepts for solar thermal energy in different branches of food production were investigated in the Greenfoods project (AEE INTEC, 2016).

Technology option	TRL	Description
Membrane separation		Catalysts are replaced by membranes. This means a shift from thermal-chemical to mechanical separation processes. Market maturity before 2040 is unlikely (Gerres et al., 2018). This information is based on a study of reduction potentials through the use of technologies and relates to the entire European food and beverage industry: <u>Emission reduction potential:</u> 19%
Electrothermal heating processes	9	Provision of heat by convective heating in all temperature ranges. Heat pumps can deliver low to medium temperatures with very high overall efficiency through the use of low-temperature sources (infrared, microwave) specifically for drying (IPPC, 2018).
Brewery: external cooling of the beverage	9	Jacket cooling of the beverage is replaced by more efficient cooling in an external heat exchanger (IPPC, 2018).
Beverages: optimised juice pasteurisation	9	Lowering supply medium temperatures from 95°C to 80°C for juices with a pH of 4.2 or less. (IPPC, 2018) <u>Emission reduction potential:</u> 20% $kgCO_{2eq}/1000l$ <u>Energy reduction potential:</u> Up to 20%

9.9 Wood and wood products

The primary energy demand of the wood industry is 8,735 GWh (2017, (Sejkora et al., 2018)). Accounting for 7.9% of the total energy demand of the industry sector, corresponding to a share of 2.4% for all of Austria. At 76%, the proportion of renewable energy sources is the highest compared to other sectors due to the high proportion of biofuels (mostly wood residue). Together with electrical energy and district heating, 85% of the required energy can be covered by renewables without technological changes. Almost half of the energy is used for industrial furnaces (46%). Stationary motors make up 23% and space heating and air conditioning 22%.

Of over 1,200 companies in the wood processing industry, around 1,000 are sawmills. In addition, the construction sector, the furniture industry, the wood-based materials industry and the ski industry, as well as a large number of smaller professions, also belong to the wood industry. The temperature level required in the wood industry is relatively low. From today's standpoint, it is conceivable that the drying (50°C to 80°C), parts of the gluing (120°C to 180°C) and the painting (50°C to 80°C) processes can be powered by heat pumps. In the case of wood drying, this is already implemented in Canada, Sweden and Japan. 80% of the required amount of heat is below 100°C and can therefore be served with state-of-the-art systems. In Austria, more than 80% of the process heat demand is below 100°C. The heat currently used (status quo) often comes from (residual) biomass (CHP) plants. Thus, substituting biomass by heat pumps here frees it for decarbonising other sectors (Geyer et al., 2019).

Technology option	**TRL**	**Description**
Heat recovery from hot air emissions		… through condensation by evaporation, heat exchangers, preheating of the air supply to the dryer and recirculation of the hot exhaust gases. (Stubdrup et al., 2016)
Superheated steam dryer		Excess energy from steam produced by processes is used to generate electricity or to exchange heat for other uses. (Stubdrup et al., 2016)
UTWS burner (German acronym: 'Umluft' (recirculation of dryer waste gas), 'Teilstromverbrennung' (post combustion of partial directed dryer waste gas stream), 'Wärmerückgewinnung' (heat recovery of dryer waste gas), 'Staubabscheidung' (dust treatment of air emission discharge from the combustion plant)) or combined heating and drying systems for particleboards and oriented strand boards		Combined heating and drying systems with heat exchangers and thermal treatment of the discharged drying gases. (Stubdrup et al., 2016)
High-temperature heat pumps		Electrically driven compression heat pumps with single or multi-stage cold vapour circuits. (Rieberer, 2015)

9.10 Textiles and leather

In 2017, this sector had an energy demand of 968 GWh, which corresponds to 1% of the industry sector or 0.3% of Austria's total energy demand. The share of renewables is in the lower range of the sectors, at 33%. The two most important energy sources are natural gas and electrical energy and cover a total of 97% of demand. Stationary motors account for 41% of the energy demand, followed by steam generation at 26% and industrial furnaces at 20%. (Geyer et al., 2019)

