Chair of Energy Network Technology

Doctoral Thesis

Transitioning towards climate neutral industrial energy systems: Analysing pathways and boundaries for the manufacturing industries in a case study of Austria

Dipl.-Ing. Peter Nagovnak, BSc

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www.unileoben.ac.at

AFFIDAVIT

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I declare that I have read, understood and complied with the "Good Scientific Practice" of the Montanuniversität Leoben.

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Date 17.07.2024

Signature Author
Peter Nagovnak

ABSTRACT

To reach the Paris Agreement's climate objectives, the decarbonisation in manufacturing industries takes a central role in shaping the energy system of the future. In 2020, the sector was responsible for one-fourth of energy and process-related European greenhouse gas emissions. On the other hand, the manufacturing industries are an important part of the Union's economic wellbeing and success. The present thesis provides a standardised approach to investigating climate-neutrality pathways and key levers of action in a case study of Austria.

State-of-the-art energy and emission balancing, which is the cornerstone of any subsequent analysis, exhibits several limitations regarding necessary subsector-specific analyses, particularly concerning energy-intensive industries as energy generation and transformation are not accounted for within the economic sectors in which they occur. Therefore, this thesis pioneers innovative energy and emission balances, tracing physical energy flows from and to economic sectors. This is enabled by introducing the sectoral gross energy balance border (SGEBB), allowing the identification of all energy activity within each sector. Secondly, the thesis establishes robust indicators based on the technical climate neutrality potential, evaluating cost-benefit ratios for alternative climate-friendly technologies. Clustered by four distinct climate neutrality pathways, the set of indicators provides both granular insights into subsectors' process necessities and a holistic overview of the general energy system. Based on this information, distinct industry scenarios are developed using the SGEBB and identified technology options. A completely novel scenario approach contrasting industry representatives' transformation measures assessment against a scientific backcasting scenario and a business-as-usual scenario allows insights into future developments of industries. Projections until 2050 show a surge in climate-neutral energy carriers, with electricity and gas consumption increasing by up to 80% each. Techno-economic analysis reveals that alternative climate-friendly technologies can compete with conventional counterparts given GHG emission costs of 200-300 €/t CO_2 or substantial funding of capital expenditures, especially for generation plants of green gases.

As accompanying research in this thesis – e.g. the Austrian national grid infrastructure plan – suggests, occurring bottlenecks can be solved not only through traditional grid expansion but also through sector coupling, e.g., through industrially-owned power-to-heat or power-to-gas units as well as storages strategically placed to decrease the stress on the electricity grid as the most critical grid in terms of time and load. The manufacturing industries can be an essential partner for both the investment and operation of these units. Future research should utilise the proposed balance border and potential analysis developed in this thesis to broaden both the range of available scenarios concerning industries and the technologies employed. Additionally, it should incorporate other economic sectors and existing infrastructure requirements to thoroughly investigate the necessary conditions for successful energy system decarbonisation.

KURZFASSUNG

Die produzierende Industrie – jährlich für rund ein Viertel der Treibhausgasemissionen in Europa verantwortlich – stellt ein Hauptaugenmerk bei der Gestaltung des zukünftigen Energiesystems dar. Gleichzeitig ist zu beachten, dass hier ein bedeutender Anteil der europäischen Wirtschaftsleistung erbracht wird. Die vorliegende Arbeit stellt einen standardisierten Ansatz für die Untersuchung möglicher Transformationspfade anhand einer Fallstudie Österreichs dar.

Aktuelle Energie- und Emissionsbilanzen, welche den Grundstein für jegliche Form von nachgeschalteten Analysen darstellen, weisen zahlreiche Limitierungen bezüglich der den industriellen Subsektoren eigenen Prozesse, insbesondere in Hinblick auf industrieeigene Energieerzeugung und -transformation auf. Durch die in der Arbeit vorgeschlagene sektorale Bruttoenergiebilanzgrenze können physische Energieflüsse zu und aus Wirtschaftssektoren bzw. industriellen Subsektoren verfolgt werden und zur Identifikation aller Aggregate im Zusammenhang mit der wirtschaftlichen Aktivität eines Sektors beitragen. Daneben ermöglicht es der Vorschlag einer standardisierten Sammlung und Berechnung von technoökonomischen Kennzahlen, basierend auf einem technischen Dekarbonisierungspotential subsektoraufgelöst jene Technologiegruppen zu erkennen, welche in der Summe der Sektoren ein vielversprechendes Verhältnis aus Emissionsreduktion und Kosten aufweisen. Auf Basis der entwickelten Bilanzgrenze und der technoökonomischen Analyse der Technologien können in weiterer Folge Transformationsszenarien formuliert werden. Ein innovatives Stakeholder-basiertes Szenario zeigt die in den Subsektoren der Industrie abgefragten bereits geplanten Transformationsmaßnahmen. Dies wird einem wissenschaftlichen Backcasting- sowie einem Business-as-usual-Szenario gegenübergestellt. Deren Berechnung bis 2050 zeigt einen signifikanten Anstieg im Bedarf der leitungsgebundenen erneuerbaren Energieträger im Strom- und Gassektor von bis zu 80%. Die technoökonomische Analyse zeigt, dass eine wirtschaftliche Transformation CO_2-Emissionskosten von 200-300 €/t CO_2 benötigt. Alternativ kommen Investitionszuschüsse, insbesondere für die Erzeugung erneuerbarer Gase, als vielversprechende Begleitmaßnahmen der Industrietransformation in Betracht.

Wie begleitende Arbeiten – etwa am integrierten österreichischen Netzinfrastrukturplan – über die Dauer dieser Dissertation darstellen konnten, kann die Industrie durch strategisch platzierte Sektorkopplungseinheiten zur Entlastung der kritischen Energieinfrastruktur durch die Anwendung von industrieeigenen Power-to-Heat oder Power-to-Gas Anlagen sowie Speichern beitragen. Weiterführende Arbeiten sollten sich der hierin entwickelten Bilanzgrenzen und Potentialanalyse bedienen, um sowohl die Bandbreite der verfügbaren Szenarien in Hinblick auf die Industrie und zum Einsatz kommende Technologien zu erweitern als auch andere Wirtschaftssektoren und bestehende Infrastrukturvoraussetzungen in die Untersuchung der notwendigen Rahmenbedingungen für eine erfolgreiche Dekarbonisierung des Energiesystems einzubinden.

Für Felix

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NOMENCLATURE

BAT	Best available technologies
BAU	Business as usual
BMK	Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology
CHP	Combined heat and power
EII	Energy-intensive industries
ENTSO-E	European Network of Transmission System Operators for Electricity
GDP	Gross domestic product
GHG	Greenhouse gas
H-DR-EAF	Hydrogen-based direct reduction and EAF deployment
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRES	International Recommendations for Energy Statistics
POI	Pathway of industry
PtG	Power to gas
PV	Photovoltaics
RES	Renewable energy sources
SGEBB	Sectoral gross energy balance border
SNG	Substitute natural gas
TCNP	Technical climate neutrality potential
UBA	Austrian Federal Environment Agency (*german:* Umweltbundesamt)
WAM	With additional measures
WEM	With existing measures
ZEM	Zero emission

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1 INTRODUCTION

For the global community to reach its climate goals according to the Paris Agreement of 2015, a ground-breaking shift in energy systems towards renewable energy sources (RES) is essential [1]. Despite the broad consensus on the fundamental goal of limiting global warming through the mitigation of greenhouse gas (GHG) emissions, many questions about the modalities of achieving it remain open, even years later. The Intergovernmental Panel on Climate Change (IPCC) estimates that the anthropogenic contribution to global warming since the beginning of industrialisation currently lies at around 1°C. To meet the goal of limiting global warming to 1.5 to 2°C compared to pre-industrial times, IPCC experts estimate that global climate neutrality must be achieved by 2070 at the latest [2]. The later profound changes in the global energy system are tackled, the longer and more complicated the path to achieving climate neutrality becomes. Hence, the global community of states faces the challenge of transforming their interdependent economic systems sustainably within a few decades, laying the foundation for a just and liveable world for generations to come. To achieve this, governments worldwide are faced with a growing need to pass supporting legislation and establish adequate boundary conditions for their economies to champion the turnaround from fossils- to renewables-based and climate-neutral energy systems.

The European Union aims to assume an international leadership role in achieving climate neutrality as the first large-scale entity by 2050. The “European Green Deal” aims at a reduction in GHG emissions in comparison to 1990 levels of 55% by 2030 before reaching complete climate neutrality by the middle of the century [3]. In line with the "Regulation on the Governance of the Energy Union," member states are obliged to regularly create scenarios, at least up to the year 2030, as projections of the effects of existing measures (scenario "with existing measures" – WEM) and additionally planned measures (scenario "with additional measures" – WAM) [4]. Thereby, the impact and success of already enacted and envisioned policy measures can be evaluated. However, as depicted in Figure 1, as of now, even the planned additional measures of member states – in many cases still a long way from being enacted into law – fail to reach the Commission's goals of -55% emissions by 2030. According to WAM projections, the Union’s GHG emissions reach approximately 2700 Mt CO_2e/a by 2030, while the Commission envisions approximately 2100 Mt CO_2e/a in its green deal goals.

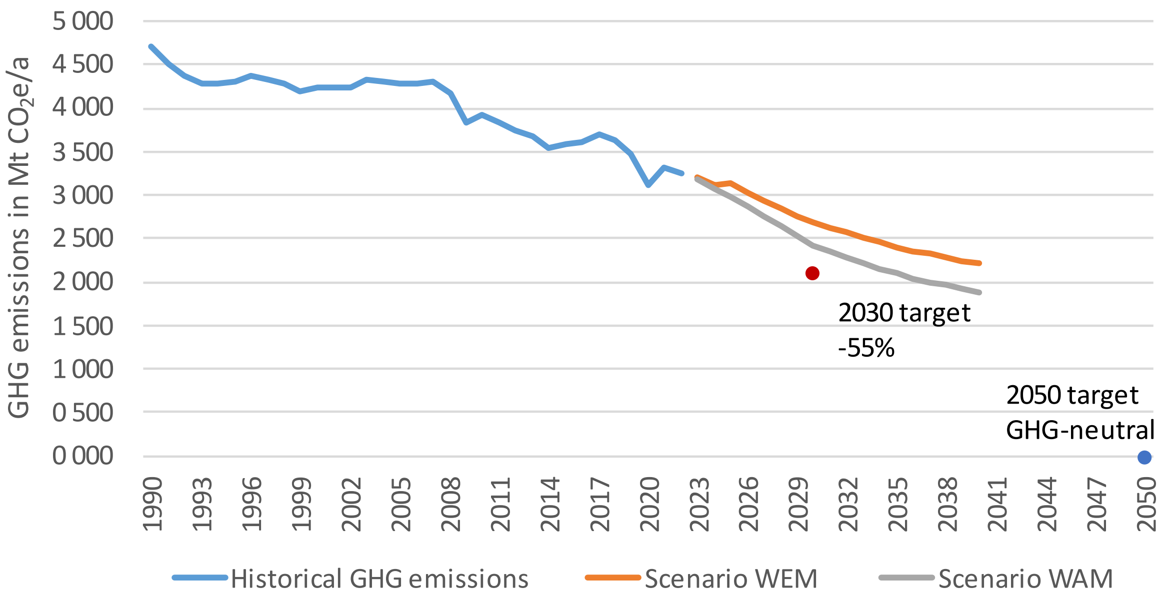

Figure 1: Historic GHG emissions in Europe and scenario pathways until 2030 and beyond [5].

Among the consumption sectors (manufacturing industries, buildings, transport, and agriculture), reaching climate neutrality in manufacturing industries takes a central role in shaping the energy system of the future. In 2020, the sector was responsible for 23% of energy and process-related European greenhouse gas emissions due to the significant dependency on fossil energy for energy-intensive production processes [6]. In addition, the total impact of the manufacturing industries sector on GHG emissions of the EU is even greater due to electricity and heat consumption from the public grid. This is because these so-called scope 2 emissions are caused by the deployment of fossil primary energy carriers – especially coal and gas – in power plants from energy suppliers. On the other hand, the manufacturing industries are an essential part of the Union's economic well-being and success, directly accounting for approximately 15% of value-added and employing 16% of its workforce [7, 8]. Therefore, finding sustainable transition pathways for the manufacturing industries must be considered as one of the keys to long-term European prosperity in light of the climate crisis [9].

Among the manufacturing industries, the energy-intensive and non-energy-intensive industrial subsectors are generally distinguished. According to the International Energy Agency (IEA), energy-intensive industries (EII) consist of iron and steel, the chemical and petrochemical industry, non-metallic minerals, non-ferrous metals, and paper, pulp and print. With the exception of paper, pulp and print production, where biogenous and therefore climate-neutral energy carriers in the form of woody biomass are used as a feedstock, these subsectors deploy large quantities of fossil energy both for the generation of high-temperature thermal energy – where especially gas is used extensively – and directly in the production process; gas and oil as feedstock in case of the petrochemical industry and coal as reducing agent to produce steel from iron ore in the iron and steel industry. Their basic material production is one of the pillars of European welfare as their output is further used and refined in subsequent manufacturing subsectors, e.g. steel for transport equipment or machinery, or cement for construction, to name a few examples. In total, the energy-intensive industries employ more than 3.5 million people unionwide while annually generating added value of over € 700 billion [10–12]. Without a doubt, a forcefield between macroeconomic importance and significant fossil-based emissions exists. Therefore, the energy-intensive industries are particularly important in any discussion of possible GHG mitigation pathways.

Swift and decisive action towards climate neutrality in European manufacturing industries becomes increasingly essential to fulfilling the continent's share of reaching the globally formulated climate goals. But how can we investigate necessary technologies, assess their impact on this path, and provide the necessary information to develop suitable framework conditions for such a successful energy transition in manufacturing industries?

For this purpose, scenario development has proven to be a valuable tool in energy systems analysis. As a form of energy system analysis, scenarios can provide substantial aid in investigating the impact of technology deployment in manufacturing industries and assessing necessary enabling framework conditions. Giannakidis et al. prove the importance of energy and emission scenarios by reviewing the impact of energy systems models' scenario output in national and supranational policymaking. They show that scenario work directly helps in overcoming barriers in acceptance, fostering understanding of critical areas of action and subsequently leading to long-term energy and emission strategy development [13]: By opening a bandwidth of options and emphasising different key areas – targets, technologies, energy carriers, strategies, etc. – comparison of results allows the identification of necessary framework conditions, technology development and innovation needs. The magnitude of the challenge of climate neutrality calls for extensive coordination of both political and industrial stakeholders. A targeted information basis is characterised by in-depth investigations where it is crucial to correctly reflect the diversity of industrial subsectors on the one hand and the ability to deduce a bigger picture for embedding industrial policies within the larger developments of national and international economies on the other.

The present thesis endeavours to contribute to the transformation of manufacturing industries by employing a multi-faceted approach within the framework of energy system modelling. For demonstration of the proposed methodologies, Austria is presented as a case study. Austria can be considered an illustrative example of a heavily industrialised economy, with manufacturing industries contributing around 25% of the national GDP, surpassing the European average due to an exceptionally high presence of energy-intensive primary subsectors (e.g., steelmaking, paper, pulp and print as well as chemical and petrochemical industries). As visualised in Figure 2(a), in 2019, the overall manufacturing industries constituted roughly 28% (133 TWh/a) of the nation's gross domestic energy consumption when considering energy input for industrial combined heat and power plants, blast furnaces, coke ovens, and chemical production. Concurrently, manufacturing industries were responsible for approximately 38% (30 Mt CO_2e) of total national GHG emissions when including upstream emissions for the provision of electricity and heat [14]. Among the industrial subsectors, the aforementioned iron and steel, paper, pulp and print, chemical and petrochemical, and non-metallic minerals are the most energy-intensive subsectors. Their energy demand and GHG emissions are highlighted more specifically in Figure 2(c), together with subsectors machinery, food and tobacco, and wood and wood products. It is well visible from this chart that the industrial transformation processes involved in basic material production (such as the reduction of iron ore through coal and coke in steel production, CH_4 for deriving chemical materials, and geogenous emissions and high-temperature process heat in the non-metallic minerals subsector) significantly drive energy demand and GHG emissions in Austria. With a substantial share of automation, machinery relies heavily on electricity, while in general, industrial subsectors rely heavily on natural gas for a broad variety of processes. In paper, pulp and print as well as wood and wood products, also in Austria residues of biogenic production resources are used energetically on-site. This can significantly lower the GHG intensity of these subsectors; while paper, pulp and print production constitutes the subsector with the second highest energy consumption in Austria, its GHG emissions are only ranked fourth highest, behind chemical and petrochemical and non-metallic minerals which both feature a significantly lower total energy consumption, albeit higher fossil energy shares.

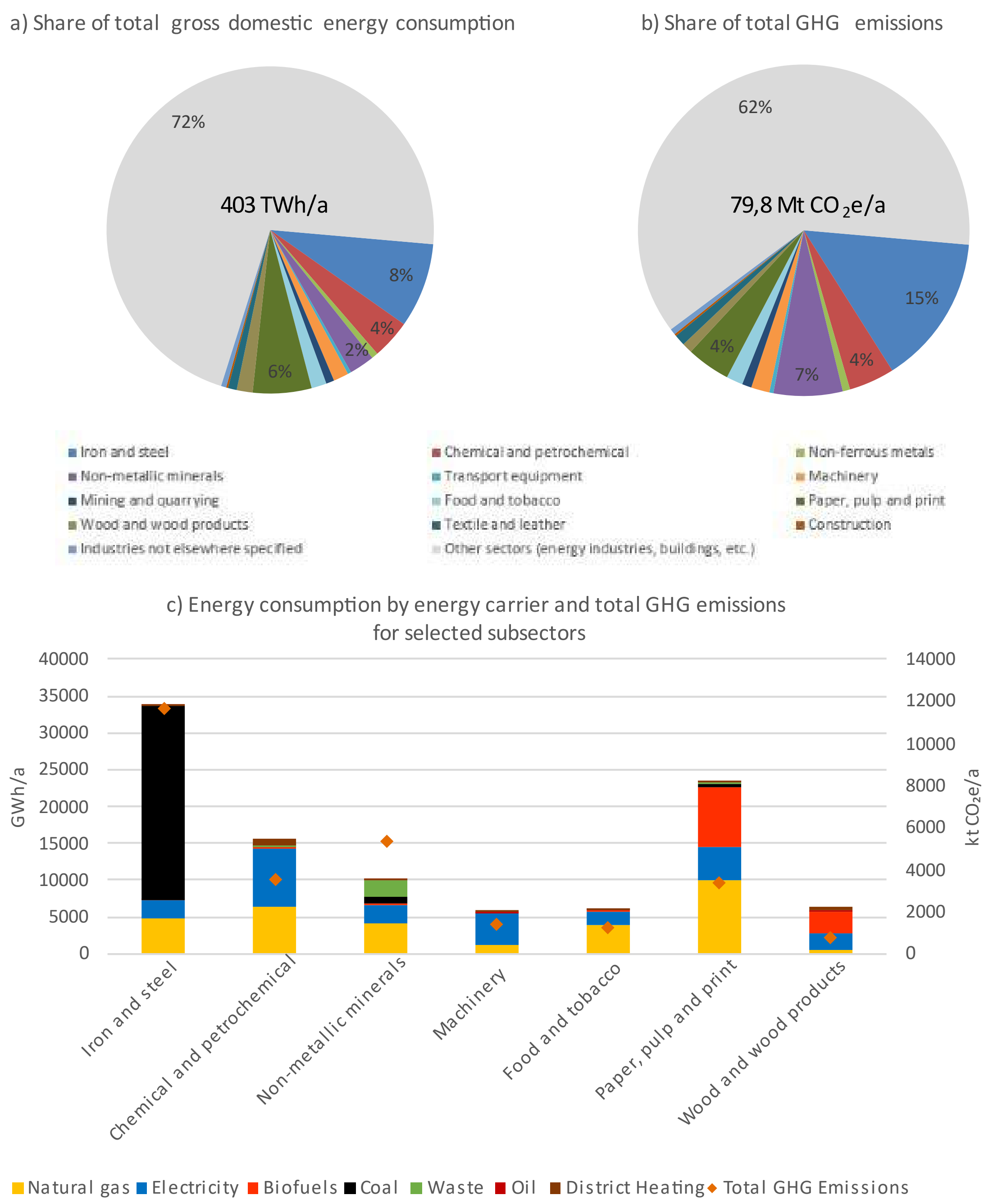

Figure 2: Manufacturing subsectors' shares of 2019 Austrian gross domestic energy consumption (a) and GHG emissions (b), and close-up investigation of energy consumption and GHG emissions for the seven most energy-intensive subsectors (c). Own illustration based on data by Diendorfer et al. [14]. Upstream GHG emissions for electricity and heat from the public energy system are included in consumption data.

In light of the current fossil energy quantities and resulting GHG emissions, both energy and process-related, the manufacturing industry requires a profound transformation to achieve climate neutrality. Advances in scaling up domestic renewable energy sources, such as solar and wind power, are crucial for powering industrial operations sustainably. However, the widespread adoption of these technologies requires substantial investment in new infrastructure, particularly for grid-bound energy carriers like electricity and gas, and the implementation of advanced energy storage solutions to manage the intermittent nature of renewable energy sources. These infrastructural developments are necessary to ensure a stable and reliable energy supply for manufacturing processes.

On the other hand, manufacturing processes must transition to clean technologies. These technological shifts demand significant financial and human resources and investment in research and development. Currently, industries face a low availability of highly skilled workers, which is necessary to realise the transition to green technologies. In addition to the challenge of transitioning existing product portfolios to greener production, the products themselves must meet the demands of a more sustainable economy. Consequently, entirely new products and production processes may be established or further developed. This industrial transformation not only affects manufacturing processes but also extends to the entire value chain, from raw material extraction to product delivery. Therefore, industries must increasingly focus on resource efficiency, recycling, and reducing waste throughout the product lifecycle and production processes.

Given the complexity and scale of the required transformation, a comprehensive analysis and strategic planning are essential. This thesis undertakes to investigate the necessary methodologies to prepare and investigate possible transformation pathways for manufacturing industries adequately:

- Firstly, the state-of-the-art energy and emission balancing methodology is investigated for its aptitude for the transformation process of energy systems, and the resulting necessary improvements are proposed.
- Secondly, a techno-economic analysis of technologies for the especially energy-intensive industrial subsectors towards climate neutrality is employed to evaluate the costs associated with the transformation process and the relative impact on greenhouse gas emission mitigation on the level of technology groups. Thereby, critical technological levers of action that align with the goal of achieving climate neutrality are identified.
- Thirdly, scenario analysis until 2050 allows a comprehensive investigation of a bandwidth of identified technology combination possibilities on an implementation pathway until 2050. This encompasses deploying diverse technologies to assess their individual impacts on energy demand and total GHG emissions of manufacturing industries. In addition to best available and breakthrough technologies, industrial stakeholders' feedback on their currently envisioned transformation pathways is considered.

Through this integrated techno-economic approach, the research aims to offer valuable methodological insights to facilitate the investigation of GHG mitigation strategies in manufacturing industries. Subsequently, these insights that may be gained from the deployment of said approach shall contribute to formulating recommendations for action and strategies to inform both industrial stakeholders and policymakers on the sustainable and efficient transformation of manufacturing industries.

The structure of this thesis unfolds as follows: Section 2 summarises the state of research within the areas of action mentioned above. From this analysis, a clear research gap is elaborated, and the key research questions of the present thesis are derived. Section 3 of this work presents an overview of the applied methodology for answering the above research questions and the thesis' contribution to scientific knowledge. Then, in section 4, the main results from the peer-reviewed journal articles are presented and discussed in the context of the overall energy system's transition to climate neutrality. The peer-reviewed articles themselves, which form the actual core of this thesis, can be found in the appendix[1]. Finally, section 5 concludes the present work and offers an outlook on possible future scientific areas of investigation.

[1] Appendix A: Peer-reviewed publications includes all three peer-reviewed journal articles in full length. Further publications are shown in Appendix B: Further scientific publications.

2 STATE OF RESEARCH AND RESEARCH QUESTIONS

In the following, the current state of research is summarised, focusing on methodologies for energy and emissions balances – particularly their shortcomings in industrial applications – techno-economic analyses of technological solutions for achieving climate neutrality in industry, and energy and emission scenarios with a particular emphasis on the industrial sector. Based on this overview, the research questions of this thesis are subsequently derived.

Generally, the manufacturing industries can be divided into thirteen subsectors (cf. Table 1) to characterise their production processes, energy demand, and resulting GHG emissions. This division is crucial because industrial subsectors feature two general types of energy conversion units, which are highly dependent on the respective subsector's production and technology portfolio: energy transformation units and end-use devices necessary for supplying useful energy in the production process. The applied temperature ranges and production technologies differ significantly by subsector and largely determine the available climate-neutral alternative pathways.

Table 1: Division of manufacturing industries into subsectors [15].

Subsector
Iron and steel
Chemical and petrochemical
Non-ferrous metals
Non-metallic minerals
Transport equipment
Machinery
Mining and quarrying
Food and tobacco
Paper, pulp and print
Wood and wood products
Textile and leather
Construction
Industries not elsewhere specified

Balance border of future energy systems

In state-of-the-art energy and emission balances, sectoral linkages between grid-based energy sources (electricity, gas, heat) – for example, in combined heat and power plants (CHP) – and energy inputs in industrial conversion processes (e.g., blast furnaces, reformers, power plants, etc.) are not primarily accounted for according to the location or sector of demand. Instead, they are categorised separately under "energy industries consumption" and "(industrial) conversion input/output," following the standards proposed in the United Nations' International Recommendations of Energy Statistics (IRES) [15]. This system relies on a three-block concept consisting of "total energy supply," "transformation and distribution", and "final consumption" as visualised in Figure 3(a). The first two blocks are generally referred to as the energy industries, while final consumers are comprised of the manufacturing industries, buildings, transport, among others.

The most recent version of IRES, published in 2018, marks the first comprehensive update since 1980. Although the current IRES standards have seen notable improvements, such as the inclusion of solar and wind power, and biofuels, the rapidly evolving energy system landscape necessitates further adaptations to address emerging challenges and optimise the future renewable energy-based energy system. In the existing literature, several key trends towards decarbonisation emerge, including:

- The rising prominence of renewable energy technologies, not only on an energy-utilities scale but also in households or industrial companies as much smaller entities
- Hydrogen's significance as a crucial energy carrier applicable to a range of energetic and non-energetic consumption technologies while also facilitating consumer-based flexibility options
- The growing competitiveness of small to mid-scale solutions for electricity, gas, or heat storage
- The integration of various energy carriers through sector coupling, enabled by new transformation and digitalisation technologies
- Heightened efforts towards implementing a circular economy in manufacturing industries

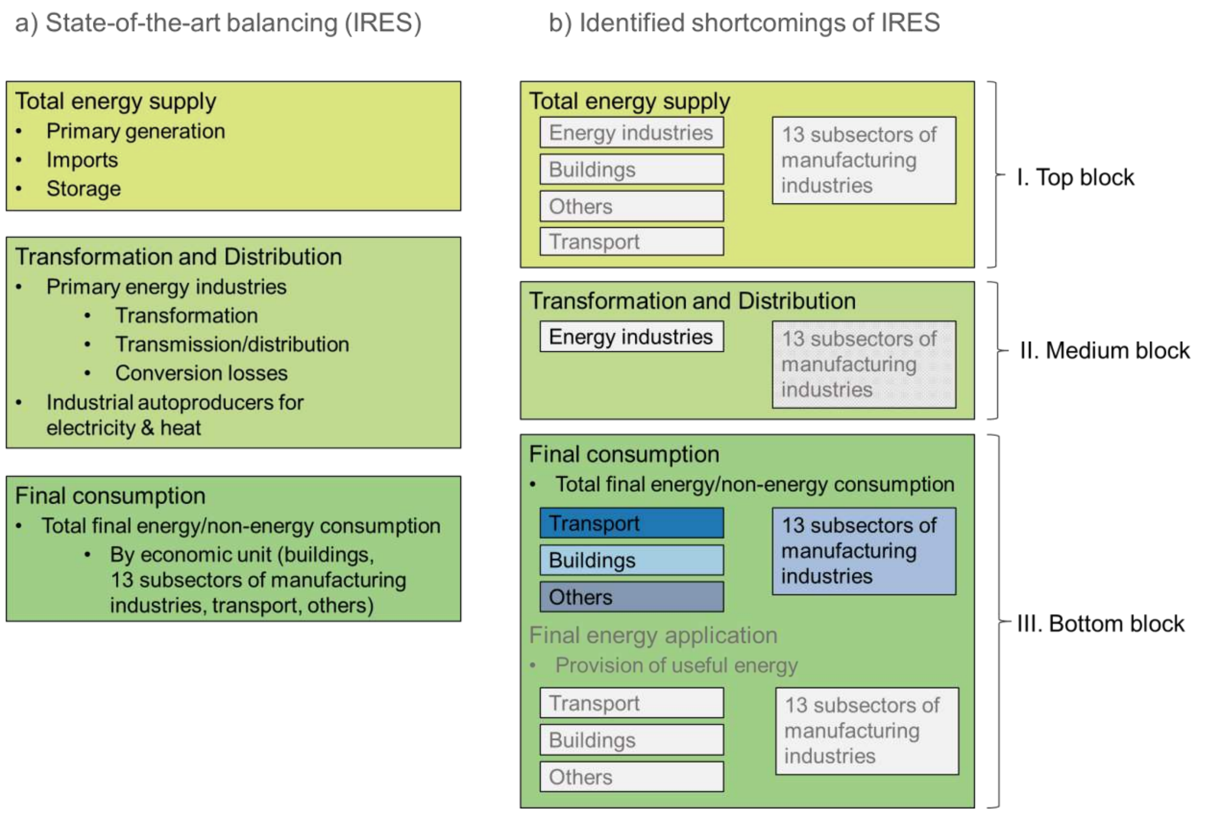

Figure 3: Scheme of state-of-the-art energy balance based on IRES [15] (a) and identified shortcomings of this standard (b). The unidentifiable components in the IRES methodology of the energy system are represented in light grey.

These trends' emergence leads to increased linkages and interactions among all energy system stakeholders. Consequently, this development presents new challenges for energy balances. As depicted in Figure 3(b), the expected interconnections in energy supply and consumption among economic sectors show significant growth. The unidentifiable components in the current IRES methodology of the (future) energy system are represented in light grey. Energy generation units outside the energy industries within the thirteen subsectors of manufacturing industries, in buildings, or transport, which can be grouped under the term prosumers, cannot be accurately attributed to the respective economic units deploying them.

In addition, the current IRES concept does not account for energy output resulting from energy transformation by prosuming sectors into the overall energy system. The categorisation lacks disaggregation into industrial subsectors. In the future, as other forms of energy transformation become more relevant, such as the production of hydrogen from electricity (PtG) or the integration of industrial waste heat into the overall energy system, the proper allocation of transformation units will require an extension of the definition of autoproducers to encompass the diverse field of energy transformation technologies used by the thirteen subsectors of the manufacturing industries.

With increasing decentralised power generation, especially from photovoltaics and storage capabilities in the buildings and transport sectors, the methodology discussed for the manufacturing industries is also essential for all other economic subsectors. Similarly, state-of-the-art IRES methodology only presents total final energy and non-energy consumption by economic unit, omitting useful energy categories representing final energy applications. Without further information on the exact application of final energy, the usefulness of alternative technology pathways cannot often be adequately assessed. This limitation hinders the development of transition pathway analyses and energy scenarios, which are crucial aspects of energy statistics' role in the policy delivery cycle.

Techno-economic analysis of alternative technologies

It is crucial to balance the necessary subsectoral detail with cross-sectoral generality to successfully navigate the multitude of technology options and their impacts on greenhouse gas emission mitigation and associated costs in manufacturing industries. Before turning our focus onto scenario development to address a combination of factors and technologies throughout all subsectors, it is important to understand available technologies, their possible application areas and total deployment costs. Within literature, two groups of studies can be identified that try to fulfil this objective when contemplating big-picture decisions for the energy and emissions transition.

The first group of literature entails specific bottom-up analyses with very detailed process and cost depictions of just one or very few industrial subsectors. These studies consider the subsectors in question as solitary units without investigating the applicability of the chosen energy carriers or technologies in other manufacturing industries or economic sectors. As an example of this group of analyses, Shahabuddin et al. [16] and Fischedick et al. [17] offer techno-economic analyses of decarbonisation options for the iron and steel industries, focusing on alternative reduction technologies, their energy consumption, emissions, and capital and operational expenditures. O’Shea et al. [18] aim to identify promising technology combinations in a multi-criteria approach for the food and beverage subsector, where GHG mitigation and capital expenditures are considered. They do not investigate single technologies that make up the investigated pathways on this level and operating costs remain unconsidered.

In the second group, numerous scientific publications have provided comprehensive, subsector-spanning solutions for manufacturing industries, often focusing on a single specialised or a very limited number of technology pathways, such as electrification or the use of biomass. Within these technology pathways, several technologies are subsumed (e.g. heat pumps and direct electric heating within electrification). For example, Madeddu et al. [19] analyse the portfolio of available technologies for electrification of industrial processes. In three stages constituting the potential advancement of electrification based on level of complexity, GHG mitigation potential and changing energy demand in a selection of manufacturing subsectors are investigated. However, no indication of associated costs is provided. Similarly, Sandberg et al. [20] argue for an industry-wide approach when analysing the potential mitigation effect of deploying electrification or biomass use in Swedish manufacturing industries. In their optimisation problem, the total use of biomass and electricity is reduced as much as possible while at the same time reaching climate neutrality or better. In contrast to the aforementioned studies, Bühler et al. [21] extend their technical analysis of electrification potentials in Danish manufacturing industries to economic considerations, taking into account electricity and gas prices, emission trading prices of CO_2 certificates, and capital expenditures for electric boilers.

In summary, without a standardised set of indicators for comparison and a balanced examination of technology pathways' applicability across various subsectors, neither of the aforementioned groups succeeds in transparently assessing the greatest possible impact of several technology options on climate neutrality. This includes considering associated indicators such as energy consumption, capital, and operational expenditures across multiple subsectors within a single approach. While the first group only achieves a balanced approach for single manufacturing subsectors, the second focuses on only a few technology pathways. Additionally, there is a significant gap in combining energy demand and GHG emission investigations with techno-economic analyses.

However, the insight into technology pathways' greatest possible impact on emission mitigation mentioned above can provide an essential knowledge base for further transitional analysis. Based on the identified most promising technology pathways and an indication of associated costs and energy demand, subsequent scenario modelling can investigate the transformation of manufacturing industries and the interaction of the modelled technology deployment.

Scenario analysis of industrial transformation

Within the scientific literature, several academic publications focus only on industrial final energy consumption in total energy system analyses, e.g. Saddler et al. [22] and Gaur et al. [23]. As they do not take into account the energy consumption of industrial energy transformation units and process-related emissions mentioned in the analysis of the energy balances above – which is especially critical in countries with a strong basic materials production such as Austria – this group of scenario studies is not further discussed within this work.

Thanks to the long history of energy and emission scenarios, a wide collection of analyses also exists that do consider the energy-intensive industries of iron and steel, chemicals, and non-metallic minerals more deeply within their transformation scenarios for manufacturing industries. For example, Sánchez Diéguez et al. [24] investigate the transformation towards climate neutrality for the Dutch manufacturing industries in four distinct technology-driven scenarios based on a temporally resolved supply and demand model. In these scenarios, the possibility of reaching climate neutrality in manufacturing industries through exclusive use of either biomass, carbon capture, electrification and hydrogen is analysed. Subsequently, a general optimisation solution is calculated with an open choice of technologies. The study thereby aims to provide information on the general cost efficiency of technology choices in manufacturing industries.

Equally representative of current state-of-the-art energy transformation scenarios, Fleiter et al. (e.g. [25, 26]) have established the FORECAST model to calculate transition scenarios for the manufacturing industries with a strong focus on the large lever of energy-intensive industries bottom-up. Similarly, Schneider et al. [27], among others, combine the use of bottom-up modelling tools with a close stakeholder integration process regarding technology availability and process peculiarities based on preliminary results to calculate transition scenarios for the German industry. The industry investigations by Fleiter, Schneider and their colleagues and subsequent analyses are generally embedded within the lead projects on the transition to climate neutrality – often referred to as the “Big 5” within Germany’s scientific community – making use of a combination of modelling tools that take into account also economic development and energy grids on a time-resolved basis [28, 29]. Thereby, the specific focus on the industrial energy transition and its particular challenges and opportunities can be weakened.

In all scenario investigations, the chosen set of narratives is at the core of the discussion, setting the focus of technology deployment in any given scenario. For the above-mentioned state of literature, generally scenario narratives have focused on the deployment of specific technologies or energy carriers, e.g. electrons in electricity versus molecules in climate-neutral gases such as CH_4 or H_2, or the use of biomass, target states of decarbonisation (e.g. climate neutrality), or a combination of these two approaches. While many studies emphasise the integration of industrial stakeholders at the modelling stage of their analyses or for verification of results, this interaction has not been extended to find reflection in the form of a scenario focus in the sense that it shows what industrial stakeholders already plan to enact.

Also in Austrian scenario modelling, the manufacturing industries are generally included in overall national scenario investigations. However, in contrast to the German Big 5-examinations, assessments on the impact of low-emission or climate-neutral technologies have so far not been able to fully consider the integrated nature and multiple pathways of industrial energy systems, especially in the context of energy-intensive industries such as iron and steel, chemical and petrochemical, and non-metallic minerals. Until recently, the Austrian reporting obligation under the Regulation on the Governance of the Energy Union fulfilled by a consortium led by the Federal Environment Agency UBA [30–32], has been the most comprehensive scenario modelling in Austria. However, the primary focus has been put on the final energy consumption, without consideration of subsector-specific energy transformation technologies in manufacturing industries and their planned deployment rates – with the exception of the iron and steel subsector, where the shift from the BF/BOF route to the hydrogen-based direct reduction has been accounted for.

To summarise, present state-of-the-art literature on energy system analysis concerning the transition to climate neutrality within manufacturing industries reveals several open research gaps:

- State-of-the-art national energy and emission balancing methodologies lack the possibility for sector-resolved analyses of energy activity ranging from energy generation through transformation to end-use and application which is necessary for analyses of future energy systems, particularly in the case of manufacturing industries.
- Understanding the cost-effectiveness and potential benefits of various decarbonisation measures across industrial subsectors is essential for informing the initial stage of subsequent scenario development and consequently guiding decision-making and resource allocation. However, a standardised approach to in-depth analysis of the cost versus emission mitigation benefit structure of technology pathways for manufacturing industries' options towards climate neutrality does not exist.

- Existing scenario narratives concerning the development of manufacturing industries lack an explicit subsector-resolved analysis of the whole manufacturing industries including resulting process-related and energy-related GHG emissions. Their scenario narratives are generally limited to the investigation of the role of different energy carriers, especially electrification versus renewable gases, and their cost-optimal deployment.

Addressing these research gaps and limitations will contribute valuable insights into the field of manufacturing industries when applied in case studies. From the results of these studies, a meaningful information basis can be achieved for policymakers, industries, and other stakeholders in formulating evidence-based strategies towards achieving climate neutrality. This merits the investigation of the following research questions:

- How can the key technological drivers shaping the future of industrial energy systems be effectively captured and analysed in energy statistics to reflect physical energy and emission streams?
- How can information on available transition technologies to investigate technological climate neutrality pathways in manufacturing industries be structured to compare alternative pathways among each other and against conventional fossil technologies, thereby providing the information basis for identifying large levers for action?
- What set of scenario narratives and framework conditions allows an unfiltered and in-depth investigation of every subsector in manufacturing industries? How can we go beyond the existing focus on technology deployment in scenario narratives and visualise the current intentions communicated by industrial representatives?

The developed methodology – interlinked with the corresponding publications and accompanying research projects – will be discussed and presented in the next section to address these research questions.

3 METHODOLOGY

This section will establish the basis for contextualising the work and presenting the applied methodology to address the overarching research questions. In particular, reference will be made to the published peer-reviewed work, highlighting the underlying connections and contributions to the scientific knowledge of these studies in accordance with the research aim.

This cumulative thesis comprises three peer-reviewed journal articles, which are interconnected and complement each other, collectively addressing the above-presented research questions. Figure 4 represents a schematic overview of this cumulative thesis structured in accordance with the three journal papers as well as a selection of additional research projects that together formed an essential knowledge basis for answering the research questions of this thesis and discussing its results in the context of the overall energy system.

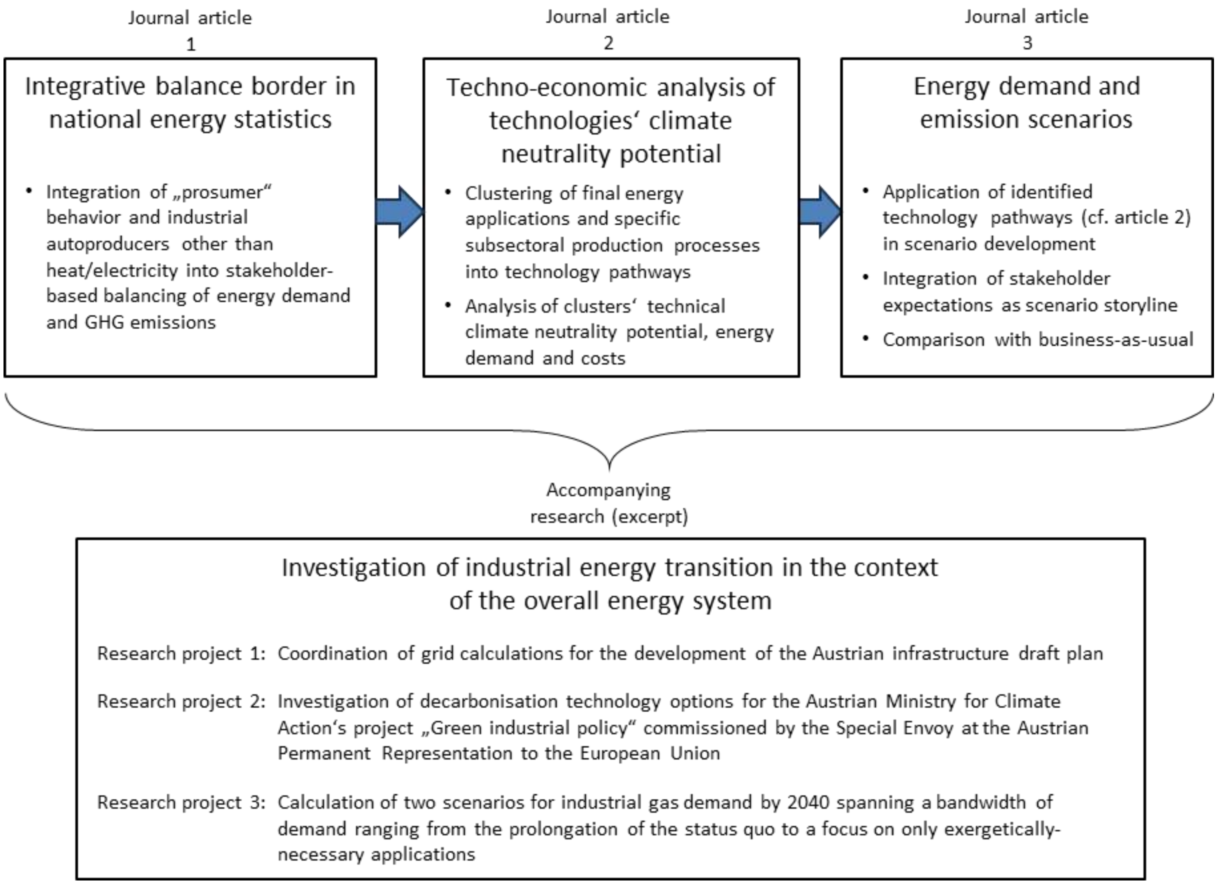

Figure 4: Methodology of this work including corresponding journal articles of the thesis and excerpt of accompanying research conducted in additional projects.

To begin with, a crucial aspect of this work involves determining the integration of the industrial into the overall energy system architecture. In pursuit of this goal, the first journal paper introduces an innovative balance border – the Sectoral Gross Energy Balance Border (SGEBB) – designed based on foreseeable and expected developments concerning renewable energy technology deployment, such as the growth of prosumers, hydrogen integration in relation with indirect electrification in manufacturing industries and storage applications across consumption sectors. The proposed methodology and balance border offers significant advantages over the conventional state-of-the-art approach, when investigating (sub)sectoral transition technologies and their impact on energy demand GHG emissions.

The second journal article presents a standardised approach to investigate the impact of climate-friendly technology deployment across industrial subsectors of the energy-intensive industries (EII) regarding emissions, energy demand and costs. The proposed methodology, which can be easily adopted for non-energy-intensive subsectors, involves calculating technical potentials to gauge the GHG mitigation potentials of technologies – to date, only a widely used technique in assessing renewable energy sources. To evaluate the mitigation impact in terms of costs, the results are complemented by considering both capital and operational expenditures, compared against fossil-based conventional technologies for each application category (space heating, process temperature above/below 200°C, stationary engines and subsector-specific processes such as primary steelmaking). As detailed in the paper, technology-specific average annual full load hours are employed to convert the calculated energy consumption into power capacities, thereby facilitating the assessment of annual capital expenditures. Additionally, the results are clustered into four distinct technological climate neutrality pathways that enable technology application as the primary approach to achieving climate neutrality, making them comparable across all subsectors. On the other hand, general efficiency measures or general process optimisation are therefore not considered. Besides integrating both transformation processes and final energy application as proposed by the SGEBB, scope 2 emissions from the upstream energy provision are estimated to transparently visualise the interdependencies between industrial climate neutrality and the overall energy system. In an exemplary case study of three energy-intensive subsectors, the applicability of the proposed methodology is proven. The analysis of technology pathways' GHG mitigation potential versus costs enables the identification of crucial focus points for subsequent scenario investigations.

In scenario development, the information compiled in the second article is utilised to pinpoint promising breakthrough technologies for a zero-emission scenario until 2050 using the backcasting methodology in the third peer-reviewed journal paper. A novel stakeholder-based scenario (“Pathway of industry” – POI) emphasises first-hand information on mid to long-term planning of key industrial representatives. Together with the previously mentioned best-case scenario (“Zero emission” – ZEM), the results of these narratives are contrasted with a business-as-usual (BAU) scenario, which extrapolates current statistical trends. In this analysis, results for all thirteen subsectors of manufacturing industries (cf. Table 1) are presented and discussed.

Scenario investigations take into account an indication of associated process and energy-related as well as upstream GHG emissions based on specific emissions factors from high-level literature such as the European and Austrian Environmental agencies. In this context, the calculation of emissions from the upstream provision of electricity and the in-grid gas composition is of particular importance. For electricity use, specific grid emission factors according to the EU Commission scenario MIX is used as a basis [33]. Since the GHG intensity of the Austrian electricity sector has historically been lower than that of the Union, we used the Austrian case as the starting point according to the emission statistics of electricity generation by the European Energy Agency [34]. Thereafter, the European development as a percentage from 2020 onwards is applied. For the gas grid, an increasing share of climate-neutral gaseous energy carriers, such as Bio-CH_4 and hydrogen, can be expected until the middle of the century, directly affecting manufacturing industries' GHG emissions. Therefore, a separate methodology for modelling the in-grid gas composition in the three scenarios has been applied. The gas supply system's evolution is shaped by increasing CO_2 costs and decreasing electrolysis production costs for hydrogen. A cost-based method is used to model the gas grid's composition in scenarios POI and ZEM, with renewable gases reaching cost parity with fossil CH_4 between 2035 and 2045. This leads to the gradual elimination of fossil gas from the overall system, unlike in the BAU scenario where fossil CH_4 remains in the system to the extent of up to 70% even by 2050.

Accompanying research projects conducted throughout the work on this thesis complement the understanding of available technological solutions for climate neutrality in manufacturing industries on the one hand and enable greater depth of analysis when discussing the industrial transformation in the context of the overall energy system on the other. While the former is already, to an extent included within the methodologies of the three research papers on manufacturing industries of this thesis, the latter is most strongly epitomised by the author’s contribution to the Austrian national grid infrastructure plan [35]. This plan promises a coordinated development of both high-level electricity and gas grids to enable a transition to renewable energy that is as frictionless and as quick as possible. The cooperation in this project has enabled findings from the Austrian case studies that were used to demonstrate this thesis’ methodologies to directly reflect in the calculation and interpretation of the grid infrastructure plan’s underlying modelling.

In total, the novel methodologies proposed in the collection of all studies developed over the course of this thesis, their standardised approaches, and scenario-based investigations together with their contextualisation within a larger energy system analysis, are aimed at contributing to a more robust base of methodologies that can be further used to informed decision-making, guiding policymakers, industries, and other stakeholders towards a sustainable and climate-resilient industrial future.

4 RESULTS AND DISCUSSION

In the following, the main results and findings with regard to the research questions posed above are presented. In section 4.1, a novel balance border that focuses on the physical location of energy operation is proposed. This enables better attributability of energy demand and thus, better understanding of the challenges and options for action in energy transition. In section 4.2, the concept of technical potentials commonly known from the investigation of RES is extended to alternative technologies' ability to move manufacturing industries towards climate neutrality. Section 4.3 investigates the development of energy demand and GHG emissions of the Austrian manufacturing industries in three scenario narratives.

In addition, section 4.4 shall provide a critical assessment of the research outcomes, offering insights into and discussions of the feasibility and implications of achieving climate neutrality within manufacturing industries in Austria and beyond. The work indicates an annual cost structure consisting of operational and capital expenditures in a green-field approach for the scenario target year 2050 and discusses possible enabling framework conditions regarding energy infrastructure, among others.

Further description of single article results can be found in the individual journal papers in Appendix A: Peer-reviewed publications.

4.1 Balance border of future integrated energy systems

As mentioned above, the state-of-the-art energy balancing methodology under the UN's International Recommendations for Energy Statistics [15] are generally based on a three-block concept (cf. Figure 3). To remedy the shortcomings of current international energy balancing identified in section 2, the Sectoral Gross Energy Balance border (SGEBB) is developed. The balance border visualised in Figure 5 allows a (sub)sector-focused investigation of all energy-related units in operation. This is not limited to energy generation and transformation but extends to end-use energy applications to be able to specify the kind of required useful energy (e.g., temperature levels of thermal energy, motive power, general electricity for lighting or IT, etc.).

Sectors beyond the energy industries – formerly exclusively energy consumers – increasingly play a role in energy generation and transformation. The generated energy flows within these sectors may undergo cascading processes before eventually reaching final consumption. Alternatively, they may exit the sector's system boundaries and return to the energy industries, where they are further distributed to serve other sectors' energy needs.

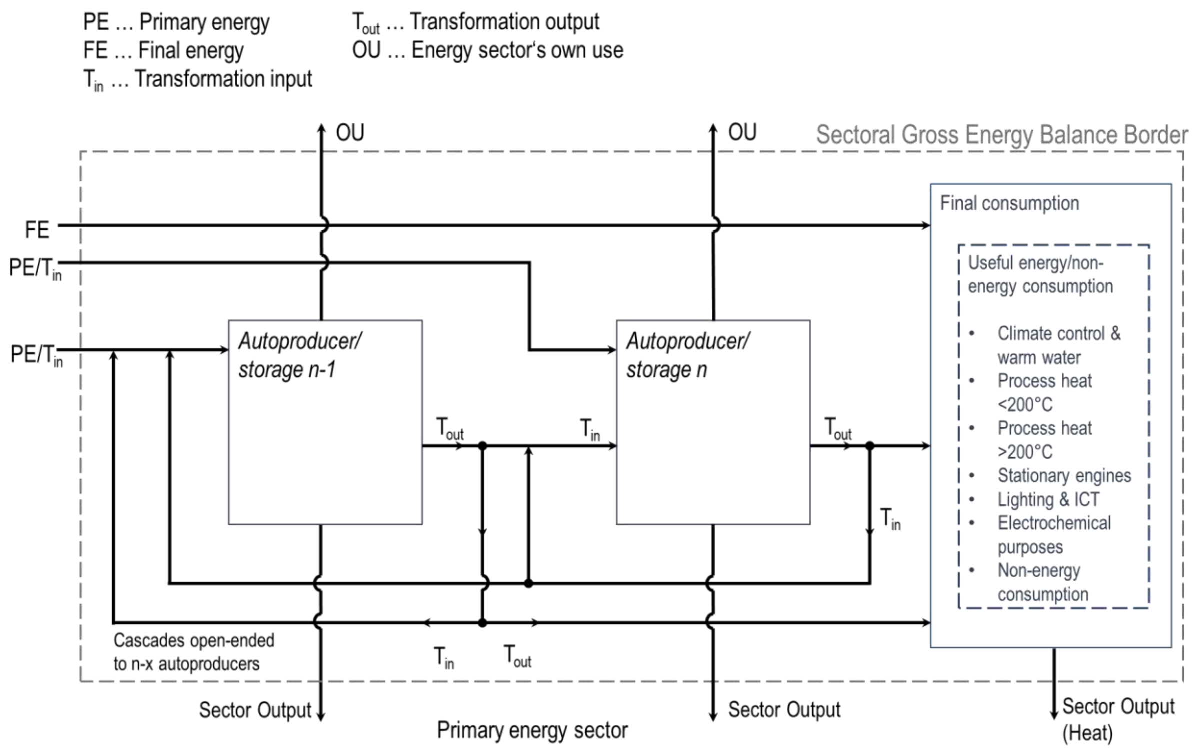

Figure 5: Detailed depiction of energy flows in prosuming sectors and the sectors' intersection with the energy industries' primary energy sector using proposed SGEBB.

The proposed SGEBB facilitates a holistic information process by establishing a theoretical physical boundary encompassing all elements of an economic sector or industrial subsector, including storage, transformation, generation units, and final energy-using devices that provide useful energy services. By applying the SGEBB, a more detailed representation of the underlying activities generating energy flows in each sector and the overall energy system, often comprising interconnected sectors, can be achieved. Thus, the approach also allows for reflecting future prosumer possibilities in historically purely consuming sectors.

When the SGEBB is applied to each economic sector or manufacturing subsector individually as formalised in Figure 6, the resulting energy flows in the balance correspond to the physical energy flows at the respective disaggregation level under investigation. Notably, the traditional block of primary energy generation is now subdivided based on the respective economic units operating the energy production plants, clarifying ownership. Similarly, energy transformation processes, commonly observed in energy-intensive industries, are accurately attributed to contributing to the overall energy demand of their respective subsectors, rather than being classified under the energy industries category. In final consumption, the provided information under applying the proposed methodology extends to the kind of end-use energy application necessary in industrial production processes (visualised by the example for iron and steel in the figure).

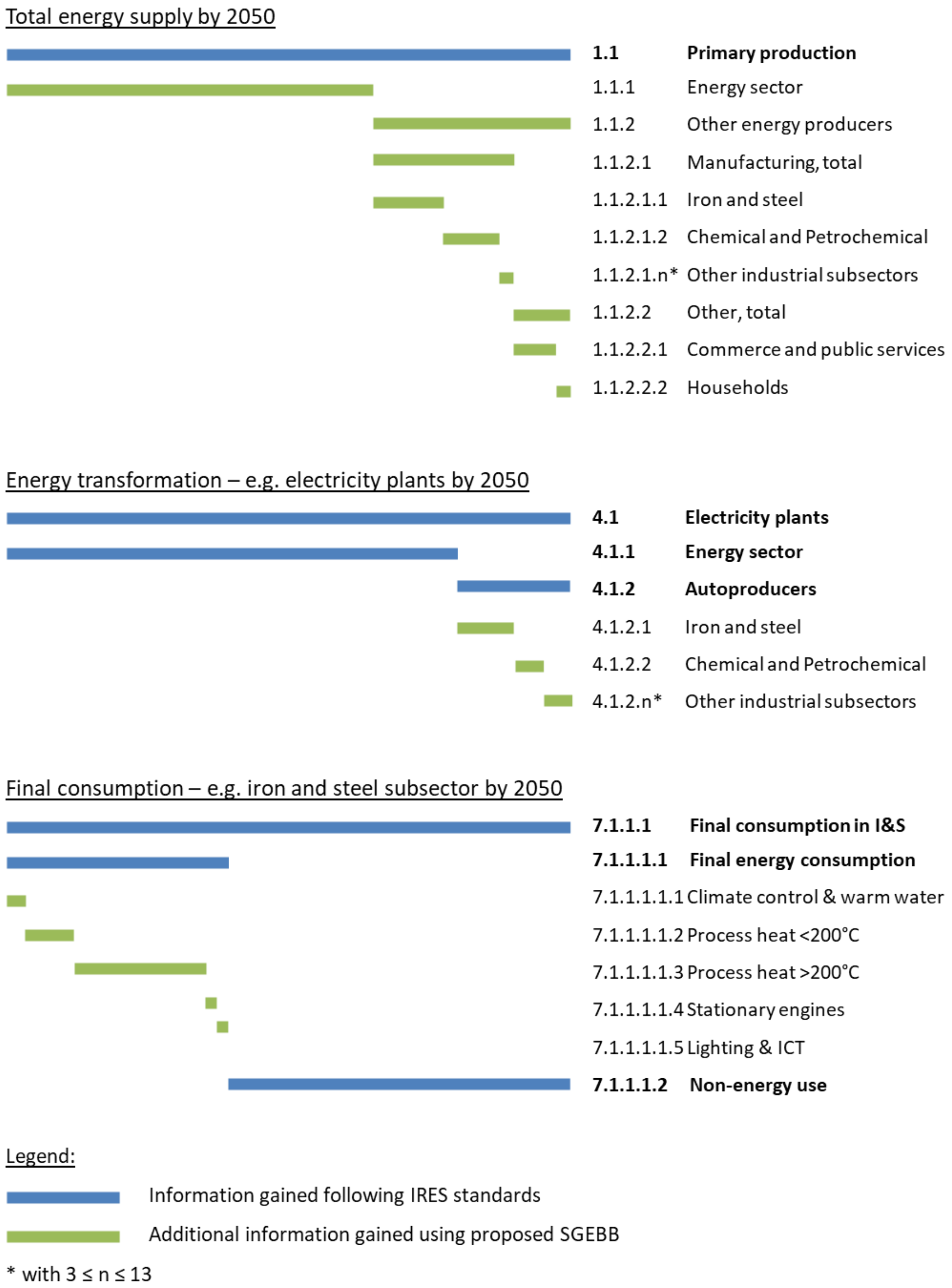

Figure 6: Comparison of shown components according to IRES standards and when using proposed SGEBB using an example case for 2050. Blue bars represent state-of-the art information as recommended by IRES. Green bars represent additional information gained by applying SGEBB.

This enhanced focus on physical energy flows enables the application of SGEBB in energy balances at various levels of detail, ranging from individual industrial plant locations or single buildings to national economic sectors and entire energy systems. In the first peer-reviewed publication of this thesis, a case study of the Austrian energy system 2050 contrasts Sankey diagrams following traditional IRES standards with diagrams prepared using the proposed SGEBB methodology for a selection of (sub)sectors and the energy system as a whole. Thereby, we visualise how the systematic approach of SGEBB provides a comprehensive understanding of the intricate interactions between the energy system and various economic sectors, paving the way for a more thorough exploration of the critical challenges and opportunities associated with achieving a sustainable and integrated RES-based energy system that is conducted in the following two subsections.

4.2 Cost-driven assessment of technologies' climate neutrality potential

For stakeholders to identify important focus points for action towards climate neutrality, it is important to keep the broader field of manufacturing industries within sight while also investigating subsectoral process details where necessary. Therefore, the second journal article of this thesis proposes clustering of technologies for industrial decarbonisation into four climate neutrality pathways:

I. *Electrification*
II. *Use of CO_2-neutral gases and biomass combustion*
III. *Circular economy*
IV. *Carbon capture*

To analyse the GHG mitigation potential on subsectoral level, analyses first dive deep into a technological and subsectoral level of assessing the applicability and impact of technologies. Thereupon, clustering of these technologies across subsectors within above pathways preserves the ability to compare large technological levers towards climate neutrality against each other across subsectors.