Technology option	**TRL**	**Description**
Discontinuous dyeing with an air flow dyeing machine		Airflow dyeing machines have lower liquor ratios than conventional jet dyeing machines by using humidified air or a mixture of steam and air. (CITEVE, 2014) Emission reduction potential: Up to 60% less fuel consumption of the machine
Heat recovery for water treatment		With heat recovery from e.g., compressor, boiler exhaust air and dyeing water, hot water can be heated up to approx. 70 °C. (G. Moser, 2016) Energy reduction potential: Up to 6.5 GWh/a heat recovery in Austrian textile sector
Microwave dyeing machine		Microwave irradiation generates heat through dielectric losses, thus heating moist goods without heating the surrounding air and the equipment itself, i.e., reduced losses. In addition, the fabric itself becomes a steam generator through internal heating, thus enabling fast and continuous dyeing. (CITEVE, 2014) Energy reduction potential: 96% fuel savings compared to beam-dyeing machines 90% electricity savings compared to beam-dyeing machines

9.11 Non-specified industry

The non-specified industry sector includes the manufacture of furniture, rubber and plastic goods, and other goods (e.g. coins, jewellery, musical instruments, toys and sports equipment). This sector includes 5,843 companies employing 77,128 workers. The added value of these companies is around EUR 5 billion. One company that is assigned to this sector is listed in the ETS: the Semperit plant in Wimpassing is responsible for the emission of approx. 16 Mt CO_2e.

Due to the aggregation of very different production processes in this sector, there are hardly any meaningful trends to be found in the useful energy analysis. Stationary motors are mostly electrified, natural gas is mainly used to provide space heating, with the proportion of high-temperature heat for processes being very small (Diendorfer et al., 2021),

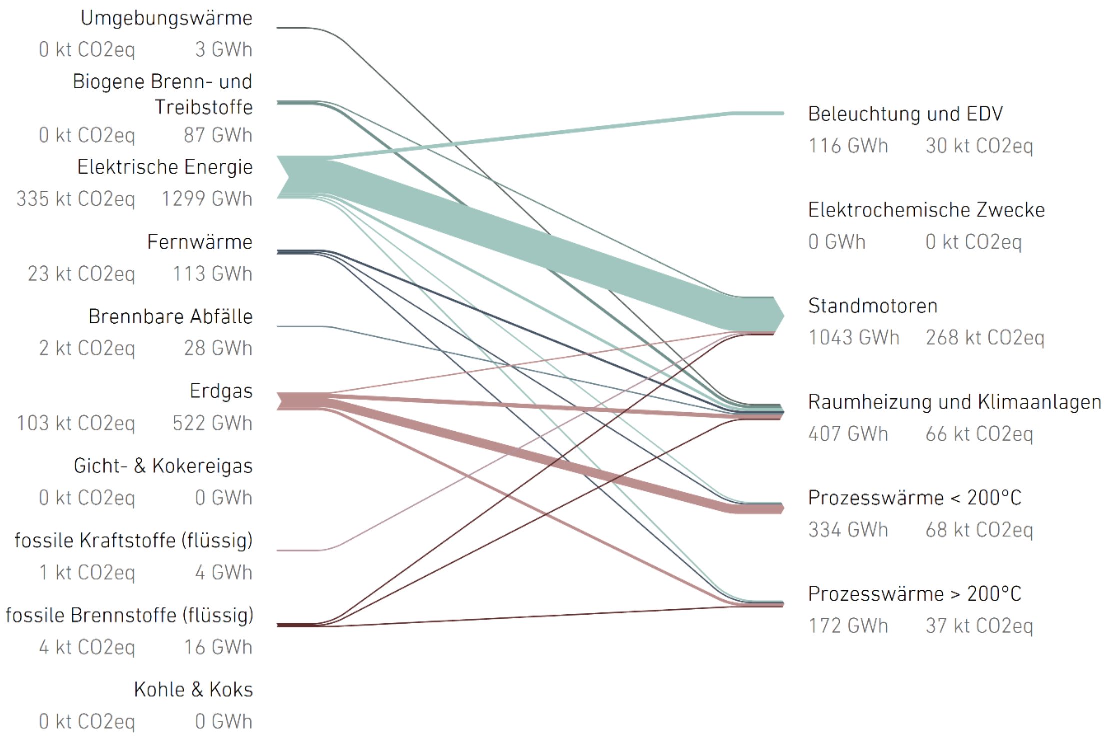

Figure 79: Energy demand and GHG intensity for supplying the various categories of useful energy in the non-specified industry sector. Whole of Austria in 2019, (Diendorfer et al., 2021)