The proposed standardised approach to assessing the availability, mitigation potential and costs of technological climate neutrality pathways is based on an advanced set of performance indicators:

- Technical Climate Neutrality Potential (TCNP): This core indicator measures the potential greenhouse gas emission reduction per pathway and subsector in kilotons of CO_2 equivalents per year (kt CO_2e/a). It serves as a crucial tool for identifying technologies and applications with the most significant potential for achieving climate neutrality. It is calculated by subtracting the emissions of the alternative technologies (GHG_{alt}) from the status quo (GHG_{SQ}) (eq. (1))).

$$TCNP = GHG_{SQ} - GHG_{alt} \tag{1}$$

- Change in energy consumption: This indicator quantifies the corresponding change in energy consumption by energy carrier in gigawatt-hours per year (GWh/a), providing insights into the impact of technology options on the energy system. It also accounts for the energy consumed during the upstream production of required energy carriers, e.g. electricity for hydrogen electrolysis.
- Capital expenditures: Capital expenditures are represented in million euros per year (M€/a) and depict the expected investment costs associated with adopting a specific technology or climate neutrality pathway. This allows for a comparison against the regular investment costs of reference conventional, fossil-based technologies. The yearly capital expenditures (A_{CAPEX}) in euros per year are determined using Equation (2) with a signifying the annuity factor[2]. In addition to utilising literature-derived values for capital expenditures in euros per kilowatt (kW) and the constant c_{inst}, expressed as a percentage of CAPEX, which encompass building and engineering costs, technology-specific average annual full load hours are employed to convert calculated energy consumption into power capacity (*P*).

$$A_{CAPEX} = P * CAPEX * (1 + c_{inst}) * a \tag{2}$$

- Operational expenditures: Operational expenditures as visualised by Equation (3) are broken down into fuel (c_f) and greenhouse gas certificate costs (c_{GHG}), as well as CAPEX-related costs, calculated as a percent of CAPEX for maintenance, tax, etc., all presented in M€/a. These figures illustrate the ongoing operational expenses incurred during the technology's functioning, which is a particularly important indicator for investment decisions in industries.

$$C_{OPEX} = c_{rel} * CAPEX + c_f + c_{GHG} \tag{3}$$

- Total annual expenditures: The sum of annual capital and operational expenditures, the resulting total yearly expenditures in million euros per year (M€/a) offer a comprehensive view of the overall costs of technology adoption.

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[2] $a = \frac{(1+i)^n * i}{(1+i)^n - 1}$ with length of depreciation period in years *n* and interest rate *i*

After investigating every industrial subsector regarding each indicator separately, overarching results can be extracted to pinpoint focal areas for subsequent scenario analysis (cf. section 4.3). Figure 7 provides an overview of the range of TCNP in kt CO_2 in relation to the total annual deployment costs in M€ for each investigated application category and climate neutrality pathway. In addition, Table C 1 in Appendix C summarises the technologies with the best TCNP-to-cost ratio. This analysis is conducted on an exemplary case of the Austrian energy-intensive industrial subsectors of iron and steel, the non-metallic minerals and the paper, pulp and print industries.

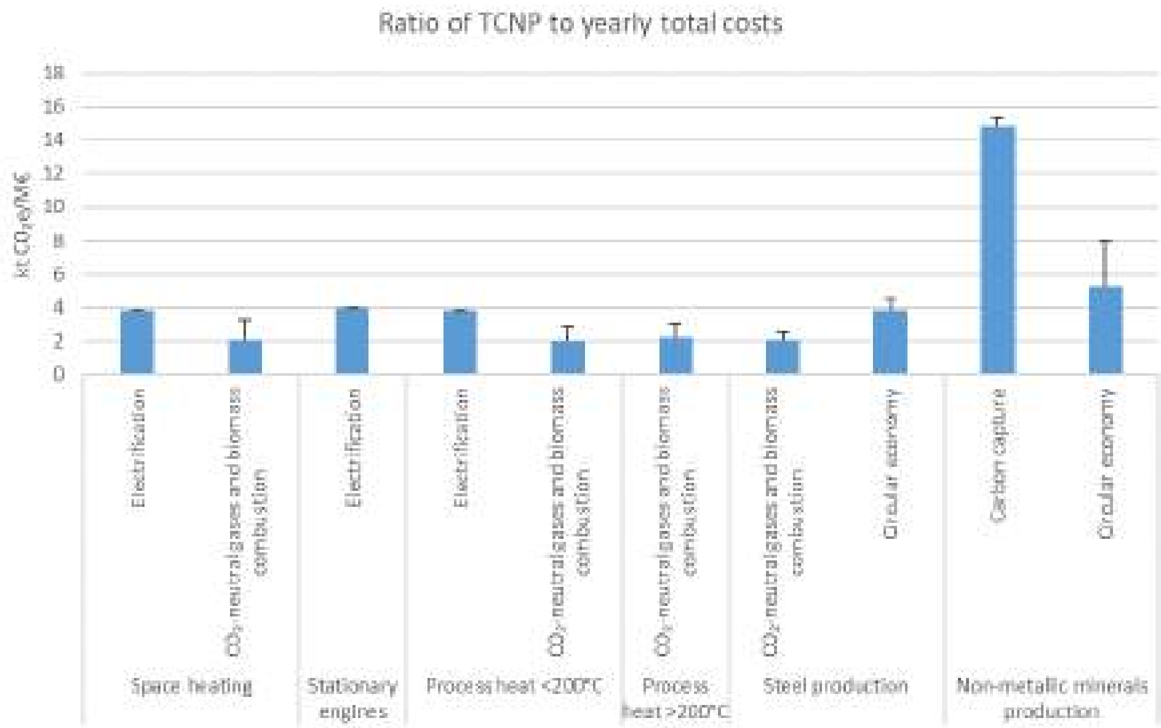

Figure 7: Ratio of TCNP in kt CO_2e to annual costs in M€$_{2020}$ by application category and climate neutrality pathway

The results indicate that due to its high level of energy efficiency (thanks to heat pumps and electric engines), electrification exhibits TCNP-to-cost ratios of approximately 4 kt CO_2e/M€ for the investigated application categories. On the other hand, CO2-neutral gases and biomass combustion, which is also available for high-temperature process heat, is characterised by a lower ratio of approximately 2 to 3 CO_2e/M€. The observed variance of approximately 1 kt CO2e/M€, indicated by the figure's error bars, is due to the four renewable gas routes investigated (H_2 from electrolysis or pyrolysis, Bio-CH_4, and SNG). Due to the upstream emissions taken into account for electricity use needed for hydrogen production, the two biobased CO_2-neutral gases feature a higher TCNP-to-cost ratios of approximately 0.5 to 1 kt CO_2e/M€ more than for Bio-CH_4.

Notably, carbon capture, which is only deployed in the non-metallic minerals subsector to mitigate hard-to-abate geogenous emissions in the case study, exhibits the highest TCNP-to-cost-ratio, nearing 15 kt CO_2e/M€ with little variance between oxyfuel combustion and amine scrubbing. However, it is important to highlight that this analysis has not investigated the necessary CO_2 storage and transport infrastructure, which would incur significant additional costs. Circular economy practices in steel and non-metallic minerals production demonstrate variable ratios, with higher efficiency but also variance observed in the latter. Similarly to the analysis of carbon capture technologies, this climate neutrality pathway's application possibilities are significantly more limited compared to the cross-sectoral technologies of electrification and the use of CO_2-neutral gases and biomass combustion.

Figure 8 provides a comparison of total TCNP and associated operational as well as capital expenditures for each of the investigated application categories and climate neutrality sectors in the Austrian case study. For each pathway, the technology with the best TCNP-to-cost ratio identified above and listed in Table C 1 is represented. The investigated subsectors currently emit approximately 19 Mt CO_2e/a through various energy and non-energy application cases. This is illustrated by the dark bar going bottom-up on the far left of Figure 8a. On the other hand, in the same figure, the calculated TCNP per climate neutrality pathway is given in light orange going top-down. Accompanying information on the cost structure – operational and capital expenditures – for the respective technology is represented in Figure 8b below. To enable a comparison with fossil alternatives, the capital and operational expenditures of conventional technologies are provided in grey.

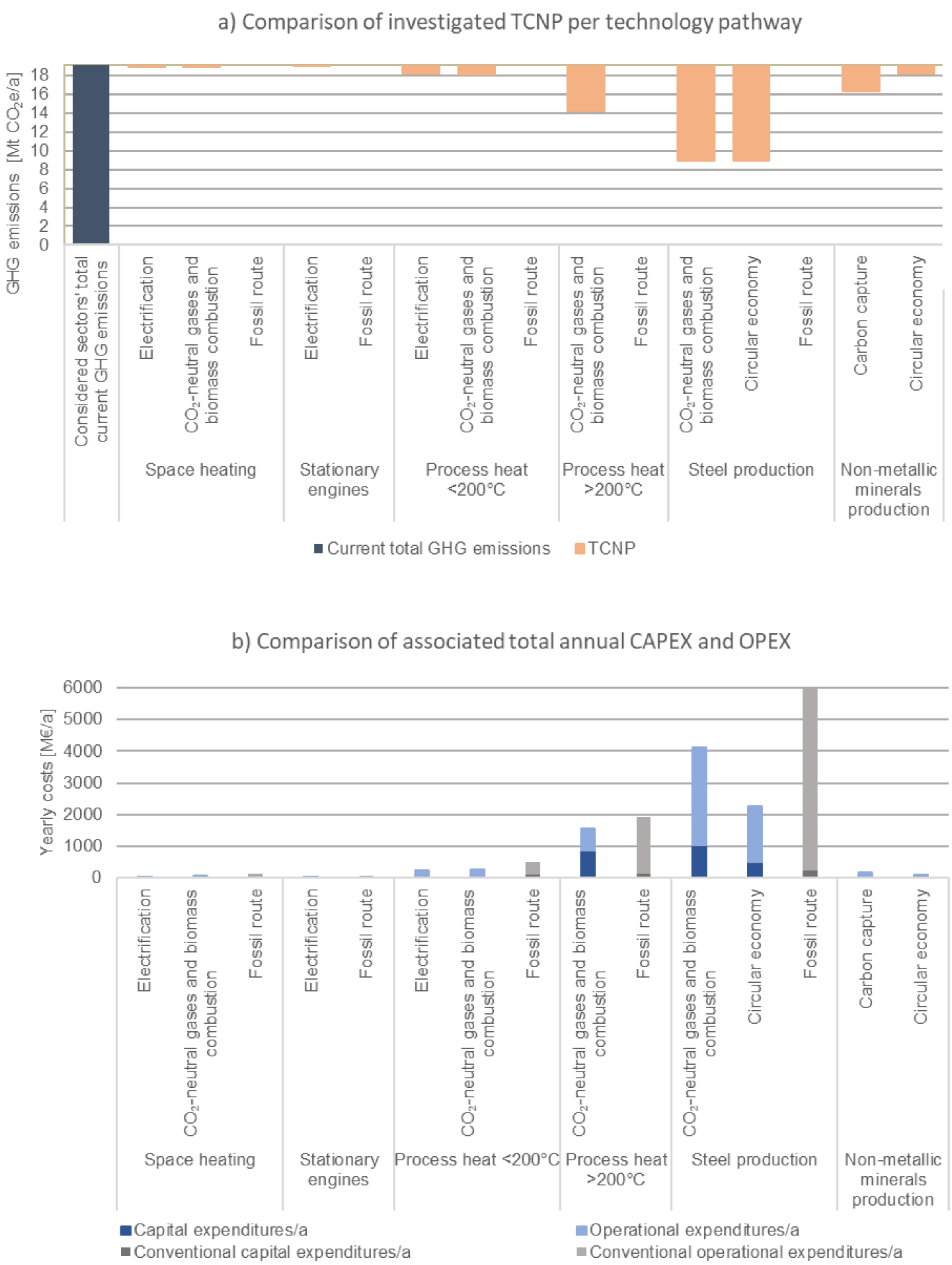

Figure 8: Comparison of investigated alternative technologies' TCNP (a) in iron and steel, non-metallic minerals, and paper, pulp and print, including associated total annual costs in €$_{2020}$ (b). The technology with the best TCNP-to-cost yearly ratio for each climate neutrality pathway is visualised (cf. Table C 1 in Appendix C).

For space heating and process heat below 200°C, electrification through heat pumps, solid biomass, and bio-CH_4 all are found to be cost-competitive options, considering GHG certificate costs. They display substantial TCNP and cost advantages over their fossil-based counterparts. The use of heat pumps, especially, can lead to significant mitigation of approximately 1054 kt CO_2e/a while at the same time contributing to the overall goal of primary energy consumption reduction. Additionally, the electrification of motive power applications offers potential cost advantages over conventional technologies. However, it is important to note that the total TCNP achievable through this means is relatively limited, with less than 100 kt CO_2e/a across all the discussed subsectors. In all these application cases, electrification provides a robust setup against volatile fossil energy prices. It allows effective decarbonisation in low to medium-temperature applications, as we have shown in a sensitivity analysis in the respective second journal article.

Regarding high-temperature applications – in this case temperatures above 200°C – especially bio-CH_4, bio-SNG, and H_2 from electrolysis demonstrate cost-competitive potential. On the other hand, pyrolysis-derived hydrogen incurs significant investments and feedstock costs, affecting its cost-effectiveness. Utilising bio-CH_4 enables the mitigation of up to 4870 kt CO_2e/a, with annual expenses amounting to 1576 M€. These costs remain significantly lower than the conventional fossil-based route's projected fuel and GHG costs (2056 M€/a).

In the steelmaking subsector, where especially process-related emissions from primary steelmaking are considered hard-to-abate, again CO_2-neutral gases offer considerable TCNP advantages over conventional technologies. They promise a TCNP between 86 % in the case of electrolysis-derived hydrogen and 98 % in the case of bio-CH_4 and bio-SNG. Circular economy principles further enhance emission mitigation, and the use of new electric arc furnaces is identified as a no-regret strategy as it is needed no matter if production is shifted from primary to secondary steelmaking or virgin resource input is maintained.

For process-related emissions in the non-metallic minerals subsector, carbon capture technologies show significant success in achieving necessary reductions. Their adoption – with capture rates of up to 90% – can also be seen as a no-regret approach, as it not only mitigates process-related emissions but also allows for the sequestration of energy-related emissions from the calcinator. Approximately half of all energy-related emissions of the subsector could be effectively captured. Integrating biogenous gases (bio-SNG or bio-CH_4) into carbon capture options even presents the potential for substantial achievements regarding negative emissions.

In total, CO_2-neutral gases demonstrate a TCNP potential of up to 16 Mt CO_2e/a across various energy-related and process-related emissions in the three investigated subsectors alone, while gas demand amounts to approximately 48.5 TWh/a. Among the investigated gaseous energy carriers and under the given assumptions, bio-CH_4 presents the most balanced cost structure between capital and operational expenditures and the best TCNP-to-cost ratio.

The case illustrates how the proposed approach offers a systematic set of indicators that bridge the gap between detailed subsector analysis and broader system-level considerations when exploring pathways towards climate neutrality in EII. The standardised structure revolving around the technical climate neutrality potential provides valuable insights into large levers of action on an industry-wide scale. As will be touched upon in the following sections, it can potentially serve as a complementary basis for formulating guidelines for investment and funding programs.

4.3 Subsector-resolved scenario pathways for manufacturing industries

Building upon the cost and GHG emission mitigation considerations discussed in the previous section, the herein presented scenario narratives can provide novel insights into the feasibility and implications of implementing climate neutrality pathways regarding the development of energy consumption and emissions. The exploration in the provided Austrian case study identifies key challenges and opportunities in realising a sustainable and integrated renewable energy-based energy system for the future. Three distinct scenario narratives are proposed for this purpose. They are described below in the order of increasing decarbonisation results.

To provide a reference line in comparison to which all other – more transformational – scenarios can be discussed against, the scenario *Business as usual (BAU)* represents a trend scenario following the methodology by Ducot and Lubben [36]. In addition, being aware of the so far, in many ways, unsuccessful impact of past climate goal pledges, it serves as a reminder of what industrial energy systems and GHG emissions may await us if decisive action is not taken or taken at a later stage. Scenario BAU is derived by extrapolating historical statistical trends of energy demand and technologies. It does not account for announced but not yet implemented projects or any policy measures that have not yet significantly influenced past energy and emission statistics. Thereby, it is chosen in contrast to e.g. WAM scenarios that are prepared according to EU regulations [4].

Scenario *Pathway of Industry (POI)* aims to represent the results of a close dialogue process with representatives of all thirteen investigated subsectors. The methodology of scenario development is most closely related to the concept of foresight scenarios coined by Martin [37]. This novel scenario approach depicts industry plans and assessment of transformation in the respective subsectors under current and foreseeable boundary conditions through to 2030. Beyond 2030, if companies do not already have plans in place, the development is extrapolated in an additional stakeholder process and involves expected evolution of technology readiness levels. For the Austrian case study, more than 80 interviews have been conducted with technology officers and similar positions within key companies from a variety of industrial backgrounds.

In scenario *Zero emission (ZEM)*, obtained through a backcasting approach introduced by Robinson [38], technology deployment is determined by scientific identification of the most suitable technologies to attain deep decarbonisation. For the EII, this technology selection is based on previous groundwork by Rahnama Mobarakeh and

Kienberger [39, 40], while for non-energy-intensive subsectors and general energy applications, primarily BAT documents from the European Commission (e.g., on energy efficiency [41]) are consulted.

The results of the three distinct scenarios for energy consumption and GHG emissions until 2050 are presented in Figure 9. For GHG emissions, also emissions excluding upstream emissions from electricity generation in scenarios POI and ZEM are visualised to enable a better comparison of chosen technologies per scenario. For the gas grid, a combined top-down and bottom-up approach is chosen which accounts for a growing share of renewable and CO_2-neutral gases in the overall gas system until 2050.

Scenario BAU falls significantly short in achieving meaningful reductions of GHG emissions compared to the base year 2019. Because an increase in economic activity is assumed, total energy consumption reaches up to 161 TWh (including 5 TWh of transformation losses for hydrogen production which are represented by a shaded bar on top as necessary electrolysis units could sit either within or outside the manufacturing industries' boundaries). However, the underlying decarbonisation trend in the gas grid does exhibit a slight counteractive effect on emissions, resulting in a modest reduction of approximately 2.5 Mt CO_2e/a.

When investigating POI results – the results based on the extensive stakeholder feedback – a more optimistic picture emerges. Scenario POI indicates that, based on a technological approach, the Austrian manufacturing industry can already achieve a GHG emission reduction of more than 96% compared to 2019 until 2050. It is an interesting and very noteworthy consensus among subsector representatives from a wide range of companies, who unanimously acknowledge the significance of specific technology pathways and therefore also energy carriers for their respective subsectors. The GHG emission mitigation potential is contingent upon the incorporation of transformation plans outlined by industry representatives and meeting enabling conditions, particularly the establishment of a largely climate neutral gas and electricity supply system. Notably, nearly 60 TWh of largely climate-neutral gases are required by 2050. Total energy consumption in scenario POI rises from 135 TWh to 151 TWh (168 TWh when electrolysis losses are accounted for). Solid biomass consumption also sees a doubling in energy demand with an increase of 18 TWh, from 17 TWh currently to over 35 TWh by 2050. Additionally, the projection for final electricity consumption by 2050 signifies a substantial increase of more than 22 TWh, reaching 48 TWh compared to 26 TWh in 2019.

The second transformation scenario, scenario ZEM, heavily relies on hydrogen deployment, especially within the energy-intensive subsectors producing basic materials; iron and steel, and the chemical and petrochemical industries. By 2050, scenario ZEM demonstrates a remarkable GHG emission mitigation of 97% in comparison to the base year. An especially substantial decrease in emissions can be observed between 2035 and 2040, attributed to hydrogen expected to reach the break-even point with fossil CH_4 and a shift of significant production volumes in iron and steel from the blast furnace/basic oxygen furnace route to hydrogen-based direct reduction (H-DR-EAF). By 2050, total energy consumption in scenario ZEM rises to approximately 172 TWh, with over 20 TWh accounted for from electrolysis losses. Similarly, solid biomass and electricity consumption increase by approximately 20 TWh/a each compared to the base year. In both scenarios, POI and ZEM, approximately 3.7 Mt CO_2e are captured by carbon capture technologies in the non-metallic minerals by 2050. In combination with the use of hydrogen, some – but not all – CO_2 can be utilised directly in the Austrian chemical and petrochemical industries.

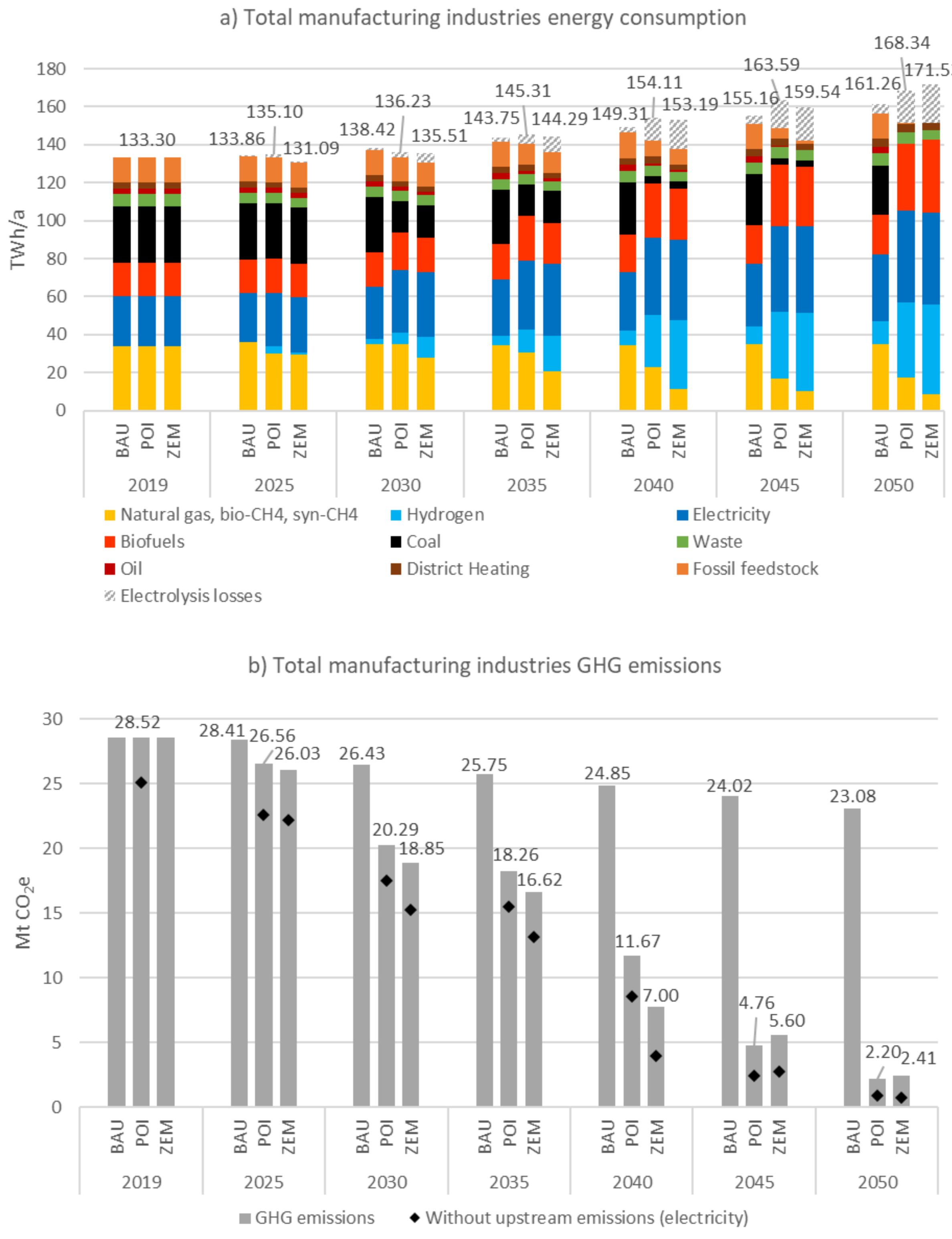

Figure 9: Total manufacturing industries results for energy consumption (a) and GHG emissions (b) for scenarios BAU, POI and ZEM. For POI and ZEM, GHG emissions excluding upstream emissions from electricity generation are also visualised.

Based on the above-presented scenario results, the impact of the four established climate neutrality pathways identified in section 4.2 can be assessed. By 2050, both transformation scenarios extensively rely on only three energy carriers: electricity, renewable gases, and biomass.

In total, approximately 50 TWh of electrical energy for final energy applications – especially heat pumps and motive power – is necessary in ZEM; in POI, this category amounts to 35 TWh. In addition, a significant surge in electrical energy stems from transforming processes in energy-intensive subsectors. Most notably, the deployment of electric arc furnaces and carbon capture units substantially increases electricity demand compared to scenario BAU.

Conversely, an increase of only 10 to 15 TWh can be observed in scenarios POI and ZEM for gaseous energy carriers. This is due to a profoundly different approach to application which develops until 2050. While in scenario BAU, gases are also extensively used for low or medium temperature and motive power, gas consumption in scenarios POI and ZEM is reserved for exergetically-valued deployment as reducing agent or feedstock in basic material production and for high temperature applications. In addition, the need for additional gaseous energy is balanced out by solid biomass consumption almost doubling compared to BAU as it reaches up to 38 TWh in scenario ZEM.

4.4 Discussion

In this section, the case study results derived from applying the proposed methodologies in this thesis are further investigated to give an indication of the associated magnitudes of the cost of realisation and discussed in the broader context of industries' transition to climate neutrality.

4.4.1 Techno-economic indication of energy transformation

To assess the magnitude of annual costs in relation to the changing industrial energy system and reach conclusions on possible enabling framework conditions, the scenario results from above are investigated using the cost structure compiled in the second journal article.

As shown in Figure 10, calculations made by virtue of additional sensitivity analyses indicate that the financial internalisation of environmental consequences of applying fossil-based production processes is crucial for greener, climate-friendly technologies to reach cost advantages by 2040/2050. This finding further underlines the results of existing research on this topic conducted mainly in the electricity and transport sectors, for example, Owen [42] and Kudelko [43], who both identify significant social and environmental cost advantages of RES through the internalisation of external costs in power generation. It must be highlighted that for alternative technologies such as H_2

or CH_4, both the upstream generation plants and their feedstock, as well as the processing plants are considered in the presented analysis. This approach provides a more comprehensive indication of the overall investments necessary for the manufacturing industries' transition to climate neutrality rather than just the direct costs of the transition. Not all companies are likely to generate all of their future hydrogen or bio-CH_4 demand themselves on-site but will pay for the upstream costs through increased energy prices.

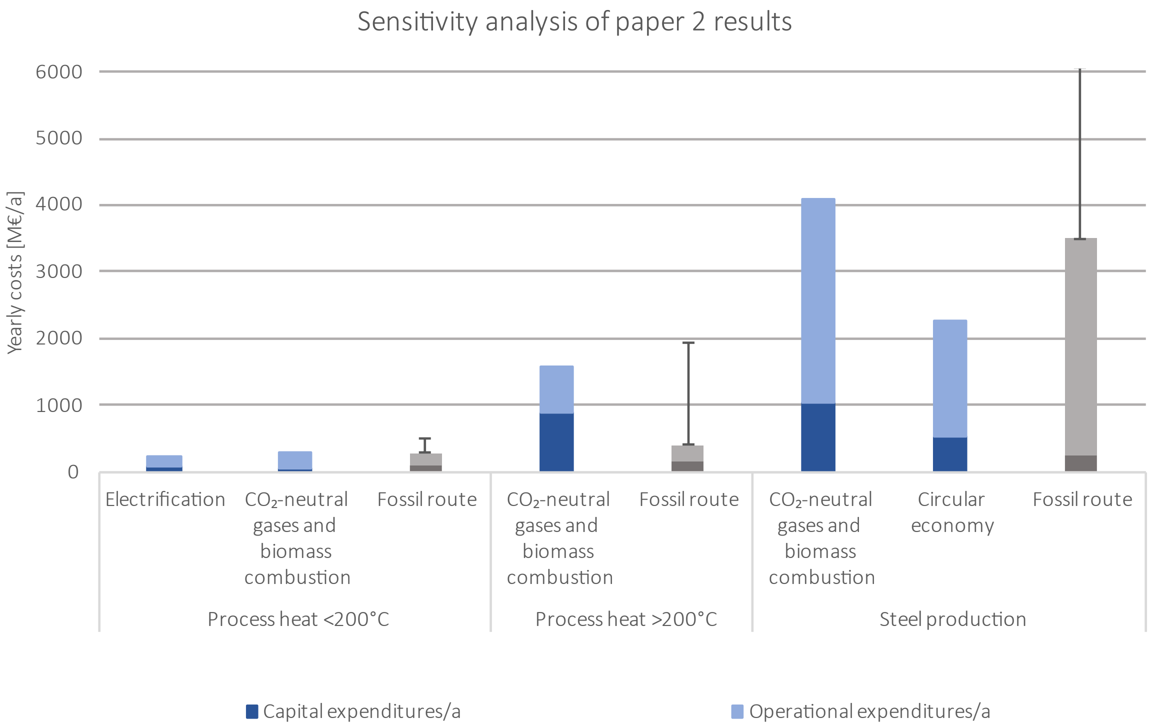

Figure 10: Comparison of transformation costs in M€$_{2020}$ per climate neutrality pathway excluding and including GHG certificate costs (visualised by error bar), as calculated in the second journal article.

To achieve necessary steering effects across all investigated application cases, GHG certificate prices are calculated to range between 200 and 300 €/t CO_2, corresponding to existing literature values by German research project ARIADNE [44]. At lower temperatures (space heating and up to approximately 200°C), alternative technologies (especially electrification using heat pumps) are already cost-competitive in many areas of application, even without additional funding or GHG costs. For higher temperature applications above 200°C, funding for green energy generation plants, such as electrolysers and biogenous gases, cannot fully substitute for lower GHG certificate prices. In steelmaking, on the other hand, the calculated OPEX are already comparable to the conventional base case. Here, CAPEX funding could substitute for missing GHG certificate prices altogether.

Figure 11 gives an indication of the resulting associated annual costs if the technology clusters' capacities deployed by 2050 in scenario ZEM were to be installed in a green-field approach under the cost assumptions of paper 2. For the chemical and petrochemical industries, which have to be investigated based on their production capacities, specific investment costs per ton of product for the production of methanol (279 €/t) [45], ammonia (815 €/t) [45] and olefines via the methanol-to-olefine route (2000 €/t) [46] are considered based on additional literature references.

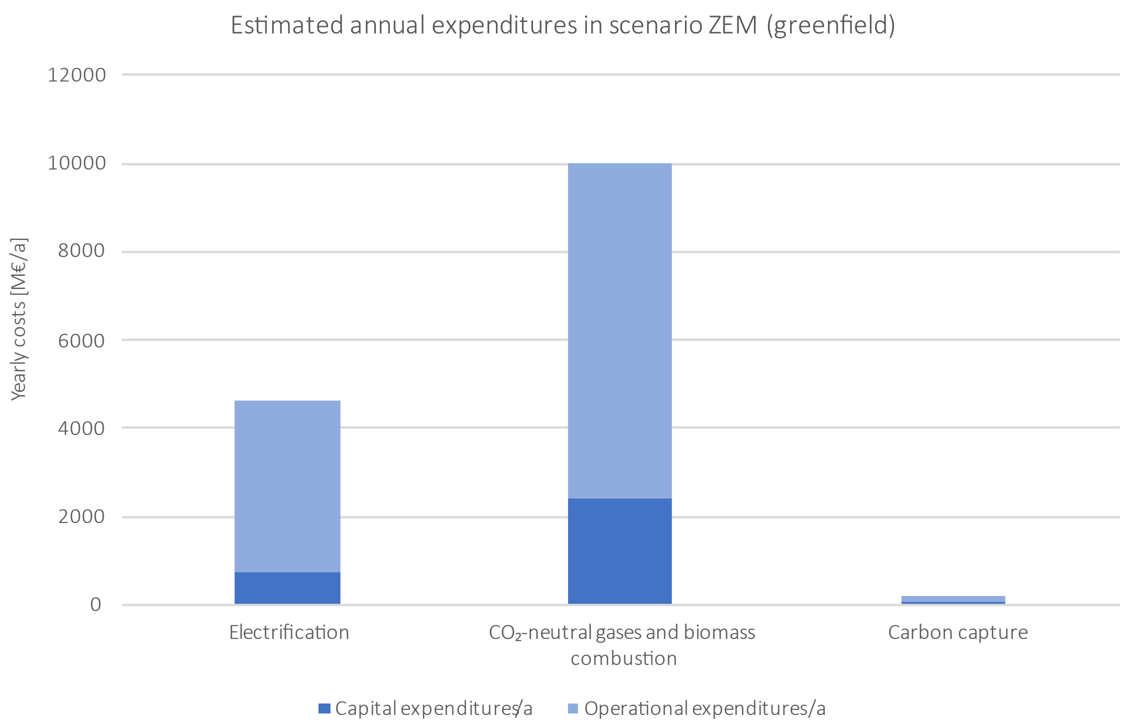

Figure 11: Indicative representation of annual expenditures in M€$_{2020}$ by climate neutrality pathway in scenario ZEM[3] based on the green-field analysis approach proposed in the second journal article.

Please note that the analysis' green-field approach only indicates annual costs and does not provide a complete techno-economic analysis of the transition to climate neutrality in Austrian manufacturing industries. Although the actual transition to climate neutrality is more incremental and must consider depreciation periods of existing plants and capital restrictions as well as production management in relation to the respective order backlog, among others, many parallels to a green-field approach can be found. For example, industrial stakeholders are faced with the opportunity to implement optimised plant layouts and efficient workflows from the ground up. In many areas,

[3] CO_2-neutral gases and biomass combustion entails also costs for chemical and petrochemical production using H_2 as feedstock for methanol and olefines production. Total CAPEX per year amount to 393 M€/a in chemical and petrochemical production. All other CAPEX in this climate neutrality pathway amount to a total of 1379 M€/a.

energy and emissions may be saved both by adopting new technologies and improved production workflows. In addition, the significant upfront investments calculated in a green-field approach by taking into account all processes in a subsector at once, must already be considered by industrial decision-makers today even when deploying the actual investments over the duration of several years or even a decade as it directly affects their running business.

The figure shows that CO_2-neutral gases and biomass combustion again exhibit significantly higher costs than the other two applied climate neutrality pathways, electrification and carbon capture. This is especially due to the substantially broader scope of application. On the one hand, CO_2-neutral gases can serve as a reducing agent and a non-energetic feedstock for primary steelmaking and chemical production. On the other, all levels of process heat can be supplied in the scenarios. In total, annual expenditures of approximately 10000 M€/a related to using CO_2-neutral gases and biomass alone are calculated, with the energy-intensive subsectors of steelmaking and chemical industries accounting for more than 40% of these costs. In electrification, which demonstrates a generally higher TCNP-to-cost ratio for final energy application than the combustion of CO_2-neutral gases and biomass, a total of approximately 4600 M€ annually must be accounted for. Carbon capture using oxyfuel technology for the subsectors in non-metallic minerals only accounts for a total of 180 M€/a, approximately split evenly between capital and operational expenditures. Again, however, no infrastructural prerequisites for transporting and storing sequestrated CO_2 have been considered here.

As summarised by Table 2, annual expenditures calculated in this way for scenario ZEM amount to approximately 14800 $M€_{2020}$/a or 14.8 $bn€_{2020}$. By contrast, the modelled Austrian GDP in scenario ZEM 2050 amounts to 532 $bn€_{2020}$, while the total manufacturing industries' GDP in 2050 is 136 $bn€_{2020}$. As a result, annual capital expenditures for the transformation to climate neutrality would make up approximately 10% of forecasted industrial or less than 3% of the national GDP in 2050. For comparison, in 2022, Austrian gross domestic product amounted to a total of 447 bn€, of which roughly 117 bn€ were accounted for by the manufacturing industries. Under the assumed green-field approach, the total annual costs of deploying the technologies modelled in scenario ZEM for the year 2050 would therefore amount to approximately 3 % of the current national GDP or 12 % of manufacturing industries' GDP [47].

Table 2: Expenditures 2050 in comparison to GDP 2022 and 2050 in bn€ [47, 48].

2050 (green-field)	2022 GDP		2050 GDP	
Total annual expenditures	National	Industrial	National	Industrial
14.8 bn€$_{2020}$	447 bn€$_{2022}$	117 bn€$_{2022}$	558 bn€$_{2020}$	142 bn€$_{2020}$

In the discussion of Figure 10 above, we have seen that assuming the realisation of an ambitious development of the costs of CO_2-emission[4], annual expenditures for climate-friendly alternative technologies will be competitive with current fossil fuel-based production processes. During the development of this thesis, insights from this thesis were also contributed to other Austrian energy scenarios in manufacturing industries within the research project transform.industry. The subsequent economic analysis has shown that national investment in the transition toward climate neutrality can positively impact GDP development. It is estimated that for every Euro spent on capital expenditures, 3-4€ in additional GDP could be generated [49]. Therefore, it can be concluded that the energy transition in manufacturing industries not only benefits the environment but also promotes economic growth by reducing total annual production costs in the long run.

4.4.2 Transformation in the context of the overall energy system

To maintain the assumed competitiveness of manufacturing industries during and after transitioning to climate-neutral production, several key accompanying framework conditions must be considered. The growing trend towards electrification and the use of CO_2-neutral gases for basic materials production necessitates an increasing supply of renewable energy sources dispersed all over Austria to varying degrees. Consequently, to supply industrial companies throughout Austria reliably with climate-neutral or low-emission energy from a wide array of RES – especially gaseous and in the form of electrical energy – well-maintained energy grids with appropriate transport capacities must be available. Apart from decarbonising by fuel and feedstock switch, hard-to-abate subsectors in the non-metallic minerals, where emissions stem from geogenous production input, can reach climate neutrality within their balance border most likely only by extensively deploying carbon capture technologies. In combination with the use of hydrogen, some – but not all – CO_2 from NMM production can be utilised directly in the Austrian chemical and petrochemical industries. Due to the gap between

[4] Current information on existing scenarios for the development of CO_2 prices and recommendations for projections have been compiled by the German Environmental Agency [59]. For progressive scenarios, a range of 150 to 220 €$_{2020}$/CO_2 is given. In this thesis, GHG certificate costs of 250 €$_{2020}$/t CO_2 have been applied to all energy and process-related emissions.

CO_2 supply and demand within the manufacturing industries, implementing innovative storage and export strategies will be necessary.

Sejkora et al. [50] have investigated the current Austrian technical potentials of renewable electricity generation from PV and wind, among others. Because hydropower potential for run-of-the-river power plants is generally considered to already range close to its maximum economic potential when considering environmentally protected areas, PV and wind power will likely join as additional important pillars of domestic electricity generation in the future. According to the Austrian Renewable Expansion Act (Erneuerbaren-Ausbau-Gesetz), a total of 11 TWh/a of PV and 10 TWh/a of wind power generation in comparison to 2018 must be installed by 2030 [51]. Technical potentials, as calculated by Sejkora et al., on the other hand, amount to approximately 55 TWh/a (PV) or 60 TWh/a (wind), respectively. Assuming a general 50% reduction of this technical potential to indicate a possible economic potential of the future, up to 50-60 TWh of electricity generation from PV and wind power together would be possible. In addition, the realisable domestic potential for biogenous gases is estimated to be approximately 20 TWh, according to Baumann et al. [52]. In comparison, scenario results of the two transition scenarios POI and ZEM above indicate a possible electricity demand in manufacturing industries alone of approximately 40 to 50 TWh and gas demand of up to ~60 TWh, enabling an indication regarding the provision of sufficient climate-neutral energy for all of Austria: Climate-neutral imports of both electricity and gas will most likely be needed for a decarbonised Austrian energy system of the future.

But not only the amount of renewable energy supply for Austria and its manufacturing industries must be of concern to policymakers and societal stakeholders. Renewable energy carriers such as PV and wind are volatile in their electricity generation character and – much like the consumers – decentralised over all of Austria. This further challenges the grids needed to supply the energy to the consumers. Therefore, the temporal and spatial resolution of future energy demand and renewable energy generation through residual load analysis can be of critical importance when investigating the impact of manufacturing industries' transformation on the overall energy system. The grid-bound energy carriers, electricity, gas, and heat, rely on a solid infrastructure to be transported from their source (e.g., CHP plants in the case of electricity and gas) to their consumers, which can lie hundreds of kilometres apart. However, the required grids are limited in their power capacity per timestep and must, therefore, be investigated in detail.

The Austrian transmission grid operator APG biannually publishes results of its own simulations for future grid requirements, which are developed in close cooperation with

European peers of ENTSO-E, the European Network of Transmission System Operators for Electricity [53, 54]. Similarly, for the high-level gas grid, Austrian Gas Grid Management AGGM also publishes its biannual planned grid developments for the next decades [55].

At the Chair of Energy Network Technology at Montanuniversität Leoben, Greiml et al. [56] have developed a multi-energy system (MES) simulation tool to investigate the impact of spatially resolved residual loads on energy infrastructure. The simulation framework *HyFlow* is based on a cellular modelling structure with all entities within one cell aggregated into its corresponding cell. As Greiml et al. explain, the term “residual load” is used to implement consumption and generation within each cell in one single term. In the research project InfraTrans2040 [57], which makes up a considerable part of the accompanying research carried out over the course of this thesis (cf. Figure 4), *HyFlow* was used to identify infrastructure bottlenecks and solution possibilities for the high-level electricity and gas lines when combining key industrial consumers identified in this thesis with the total energy system also comprising transport, buildings and agriculture, among others, and under consideration of renewable electricity generation targets under the Renewable Expansion Act [51].

The methodology developed within InfraTrans2040, along with key results and insights gained throughout this thesis on the manufacturing industries landscape in Austria – particularly regarding the spatial and temporal resolution of industrial demand – directly contributed to the calculations for the national grid infrastructure plan recently published by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) [35]. Based on the Federal Environment Agency’s most recent scenario Transition [58], this plan lays out the necessities in the electricity and gas grids until 2033 and beyond.

The scenarios investigated within the grid infrastructure plan and similar investigations of the project InfraTrans2040 [57] conducted during this thesis, indicate that the need for grid reinforcements on the investigated network level is predominantly driven by the assumed renewable generation capacities, less so by consumers' electricity demands. In general, power grid overloads can be detected along the primary transmission lines going from the east with high renewable generation potentials to the west with important consumers on the way on the one hand and large pumped hydro storage capacities in the central Alps to buffer the negative residual loads on the other.

Upon identifying bottlenecks in the electricity grid, which represent the most critical aspects of the energy infrastructure in terms of time and load, a diverse range of energy carrier overarching flexibility options and storage options can be explored. The effects of these options are assessed by observing changes in their respective grid utilisation categories. Figure 12 presents the national grid infrastructure plan for the electricity network level 1 by 2030 in a scenario where grid-supporting flexibility options are widely deployed throughout Austria. To represent and identify bottlenecks in the electricity grid within this analysis, all electricity lines are categorised based on their utilisation rates and duration of use [57]. Category 1 encompasses lines with exceptionally high utilisation, comprising those that operate at a rate exceeding 110% during a single hour of the year. Furthermore, category 2 (high load factor) includes lines utilised for more than 24 hours with a utilisation rate of over 100%, provided they have not already been allocated to category 1. To account for a simplified (n-1) criterion, lines are assigned to category 3 if they are used for more than 50 hours per year, exceeding 60% utilisation, and have not been previously allocated to categories 1 or 2. This systematic classification of lines allows for a clear and concise representation of grid bottlenecks for each year, presented in a single graph.

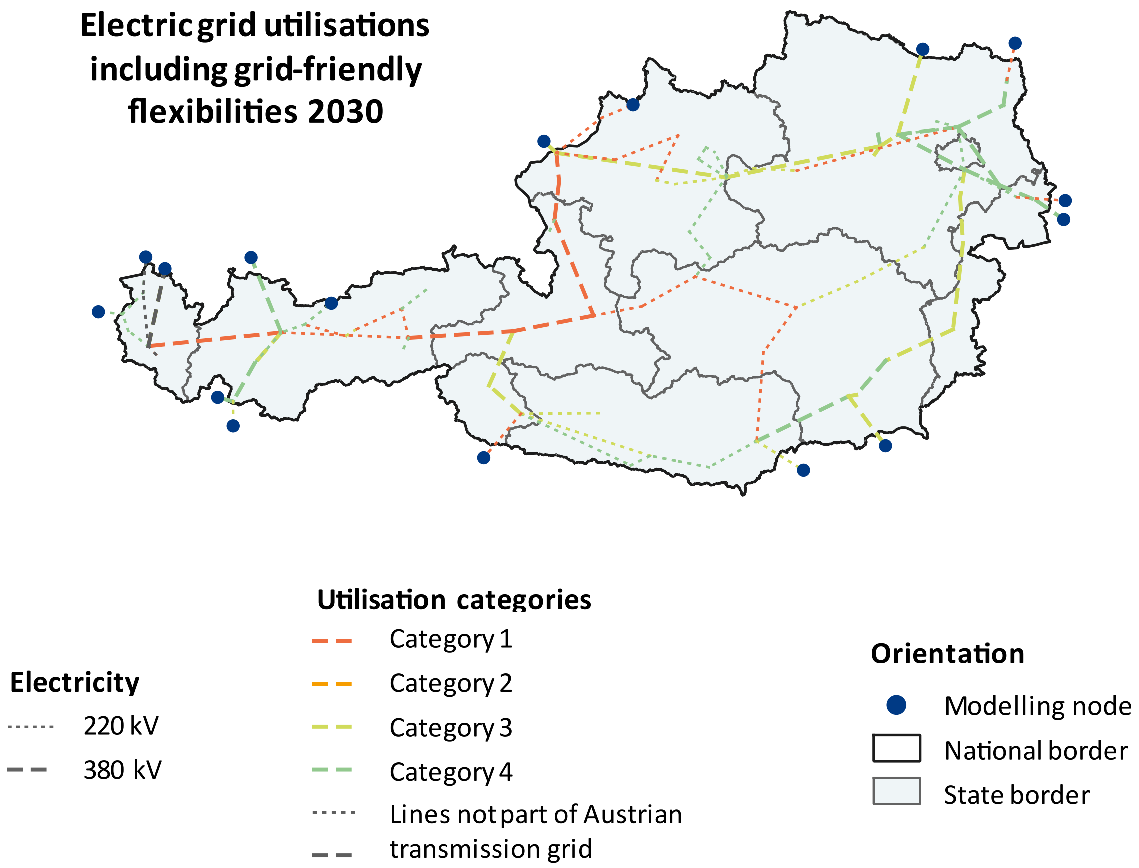

Figure 12: 2030 electric grid utilisations in network level 1 in the scenario "grid-supporting flexibility options" of the Austrian national grid infrastructure plan [35].

In the figure, flexibility units, such as batteries, electrolysers, and power-to-heat units, such as heat pumps, are deployed to help the electricity grid by shifting some of the negative residual load that occurs due to the renewable electricity generation into the grids or direct consumption of other energy carriers. Unfortunately, areas of high negative residual loads very often do not match regions with high industrial energy demand, so these flexibility options cannot always be provided by the manufacturing industries. As many lines remain in utilisation categories 1 or 2 even after the deployment of flexibility units, grid reinforcements through normal grid expansion will also be necessary to enable a reliable and secure energy supply in the future. In this context, it is essential to emphasise that this expansion does not necessarily need to occur at the exact location of the grid bottleneck. Instead, it can be achieved through reinforcements in the meshed grid, particularly by establishing ring circuits or parallel branches.

Figure 13 visualises the expected transformation of the Austrian high-level gas grid until 2030 to account for an increased need for hydrogen transport infrastructure. Based on the international initiative of the European Hydrogen Backbone, one branch of several key pipelines already or soon featuring two branches of transport, such as the Trans-Austria-Gasleitung (TAG) and the West-Austria-Gasleitung WAG[5], will be repurposed to transport hydrogen instead of CH_4. This development of increased import and transport capacities via important transmission lines connecting Austria to international hydrogen hubs, is further complemented by adjoining lines repurposed and retrofitted to supply additional domestically and grid-friendly produced hydrogen to large industrial centres whose processes and gas demand were investigated within this thesis and found reflection within the discussed grid infrastructure plan, e.g., from electrolysers in the east of Burgenland to Linz for steelmaking using H-DR-EAF. On the other hand, great care must be taken to ensure that the gas infrastructure of this transitional phase remains able to securely supply still necessary fossil methane to consumers on the one hand and allows future domestic bio-CH_4 or bio-SNG input into the gas grid to strengthen Austria's national green energy generation further. These potentials are generally widely dispersed, which poses a significant challenge when organising the gas grids of the future and balancing the need for H_2 and CH_4 lines.

[5] For WAG, the building of a continuous second branch with the first stage being the WAG Loop 1 project, is currently in the stage of financing and still misses a final investment decision [60].

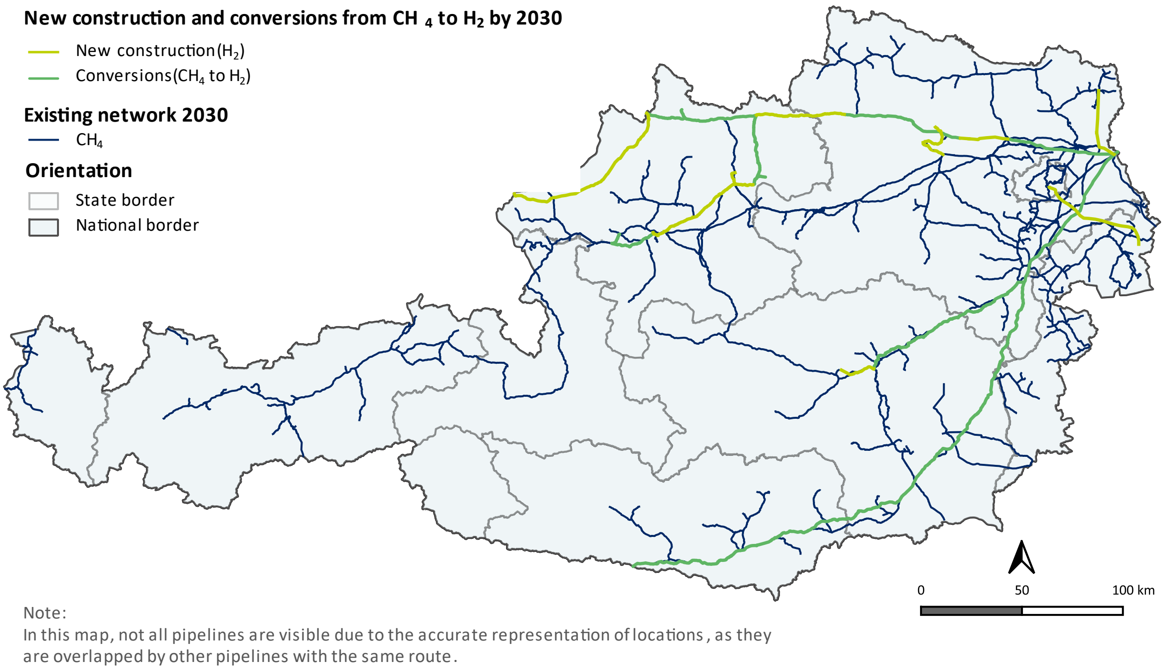

Figure 13: Construction of new pipelines and conversion of CH_4 to H_2 pipelines by 2030 according to the Austrian national grid infrastructure plan [35].

5 CONCLUSION AND OUTLOOK

For a successful transition to climate neutrality in manufacturing industries, it is imperative for political and industrial decision-makers to understand the implications of their actions. This research has demonstrated that a standardised approach to energy system analysis of manufacturing industries, when it can provide both detailed subsectoral information and a comprehensive understanding of the interrelations of industries with the overall energy and economic system, can be a powerful tool for information. From the results and findings of this thesis the following conclusions can be drawn:

- Establishing a robust dataset that covers the existing state of the national energy system based on physical energy flows and economic sectors, spanning energy generation, transformation, and consumption, is vital for a comprehensive analysis of manufacturing industries. Therefore, it is imperative to advance international standards of energy statistics to encompass these aspects. The proposed unified approach must be consistently employed across all dimensions of subsequent analysis of manufacturing industries.
- By choosing an adequate set of investigation parameters, the impact of technological measures towards climate neutrality can be investigated in the light of associated implementation costs. In Austria, as an indication for European manufacturing industries, alternative technologies within the four primary climate neutrality pathways can function with comparable total annual costs to their conventional, fossil-based counterparts if GHG certificate prices for fossil emissions are set at a minimum of approximately 200 to 300 €/t CO_2e. Alternatively, capital expenditures, especially in the area of green gas production, could be subsidised to help reduce fuel costs associated with climate-neutral technologies.
- Scenario development must strive to open a bandwidth of opportunities towards climate neutrality rather than aiming for finding a most likely scenario. Thereby, key levers of action can be identified from the comparison of scenarios. Subsequently, this information can help decision-makers in preparing their necessary boundary conditions for a successful energy transition. The key levers for attaining far-reaching climate neutrality from a system point of investigation are using CO_2-neutral gases and biomass, as well as electrification. General efficiency improvements, carbon capture in subsectors with geogenous emissions and the uptake of circular economy measures wherever possible can supplement these focal areas.

- A successful transformation of the manufacturing industries towards climate neutrality relies on the provision of essential services of the general energy system, especially an adequate infrastructure for grid-bound energy carriers such as electricity, CH_4 and H_2, and their abundant supply. The emergence of decentralised renewable energy generation challenges existing infrastructure. Occurring bottlenecks can be solved not only through traditional grid expansion but also through sector coupling, e.g., through power-to-heat or power-to-gas units strategically placed to decrease the stress on the electricity grid as the most critical grid in terms of time and load. The manufacturing industries can be an essential partner for both the investment and operation of these units. The supply of CO_2-neutral gases will most likely have to be secured through strategic domestic generation – among others used as bottleneck solvers in the electricity grid – *and* large imports.

Considering the outlined magnitude of the challenge of attaining climate neutrality in manufacturing industries and the overall energy system, the presented thesis' line of research can and must be further expanded by future work. The proposed innovative balance border SGEBB can considerably help these efforts if it is further deployed nationally and internationally by statistics agencies and researchers.

In addition, a substantial scope for conducting further comprehensive and intricate analysis of the pathway to climate neutrality across all thirteen subsectors exists as grouped below:

With regards to the applied methodology:

<u>Exploration of additional technologies</u>

The trajectory until 2030 already exhibits a certain level of clarity – partly due to the limited remaining time. On the other hand, the temporal framework between 2030 and 2040, which is crucial for reaching climate neutrality by the middle of the century, exploring additional novel technologies that may have a lower current TRL in combination with new or adapted scenario narratives will be of interest. In addition, this thesis has focused on the role of technological levers of action to reach climate neutrality in manufacturing. At the same time, general process optimisation and energy efficiency have not been investigated in detail. Thus, additional room for investigation regarding the potential of efficiency in process design and resulting dynamics with technological solutions exists in future works.

<u>Upfront integration of available existing infrastructure</u>

The approach used in this thesis and its discussion, wherein energy demand scenarios precede an assessment of their impact on energy infrastructure, could also be elevated to a higher level of integration where the available infrastructure and its level of utilisation could favour or hinder the deployment of certain energy carriers within the demand scenarios. Consequently, the formulation of energy demand scenarios would be inherently influenced by the availability of renewable energy supply within the possibilities of energy infrastructure, thereby generating innovative inputs for the spatial planning of energy resources and even market design.

Expansion of scenario development

The expansion of scenario development holds the potential to highlight additional no-regret actions for policy and other decision-makers in the quest for adequate framework conditions for transitioning towards climate neutrality in manufacturing industries. In particular, the evolution of CO_2 and gas (CH_4 and H_2) infrastructure is still subject to a great degree of uncertainty. This uncertainty primarily emanates from legal frameworks. On the gas side, the interconnection in domestic hydrogen production between the electricity and gas grids on the one hand, and the dispersed potential of domestic green CH_4, on the other, are some of the biggest challenges. For CO_2, where sequestration may be without alternative in hard-to-abate subsectors such as the non-metallic minerals, the areas of transport, subsector-overarching use and currently unlawful storage in Austria represent further research fields.

With regards to scenario narratives:

Production interrelations of subsectors

Expanding the repertoire of scenarios would facilitate the exploration of disruptive developments and provide a critical field for investigating the diverse production interrelations between subsectors, supply chains, and economic development assumptions. In this context, circular economy becomes particularly significant. Future investigations should encompass not only the reintegration of consumer products into the production cycle but also the possibility of increased utilisation of by-products and waste across various subsectors. On one hand, such an approach is essential for enhancing material efficiency and conserving resources. On the other hand, additional energy may be necessary for adequate preparation of end-of-life products and transport, among others, which must be considered.

With regards to additional analyses in connected fields of research:

Integration of other economic sectors

The present thesis has purposefully focused exclusively on the manufacturing industries' options towards climate neutrality, enabling deep insights into process peculiarities in each of the thirteen industrial subsectors. As other sectors also develop more and more towards prosumer sectors thanks to small-scale PV plants and storage possibilities, among others, general parts of the proposed methodology can be applied to economic sectors other than manufacturing industries, e.g., buildings. Overarching scenario development including households, tertiary services, transport, etc. allows for the identification of interdependencies and synergies between sectors.

Macroeconomic analyses and regulatory dynamics

In a broader context, this research trajectory could further expand towards general macroeconomic analyses, the evolution of RTI initiatives and regulatory dynamics. This holistic approach, together with the integration of other economic sectors mentioned above, would yield an expansive spectrum of studies, ready to equip European and Austrian stakeholders in manufacturing industries with a detailed yet broad and robust set of possible transition pathways that can prepare and inform the actual path we will go down in the years to come in a continuous feedback loop.

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APPENDIX A: PEER-REVIEWED PUBLICATIONS

First Journal Article

Nagovnak, P., Kienberger, T., Baumann, M., Binderbauer, P., & Vouk, T. (2022). Improving the methodology of national energy balances to adapt to the energy transition. Energy Strategy Reviews, 44.2022(November), [100994]. https://doi.org/10.1016/j.esr.2022.100994

Table A 1. Author statement to the first journal article

Activity	**Contributing authors (the first-mentioned is the main author)**
Conceptualisation	P. Nagovnak, T.Kienberger
Methodology	P. Nagovnak, T. Kienberger
Investigation and analysis	P. Nagovnak
Visualisation	P.Nagovnak, P. Binderbauer, T. Vouk
Writing (original draft)	P. Nagovnak
Writing (review and editing)	P. Nagovnak, T. Kienberger, M. Baumann, P. Binderbauer
Funding acquisition	T. Kienberger
Supervision	T. Kienberger

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Improving the methodology of national energy balances to adapt to the energy transition

P. Nagovnak [a,*], T. Kienberger [a], M. Baumann [b], P. Binderbauer [a], T. Vouk [a]

[a] *Chair of Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef Straße 18, A-8700 Leoben, Austria*
[b] *Austrian Energy Agency, Mariahilfer Straße 136, A-1150 Vienna, Austria*

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ABSTRACT

An adequate information basis is important for designing and evaluating policy measures to reach international climate goals. Current energy statistics are primarily based on the UN's International Recommendations for Energy Statistics (IRES). We have examined changes in the energy system and how they can be depicted in energy balances, using IRES methodology as the benchmark. We have found that the increasing variety in energy generation through prosumers cannot be illustrated currently. In the manufacturing industries, state-of-the-art balancing limits the depiction of autoproducers' output other than electricity and heat. Their numbers will increase due to hydrogen demand for decarbonisation, among others. In efforts to inform necessary decision-making regarding decarbonisation, an additional focus must also be set on the representation of energy services in demand. Including useful energy categories allows the development of specific useful energy demands, enabling application-driven technology and energy carrier deployment. To remedy the identified shortcomings, the Sectoral Gross Energy Balance Border enables the identification of involved economic units (e.g. manufacturing industry sectors, households, services and energy industries). It features a sector-interrelated approach, in which energy flows follow the physical location of energy operation. Thereby, energy balances can illustrate the multiple transformations in the energy system and better inform policymaking.