9.12 Construction

The construction sector is heterogenous and comprises almost 38,000 companies with over 300,000 employees. The gross value added of the sector was EUR 19 billion in 2019. Strabag SE is by far the largest construction company in Austria with net sales of over EUR 16.6 billion, followed by Porr AG with around EUR 3.5 billion. No company in the construction sector is listed in the ETS. The energy consumption of the construction industry in 2019 was 3,494 GWh. This corresponds to 0.8% of Austrian and 3.2% of industrial energy requirements.

The useful energy category with the highest GHG emissions is stationary engines, which are mainly operated with fossil fuels (primarily diesel). In addition to actual stationary engines, this category also includes off-road vehicles, which means that all construction machinery is also included in this category. According to air emissions statistics, GHG emissions from other sources were only 3.8% (Diendorfer et al., 2021).

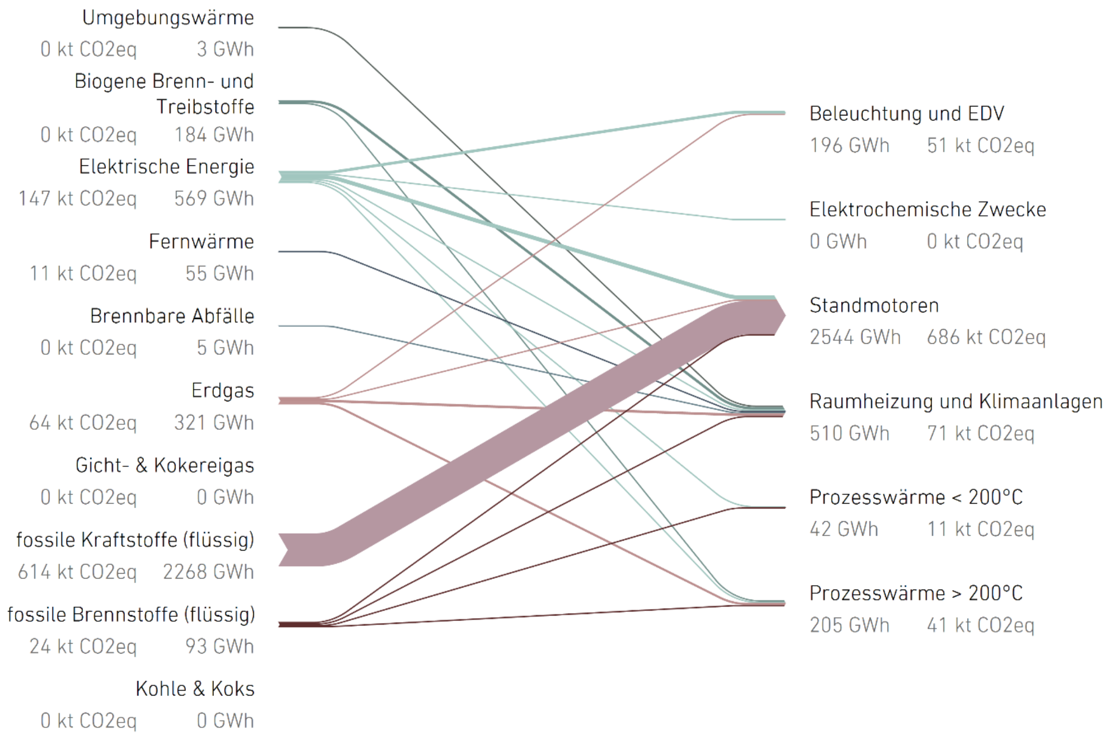

Figure 80: Energy demand and GHG intensity for supplying the various categories of useful energy in the construction sector. Whole of Austria in 2019, (Diendorfer et al., 2021)

9.13 Mining

The Austrian mining sector consists of 318 companies employing around 6,000 people. The sector's gross value added is around EUR 630 million. This sector includes the extraction of ores (3 companies with 670 employees and a gross value added of EUR 117 million) and the extraction of stones and other geological products. 292 companies with approx. 4,500 employees and a gross value added of EUR 391 million are active in the quarrying of natural stone and limestone (including gravel, sand and clay). Two companies in the mining sector are listed in the ETS and together emit 264 kt CO_2e.