1. Introduction

For the global community to reach its climate goals according to the Paris Agreement, a ground-breaking shift in energy systems towards renewable energy sources (RES) is essential [1]. Governments worldwide are faced with a growing need to pass supporting legislature for their economies to champion the turnaround from fossils- to renewables-based and climate-neutral energy systems. Policymakers need energy balances as a fundamental tool for effective and sound decision-making pertaining to many efforts toward a low-carbon future [2]. Energy balances assist this process at several stages of the policy delivery cycle. Firstly, they provide an essential basis for identifying potentials and assessing previous measures and policies. Secondly, often accomplished through scenario development, options are appraised on their potential outcome and impact. Prominent examples of such scenarios include the International Energy Agency's World Energy Outlook and the EU-mandated scenarios on energy and greenhouse gas emissions depicting development "with existing measures" and "with additional measures" in each member state. When policy options are implemented, timely and holistic reports enable fast responses and continuous improvement [3].

The success of the above-described policy cycle is strongly influenced

Abbreviations: BF/BOF, Blast furnace/blast oxygen furnace; CH_4, Methane; CHP, Combined heat and power; DECHEMA, *german*: Gesellschaft für Chemische Technik und Biotechnologie; e.g., exempli gratia; etc., et cetera; EII, Energy-intensive industries; Eurostat, Statistical Office of the European Communities; Exp, Export; FC, Final consumption; GHG, Greenhouse gas; GWh, Gigawatt-hour; H_2, Hydrogen; H-DR-EAF, Hydrogen-based direct reduction and electric arc furnace; IB, International bunkers; ICT, Information and communications technologies; i.e, id est; IIASA, International Institute for Applied Systems Analysis; Imp, Import; IP, Indigenous Production; IPCC, Intergovernmental Panel on Climate Change; IRES, International Recommendations for Energy Statistics; OU, Own use; PV, Photovoltaic; PtG, Power-to-gas; R&D, Research & development; RES, Renewable energy sources; RET, Renewable energy technologies; SGEBB, Sectoral Gross Energy Balance Border; SNG, Synthetic Natural Gas; TES, Total energy supply; T_{in}, Transformation input; T_{out}, Transformation output; TWh, Terawatt-hour; UK, United Kingdom; UN, United Nations; VtG, Vehicle to grid.

* Corresponding author.
E-mail address: peter.nagovnak@unileoben.ac.at (P. Nagovnak).

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by the accuracy with which the energy balances are prepared. Therefore, they must reflect the respective sectors' realities regarding final energy demand and shares in primary energy generation, energy transformation and storage. Due to already observable and likely additionally expectable changes in energy system infrastructure, it is necessary to investigate the aptitude of the current balancing methodology for the energy system transition. The United Nation's International Recommendations for Energy Statistics (IRES) serve as a general reference document for energy balances for national and international statistics agencies worldwide [4,5]. IRES aims to ensure comparable, consistent energy balances to provide useful information to all relevant stakeholders. Therefore, we have chosen IRES as the benchmark for our analysis. Specifically, this paper addresses the following questions:

- Is state-of-the-art balancing methodology fit to depict the increasingly diversified group of energy producers in light of the future energy system, especially in the buildings and industrial sectors? If not, what must an energy balance sheet look like to fulfil this demand?
- Is the currently considered depth of detail of energy consumption (final energy and final non-energy demand) sufficient to provide a solid basis for understanding energy systems on the consumer side? What are the additions needed to support the presentation of the transformation challenges?
- Are the currently employed Sankey diagrams for visualising energy balances suitable to depict the future energy system architecture? If not, what is the best way to express national energy flows to guarantee quick understanding and frictionless creation of energy balances and vice versa?

To answer these questions, we have structured the paper as follows. In chapter 2 of this work, we will argue that, given the described shift in energy system architecture, several shortcomings of the status quo of energy balancing can be identified both in depth and width of presentation. In chapter 3, this work will introduce the Sectoral Gross Energy Balance Border, which enables the development of more comprehensive energy balances. Chapter 4 illustrates the proposed improvements through the example of Austria. Chapter 5 offers a conclusion and an outlook on policymaking and scenario development implications if the proposed modifications and additions are adopted.

2. Status quo of energy balancing

2.1. How are energy balances currently structured?

To assess shortcomings and propose improvements, it is first necessary to investigate the current international methodology of energy balances. The International Recommendations for Energy Statistics this work refers to are a compilation of "recommendations on concepts and definitions, classifications, data sources, data compilation methods, institutional arrangements, approaches to data quality assessment, metadata and dissemination policies" provided by the United Nations Statistics Division [4]. Its target group comprises many diverse stakeholders, ranging from statisticians to policymakers, researchers and the general public, among others.

In IRES, the discussion on energy flows is at the core of the manual, describing energy flows and the main groups of economic units relevant to the collection of energy data. This analysis of energy flows within a system lays the very foundation of energy statistics products. Based on the collected energy flows, energy balances, which this work focuses on, represent the necessary accounting framework for the compilation and reconciliation of all data related to energy products entering, exiting and used within the national territory of interest. IRES categorise three general economic sectors in any given energy system that can generate energy flows: *Energy industries, other energy producers, and energy consumers*. *Energy industries* are defined as economic units "whose principal activity is primary energy production, transformation, or distribution of energy." For *energy consumers*, it is distinguished between the economic units of manufacturing industries with thirteen industrial subsectors, the seven subsectors of the transport sector, agriculture, fishing, commerce and public services, households and remaining non-specifiable (for example, energy consumption in connection with defence activities) [6]. According to the IRES definition, *other energy producers* relates to all economic units outside the energy industries that produce or transform energy in support of their primary activity, e.g. producing goods in the manufacturing industries. Therefore, they coincide with economic units also listed under *energy consumers*. As visualised in Fig. 1, all correspond to the energy balances according to a three-block concept. Their respective energy operations are given as bullet points.

- Top block: The total energy supply (TES), calculated according to (1), is the sum of indigenous production of primary energy (IP), the difference between import (Imp) and export (Exp) of primary and secondary energy, and the stock change (ΔStock), minus energy going into international (aviation or marine) bunkers (IB). As currently proposed by Refs. [4,6], no differentiation is made in published balance sheets regarding the economic unit in which the indigenous production of primary energy was achieved.

$$TES = IP + Imp - Exp \pm \Delta Stock - IB \tag{1}$$

- Medium block: In the medium block, all energy transformation, for primary and secondary purposes within the total of all economic sectors is accounted for within the energy industries. The only exception is the concept of *autoproducers* for heat and electricity in manufacturing industries, which allows the allocation of energy transformation units outside the energy industries, although without further specification of the concerned industrial subsectors. Energy transformation is disaggregated according to (2), with T_{in} and T_{out} representing transformation input and output, respectively. The energy industries' own use (OU) means the consumption of own-produced energy and energy purchased for operating installations in connection with energy transformers, as well as storage cycle losses. It is thus not available for distribution to the bottom block [5].

$$T_{in} = T_{out} + OU \tag{2}$$

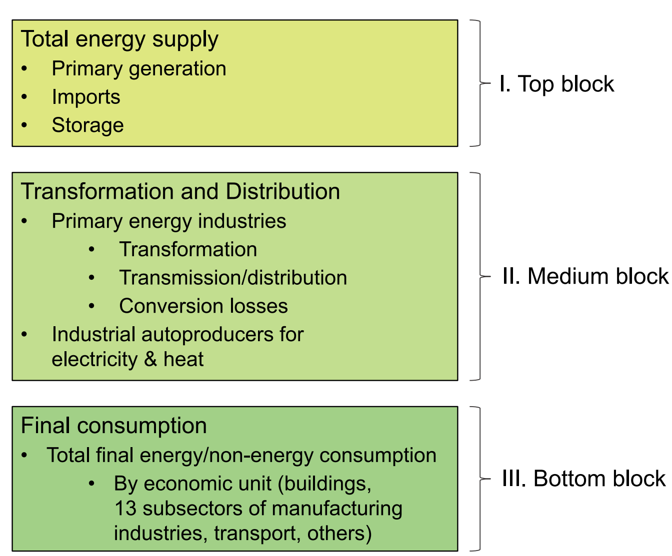

Fig. 1. Scheme of state-of-the-art energy balance, based on [4] and expanded by economic sectors potentially contributing to the respective block.

- Bottom block: The bottom block consists of the final consumption by energy consumers, which is in turn comprised of final energy consumption and final non-energy consumption. Resulting from the two blocks mentioned above, the energy available to these sectors for final consumption (FC) is calculated as follows:

$$FC = TES - T_{in} + T_{out} - OU \tag{3}$$

Contrary to the middle block, transformation (i.e. end-use conversion) technologies for the supply of useful energy demand are not considered in the bottom block.

Primarily, the results of energy balances are presented as a list according to the three-block system outlined above. Another method of presentation frequently used are Sankey diagrams. Sankey diagrams have long enjoyed high regard as a valuable and proven tool for visualising complex energy and material balances [7]. National Sankey diagrams of energy flows have been reviewed in Ref. [8] and are annually prepared by the International Energy Agency, Eurostat and national statistics agencies, among others [9–12]. Traditionally, depicted energy flows follow the three-block system, using a horizontal logic from left to right.

Countries use energy statistics products based on the above-explained methodology to support policy-making questions and monitor existing measures' progress. Two ways mentioned in IRES that energy balances specifically support the policy delivery cycle are through the compilation of energy and GHG emission indicators. Energy indicators compilable from IRES can be attributed to the social, economic or environmental dimension as well as according to themes and sub-themes. The choice of the respective set of indicators selected and compiled by a country further depends on national circumstances and priorities. According to the authors of IRES, a growing interest among policymakers in such indicators, especially regarding energy efficiency, has been observable. Energy balances are also an essential basis for estimating and monitoring GHG emissions. Countries worldwide produce GHG inventory reports based on the guidelines set out by the IPCC and use the energy data compiled under IRES standards for their calculation [13].

Given growing global concerns for climate change and accompanying mitigation efforts, the availability of detailed, reliable and accurate energy balances is essential to targeted policy action. The latest version of IRES was released in 2018, while before this publication, no general update had been undertaken since 1980. In many areas, current IRES standards have already undergone significant improvements, e.g., including solar and wind power and biofuels. However, as we will outline below, the energy system architecture is further changing dramatically, leaving additional room for much-needed adaptions.

2.2. Challenges by the future energy system

To comply with expected RES-based future energy systems, we have set out to identify the most critical challenges to the current international energy balance methodology below.

Within the literature, there are several key trends toward decarbonisation that can be identified, among which:

- The emergence of renewable energy technologies (RET).
- Hydrogen as an important energy carrier for application in a wide range of energetic and non-energetic consumption technologies and an enabler of consumer-based flexibility options.
- More competitive small-to mid-scale solutions for electricity, gas or heat storage.
- Sector coupling across energy carriers thanks to new transformation and digitalisation technologies.
- Increasing efforts towards the deployment of a circular economy in manufacturing industries.

The advent of many of these trends brings an increased linkage and interaction between all energy system actors. This development also causes new challenges for energy balances. Fig. 2 illustrates the expected interconnections in energy supply and consumption between the economic units introduced in section 2.1, many of which can already be seen growing today (A to E). Following the colour code introduced in Fig. 1, the energy operations of the three balance blocks are now assigned to the respective economic units they are and will be performed by in the future. Additional and more sector-specific forms of the trends mentioned above and resulting challenges for energy balances are outlined below the figure, according to the shown lettering. Their description lays the foundation for answering the introductory questions in section 1.

2.2.1. Buildings

In the buildings sector, households and tertiary services are increasingly expanding their share of renewable energy production, particularly through rooftop PV installations. The emergence of these so-called prosumers, also referred to as active consumers or energy citizens, is aided by the development of smart energy meters, monitoring devices and an increasing technology portfolio, both in generation and storage [14]. As technologies for harvesting renewable energies have developed, research on energy prosumers has also increased, especially with the beginning of the past decade. This research has focused not only on technological aspects of prosumerism (e.g. Refs. [15,16]). Still, it extends beyond the borders of engineering into the social sciences and prosumers' role in and potential for the energy transition (e.g. Ref. [17]). These studies concluded that, due to its decentralised nature, realising the PV potential in densely populated areas can only be successful through integrating private stakeholders in the housing sectors. The particular emphasis needed concerning the involved stakeholders is highlighted by Kotilainen [14]. Kotilainen has used a combination of approaches from the research areas of innovation studies, policy sciences and sustainability transition research to show the importance of well-designed and targeted policy instruments in convincing consumers to contribute to RET installations. Currently, the prosumer character of the building sectors is not visualised.

2.2.2. Transport

The transport sector is an aggregation of a very heterogeneous group of stakeholders, as both private and economic activities are represented by the seven subsectors, as mentioned. In contrast to the other sectors in discussion in this section, changes to the structure of the energy system due to technological developments in the near future cannot be foreseen. On the other hand, flexibility solutions based on vehicle storage in connection with the emergence of battery electric or fuel cell vehicles (e.g. vehicle to grid (VtG)) have to be considered, thereby adding the task of energy storage into the transport sector. The increasing value of integration of VtG and its optimised interrelation with the energy network has been investigated by Refs. [18–20], among others.

2.2.3. Manufacturing industries

As mentioned, the manufacturing industries are divided into thirteen industrial subsectors. Apart from primary energy generation from RES, which is generally relatively detached from the process technologies in use, industrial subsectors feature two general types of energy conversion units especially dependant on the respective subsector's production and technology portfolio – energy transformation units (secondary to final energy transformation) and end-use devices (final energy to useful energy and non-energy conversion).

Already today, national energy balances do not always match with subsector-specific considerations for greenhouse gas emissions or fuel mix adaptations. For example, coke ovens and blast furnaces of the iron and steel industry or steam reformers of the chemical industry are reported under energy industries because they are not autoproducers of heat or electricity. However, their operation is determined by the primary activity of their respective manufacturing industry. The further

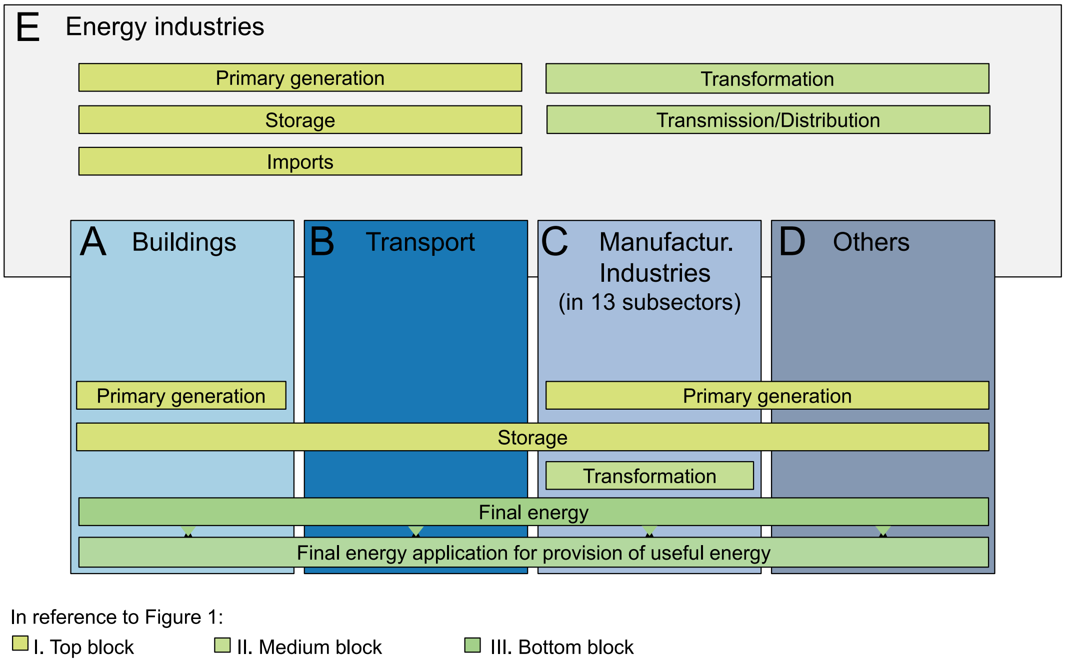

Fig. 2. Future energy system architecture and interrelation of energy supply and consumption in economic sectors.

usage of these units' transformation output is correctly presented in the respective sectors' final consumption. This already diverse status quo presents an enormous challenge concerning the correct energy balancing, especially with more complex energy system architecture to be expected in the future.

The carbon-neutral transformation of energy-intensive industries (EII) is one of the centrepieces of decarbonisation for industrially-developed economies. As such, it is the topic of much investigation in scientific literature. On a technology level, studies explore sustainable technologies for each industrial subsector separately, assessing the impact of technologies on GHG emissions and energy demand based on a sectoral balance border. The literature examples below show that these sector investigations generally ignore the national energy balance methodology. Balance borders are drawn individually, integrating industrial upstream transformation processes and the impact of their removal or addition on the parameters mentioned above:

The largest share of greenhouse gas emissions in iron and steel stems from process emissions in primary steelmaking via the blast furnace/basic oxygen furnace route (BF/BOF). Although it constitutes the primary process of steel production, the process is currently primarily attributed to the energy industries, holding the problem that the decarbonisation potential of the sector is not clearly attributable under current energy balances. The efficiency of the BF/BOF process is generally viewed to be developed to close to the thermodynamic limit [21]. The use of hydrogen in the blast furnace as an additional reducing agent is limited to reducing emissions by 20% at most [22]. Therefore, new and alternative process technologies will be introduced to decarbonise the subsector. The most promising of these technologies within the considered timeframe until the middle of the century is considered to be hydrogen direct reduction in combination with electric arc furnaces (H-DR-EAF) [23]. For the complete investigation of the feasibility of transitioning to cleaner primary steelmaking, besides the H-DR-EAF route calculations, [23,24] have included aspects of necessary upstream hydrogen production, demonstrating the need to include the total energy conversion chain of transformational manufacturing processes. Several European industry representatives in steelmaking are also exploring the technological feasibility of H-DR-EAF, the relevant upstream hydrogen production and its requirements (e.g. in R&D projects like H2FUTURE, GrInHy, HyBit, as compiled in Ref. [23]). Using the existing balancing structure means that the traditional BF/BOF route must be detached from the energy industries and replaced by an energy conversion unit (electrolysis), a final non-energy consumption unit (direct reduction), and a final energy consumption unit (electric arc furnace). As seen in section 4, a significant change in the amount of energy reported going into the sector may be observed.

Globally, the chemical and petrochemical industries have the largest primary energy demand of any industrial sector and are responsible for 7% of industrial GHG emissions [25]. Because of including both the chemical and the petrochemical industries, the sector is very heterogeneous in terms of energy conversion chains, which makes for additional challenges in decarbonisation. In the chemical industries, the synthesis of ammonia, the most important feedstock for agricultural fertilisers, is critical. Currently, H_2 is mainly produced in steam reformers from fossil CH_4, making the subsector one of the biggest hydrogen producers today but also contributing significant amounts of GHG emissions. In the future, these reformers will have to be replaced by more sustainable and carbon-neutral hydrogen production, for example, electrolysis, pyrolysis or by using Bio-CH_4.

On the other hand, the petrochemical industries are closely linked to the energy industries, as many basic chemicals are produced out of refineries' output (e.g. ethylene, propylene, aromatics from naphtha). Over recent years, chemical and petrochemical subsector assessments have been performed worldwide. Among these, the technology roadmap by the International Energy Agency, in cooperation with the German Society for Chemical Engineering and Biotechnology (DECHEMA), has been at the forefront of interest [26]. Several regional and national reports have followed, for example [27] for Germany, [28] for Austria or [25] for the UK. All of them have identified alternative breakthrough technologies suitable for the decarbonisation of these chemicals' production based on hydrogen, among others. Consequently, hydrogen production through various sustainable production methods is a critical technology for the subsector's decarbonisation. It is discussed not as a separate issue of energy industries but within the subsector [26–29]. However, IRES methodology does not share this approach. The existing energy balance structure separates this problem into upstream energy conversion in the energy industries and actual production in the chemical and petrochemical industries.

Other EII, for example, non-metallic minerals or non-ferrous metals, are faced with the challenge of supplying their high-temperature processes with suitable yet sustainable and GHG-neutral energy carriers. The alternatives seem relatively limited, but secondary energy production may become more attractive for these industries. As seen from the example in iron and steel or the chemical industry above, integrating aspects of the energy industries within the manufacturing industries is currently impossible in IRES. However, in a decarbonised energy system architecture, more and more industrial subsectors may choose to employ forms of energy conversion units. [30] propose the integration of biogas production facilities into plants of the building materials industry like cement or lime to increase the overall market competitiveness of biogas by energy efficiency optimisation. The increased spread of RET may trigger additional investments in the on-site production of green energy carriers. For example, hydrogen from electrolysis may act as a way to decarbonise hard-to-electrify industries like aluminium or glass production [31,32].

As pressure for decarbonisation is rising, less energy-intensive industries may also follow this approach of using self-generated electrical energy to supply some of their gas demand, e.g. for fuel cells in factory traffic [33]. As transformation units are installed, new economic possibilities may arise outside the traditional field of business, e.g. partaking in the electricity-balancing market via power-to-gas (PtG) technologies or providing district heat. To raise the efficiency of the overall energy system, industrial waste heat recovery for district heating has also enjoyed increasing focus over recent years. [34] estimates current industrial waste heat potential in Europe to amount to close to 400 TWh. Fourth-generation district heating systems aid the realisation of this potential, also allowing the use of lower temperature levels and more diffuse heat sources within plants [35]. Their economic and technological feasibility has been proven in several pilot cases, as described by Refs. [36–38], but their realisation could not be adequately shown in the IRES energy balance structure.

2.2.4. Others

In Fig. 2, we have summarised agriculture, forestry, fishing, and sectors not elsewhere specified within Others. These sectors may also elect to participate in aspects traditionally located in the energy industries. For example, they can contribute to the energy system through primary energy generation. Among electricity generation, the spread of photovoltaics especially yields potentially significant impacts on agricultural stakeholders. Agrivoltaics investigate the suitability of different farm characteristics for adopting dual-land use concepts, combining the sectoral primary economic activity with energy production through photovoltaics [39].

2.2.5. Energy industries

While the principal functions of the energy industries will remain the same, they will be faced with in-depth changes to their business procedures. To connect all stakeholders of the future energy system and keep grid stability and energy security, the energy industries will have to use flexible and central power generators and sector-overarching digitalisation solutions. These can aid in load flow management and pricing. Thus, demand and supply will be balanced based on available grid capacities, minimising the risk of supply shortages and grid outages [40]. Sector coupling, both between energy carriers and economic sectors, will play an important role in balancing supply and demand over time and space [41] and will become the core task of the energy industries.

To the best of our knowledge, regarding an improvement in energy balances of energy supply and transformation, only sector-based propositions for improvements to national energy balances have been brought forward by the international scientific community. [42] points out the importance of internationally comparable balance borders in assessing energy efficiency performance in steel production plants. In these cases, a standard sector-based definition of fundamental processes (within boundaries) and upstream processes (outside of boundaries) can aid in increasing the comparability of data. [43] for Italy, as well as more generally [44,45] using Germany and the Netherlands as respective case studies, have investigated the chemical and petrochemical industry's non-energy related CO_2 emissions. All three studies find significant deviations in actual emissions upon comparing existing national statistics with bottom-up analyses. [44,45] especially point out the need for improvements in the statistical process and locate a strong lever of action in the international harmonisation of system boundaries.

Based on the observable changes in the energy system and existing literature, we propose to revise the International Recommendations for Energy Statistics to accommodate the elaborated transformations in energy systems to be expected around the globe within the coming decades. The revision has to fulfil two main tasks:

1.) To adequately mirror the newly established energy system architecture.
2.) To inform the transition process on a sectoral stakeholder level.

In addition to the side of energy supply and transformation in various economic units, information on the provided and demanded energy services within a system is also necessary to inform the decisions towards a successful transformation. Such information is often used in scenario development, integral to informing the above-mentioned policy delivery cycle. Within the literature, a common way to investigate decarbonisation potentials or current technology efficiencies in any given sector is based on the amount of useful energy needed. Based on the character of the useful energy in demand, corresponding technologies and energy carriers can be deployed. However, the methodology to attain this important parameter varies significantly because energy balances prepared following IRES do not provide such information.

Among others, the LEAP modelling tool (Low Emissions Analysis Platform) is used extensively and in many studies to explore decarbonisation pathways and assess mitigation potentials (e.g. Refs. [46–50]). To do so, it features a useful energy demand analysis which allows the investigation of efficiency improvements of end-use devices and fuel or technology switching [51]. The International Institute for Applied Systems Analysis (IIASA) operates a database on energy use for 20 regions, specifically highlighting the importance of useful energy as a primary driver of the energy system [52]. [8,53,54] have assumed mean technology efficiencies of end-use conversion devices in their studies on decarbonisation potentials and applied these factors to the given final energy consumption based on general sector characteristics to attain useful energies, further highlighting the vacuum in methodology and data availability.

To devise an internationally valid energy balancing methodology, disaggregation on the level of useful energy might be too high a level of detail as end-use devices and their corresponding efficiencies vary significantly by the considered economy. Therefore, some national agencies, for example Statistik Austria, issue tables of useful energy analysis broken down per sector [55]. The wide field of methodologies for recovering some of the energy consumption information lost through the general structure of current energy balancing according to IRES is a valuable indication of an essential missing piece of information, namely, "what is the reported final energy being used for?".

2.3. Identified shortcomings of current methodology for national energy balances

The answers to questions on the status quo, like the one above, build the foundation of our energy transition. The changes necessary for a sustainable transformation of the overall energy systems worldwide spread out over all sectors of the economy. Energy balances can aid roadmapping the transition to a sustainable energy system by providing holistic and detailed information on energy flows and energy services in demand. As long as their methodology stays up-to-date with the challenges of a changing energy system, they provide a valuable tool for decision-makers worldwide.

However, upon applying the above-described possible characteristics of the future energy system and discussing the necessary level of information depth to devise the pathways to get there, we have identified the following shortcomings of the state-of-the-art methodology. In Fig. 3, the currently not identifiable components of the energy system are depicted in light grey.

- Energy generation units outside the energy industries cannot be assigned to the respective economic units by whom they are deployed. Differentiation of primary generation by economic unit is therefore currently not possible, though needed to inform targeted policy measures for swift deployment of renewable energy sources.
- In addition to primary energy generation, energy output due to energy transformation from prosuming sectors into the overall energy system is not conveyed. The current concept only accounts for industrial autoproducers for electricity and heat without disaggregation into industrial subsectors. In the future, other forms of energy transformation in support of the economic units' primary activity will also become more relevant. This can include the production of hydrogen from electricity (PtG) or the integration of industrial waste heat into the overall energy system for the provision to other economic units. Therefore, the correct allocation of transformation units to be introduced requires the extension of the definition of autoproducers beyond the production of electricity and heat to reflect the diverse field of energy transformation technologies used by the thirteen subsectors of the manufacturing industries in the future.
- Following the current methodology, only total final energy and non-energy consumption by economic unit are shown. Useful energy categories to show final energy applications are not considered. This hinders the development of transition pathway analyses and energy scenarios which are an important aspect of energy statistics' role in the policy delivery cycle.

Therefore, a revised concept for energy balances should recognise the need for the following:

- An investigation of each economic sector and subsector regarding all energy-related units in their respective operation. On one side, this entails energy generation and transformation units; on the other, end-use applications must be introduced.
- An analysis of each economic sector's and subsector's interconnection with the overall energy system maintained by the energy industries (i.e. energy input and output of the sector by energy carrier).
- A supporting visualisation through tables and Sankey diagrams that consider the above-noted changes.

The introduction of the Sectoral Gross Energy Balance Border (SGEBB) in this work is meant as a way of compiling and presenting energy balances in-line with the identified requirements.

3. Proposed improvements to national energy balances

A universal balance border concept is necessary to enable the sector- and subsector-based investigation. In section 3.1, the SGEBB is explained and exemplified for application in all economic units. Section 3.2 discusses data availability and collection needed for the proposed concept.

3.1. Introduction of the Sectoral Gross Energy Balance Border

The concept of SGEBB in Fig. 4 illustrates the diverse reality of prosuming sectors and should be the basis for any national energy balancing effort. As outlined, the sectors outside the energy industries can also participate in energy generation and transformation. Therein generated energy flows can enter into cascades within the sector before eventually entering final consumption or leave the sector's system boundaries and flow back into the energy industries where they are distributed to supply other sectors.

When using the concept of SGEBB, the actual flow charts of economic units can look very different. This will be shown using a case study in section 4. The applied concept of n-1 autoproducer or storage blocks within the balance border allows for the depiction of primary energy generation and transformational energy cascades in any necessary length, making the concept applicable to all prosumer sectors. For example, transport generally consumes final energy exclusively, while using a storage block can visualise VtG cycle losses. This is also shown in

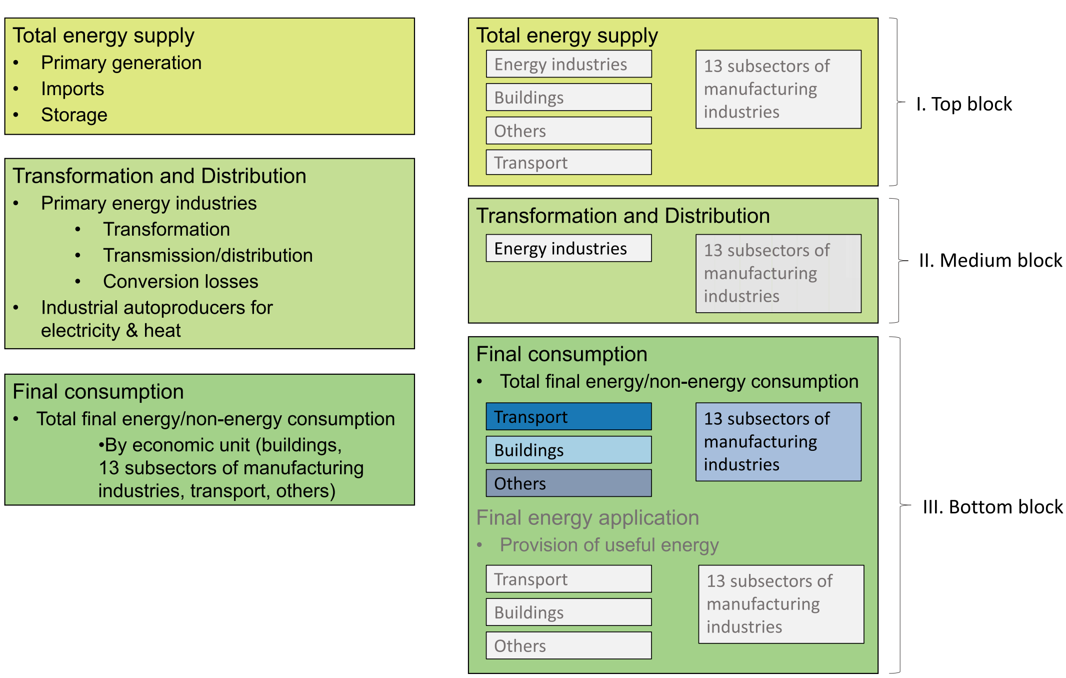

Fig. 3. Identified shortcomings of the current national energy balance methodology. In IRES, information on energy transformation in manufacturing industries exists without disaggregation into subsectors and only for autoproducers for electricity and heat.

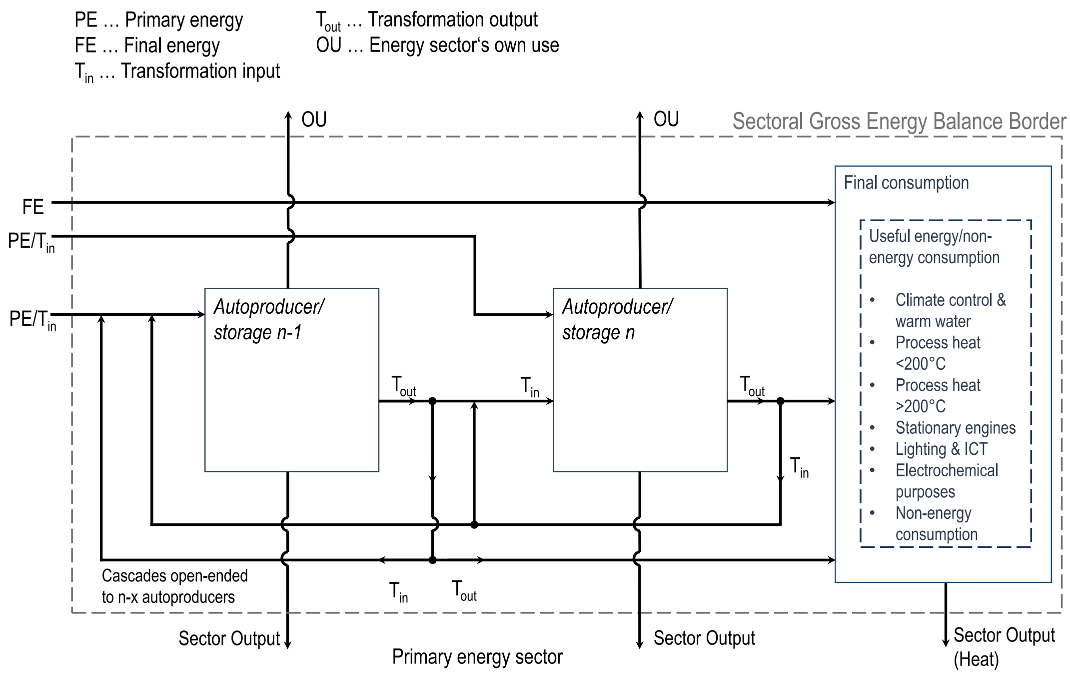

Fig. 4. Detailed depiction of energy flows in prosuming sectors with n-1 secondary/ancillary energy production in autoproducers and storage units and the sector's intersection with the energy industries' primary energy sector using proposed SGEBB.

the use-cases example in section 4. Similarly, households, agriculture or services increasingly offer energy production, especially through photovoltaic units. This is depicted by the autoproducer block. Using the introduced concept for manufacturing industries, some subsectors may show several autoproducers to aid their primary economic processes and use energy carriers in cascades.

In contrast, others' final energy demand is exclusively fuelled by external energy supply. The demand for final energy in all sectors is determined by the amount of useful energy needed. The supplied energy application can best be characterised according to the listed useful energy categories on the right side of Fig. 4, which have been chosen following the methodology used by the Austrian national statistics agency Statistik Austria [55]. For households, process heat <200 °C is viewed synonymously with energy application for cooking, while stationary engines subsume energy for refrigerators and appliances such as washing machines or dishwashers. Industrial processes' waste heat leaving the industrial premises can be accounted for as additional district heat output.

The SGEBB aids a holistic information process by using a theoretical physical border around all properties of an economic sector. These properties can consist of storage, transformation or generation units, and final energy using devices that provide useful energy services. As summarised in Table 1, applying the SGEBB can help with a more detailed representation of the underlying activities that generate energy flows in each sector and the overall energy system with its – often coupled – sectors. Thus, future prosumer possibilities of historically purely consuming sectors can be reflected. If one applies the SGEBB to each economic sector individually, the resulting energy flows correspond to the physical energy flows of the respective disaggregation level investigated. The traditional block of primary energy generation is split up according to the respective economic units to clarify the economic unit operating the energy production plant. Similarly, energy transformation processes, as often found in energy-intensive industries, are now shown to contribute to the overall energy demand of their respective subsector rather than the energy industries. Due to its focus on physical energy flows, it can be applied in energy balances on any level

Table 1
Comparison of possible levels of depth using current IRES methodology and proposed SGEBB concept.

Data visibility of...	Using current methodology	Using SGEBB
...primary generation by economic unit	✗	✓
...energy storage by economic unit	✗	✓
...energy transmission including sources and sinks	✗	✓
...energy transformation by economic unit	✗	✓
...total final energy/non-energy consumption by economic unit	✓	✓
...application of final energy by economic unit	✗	✓

of detail, from industrial plant location or a single building, up to national economic sectors and energy systems, as used in the case study below in section 4.

3.2. Discussion of data availability

While we believe the presented concept is vital to reach the required level of depth for energy balances to overcome the challenges imposed by the transformation of the energy system, we recognise a potential for practical hindrances regarding data collection as countries can significantly differ in their abilities of data collection. It is important to note, however, that the proposed concept enables more detailed energy system representation in countries where required data collection is possible while at the same time leaving room to maintain the current level of aggregation in cases where this is not possible.

In many cases, national or international actors already have set up data collection and dissemination methodologies, though this information is not incorporated into the national energy balances. For primary generation from photovoltaics, for example, the IEA already publishes yearly reports on the distribution of installations between "utility-scale, commercial and industrial, and residential" [56]. For industrial energy transformation units, data on autoproducers must already be collected today by industrial subsector. For example, data on energy generation or transformation by autoproducers in economic sectors outside the energy industries are already encouraged to be reported to IEA, Eurostat and the UN based on autoproducer units [57]. In the European Union, this approach has been mandatory since 2012 to allow policymakers "to understand easily how this field develops" [58]. However, under IRES methodology, this information is then aggregated. In line with our proposed extension of the concept of autoproducers, the collection methodologies can be investigated to also include other energy transformation units in the future. Of course, in these cases, national statistics agencies would still have to stay cautious with the publication of data where statistical anonymity cannot be guaranteed to ensure companies do not have to fear revealing strategic information to competitors.

While for primary generation and energy transformation the challenge seems to sit with the adequate disaggregation of largely already available data for integration in the proposed SGEBB methodology, little information exists in most countries regarding relevant energy application areas on the demand side, presented above as useful energy categories. For households, Eurostat, as well as the International Energy Agency, have already compiled lists with similar categories for households (space heating, lighting, appliances, cooking, etc.) as reported by their member countries [59,60]. This data could be rearranged for the concept outlined in this work. While no such information exists for the manufacturing industries yet, data collection in this sector can be attained by adapting existing surveys. In many countries, companies are already surveyed on their respective use of energy carriers. These surveys, e.g. on industrial autoproducers as outlined above, seem appropriate to be extended to include systematic questions on energy application based on the proposed useful energy categories.

4. Case study for investigating the proposed improvements

To illustrate our proposed improvements in a case study, we have chosen to continue representing energy balances through Sankey diagrams. However, their method of preparation and concept of orientation have been changed to fit the above propositions. Below, we will present a case study of the Austrian energy system for a decarbonisation scenario in 2050 using the SGEBB and compare it with the current standard methodology, as exemplified by IRES. The scenario represents a combination of a decarbonisation study by the Austrian federal environment agency and the industrial decarbonisation initiative NEFI – New Energy for Industry [61–64]. The scenario is characterised by the use of 100% renewable energies. It includes process changes in the industrial subsectors of iron and steel, chemical and petrochemical industry, as well as the Oxyfuel carbon capture technology for removing geogenic emissions in the non-metallic minerals sector.

For the energy balance preparation, we have applied the SGEBB for each subsector individually before aggregating these results to the level of the overall energy system, including the energy industries. As outlined above, this level of refinement is necessary to distinguish between subsector-specific process peculiarities and deployed generation and transformation units (autoproducers). To completely reflect the transformed energy system of the future, we have added both hydrogen and excess heat as energy commodities. These are currently not considered under IRES. Both subsector and overall energy system balances should be published to guarantee a holistic information process.

As an example, for the buildings sectors, the top of Fig. 5 is a depiction of the scenario for households, prepared with the current methodology. In contrast, the bottom was designed using the SGEBB. As can be seen, a significant increase in detail and clarity can be achieved. Neither the prosumer character of the sector nor its energy services in demand can be understood from the current presentation concept.

The presentation based on the SGEBB, on the other hand, allows information on the prosumer character of the sector and delivers detailed knowledge on the needed energy services. For households, the useful energy category for process heat <200 °C stands synonymous with energy application for cooking. It can be seen that the largest energy demand in this economic unit is caused by the need to control the room climate, in this case primarily by heating. Thanks to the added level of detail, it is also possible to understand what energy carriers are predominantly used for this energy service. The investigated scenario considers already established supply structures for biomass in rural areas and relies on district heat in more urban regions. In this case, the comparison with a Sankey diagram on the status quo of Austria would show an especially ambitious substitution of CH_4-based heating systems by district heating.

Exemplary for all industrial subsectors, Fig. 6 shows the iron and steel sector flow diagram, again comparing the two concepts. At the top, the information presented under current guidelines is visualised. On the bottom, energy flows according to the proposed SGEBB are presented.

Due to the high temperatures in steelmaking and the hydrogen demand for future direct reduction, large amounts of renewable gases are needed. In this scenario, only some of this demand is covered by on-site electrolysers thanks to industry-owned PV and hydropower, with most of the gas being provided by the energy industries. In this sector, the scenario-specific application-orientated use of energy carriers is well noticeable. CH_4 and H_2 are reserved for high-temperature applications and as reducing agents where limited alternatives are available. On the other hand, heat pumps and excess heat of CHP cogeneration are deployed for low-temperature processes and climate control. In the state-of-the-art depiction, all hydrogen production is summarised within the energy industries, prompting significant underestimation of the need for electrical energy by the respective companies and the associated infrastructural grid demands. The sector's energy intensity holds strong potential for using excess heat for neighbouring district heat grids. In the proposed improvement, the excess heat not clearly attributable to any one energy service is presented as a total on the sector border. As the sector also delivers some hydrogen and electricity to the overall energy system, these energy flows out of the balance border are also depicted.

The energy balance of the total Austrian energy system in the decarbonisation scenario 2050 using a traditional three-block approach is shown in Fig. 7.

For its creation, we have aggregated all economic demand units into the four groups introduced in section 2; manufacturing industries, buildings, others (comprised of agriculture, fishing), and transport (comprised of navigation, aviation, rail and road traffic). It is evident from viewing the figure that the sector-specific peculiarities cannot be conveyed:

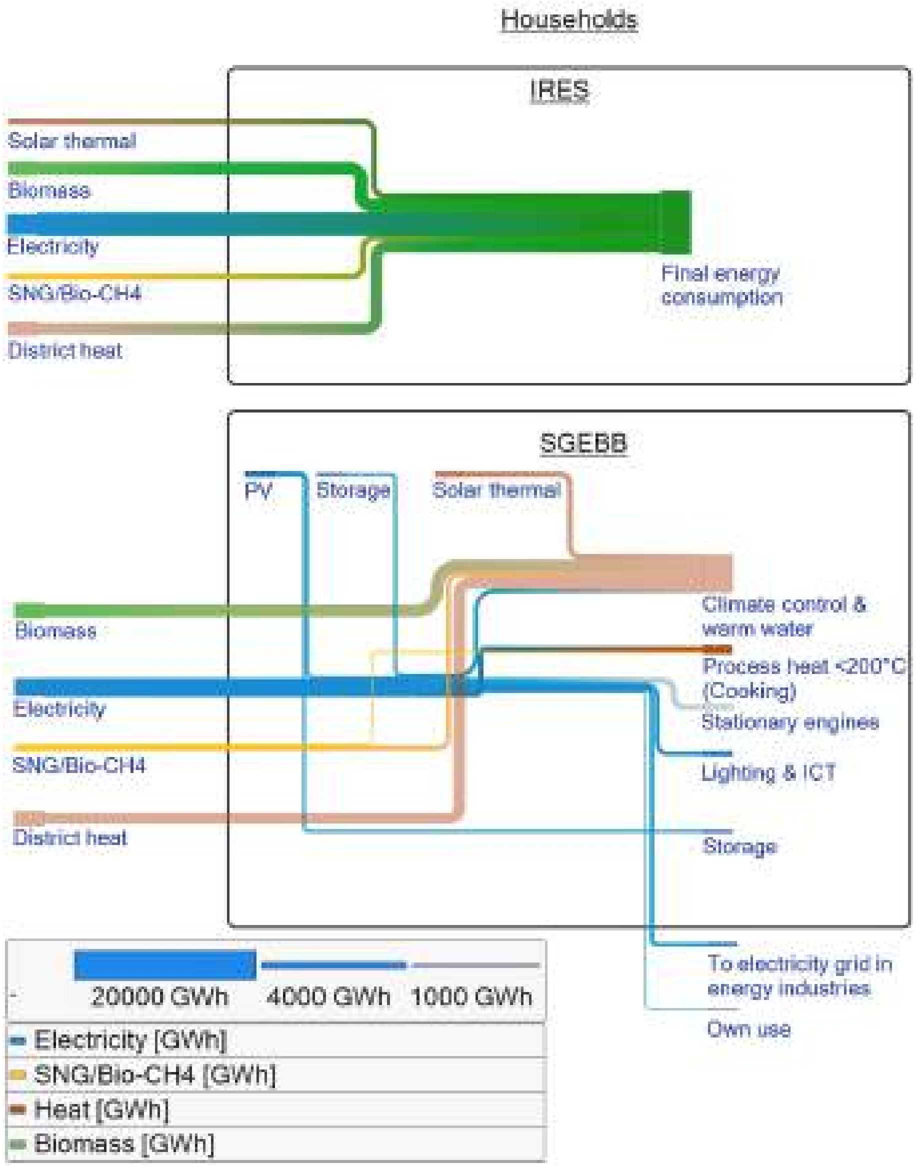

Fig. 5. Comparison of Sankey diagrams of energy balance in the household sector 2050. Top: Following current IRES standards. Bottom: Prepared using proposed SGEBB methodology.

- Industrial autoproducers (CHP plants and electrolysers) are located in the energy transformation block in the middle of the diagram.
- Primary energy generation is not disaggregated, therefore not conveying any information on the economic units associated with the generation.
- Sector interrelation with the overall energy industries (demand and supply) is not presented.
- No information on the energy services in demand in any given prosumer sector is provided. Therefore, the efficient and application-orientated use of energy carriers and technologies cannot be conveyed.

We maintain the same level of granularity for the presentation of the proposed improvements using SGEBB in Fig. 8. This is because it is most suitable to distinguish the sectors of primary energy generation and the interaction of prosuming sectors with the energy industries. Each prosuming sector can feed excess energy to the overall energy system. For clarity, in the depicted visualisation, these surpluses leave the respective sectors in the bottom sector boundary and enter on the left side of the figure into the energy industries one level below the primary energy generation by energy industries. It can be seen that building sectors outside the manufacturing industries generate electricity mainly through photovoltaic installations, with own-use rates in the scenario in the range of 30–50%. The remaining electric energy is fed into the energy sector for distribution to and use in other sectors, e.g. tertiary services or transport. Similarly, manufacturing industries' excess heat from CHP plants and harvested internal waste heat is provided to other sectors via the energy industries' transmission and distribution grids in the same way as any excess industrially produced hydrogen. This presentation shows the energy industries' important task of coupling the prosumer sectors in their individual energy supply and demand. The production of biomass, though initially located in agriculture or housing (e.g. organic waste), only becomes an energy commodity once it is introduced into the energy industries, which is why it is located within the energy industries sector. The same concept applies to substitute fuels, e.g. waste.

5. Conclusion and policy implications

For international climate goals to be reached successfully, a solid

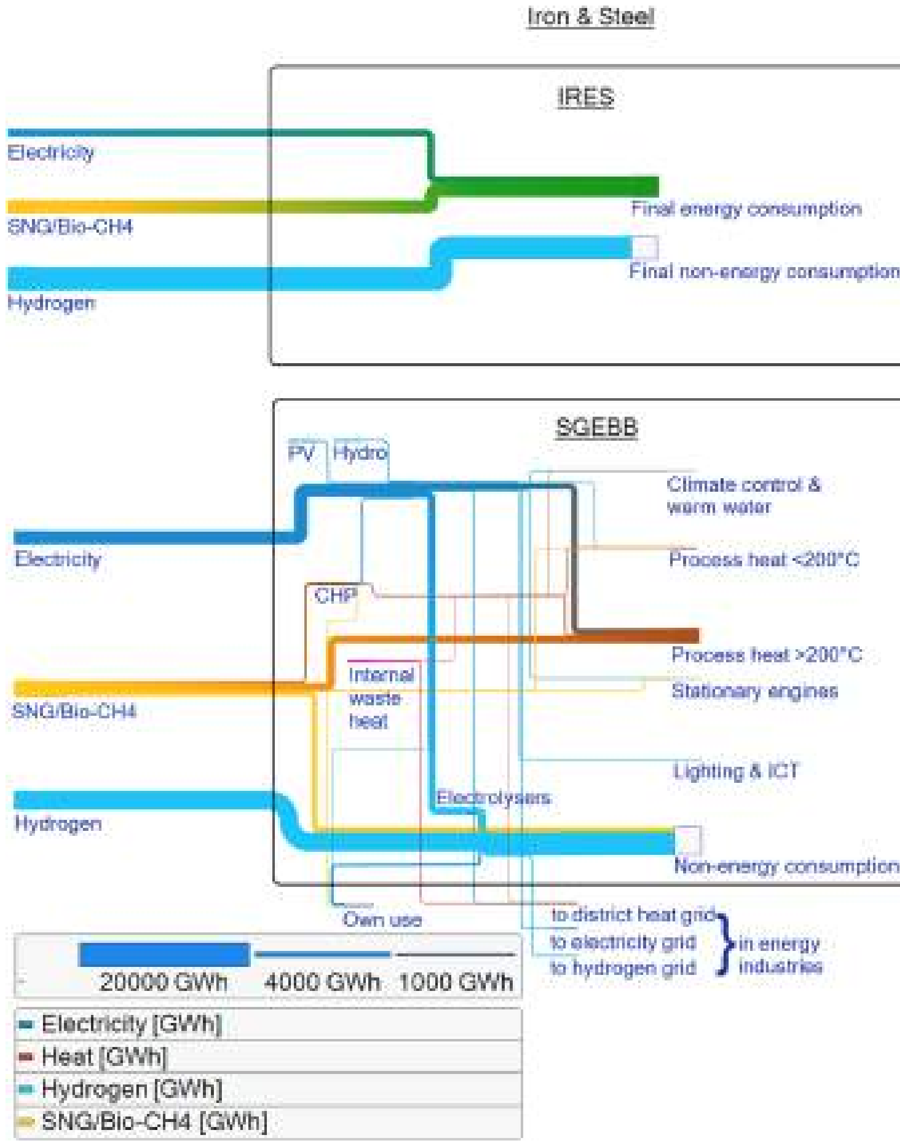

Fig. 6. Comparison of Sankey diagrams of energy balance in the iron & steel sector 2050. Top: Following actual IRES standards. Bottom: Prepared using proposed SGEBB.

information basis is essential for designing and evaluating adequate policy measures. Current energy statistics publications by national and international agencies are primarily based on the United Nation's International Recommendations for Energy Statistics, which we used as general reference to develop constructive improvements to energy balances. In our investigation, we have found the following:

- The increasing heterogeneity in energy production among formerly exclusive consumers, especially in the manufacturing industries and in buildings, is a growing challenge for the depth of information content of current energy balances. In the manufacturing industries, disaggregation into industrial subsectors is necessary due to diversified evolution paths. Autoproducers' output other than electricity and heat will increase significantly (e.g. PtG).
- Directly connected with the above point, hydrogen will become an important energy commodity and enable secondary energy production in autoproducers as an additional activity across several subsectors. However, development can be expected to be diverse across countries as well as subsectors and companies.
- The increasing numbers of RET in former consumer sectors, for example, PV on buildings, also cannot be illustrated currently and is instead accounted for within the energy industries.
- To support the energy transition, besides the energy generation and transformation sector, additional focus needs to be set on the representation of energy services in demand which is currently not exhaustively depicted. However, this information is an integral part of devising more efficient and application-orientated pathways of energy use for a climate-neutral energy system. The extension to include useful energy and non-energy categories allows the development of specific useful energy demands according to the predominant technologies used in any given country, both enabling standardisation and individualisation where necessary.
- As a consequence of the developments mentioned above, information on involved stakeholders in the energy transition cannot be conveyed to policymakers. Considering physical balance borders as proposed can add information value to statistics and allow precise identification of relevant processes and involved stakeholders. It can thereby deliver on the need for more detailed energy statistics voiced by national and international policymakers and science.

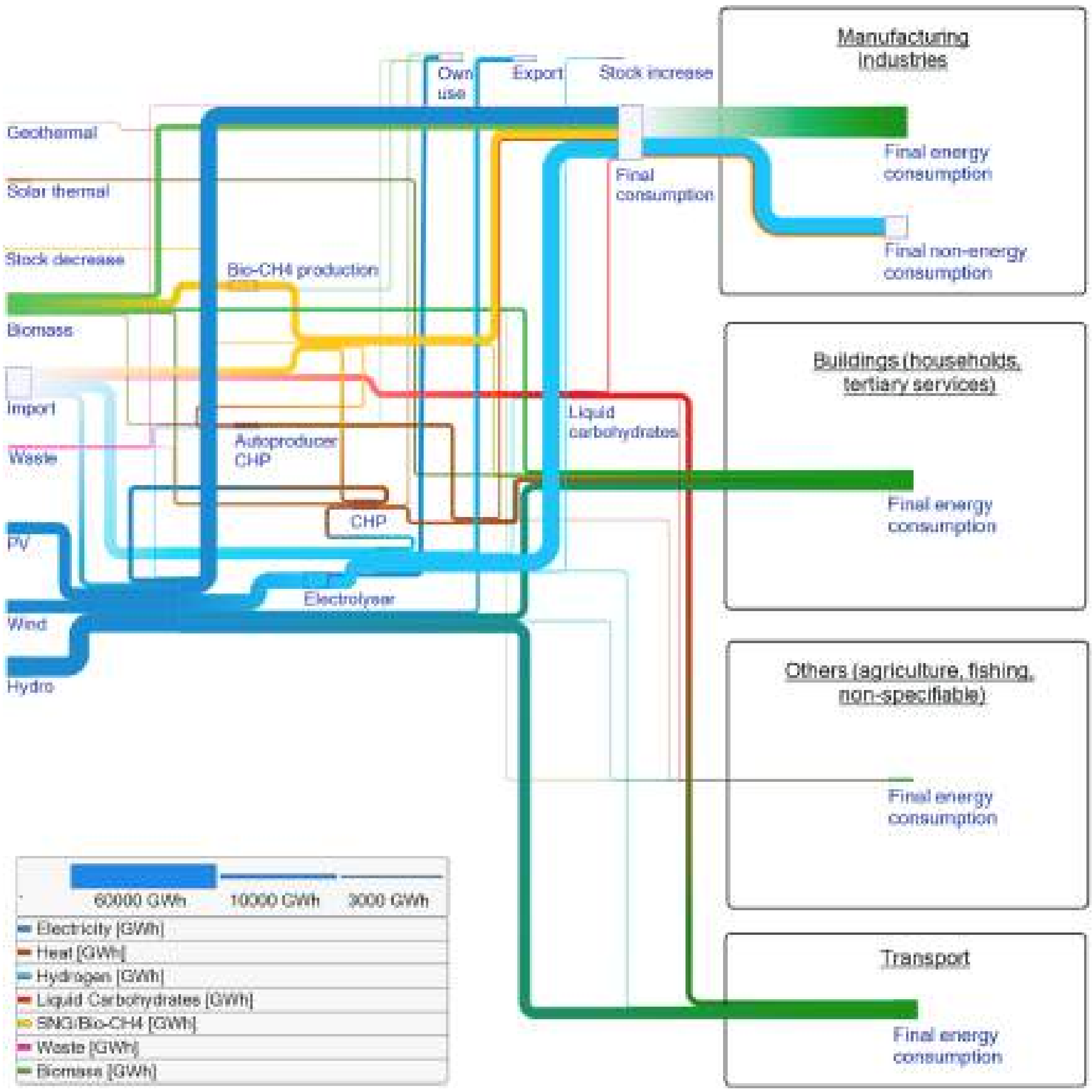

Fig. 7. Sankey diagram of Austrian energy balance 2050 following IRES standard.

- Sankey diagrams are a valuable tool to depict energy balances of future energy system architecture and increase their impact. Using the principles of the SGEBB allows a transparent allocation of all aspects of the energy system. It provides information on involved economic units like manufacturing industry sectors, households, services and energy industries. The conventional horizontal orientation of energy operations (three blocks of *production*, *transformation* and *consumption*) can be substituted by a more sector-interrelated approach, in which reported energy flows follow the physical location of energy operation.

In closing, consideration of the proposed Sectoral Gross Energy Balance Border in energy balancing allows the illustration of the increasing vertical interlinkage between all sectors in the energy system brought about by the decarbonisation trend. In many areas of the changing energy system architecture, statisticians and policymakers have already recognised the need for more detailed data to support further decision-making. However, no internationally standardised way of presenting this information in national energy balances has been proposed. By drawing sectoral balance borders around all aggregates and processes of an economic sector following the proposed SGEBB, all energy flows going in and out of a sector, as well as energy cascades within a sector, if applicable, can be accounted for. This internationally standardises and improves the level of detail of national energy balances. Thereby, the SGEBB contributes to energy balances being able to continue providing an important basis for decisions regarding the development of economies, especially in the face of global climate change. The information content of IRES as important means of international standardisation would benefit significantly from this approach and aid its mission of facilitating the analysis, dissemination and use of energy statistics worldwide. In turn, societies worldwide can continue to turn to energy statistics as an important tool in delivering focused and target-driven policies that enable climate neutrality.

Credit author statement

Peter Nagovnak: Conceptualisation, Methodology, Investigation, Visualisation, Writing – Original Draft, Writing – Review & Editing, Thomas Kienberger: Conceptualisation, Methodology, Writing – Review & Editing, Funding acquisition, Supervision, Martin Baumann: Writing: Review & Editing, Paul Binderbauer: Visualisation, Writing – Review & Editing, Thomas Vouk: Visualisation.