Most of the energy is required to provide process heat below 200°C, followed by the operation of stationary motors and engines which are largely electrified (Diendorfer et al., 2021),

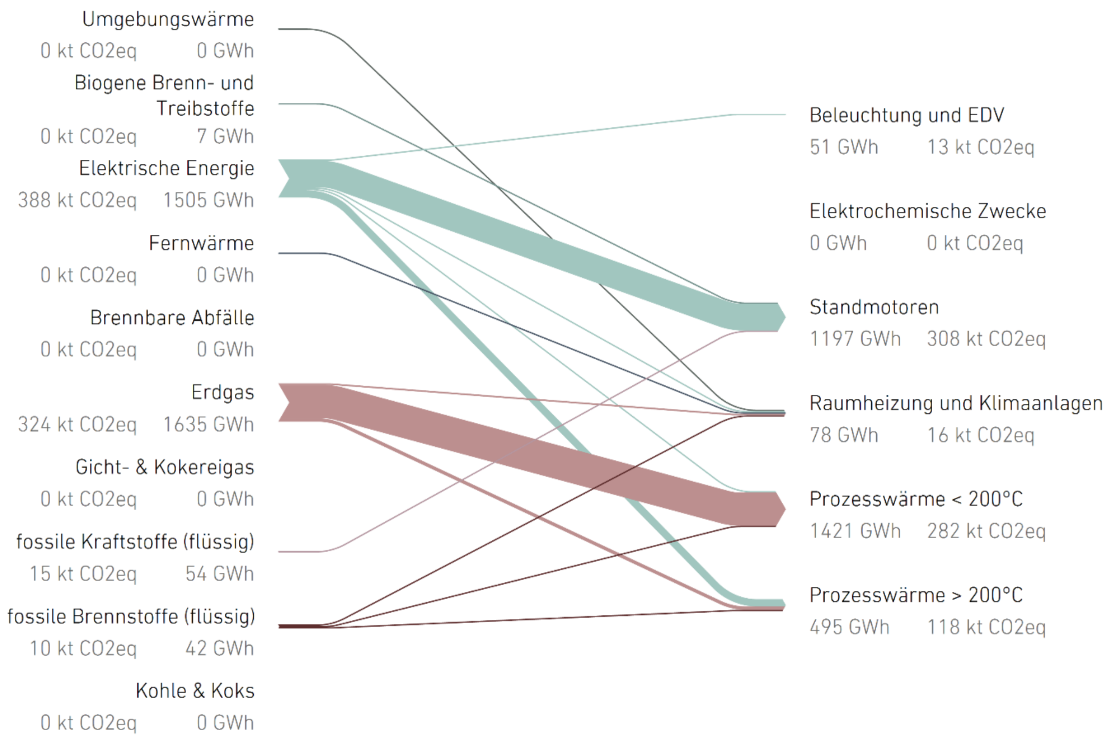

Figure 81: Energy demand and GHG intensity for supplying the various categories of useful energy in the mining sector. Whole of Austria in 2019, (Diendorfer et al., 2021)

10. Appendix: Modelling details

Table 20: Classification of industry by subsector and related economic activities (ISIC, 2018), (NACE, 2018)