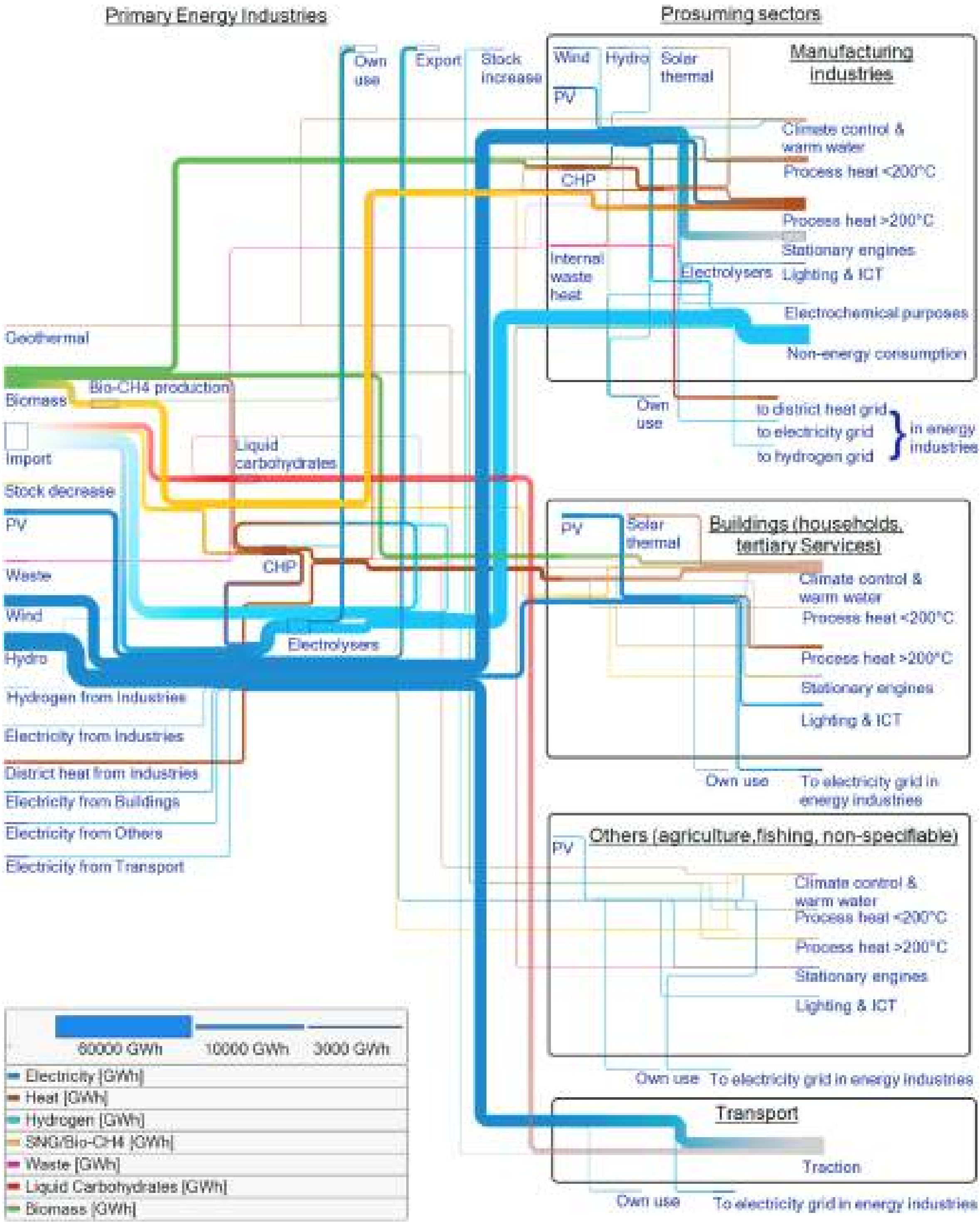

Fig. 8. Sankey diagram of Austrian energy balance 2050 prepared using proposed SGEBB.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

Table A.1 below offers a SGEBB-based revision of the template of a detailed energy balance (prepared in accordance with current IRES standards as presented in Ref. [4]) in accordance with the approach described in section 3 of this work.

Table A.1
The proposed aggregated template for energy balances is based on the SGEBB methodology. The form of presentation is in accordance with [4]. Subcategories for 4.1 and 4.2. exemplary for 4.3–4.16.

		Energy products			
Item code	Flows	E_1	E_2	…	Total
1.1	Primary production				
1.1.1	Energy sector				
1.1.2	Other energy producers				
1.1.2.1	Manufacturing, total				
1.1.2.1.1	Iron and steel				
1.1.2.1.2	Chemical and petrochemical				
1.1.2.2	Other, total				
1.1.2.2.1	Commerce and public services				
1.1.2.2.2	Households				
1.2	Imports				
1.3	Exports				
1.4	International bunkers				
1.5	Stock changes				
1	Total energy supply				
2	Statistical difference				
3	Transfers				
4	Transformation processes				
4.1	Electricity plants				
4.1.1	Energy sector				
4.1.2	Autoproducers				
4.1.2.1	Iron and steel				
4.1.2.2	Chemical and petrochemical				
4.1.2.3	Non-ferrous metals				
4.1.2.4	Non-metallic minerals				
4.1.2.5	Transport equipment				
4.1.2.6	Machinery				
4.1.2.7	Mining and quarrying				
4.1.2.8	Food and tobacco				
4.1.2.9	Paper, pulp and print				
4.1.2.10	Wood and wood products				
4.1.2.11	Textile and leather				
4.1.2.12	Construction				
4.1.2.13	Industries not elsewhere specified				
4.2	CHP plants				
4.2.1	Energy sector				
4.2.2	Autoproducers				
4.2.2.1	Iron and stee				
4.2.2.2	Chemical and petrochemical				
4.2.2.3	Non-ferrous metals				
4.2.2.4	Non-metallic minerals				
4.2.2.5	Transport equipment				
4.2.2.6	Machinery				
4.2.2.7	Mining and quarrying				
4.2.2.8	Food and tobacco				
4.2.2.9	Paper, pulp and print				
4.2.2.10	Wood and wood products				
4.2.2.11	Textile and leather				
4.2.2.12	Construction				
4.2.2.13	Industries not elsewhere specified				
4.3	Heat plants				
4.3.1	Energy sector				
4.3.2	Autoproducers				
4.4	Patent fuel plants				
4.4.1	Energy sector				
4.4.2	Autoproducers				
4.5	Brown coal briquette plants				
4.5.1	Energy sector				
4.5.2	Autoproducers				
4.6	Coal liquefaction plants				
4.6.1	Energy sector				
4.6.2	Autoproducers				
4.7	Gas works				
4.7.1	Energy secto				
4.7.2	Autoproducers				
4.8	Blast furnaces				
4.8.1	Energy sector				

(continued on next page)

Table A.1 (*continued*)

Item code	Flows	Energy products			
		E_1	E_2	…	Total
4.8.2	Autoproducers				
4.9	Peat briquette				
4.9.1	Energy sector				
4.9.	Autoproducers				
4.10	Natural gas blending plants				
4.10.1	Energy sector				
4.10.2	Autoproducers				
4.11	GtL plants				
4.11.1	Energy sector				
4.11.2	Autoproducers				
4.12	Oil refineries				
4.12.1	Energy sector				
4.12.2	Autoproducers				
4.13	Petrochemical plants				
4.13.1	Energy sector				
4.13.2	Autoproducers				
4.14	Charcoal plants				
4.14.1	Energy sector				
4.14.2	Autoproducers				
4.15	Waste Heat				
4.15.1	Energy sector				
4.15.2	Autoproducers				
4.16	Other transformation processes				
4.16.1	Energy sector				
4.16.2	Autoproducers				
5	Energy industries own use				
5.1	Energy sector				
5.2	Other energy producers				
5.2.1	Manufacturing, total				
5.2.1.1	Iron and steel				
5.2.1.2	Chemical and petrochemical				
5.2.2	Other, total				
5.2.2.1	Commerce and public services				
5.2.2.2	Households				
6	Losses				
6.1	Energy sector				
6.2	Other energy producers				
6.2.1	Manufacturing, total				
6.2.1.1	Iron and steel				
6.2.1.2	Chemical and petrochemical				
6.2.2	Other, total				
6.2.2.1	Commerce and public services				
6.2.2.2	Households				
7	Final consumption				
7.1	Final energy consumption				
7.1.1	Manufacturing, const. & non-fuel mining industries, total				
7.1.1.1	Iron and steel				
7.1.1.2	Chemical and petrochemical				
7.1.1.3	Non-ferrous metals				
7.1.1.4	Non-metallic minerals				
7.1.1.5	Transport equipment				
7.1.1.6	Machinery				
7.1.1.7	Mining and quarrying				
7.1.1.8	Food and tobacco				
7.1.1.9	Paper, pulp and print				
7.1.1.10	Wood and wood products				
7.1.1.11	Textile and leather				
7.1.1.12	Construction				
7.1.1.13	Industries not elsewhere specified				
7.1.2	Transport, total				
7.1.2.1	Road				
7.1.2.2	Rail				
7.1.2.3	Domestic aviation				
7.1.2.4	Domestic navigation				
7.1.2.5	Pipeline transport				
7.1.2.6	Transport not elsewhere specified				
7.1.3	Other, total				
7.1.3.1	Agriculture and forestry				
7.1.3.2	Fishing				
7.1.3.3	Commerce and public services				
7.1.3.4	Households				
7.1.3.5	Not elsewhere specified				
7.2	Non-energy use				
7.2.1	Manufacturing, const. & non-fuel mining industries, total				

(*continued on next page*)

Table A.1 (*continued*)

Item code	Flows	Energy products			
		E_1	E_2	…	Total
7.2.1.1	Iron and steel				
7.2.1.2	Chemical and petrochemical				
7.2.1.3	Non-ferrous metals				
7.2.1.4	Non-metallic minerals				
7.2.1.5	Transport equipment				
7.2.1.6	Machinery				
7.2.1.7	Mining and quarrying				
7.2.1.8	Food and tobacco				
7.2.1.9	Paper, pulp and print				
7.2.1.10	Wood and wood products				
7.2.1.11	Textile and leather				
7.2.1.12	Construction				
7.2.1.13	Industries not elsewhere specified				
7.2.2	Transport, total				
7.2.2.1	Road				
7.2.2.2	Rail				
7.2.2.3	Domestic aviation				
7.2.2.4	Domestic navigation				
7.2.2.5	Pipeline transport				
7.2.2.6	Transport not elsewhere specified				
7.2.3	Other, total				
7.2.3.1	Agriculture and forestry				
7.2.3.2	Fishing				
7.2.3.3	Commerce and public services				
7.2.3.4	Households				
7.2.3.5	Not elsewhere specified				

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Second Journal Article

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Table A 2. Author statement to the second journal article

Activity	Contributing authors (the first-mentioned is the main author)
Conceptualisation	P. Nagovnak, M. Rahnama Mobarakeh, C. Diendorfer, G. Thenius, H. Böhm, T. Kienberger
Methodology	P. Nagovnak, C. Diendorfer, T. Kienberger
Data curation	P. Nagovnak
Investigation and analysis	P. Nagovnak. M. Rahnama Mobarakeh, G. Thenius, H. Böhm
Visualisation	P. Nagovnak
Writing (original draft)	P. Nagovnak
Writing (review and editing)	P. Nagovnak, T. Kienberger
Funding acquisition	T. Kienberger
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Article

Cost-Driven Assessment of Technologies' Potential to Reach Climate Neutrality in Energy-Intensive Industries

Peter Nagovnak [1,*], Maedeh Rahnama Mobarakeh [1], Christian Diendorfer [2], Gregor Thenius [3], Hans Böhm [4] and Thomas Kienberger [1]

1 Chair of Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef Straße 18, A-8700 Leoben, Austria; maedeh.rahnama-mobarakeh@unileoben.ac.at (M.R.M.); thomas.kienberger@unileoben.ac.at (T.K.)
2 Austrian Institute of Technology, Giefinggasse 4, A-1210 Vienna, Austria; christian.diendorfer@ait.ac.at
3 Austrian Energy Agency, Mariahilfer Straße 136, A-1150 Vienna, Austria; gregor.thenius@energyagency.at
4 Energieinstitut an der Johannes-Kepler-Universität, Altenberger Straße 69, A-4040 Linz, Austria; boehm@energieinstitut-linz.at
* Correspondence: peter.nagovnak@gmx.at

Abstract: Efforts towards climate neutrality in Europe must prioritise manufacturing industries, particularly the energy-intensive industry (EII) subsectors. This work proposes a novel approach to assessing transformation options for EII subsectors. At the center of this approach we position a *potential analysis* of technologies' impact on subsector decarbonisation—an approach only known so far from the investigation of renewable energy potentials. These so-called *technical climate neutrality potentials*, supplemented by a set of indicators taking into account energy consumption, capital and operational expenditures, and GHG taxation programs per technology and subsector, enable cross-sector comparisons. The indicators allow the reader to compare the impact on GHG emission mitigation, energy demand, and cost for every considered technology. At the same time, we keep an open mind regarding combinations of technological solutions in the overall energy system. This ensures that the technology pathways with the greatest climate neutrality potential are easily identified. These focal points can subsequently serve in, e.g., narrative-driven scenario analyses to define comprehensive guides for action for policymakers. A case study of Austria for the proposed potential analysis demonstrates that bio-CH_4 and electrolysis-derived H_2 are the most economical green gases, but GHG certificate costs will be necessary for cost-competitiveness in high-temperature applications. Electrification offers advantages over conventional technologies and CO_2-neutral gas alternatives in low-to-mid temperature ranges. Under the given assumptions, including GHG emission certificate costs of 250 EUR/t CO_2, alternative technologies in the identified climate neutrality pathways can operate at total annual costs comparable to conventional fossil-based equivalents.

Keywords: energy-intensive industries; climate neutrality; technology options; industrial climate policy

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1. Introduction

Reaching European climate goals associated with the Paris Agreement needs comprehensive action in all sectors of the economy. In all efforts, measures towards climate neutrality have to be balanced with economic interests. A special focus will have to lie on the manufacturing industries as, in 2020, manufacturing industries were responsible for approximately 20% of European greenhouse gas (GHG) emissions [1]. Manufacturing industries are generally differentiated into energy-intensive and non-energy-intensive industrial subsectors. According to the well-used definition of the IEA, energy-intensive industries (EIIs) consist of the iron and steel, chemical and petrochemical, non-metallic mineral, non-ferrous metal, and pulp and paper industries. Their basic material production is one of the pillars of European welfare, and they employ more than 3.5 million people unionwide while annually generating added value of over EUR 700 billion [2–4].

Following the European Union's commitment to the <2 °C target [5], EIIs are faced with fundamental changes to their production processes. Because of EIIs' positioning in the force field between their macroeconomic importance and their heavy weight regarding climate neutrality, public support through policies and RTD programmes will be needed. Policymakers have recognized this need, which can be seen by the installation of high-level working groups on energy-intensive industries on national and supranational levels in recent years, for example, the EU High Level Expert Group on Energy-Intensive Industries [6]. The policy development process for attaining climate neutrality in an EII can be supported by studies that feature both a cross-sectoral dimension and an appropriate level of subsector detail. For their preparation, a coordinated approach must be found. Regarding the state of the literature on these climate neutrality options for EIIs, two groups of studies can be identified that usually fulfill only either one or the other criterion.

On one hand, several scientific publications have supplied subsector-overarching solutions for EIIs comprehensively, e.g., Fais et al. [7] for the UK, Nurdiawati and Urban [8] for Sweden, Gerres et al. [9] for the European Union, and Teske et al. [10] globally. These studies are generally characterised by a top-down approach in combination with scenario modelling to achieve pre-mandated climate neutrality. The deployment rate of sector-specific technologies in these scenarios over time is typically assessed by anticipated levels of technology (TRLs) and the market readiness level (MRL) and is based on predefined scenario narratives. However, such an a priori approach rules out the deployment of competing solutions, leaving an information gap on possibly relevant transformation routes when contemplating big-picture decisions. The main methods for reaching climate neutrality vary on a country-to-country and study-to-study basis, from the use of biomass to increasing electrification, the deployment of natural gas or hydrogen, or carbon capture solutions. The obtained technological solutions are further applied top-down to all subject areas. This poses the problem of not adequately taking into account subsector-specific process peculiarities, feasibilities, and costs. In addition, as Gerres et al. [9] point out, a comparison of private and public stakeholders' studies reveals a high degree of inconsistency in expected technologies and deployed energy carriers.

On the other hand, subsector-specific bottom-up analyses with very detailed process depictions have been conducted by subsector interest and research groups on the technology or production process level. For example, the European subsector associations for iron and steel [11] and cement [12] have both published roadmaps for their respective subsectors to provide guidelines for future technology development and implementation in light of the European Green Deal. The scientific literature also provides an investigation of subsector-based climate neutrality options for the above-mentioned subsectors. Harpprecht et al. [13] and Keys et al. [14] investigate climate neutrality pathways for the iron and steel industry in Germany and the Netherlands. Options for the Dutch Polyolefins industry are explored by Negri and Ligthart [15]. For the UK, Griffin et al. [16] investigate pulp and paper production. The studies of this analysis group consider EII subsectors unique entities. They do not consider the applicability of technological solutions in other EIIs or the boundary conditions of the overall energy system and its energy availabilities. They are thus complicating the deduction of big-picture recommendations for policy action.

Necessary investment costs for total EU climate neutrality by 2050 are estimated to amount to EUR 28 trillion. Approximately 2% of these are located exclusively in the industrial sector [17]. However, studies that have investigated such transformation costs often lack comparable cost analyses of different climate neutrality options in combination with technological cost assessments. Such a data basis could significantly help with the estimation of necessary industrial expenditures and inform decision making on funding instruments and other policy tools in promoting industry transition while at the same time allowing for an open comparison between different technological pathways.

In this paper, an innovative systematic approach to assessing and standardising technological options for reaching climate neutrality per EII subsector is introduced. The approach aims to fill the following research gaps:

- The current subsector-overarching literature on industrial climate neutrality often lacks sector-specific information—we aim to provide a novel level of detail for subsectors' processes while the ability to deduce an overarching picture for EIIs is preserved by grouping technologies into four climate neutrality pathways.
- Techno-economic analyses of technology options are mostly limited to studies that only investigate one specific subsector (e.g., iron and steel)—we aim to provide accompanying investment costs, fuel, and GHG certificate costs for technologies needed for climate neutrality in EIIs and compare them to conventional fossil-based routes.

Firstly, in Section 2, we present this paper's fundamentals and core methodology and introduce the "technical climate neutrality potential" (TCNP) of energy-intensive industry subsectors as a way of standardising industries' climate neutrality possibilities. Secondly, Section 3 introduces a case study in which we have applied this standardisation concept for three EII subsectors in Austria. In Section 4, we discuss the case study's results and further challenge them by utilising a sensitivity analysis. We conclude this work in Section 5, highlighting the merits of the proposed approach to reach climate neutrality in energy-intensive industries.

2. Methodology

In this section, we explain our chosen methodology as well as the applied balance border. We employ existing techniques of calculation—especially and specifically known from the area of renewable potential research—to generate a unique set of indicators that can inform the transformation of EIIs towards climate neutrality. To preserve the ability to compare subsector results on a larger scale and deduce big-picture conclusions, it is first necessary to define pathways into which the technological options can be clustered in Section 2.1. Subsequently, the modelling approach is presented.

2.1. Clustering of Climate Neutrality Pathways; Potential and Balance Border Definitions

Based on previous works by Agora Energiewende [18] and Mobarakeh and Kienberger [19], we have identified four general technology-based pathways towards industrial climate neutrality that can be applied across all subsectors of EIIs. We have chosen these clusters, which are discussed below, to explore technology applications within industries as the primary approach to achieving climate neutrality. General efficiency measures or process optimisation, on the other hand, require a different level of investigation and are not suited for the methodology proposed below. Therefore, we have excluded these from our analysis. In Section 3.1.2, we present an overview of the deployed technologies per climate neutrality pathway in the case study.

I. Electrification;
II. The use of CO_2-neutral gases and biomass combustion;
III. Circular economy measures;
IV. Carbon capture.

I. Electrification opens up significant potential for GHG emission reduction in the industrial sector [20,21]. For example, Madeddu et al. [22] identify three stages of electrification potentials for manufacturing industries (including non-energy-intensive subsectors) depending on the level of technological complexity. Within the two lower stages for process heat of up to approximately 400 °C, where already available technologies are considered, the direct electrification of up to 50% of the total useful energy demand, including feedstocks, is considered possible in all manufacturing industries. Above this temperature range, the additional potential is limited and connected with high technological uncertainties which are especially linked to the production of basic materials in energy-intensive subsectors. As one of the biggest fields of application for electrification across all subsectors, the generation of process heat up to approximately 200 °C can be provided through heat pumps, benefitting from a high exergetic efficiency and the possibility to include local waste heat potentials, among others. In order to successfully mitigate industrial activity emissions through electrification, the availability of climate-neutral or near-climate-neutral electricity—both in the amount of energy and the power level of connectivity—is essential [19,20].

II. The use of CO_2-neutral gases and biomass combustion is characterised by the combustion of energy carriers without or nearly without a negative climate effect. In this work, bio-CH_4 is used synonymously with gas from anaerobic fermentation, while bio-SNG is used for thermal gasification. Depending on its upstream production process, H_2 can be another climate-neutral gaseous energy carrier [23]. Both CH_4 as well as H_2 are especially important for high-temperature applications above 500 °C and as feedstock for specific production processes in basic industries. In both of these applications, as pointed out above, electrification is not yet fully developed or is not possible with foreseeable technologies. In addition to CO_2-neutral gases, solid biomass can also be used as a substitute for fossil energy carriers [24]. However, its temperature range for deployment is more limited as it generally can only be used for indirect heating (e.g., via steam, thermal oil, hot gas) [25]. Several industry subsectors already boast high shares of biomass use in their energy mix due to cascading use, both as feedstock and as an energy carrier (e.g., integrated pulp and paper plants) [26].

III. Circular economy measures can maximise resource efficiency in many subsectors of EII, thereby contributing to energy and resource savings and GHG emission reductions. The deployment of circular economy measures varies greatly from subsector to subsector in both the degree of application and impact [19]. Within the literature, the iron and steel, aluminium, and cement and chemical industries have been especially studied. All studies find significant potential for the use of end-of-life materials to substitute what previously needed to be made from primary resources. For the European Union, for example, Agora Industry estimates the potential of circular material flows in these subsectors to amount to up to a 24% GHG reduction until 2050 [27]. In addition to the possible GHG emission reduction, changing energy flows and energy carriers, both for pre-processing and final production due to the integration of end-of-life materials, must be considered and assessed.

IV. Carbon capture technologies generally need to be combined with a utilisation technology or storage possibility [28]. In the present paper, only the carbon sequestration step is evaluated. This technology may play an indispensable part in reaching climate neutrality in basic industries for reducing geogenous emissions (e.g., in cement or magnesia production). In these subsectors, approximately 50% of total emissions stem from the conversion of mineral compounds such as $CaCO_3$ or $MgCO_3$ into oxides (CaO and MgO) and are therefore not related to the energy carrier deployed [29]. In general, carbon capture technologies can be divided into three subcategories: post-combustion, pre-combustion, and oxyfuel combustion [30]. Within these categories, technologies' effectiveness, maturity, and cost structure vary significantly, as reviewed by Plaza et al. [31].

The magnitude of impact per subsector and technology depends on a variety of factors, e.g., economic or legal boundary conditions [32–34]. In this work, we investigate climate neutrality options per pathway on the level of technical potentials, commonly known from the investigation of renewable energy sources. This can be one of several necessary building blocks used to inform stakeholders and policymakers about changes needed in regulatory or funding framework on the road to industrial climate neutrality. The core indicator of TCNP is the value of the GHG emission reduction for each technology pathway which is seen to be technically feasible within the given time frame, i.e.,until 2040, as in this paper. It is important to note that we maintain product placement within the market, manufacturing numbers, and product quality for the purposes of comparability and result relevance. In contrast to realisable or economic potentials, the profitability of deployed technologies is not accounted for as a reducing parameter of TCNP. Instead, costs are investigated as an important accompanying set of information.

Regarding the determination of technical potentials to reach climate neutrality in EIIs, the applied balance border around the industrial subsectors is of special importance. Table 1 offers an overview of energy- and process-related emissions considered. the energy consumption and GHG emissions of the industrial energy system are driven both by final energy consumption through end-use devices and energy transformation units such as electrolysis, coking, or blast furnace plants. Additionally, as mentioned previously, process-related emissions can also occur through the use of CO_2-containing minerals as production feedstock (e.g., $CaCO_3$ in the cement industry).

Table 1. Description of considered energy- and process-related GHG emissions.

Type of Emissions	Description
Energy-related emissions	• Emissions from the incineration of carbonaceous energy carriers; • Emissions of upstream electricity (under global reporting standards [35]), herein further extended to H_2 generation.
Process-related emissions	• Emissions from industrial transformation (e.g., coke oven, blast furnace) or production processes (e.g., carbonaceous minerals).

As previously discussed by the authors [36], state-of-the-art energy balances based on the United Nations' International Standards of Energy Statistics [37] rely on a three-block concept consisting of the "total energy supply", "transformation and distribution", and "final consumption". The first two blocks are generally referred to as energy industries, while the final consumers comprise manufacturing industries, buildings, and transport, among others. While this approach works adequately for final energy consumption, this means that industrially owned energy transformation units such as CHP plants, coke ovens, or blast furnaces are not accounted for within industrial consumption but in the energy industries. However, their operation is determined by the primary activity of their respective manufacturing industry. As we approach the transition to CO_2-neutral production in EIIs, we have seen that the examination of transition pathways usually ignores the official balancing methodology and instead opts for a balance border that integrates "industrial transformation processes and the impact of their removal or addition [on energy demand and GHG emissions] in manufacturing" [36].

For clarity and the assignability of energy consumption and GHG emissions in our present work, the industrial balance border based on the proposed improvements to energy balances illustrated in Figure 1 is employed. The applied balance border is drawn around all industrially operated units in the considered industrial subsector. However, when exploring the impact of EII climate neutrality options, the related energy consumption and GHG emissions in the upstream public energy sector should always also be taken into account to ensure a holistic interpretation of industry transformation and avoid merely shifting emissions from one sector to another.

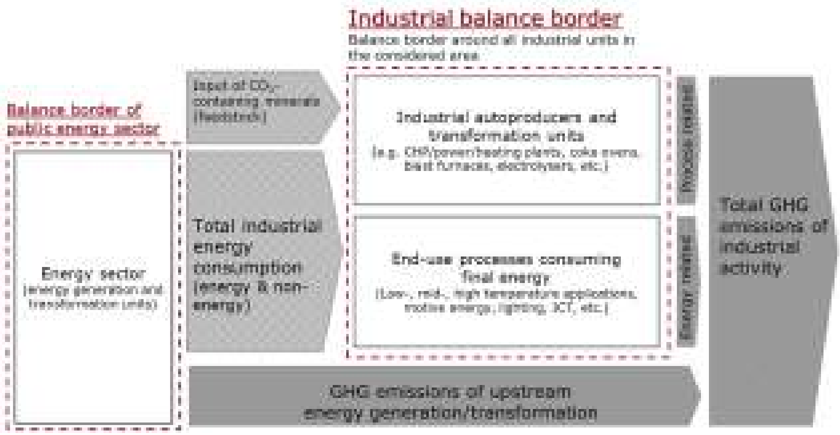

Figure 1. Industrial balance border for total industrial energy consumption and both energy- and process-related GHG emissions (adapted from [38]).

2.2. Modelling Approach

The modelling approach illustrated in Figure 2 enables the calculation of several indicators which enable a systemic analysis of the investigated technologies across EII subsectors.

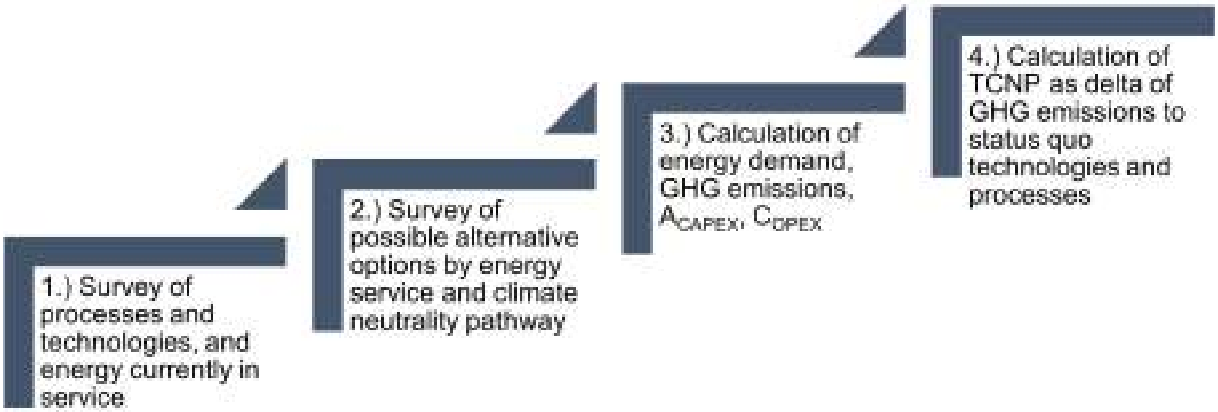

Figure 2. Process of the calculation of the proposed set of indicators consisting of the TCNP, the change in energy balance, and associated costs.

The first step, the survey of energy currently in demand and the associated energy as well as process-related CO_2 emissions, is performed based on subsector-specific information. As mentioned in the description of the applied balance border, in addition to the final energy consumption, energy transformation units and their substitutes must also be considered. We have chosen five application categories, as listed below. The chosen application categories allow for a targeted choice of technologies, especially concerning energy efficiencies and process temperature levels.

- Space heating;
- Stationary engines;
- Process heat < 200 °C;
- Process heat > 200 °C;
- Subsector-specific production processes (e.g., steelmaking or cement production).

After the identification of the necessary alternative technologies to be investigated in step 2, we apply a combined bottom-up/top-down approach for the calculation of several important indicators in steps 3 and 4 that together enable a cross-sectoral picture of the technologies' levers of action:

- The technical climate neutrality potential (TCNP) per pathway and EII subsector in kt CO_2e/a as the core indicator identifying the technologies and applications with the greatest lever for attaining climate neutrality.
- The corresponding change in energy consumption by energy carrier in GWh/a to indicate the impact of technology options on the energy system. In addition, the energy consumption of the upstream production of required energy carriers (e.g., electricity for hydrogen electrolysis) is denoted individually.
- Corresponding capital expenditures in MEUR/a show the expectable investment costs that can be put against the regular investment costs of the reference fossil-based technology.
- Corresponding operational expenditures, including fuel and GHG certificate costs, as well as maintenance costs in MEUR/a, to visualise expenditures due to the operation of the technology.
- The resulting total annual expenditures in MEUR/a, taking into account depreciation rates, to show the total costs of technology adoption in the long term.

Using a bottom-up approach, we investigate subsector-specific breakthrough technologies (e.g., direct reduction for primary steelmaking, the avoidance of geogenous emissions in cement production through carbon capture, etc.) with their respective energy conversion efficiencies. For specific future production processes in the EII, technology parameters per output unit or treated ton of CO_2 are used. Technology-related results, *R*, for energy demand and emissions are calculated according to Equation (1) based on the total yearly production, *N*, with *s* signifying specific values per output unit for energy consumption by energy carrier and emissions, respectively.

$$R = N \times s \tag{1}$$

Using a top-down approach, the compilation of possible substitute technologies is based on today's useful energy consumption, which is kept constant through to 2040 for our purposes. The relevant basis for this calculation approach consists of national energy statistics and general subsector research work, especially pertaining to necessary temperature levels and useful energy consumption in manufacturing. The top-down analysis is used in all application cases in which only the form of energy provision but not the process itself needs to be changed for attaining climate neutrality. Technologies consuming final energy are calculated on specific conversion efficiencies. In accordance, GHG emissions, both energy- and process-related, are calculated based on specific emission factors in the mass of CO_2 per production output or consumed energy.