Industry Subsector	Activities
Iron and steel	Melting and/or refining ferrous metals from ore, pig or scrap, using electrometallurgical and other process metallurgic techniques.
Non-ferrous metals	Melting and/or refining non-ferrous metals (aluminium, copper, lead, brass, titanium, beryllium, nickel, zinc, etc.) from ore, pig or scrap, using electrometallurgical and other process metallurgic techniques.
Non-metallic minerals	Manufacturing activities from raw materials to finished products of cement and plaster, lime, ceramic, tiles and baked clay products, glass and glass products (flat and hollow glasses, fibres, technical glassware etc.), etc.
Chemical and petrochemical	Manufacturing of basic chemicals, fertilisers and nitrogen compounds, rubber and plastics, pesticides and other agrochemical products, varnishes and similar coating, soap and detergents, perfumes, cleaning and polishing preparations and man-made fibres, basic pharmaceutical products and pharmaceutical preparations.
Paper, pulp and print	Manufacture of pulp (separating cellulose fibres from wood, dissolving used paper and binding the fibres), paper and converted paper products (wallpaper, gift wrap etc.), printing and publishing of products (newspapers, books, etc., and associated support activities including data imaging).
Transport equipment	Manufacture of transportation equipment such as ships, boats, railroad rolling stock and locomotives, air and spacecraft, motorcycles, bicycles and other transport equipment.
Machinery	Manufacture of machinery and equipment, such as general-purpose machinery, engines and turbines, pumps, compressors, taps and valves, gearing and driving elements, ovens, furnaces and furnace burners, lifting and handling equipment, agricultural, forestry, food, beverage and tobacco processing machinery, textile, apparel and leather production machinery, manufacture of computer, electronic and optical products and electronic equipment (batteries and accumulators, wiring devices, domestic appliances, electric lighting and other electrical equipment).
Food and beverages	Processing of agriculture, forestry and fishing products into food for humans or animals and includes the production of various intermediate products that are not directly food products. Beverage manufacture covers alcoholic and non-alcoholic beverages and mineral water. Tobacco covers processing the agricultural product tobacco into a form suitable for final consumption.
Textiles and leather	Preparation, spinning, weaving and finishing of textile and textile fibres, tailoring and wearing apparel and all items of clothing and accessories. Also dressing and dyeing of fur and the transformation of hides into leather by tanning or curing and fabricating the leather into products for final consumption.
Wood and wood products	Sawmilling and planing of wood, manufacture of wood products (lumber, plywood, veneers, containers, flooring, trusses, and prefabricated wood buildings) through the processes of sawing, planing, shaping, laminating, and assembling wood products.
Construction	General construction and specialised construction activities for buildings and civil engineering works such as motorways, bridges, tunnels, railways, etc.
Mining and quarrying	Mining of metal ores, coal and lignite, extraction of crude oil and natural gas, dredging of alluvial deposits, rock crushing and the use of salt marshes, supportive service activities of mining like exploration, drilling, draining and pumping mines, etc.
Non-specified industry	Other production activities not included above.

Modelling approach

The energy demand of each subsector is driven by the level of its economic activity (quantified in terms of GDP-VA), the energy intensity (EI) of the useful energy, and the efficiency of end-use technologies. Industrial products are produced using a well-matched combination of mechanical, thermal and electronic processes that dictate the type of final energy form needed to provide the required useful energy in the form of heat, motive energy and specific electricity use. The useful energy demand for providing the energy services is exclusively divided into three categories:

- Electricity for specific uses: lighting, appliances, information processing and controlling, electrolysis, etc.
- Motive energy: for driving motors, machines, conveyers (at the production sites)
- Heat for thermal uses: the main useful energy category for industrial processes. Currently, thermal energy needs account for about 72% of Austrian industry's total final energy demand (Statistics Austria, 2021) and consequently has a significant impact on the overall energy efficiency of the industry sector. The temperature at which the useful thermal energy is provided has an essential impact on the overall energy efficiency of industrial processes. In general, the higher the temperature, the lower the process efficiency, and thus the greater the potential for improving the process efficiency. Three temperature levels are defined: low temperature (LT) below 150°C, medium temperature (MT) in the range of 150°C-400°C, and high temperature (HT) above 400°C. Figure 82 depicts the application of this classification scheme for the different industry subsectors (Horta, 2018). The data are calculated based on IEA energy statistics for 32 countries including all EU Member States. A similar trend is documented by a study of Euroheat & Power (ECOHEATCOOL, 2006). The share of each of the three process heat levels depends on the industry subsector and the dominant industrial processes and are addressed by corresponding penetration rates. The three temperature levels are directly correlated with the type of the heat provision as follows:
    - Space and water heating (low temperature: LT),
    - Steam generation (medium temperature: MT),
    - Furnace and direct heat (high temperature: HT).

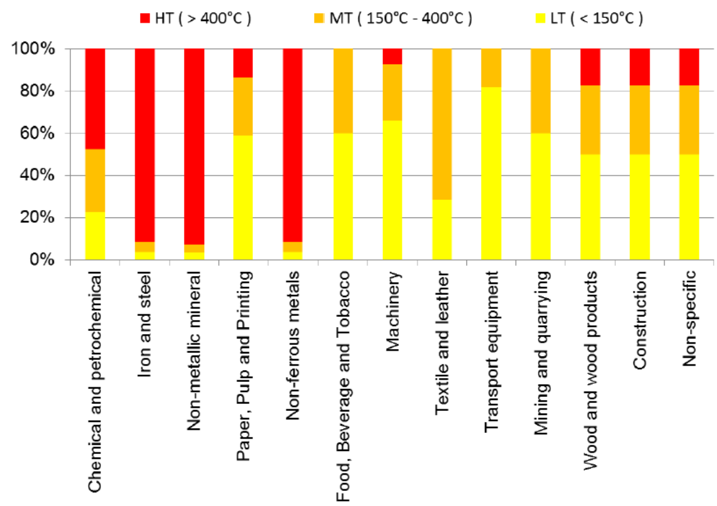

Figure 82: Classification of industry heat demand by the level of temperature and industry subsector (Horta, 2018).

An additional group of useful energy refers to the so-called non-energy consumption and is devoted to the use of mainly fossil energy carriers as feedstock for industry processes (i.e., not for combustion purposes) such as coke used for pig iron production (e.g., in blast furnace) and feedstock requirements in the petrochemical industry (e.g., gas or naphtha) (IPCC, 1996), (UBA, 2019a).

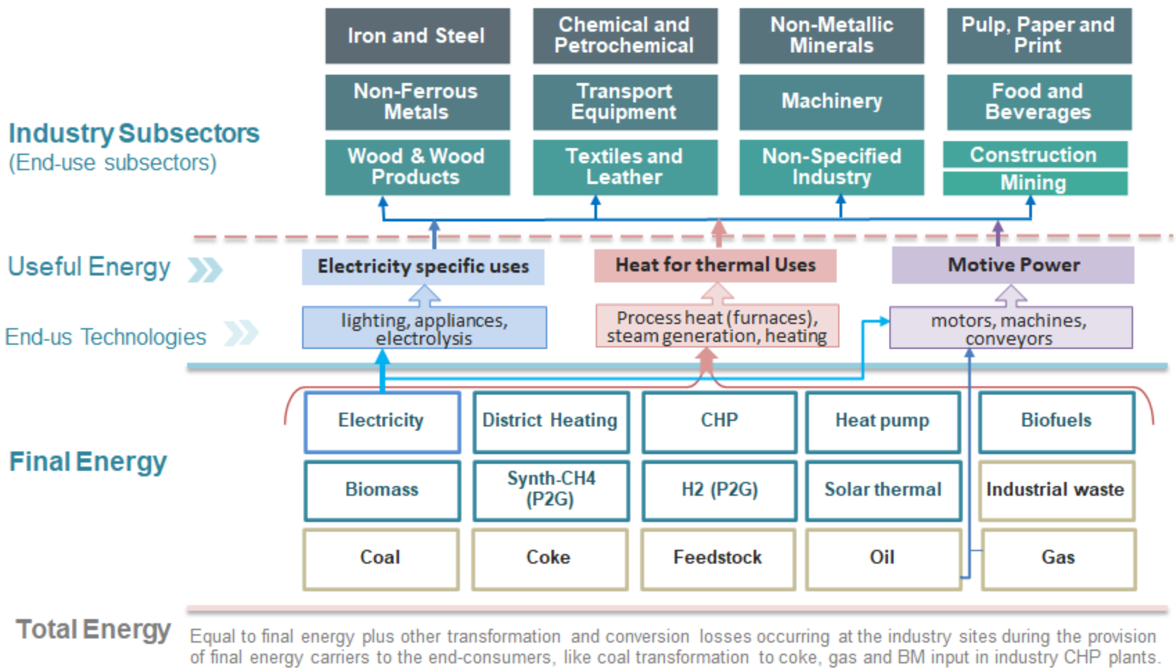

Figure 83: Methodological approach of MAED-IND in mapping useful energy demand and disaggregating final energy demand by fuel and industry subsector.

Table 21: Anticipated long-term development of Austrian GDP in the BAU, POI, ZEM scenarios (Statistics Austria, 2020a), (World Bank, 2020), (Sommer et al., 2017)

	2017	2018	2019	2020	2021	2025	2030	2035	2040	2045	2050
GDP (billion €2015)	360.1	368.9	374.8	321.8	329.2	373.0	405.8	441.5	478.0	517.5	560.2
GDP growth rate (% p.a.)	2.48	2.42	1.61	-6.60	2.30	3.00	1.70	1.70	1.60	1.60	1.60
Industry share in the GDP (%)	24.8	24.8	24.8	24.8	24.9	25.0	25.1	25.3	25.4	25.6	25.7

Table 22 summarises the quantitative assumption about the evolution of useful energy intensity by subsector. The resulting average annual growth rate decrease in useful energy intensity amounts to -0.26%. Table 22 presents the applied assumptions for the improvement of final energy efficiency improvement for thermal uses by level of temperature, based on the example of the pulp and paper industry. The resulting average annual rate of end-use efficiency improvement amounts to about 0.07%. All other subsectors develop similarly.

Table 22: Assumptions of useful energy intensity development by subsector, normalised to the base year, BAU scenario

	Unit	2017	2018	2019	2020	2021	2025	2030	2035	2040	2045	2050
Useful energy intensity index (2017=100): Useful energy consumed per unit of industry product expressed in GDP-VA (kWh/€). **It constitutes of heat, motive power and specific electricity use. The decreas implies efficienter industry processes.**												
Iron and steel	**Ratio**	100.0	99.7	99.5	99.2	98.9	97.8	96.4	95.1	93.7	92.3	90.9
Chemical & petrochemical	**Ratio**	100.0	99.7	99.5	99.2	99.0	98.0	96.7	95.5	94.2	93.0	91.7
Non-ferrous metals	**Ratio**	100.0	99.8	99.5	99.3	99.1	98.1	96.9	95.7	94.5	93.4	92.2
Non-metallic minerals	**Ratio**	100.0	99.7	99.5	99.2	98.9	97.8	96.5	95.1	93.7	92.4	91.0
Transport equipment	**Ratio**	100.0	99.8	99.6	99.3	99.1	98.2	97.2	96.1	95.0	93.9	92.8
Machinery	**Ratio**	100.0	99.8	99.6	99.4	99.1	98.3	97.2	96.1	95.0	93.9	92.9
Food and beverages	**Ratio**	100.0	99.7	99.5	99.2	99.0	98.0	96.7	95.5	94.2	93.0	91.7
Paper, pulp and print	**Ratio**	100.0	99.7	99.5	99.2	98.9	97.9	96.5	95.2	93.9	92.5	91.2
Wood and wood products	**Ratio**	100.0	99.7	99.5	99.2	99.0	97.9	96.6	95.3	94.0	92.7	91.4
Textiles and leather	**Ratio**	100.0	99.8	99.6	99.3	99.1	98.3	97.2	96.1	95.0	93.9	92.8
Non specified industry	**Ratio**	100.0	99.8	99.6	99.4	99.2	98.4	97.4	96.3	95.3	94.3	93.3
Total MAN	**Ratio**	100.0	99.7	99.5	99.2	99.0	98.0	96.7	95.4	94.1	92.8	91.6

11. Abbreviations

BAU	Business as usual
BAT	Best available technologies
BTT	Breakthrough technologies
	In contrast to incremental technological inventions, breakthrough technologies are new innovations which offer order-of-magnitude scale improvements in the price versus performance ratio. They are considered as foundational inventions that serve as the basis for many subsequent technological inventions (Art & Veugelers, 2013)
CET	Currently existing technologies
DT	Disruptive technologies
EMT	Emerging technologies
KICET	Key indicators for clean energy transition
MAED-IND	Model for Analysis of Energy Demand of the Industry
CCUS	Carbon capture, utilisation and storage
POI	Pathway of industry
ZEM	Zero emission