For stakeholders to be able to fully comprehend the impact of a technology or climate neutrality pathway on the energy and emission transition, cost structures are also calculated. Because we calculate costs for each technology cluster individually without any kind of pathway analysis, opportunity costs are not considered. To maintain the comparability of climate neutrality options, all investment costs covered by the balance border introduced in Figure 1 are taken into account for both conventional and alternative technologies. Annual capital expenditures, $A_{CAPEX,}$ in EUR/a are calculated according to Equation (2) based on values from the literature for the CAPEX in EUR/kW and c_{inst} in the percentage of the CAPEX, which covers costs for building and engineering. Technology-specific average annual full load hours are used to translate the calculated energy consumption into power capacity P.

$$A_{CAPEX} = P \times CAPEX \times (1 + c_{inst}) \times a \tag{2}$$

With the annuity factor a calculated as

$$a = \frac{(1+i)^n \times i}{(1+i)^n - 1} \tag{3}$$

The annual operational costs C_{OPEX} are divided into CAPEX-related costs c_{rel} in the percent of the CAPEX for maintenance, tax, etc.; fuel and feedstock-related costs c_f; and GHG certificate costs c_{GHG} (Equation (4)). For many technologies—especially general final-energy applications such as engines—this cost position must be estimated for the work's purpose. However, in general, these costs can be expected to have a relatively low impact on total costs in comparison with capital investments and fuel/feedstock costs. For technologies in which this position can become of greater importance (e.g., in EAF-based crude steel production), generally applicable values from the literature are easier to find and therefore underly a smaller uncertainty. By incorporating c_{GHG}, the externalities associated with burning fossil fuels, whether upstream or for final energy applications, can be internalised in the economic activities of EIIs for each investigated technology.

$$C_{OPEX} = c_{rel} * CAPEX + c_f + c_{GHG} \tag{4}$$

With absolute values for the alternative technologies' energy consumption, greenhouse gas emissions, and costs available per subsector, the calculated emissions of the alternative technologies (GHG_{alt}) are subtracted from the status quo (GHG_{SQ}) to receive the technical climate neutrality potential (*TCNP*) of each technology (Equation (5)).

$$TCNP = GHG_{SQ} - GHG_{alt} \quad (5)$$

Following the approach described for the climate neutrality potential, the total impact of alternative technologies on the energy balance is calculated. Therefore, the calculated values for the energy consumption of the considered alternative technologies are again subtracted from the value of the status quo of the fossil-based routes. For costs, both capital and operational expenditures, alternative pathways are compared with conventional fossil-based routes under a green-field assumption. This means that no existing infrastructure is considered.

3. Case Study for Energy-Intensive Industries in Austria

In the following case study, Austrian EIIs are investigated using the examples of iron and steel, pulp and paper, and non-metallic minerals. Their subsector-specific technical climate neutrality potentials are assessed by pathway for 2040 as it signifies the official target year for climate neutrality in Austria [39]. The remaining subsector of energy-intensive industries, the chemical and petrochemical industry, will be investigated separately in a subsequent publication based on the approach proposed herein. This case study fulfills the objective of providing a first exemplary application of the methodology described above; its results can guide additional research, especially in the fields of policy needs and transitional scenario analyses for manufacturing industries' transition to decarbonisation.

3.1. Case Description

This section provides the necessary general information for the calculation of the subsector results and the respective references used. Both fuel and feedstock as well as investment-related costs and general technology assumptions are presented for the considered technologies in each climate neutrality pathway.

3.1.1. General Framework Conditions for 2040

To forecast 2040 costs for both fossil and non-fossil fuels and GHG certificate costs, high-level references from the European Union and the Austrian environmental agency are used. According to Commission recommendations, GHG certificate costs of 250 EUR_{2020}/t CO_2 are applied to all energy- and process-related emissions [40]. For the international costs of energy carriers, the reference prices illustrated in Table 2 are used. The sensitivity analysis in Section 4 provides a useful tool to investigate the effect of volatile fuel prices on the total costs for each applied technology and the applicability of the chosen GHG certificate costs in relation to incentivising the transition to the assumed prices of fossil-based technologies.

Table 2. Assumed reference prices 2040 in EUR_{2020}/MWh.

Energy Carrier	Assumed Reference Prices in 2040 in EUR_{2020}	Reference
Oil	58.7 EUR/MWh	[40]
Natural gas	40.7 EUR/MWh	[40]
Coal	12.0 EUR/MWh	[40]
Electricity	101.6 EUR/MWh	[41]
Electricity (spot market) [a]	35.0 EUR/MWh	[42]
Biomass for anaerobic fermentation	Ø32.0 EUR/MWh	[43]
Solid biomass (incl. for gasification)	55.7 EUR/MWh	[44]

[a] electrolysis and pyrolysis for hydrogen production are considered part of the energy sector. A mix of wind and PV levelised cost of electricity (LCOE) values are applied. Electricity grid tariffs and charges are based on an Austrian framework from 2020 [42].

3.1.2. Technology Framework

The predominant temperature levels of each sector are of special importance to the investigation of the applicability of climate neutrality pathways explained below. For the Austrian case study, we applied the shares of the temperature levels of total process heat consumed, as given by Sejkora et al. [45] and shown as an excerpt in Table 3, to the energy consumption provided by the Austrian statistics agency Statistics Austria [46,47]. The climate neutrality pathways as well as the conventional technologies used as a base case in each exemplary subsector refer to them accordingly.

Table 3. Share of process temperature levels in selected industrial subsectors according to Sejkora et al. [45].

Subsector	Space Heating	<100 °C	100–200 °C	200–300 °C	300–500 °C	>500 °C
Iron and steel	0.1%	0.6%	0.9%	0.1%	0.7%	97.6%
Non-metallic minerals	0.1%	1.4%	1.2%	0.0%	0.8%	96.5%
Pulp and paper	0.6%	18.6%	45.5%	1.9%	33.3%	0.0%

When discussing the costs of climate-neutral or near-climate-neutral alternative technologies to decarbonise energy-intensive industries, we need conventional technologies' values as a baseline. For this purpose, Table 4 shows an overview of the considered conventional fossil-based technologies and their typical cost parameters for industrial application. The calculation of costs follows the methodology mentioned in Section 2. In all instances, for both conventional and alternative pathways, yearly investment costs are calculated based on an assumed depreciation period of 20 years.

Table 4. Considered technologies for conventional fossil-based energy applications.

	Full Load Hours	CAPEX in EUR_{2020}	c_{inst} in $\%_{CAPEX}$	c_{rel} in $\%_{CAPEX}$	Reference For Costs
Coal furnace	4000	147 EUR/kW_{th}	50	1.5	[48]
Oil furnace	4000	30 EUR/kW_{th}	70	4.0	[48]
Gas furnace	4000	250 EUR/kW_{th}	Included in CAPEX	4.0	[48,49]
Diesel engine	4000	100 EUR/kW_{mech}	20	4.0	Own assumptions
Gas engine	4000	100 EUR/kW_{mech}	20	4.0	Own assumptions
Rotary kiln (cement)	-	190 $EUR/t_{Clinker}$	Included in CAPEX	2.0	[50]; own assumption for c_{rel}
BF/BOF (prim. steelmaking)	-	442 $EUR/t_{Crude\ steel}$	Included in CAPEX	60.0 [a]	[51,52]

[a] includes iron ore and fluxes.

On the other hand, the investigated alternative technologies in the subsectors were chosen following investigations of German and Austrian manufacturing industries carried out by Agora Industry [18] and Mobarakeh and Kienberger [19]. An overview of the technologies considered for the above-mentioned industrial subsectors is discussed below and provided in Table A1 in Appendix A.

3.1.3. Electrification

It is assumed that the supply of process heat up to 200 °C by electric heat pumps will be possible by the target year 2040 [53,54]. For the electrification of space heating and process heat below 200 °C, electric low-temperature (LT) and high-temperature (HT) heat pumps are deployable [55]. The investment costs of LT heat pumps with a COP of up to 3 are taken into account, with specific costs of 400 EUR/kW_{th} of installed thermal power and average full load hours of 2200 h/a. Heat pumps for high temperatures up to 200 °C average 4000 full load hours per year and are calculated at 520 EUR/kW_{th} [56]. While the specific investment costs per kW_{th} are similar, calculations for high-temperature heat pumps include significantly higher installation costs [48]. Stationary engines currently supplied by fossil fuels can be completely electrified. For the calculation for necessary electric engines, 100 EUR/kW_{el} and 4000 full load hours are taken into account. In the iron and steel industry, electric arc furnaces (EAFs) occupy major role due to the establishment of direct reduction (DR) for primary steelmaking [57]. For this work, they are considered part of the climate neutrality pathway of using CO_2-neutral gases and are therefore discussed in the paragraph below. For all electricity-consuming technologies, indirect GHG emissions from electricity production are included. In line with the scenario MIX by the European Commission impact assessment, a specific emission factor of 56 g CO_2e/kWh of electricity is used [58].

3.1.4. Use of CO_2-Neutral Gases and Combustion of Solid Biomass

For the combustion of solid biomass for process heat up to a maximum of 500 °C, specific investment costs totalling 600 €/kW_{th} are assumed [59]. With iron and steel as well as non-metallic minerals, solid biomass combustion is only investigated for temperature ranges up to 200 °C due to data availability and extremely low shares of this temperature range in total process heat consumption, as shown in Table 3. CO_2-neutral gases for reaching climate neutrality in final energy applications can be used in any application in which fossil fuel is currently used. The sustainable gases differ in their chemical composition (H_2 or CH_4) and considered upstream production chains. In this case, costs for furnaces and the upstream generation of these gases are considered separately. For the generation of hydrogen, electrolysis and methane pyrolysis are considered, each with its respective required upstream energy carriers. The same applies to the generation of bio-SNG from the gasification of solid biomass. On the other hand, as bio-CH_4 predominantly requires agricultural space for its production, upstream energy inputs are not part of our analysis. In the case of all of these CO_2-neutral gases, the primary cost driver of final energy applications is not the incineration technology but the upstream generation method. For bio-CH_4 from anaerobic fermentation, the specific investment costs are assumed to amount to 2700 EUR/kW_{CH4} with 8000 full load hours [60]. The CAPEX for bio-SNG from solid biomass gasification are taken into account at 2000 EUR/kW_{SNG} [34]. Investments for electrolysis for the production of hydrogen are assumed to cost 515 EUR/kW_{el} when full load hours are around 3500 h/a [34,61]. The investment costs for hydrogen production through methane pyrolysis are estimated at 475 EUR/kW in 2040 [61]. For all generation routes, additional possible revenues for excess heat or carbon are not considered within the scope of this case study.

In contrast to final energy applications for the provision of heat, new applications have to be deployed when using CO_2-neutral gases for primary steelmaking to reduce process-related emissions. Here, direct reduction in combination with the above-mentioned electric arc furnaces is considered. In primary steelmaking, direct reduction (both CH_4 and H_2-based) in combination with EAF is assumed to cost 400 EUR/t of produced crude steel (CS) [61]. Due to the chosen green-field assumption mentioned above, all auxiliary elements of crude steel production are also included in our investigations of GHG emissions, energy demand, and costs.

3.1.5. Carbon Capture

Within our case study, carbon capture technologies remain only in the non-metallic mineral subsector to mitigate the emission of geogenous emissions brought in through carbonaceous feedstock. In this subsector, carbon capture technologies are widely viewed as playing an indispensable role on the path towards climate neutrality [62]. Carbon capture for cutting emissions in steelmaking, on the other hand, was identified as not feasible for use in the present blast furnace/basic oxygen furnace route in Austria by Mobarakeh and Kienberger [19] and is therefore not considered further here. Two technologies have been investigated for use in the non-metallic mineral subsector: the use of the oxyfuel technology is calculated to cost 220 EUR/t_{CO2} of treated clinker production, and amine washing costs 131 EUR/t_{CO2} [63].

3.1.6. Circular Economy

In some subsectors, circular economy aspects can significantly increase energy and resource efficiency. In the iron and steel industry, the use of electric arc furnaces opens up the possibility of increasing the use of scrap metal. Assuming a maximum of 50% scrap share in EAF steelmaking, the need for H_2- or CH_4-based direct reduction can be reduced accordingly. In cement production, a significant amount of research is currently being carried out regarding the recycling of concrete. Due to the significant increase in the necessary process preparation of scrap concrete, investment costs of approximately 1 EUR/t concrete are used [64].

3.2. Iron and Steel

In the iron and steel industry, the energy demand—and consequently cost structure—is largely dominated by primary steelmaking and high-temperature process heat. The conventional technologies considered are given in Table 5. For primary steelmaking, the blast furnace/basic oxygen furnace route (BF/BOF) is currently deployed with a total energy demand of almost 27 TWh/a, producing 6.9 Mt of crude steel [19]. An additional 5 TWh of fossil energy is used in gas furnaces for high-temperature process heat at temperatures of up to 1000 °C. With 245 MEUR/a of annual capital expenditures and a C_{OPEX} of 5808 MEUR/a, the BF/BOF route is also the most expensive single technology in the subsector by far.

Table 5. Conventional routes in iron and steel production per application case and the respective energy demand, GHG emissions, and yearly costs.

		Energy Demand	Emissions	A_{CAPEX}	C_{OPEX}	Total Costs
		[GWh/a]	[kt CO_2e/a]	[MEUR/a]	[MEUR/a]	[MEUR/a]
Space heating	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	9.5	2.8	0.0	1.3	1.3
	Gas furnace	329.5	65.7	1.7	29.9	31.6
Stationary engines	Diesel engine	6.1	1.8	0.0	0.8	0.8
	Gas engine	87.9	17.5	0.2	8.0	8.2
Process heat < 200 °C	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	5.4	1.6	0.0	0.7	0.7
	Gas furnace	121.6	24.2	0.6	11.0	11.6
Process heat > 200 °C	Coal furnace	1866.9	620.7	8.3	177.7	186.0
	Oil furnace	0.0	0.0	0.0	0.0	0.0
	Gas furnace	5287.1	1054.5	26.5	479.9	506.4
Primary steelmaking	BF/BOF	26,777.0	10,200.0	244.7	5808.3	6053.0

In contrast to the conventional technologies above, Table 6 offers an overview of investigated alternative technologies, aggregated by climate neutrality pathway. The investigated DR/EAF route uses both climate neutrality pathways, electrification and CO_2-neutral gases. Below, it is considered within the climate neutrality pathway of the "use of CO_2-neutral gases and solid biomass combustion". As explained above, carbon capture for cutting emissions in steelmaking, on the other hand, has been identified as not feasible for use in the present BF/BOF route in Austria [19]. Therefore, its respective line is grey.

In the above table, technologies for both the mitigation of energy-related emissions and process-related emissions are considered. For the presentation of their TCNPs and accompanying indicators, we rely on two separate tables below. Table 7 presents the results for the mitigation of energy-related emissions, while Table 8 shows results for the mitigation of process-related emissions in iron and steel. TCNP values by climate neutrality pathway and technology are shown next to the respective resulting change in energy balance and the technologies' annual capital and operational expenditures as well as their annual sum. For capital expenditures in the case of CO_2-neutral gases, we differentiate between expenditures for upstream gas generation on one hand and investments for the installation of furnaces and direct reduction plants on the other hand.

Table 6. Considered alternative technology options in iron and steel.

Climate Neutrality Pathway	Source of Emission	Technology	Application
Electrification	Energy-related	Use of heat pumps	Space heating Process heat < 200 °C
	Energy-related	Electric engines	Stationary engines
Use of CO_2-neutral gases and solid biomass combustion	Process-related [(a)]	Electric arc furnace	Primary steelmaking in combination with direct reduction
	Process-related	Direct reduction of iron ore with gases	Primary steelmaking in combination with EAF
	Energy-related	Bio-CH_4	Space heating Process heat </> 200 °C
	Energy-related	H_2 from electrolysis	Space heating Process heat </> 200 °C
	Energy-related	H_2 from pyrolysis	Space heating Process heat </> 200 °C
	Energy-related	Solid biomass comb.	Space heating Process heat < 200 °C
Carbon capture [(b)]			
Circular economy	Process-related	Using EAF	Increased use of scrap metals

[(a)] EAF in combination with DR considered in the use of CO_2-neutral gases.[(b)] Marked grey because no technology options were investigated within this pathway and subsector.

Table 7. Technologies, respective TCNP values, and changes in energy consumption and cost structure for energy-related emissions in the iron and steel industry.

Technology	Application	TCNP [ktCO_2e/a]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Electrification						
LT heat pumps	Space heating	−63	Fossil: −339 Electr.: +100	7.3	11.6	18.9
HT heat pumps	Process heat < 200 °C	−23	Fossil: −127 Electr.: +42	2.2	4.9	7.1
Electric engines	Motive power	−17	Fossil: −94 Electr.: +44	0.1	5.1	5.2
Use of CO_2-neutral gases and solid biomass combustion						
Bio-CH_4	Space heating	−69	Fossil: −339 Bio-CH4: +339	12.4 Bio-CH_4 1.7 Furnace	11.2	25.3
	Process heat < 200 °C	−26	Fossil: −127 Bio-CH_4: +128	4.7 Bio-CH_4 0.6 Furnace	4.2	9.5
	Process heat > 200 °C	−1675	Fossil: −7154 Bio-CH_4: +7154	261.6 Bio-CH_4 35.9 Furnace	235.8	533.2

Table 7. *Cont.*

Technology	Application	TCNP [ktCO_2e/a]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Bio-SNG	Space heating	−69	Fossil: −339 Bio-SNG: +339	9.2 Bio-SNG 1.7 Furnace	19.2	30.1
	Process heat < 200 °C	−26	Fossil: −127 Bio-SNG: +128	3.5 Bio-SNG 0.6 Furnace	7.2	11.4
	Process heat > 200 °C	−1675	Fossil: −7154 Bio-SNG: +7154	193.7 Bio-SNG 35.9 Furnace	404.9	634.6
H_2 from electrolysis	Space heating	−45	Fossil: −339 H_2: +305 *Electr.: +427*	6.8 H_2 1.5 Furnace	15.3	23.6
	Process heat < 200 °C	−17	Fossil: −127 H_2: +114 *Electr.: +160*	2.6 H_2 0.6 Furnace	5.7	8.8
	Process heat > 200 °C	−1170	Fossil: −7154 H_2: +6438 *Electr.: +9014*	143.7 H_2 32.3 Furnace	322.7	498.7
H_2 from methane pyrolysis	Space heating	−64	Fossil: −339 H_2: +305 *CH_4: +570* *Electr.: +87*	4.5 H_2 1.5 Furnace	26.5	32.5
	Process heat < 200 °C	−24	Fossil: −127 H_2: +114 *CH_4: +213* *Electr.: +33*	1.7 H_2 0.6 Furnace	9.9	12.2
	Process heat > 200 °C	−1572	Fossil: −7154 H_2: +6438 *CH_4: +12,040* *Electr.:+1837*	94.6 H_2 32.3 Furnace	559.3	686.3
Solid biomass	Space heating	−68	Fossil:−339 Biomass:+339	2.0	18.9	21.0
	Process heat < 200 °C	−25	Fossil:−127 Biomass:+127	0.8	7.1	7.9

Table 8. Technologies, respective TCNP values, and changes in energy consumption and cost structure for process-related emissions in the iron and steel industry.

Technology	Application	TCNP [ktCO_2e]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Use of CO_2-neutral gases and solid biomass combustion						
Bio-CH_4-DR/EAF	Primary steelmaking incl. EAF	−9977	Fossil: −26,777 Bio-CH_4: +21,900 Electr.: +3983	221.5 DR-CS 800.7 Bio-SNG	3127.7	4149.9
Bio-SNG-DR/EAF	Primary steelmaking incl. EAF	−9977	Fossil: −26,777 Bio-SNG: +21,900 Electr.:+3983	221.5 DR-CS 593.1 Bio-CH_4	3646.8	4461.3
H_2-DR/EAF (electrolysis)	Primary steelmaking incl. EAF	−8547	Fossil: −26,777 H_2: +18,235 *Electr.: +25,530* Bio-CH_4/SNG: +3726 Electr.: +3985	221.5 DR-CS 406.9 Electrolysis	3623.4	4251.8
H_2-DR/EAF (pyrolysis)	Primary steelmaking incl. EAF	−9686	Fossil: −26,777 H_2: +18,235 *CH_4: +34,100* *Electr.: +5197* Bio-CH_4/SNG: +3726 Electr.: +3985	221.5 DR-CS 268.1Pyrolysis	4298.9	4788.5
Circular economy						
EAF Reducing need for Bio-CH_4-DR	50% scrap metal input in steelmaking	−9977	Fossil: −26,777 Bio-CH_4: +10,950 Electr.: +3983	110.7 DR-CS 400.3 Bio-CH_4	1794.1	2305.2
EAF Reducing need for Bio-SNG-DR	50% scrap metal input in steelmaking	−9977	Fossil: −26,777 Bio-SNG: +10,950 Electr.: +3983	110.7 DR-CS 296.5 Bio-SNG	2053.6	2460.9
EAF Reducing need for H_2-DR (electrolysis)	50% scrap metal input in steelmaking	−9233	Fossil: −26,777 H_2: +9118 *Electr.: +12,765* Bio-CH_4/SNG: +1863 Electr.: +4499	110.7 DR-CS 203.5 Electrolysis	2101.4	2415.7
EAF Reducing need for H_2-DR (pyrolysis)	50% scrap metal input in steelmaking	−9803	Fossil: −26,777 H_2: +9118 *CH_4: +17,050* *Electr.: +2599* Bio-CH_4/SNG: +1863 Electr.: +4499	110.7 DR-CS 134.0Pyrolysis	2439.2	2684.0

3.2.1. Energy-Related Emissions

Electrification: Supplying space heating and process heat below 200 °C through heat pumps can contribute to only a minor GHG reduction of up to 86 kt CO_2e. The largest share of electrification costs is accounted for by the adoption of heat pumps for space heating (a total of 18.9 MEUR). With GHG certificate costs taken into account, all electrification options feature cost leadership over their respective conventional fossil-based counterparts (cf. Table 5). Electrified space heating exhibits the greatest gap in comparison to the respective conventional route with savings of 14 MEUR/a.

CO_2-neutral gases and biomass combustion: For process heat above 200 °C, CO_2 -neutral gases or biomass combustion are necessary, but they can also be applied for lower temperature ranges. Because of the small share of energy consumption in the iron and steel industry in lower temperature ranges, the TCNP of biomass combustion is limited to just 93 kt CO_2e. On the other hand, depending on the upstream chain used, emission savings of up to 1770 kt CO_2e (in the case of bio-CH_4 and bio-SNG) could be realised through CO_2-neutral gases. These biobased gases differ significantly in their cost structures; in the case of bio-CH_4, annual capital and operational expenditures are approximately even and sum up to 568 MEUR/a, while the C_{OPEX} values for bio-SNG are double the amount of necessary investment costs due to the more expensive feedstock (totalling 676 MEUR/a). Hydrogen from electrolysis, on the other hand, shows similar costs to bio-CH_4, with its TCNP reduced to 1232 kt CO_2e due to the assumed emission intensity of electricity and the large amounts of electrical energy necessary. With total annual costs of 531 MEUR, it features the lowest annual costs of all four investigated gaseous energy carriers. H_2 from pyrolysis, on the other hand, offers only small electricity-related TCNP reductions (−110 kt in comparison to biobased gases) but is found to be the most costly option of employing CO_2-neutral gases for reducing energy-related emissions in iron and steel. This results in annual costs of 731 MEUR, the only technology in this climate neutrality pathway above the costs for conventional technologies, which are calculated at 706 MEUR/a for the application cases of space heating and process heat. In both hydrogen cases, the necessary upstream energy provision in the form of CH_4 and electricity is presented in italics.

3.2.2. Process-Related Emissions

CO_2-neutral gases: In the iron and steel industry, the use of CO_2-neutral gases is especially important in the future mitigation of process-related emissions currently resulting from primary steelmaking via the BF/BOF route. As shown in Table 8, due to the high shares of primary metallurgy in Austrian steelmaking, substituting the BF/BOF-route with a DR/EAF-route can reduce emissions by up to almost 10 Mt of CO_2e (in the case of bio-CH_4 and bio-SNG)—approximately 13% of Austria's overall CO_2 emissions per annum [65]. Due to the specific GHG emission of upstream electricity production of 56 g CO_2/kWh, the mitigation potential of electrolysis-derived H_2 is reduced by approximately 1430 kt CO_2e to 8547 kt, while using pyrolysis reduces the potential due to the lower electricity share in this channel by ~300 kt to 9686 kt CO_2e. On the other hand, annual costs for direct reduction based on electrolysis-derived hydrogen lead pyrolysis-derived hydrogen by savings of 537 MEUR/a, with a total of 4251.8 MEUR/a. With annual costs of 4150 MEUR/a for direct reduction based on bio-CH_4 and 4461 MEUR/a for direct reduction based on bio-SNG, these options show a cost range comparable to the electrolysis-based option. All four investigated options lie well below the projected costs of 6053 MEUR/a for conventional coal-based primary steelmaking via BF/BOF. Further analysis shows that a GHG certificate price of approximately 100 EUR/t CO_2 suffices for alternative technologies to be more economical for primary steelmaking.

Circular economy: For circular economy measures, the use of scrap metal in newly built EAFs allows for the minimisation of energy-intensive primary steelmaking from iron ore. While the TCNP remains unchanged in comparison to biobased direct reduction technologies using CH_4, important effects can be generated in all investigated pathways regarding resource efficiency, energy demand, and costs. Using bio-CH_4 as an example, energy demand can be reduced by 11 TWh/a. For CO_2-neutral gases with more elaborated upstream generation processes and transformation losses, most notably hydrogen, energy savings increase to more than 14 TWh in the case of electrolysis and to 21 TWh in the case of pyrolysis annually. Based on these energy savings, increasing the circular economy also offers significant monetary rewards, as all four cases (bio-CH_4 and SNG, hydrogen from electrolysis, and pyrolysis) offer annual cost reductions of approximately 1800 to 2100 MEUR/a in comparison to steelmaking with a current primary production output via above-described DR/EAF route.

3.3. Non-Metallic Minerals

Similar to the subsector above, in the non-metallic mineral subsector, energy demand—and consequently also cost structure—is largely dominated by high-temperature process heat. In addition, process-related emissions stemming from the extraction of geogenous CO_2 during calcination present a large source of hard-to-abate GHG emissions. The conventional technologies used in this subsector are given in Table 9. For processes above 200 °C, the rotary kiln used in the cement industry is listed as a separate technology along with fossil-based furnaces. Cement production is the largest subsection of the non-metallic mineral subsector, both in terms of energy demand and GHG emissions, in Austria as well as globally [19]. Therefore, it is investigated more closely than other subsections in this work. For approximately 5.5 Mt of cement, 3.5 Mt of clinker is produced annually in Austria [19]. In total, high-temperature process heat that is also used for other minerals, such as lime, magnesia, and glass, consumes approximately 6.5 TWh/a of fossil energy, while process heat below 200 °C, space heating, and stationary engines are calculated to consume approximately 600 GWh/a. The total yearly costs of the investigated conventional technologies are most strongly influenced by the above-mentioned process-related emissions, adding approximately 1800 kt CO_2e and 460 MEUR/a in projected GHG certificate costs to the total yearly cost of the rotary kiln. Their mitigation cannot be achieved through the substitution of fossil energy carriers with CO_2-neutral alternatives.

Table 9. Conventional routes in non-metallic minerals per application case and their respective energy demand, GHG emission, and yearly cost values.

		Energy Demand	Emissions	A_{CAPEX}	C_{OPEX}	Total Costs
		[GWh/a]	[ktCO_2e/a]	[MEUR/a]	[MEUR/a]	[MEUR/a]
Space heating	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	26.9	7.9	0.0	3.6	3.6
	Gas furnace	319.1	63.6	1.6	29.0	30.6
Stationary engines	Diesel engine	46.4	13.6	0.1	6.1	6.3
	Gas engine	0.6	0.1	0.0	0.1	0.1
Process heat < 200 °C	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	0.7	0.2	0.0	0.1	0.1
	Gas furnace	208.3	41.54	1.0	18.9	20.0
Process heat > 200 °C	Rotary kiln	3321.0	972.9	73.2	722.5	795.7
	Coal furnace	215.7	71.7	1.0	20.5	21.5
	Oil furnace	94.5	27.7	0.1	12.5	12.6
	Gas furnace	3181.8	634.6	16.0	288.8	304.8

As Table 10 visualises, carbon capture and circular economy measures are additionally investigated to attain far-reaching climate neutrality in the subsector. Carbon capture is necessary to reduce the number of geogenous emissions stemming from CO_2-containing minerals that are necessary to produce cement or magnesia. A circular economy allows for increases in the resource efficiency of already produced concrete for cement production, thereby lowering the process-related emissions of primary cement production.

Table 10. Considered alternative technology options in non-metallic minerals.

Climate Neutrality Pathway	Source of Emission	Technology	Application
Electrification	Energy-related	Use of heat pumps	Space heating Process heat < 200 °C
		Electric engines	Stationary engines
Use of CO_2-neutral gases and biomass combustion	Energy-related	Bio-CH_4	Space heating Process heat </> 200 °C
		H_2 from electrolysis	Space heating Process heat </> 200 °C
		H_2 from pyrolysis	Space heating Process heat </> 200 °C
		Solid biomass comb.	Space heating Process heat < 200 °C
Carbon capture	Process-related	Oxyfuel-combustion Amine scrubbing	Production
Circular economy	Process-related	Concrete recycling	

Tables 11 and 12 below present results for the mitigation of energy-related and process-related emissions in non-metallic minerals. Their format follows the above-described subsector of iron and steel.

Table 11. Technologies and respective TCNP, change in energy consumption, and cost structure values for energy-related emissions in non-metallic minerals.

Technology	Application	TCNP [$ktCO_2e$]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Electrification						
LT heat pumps	Space heating	−66	Fossil: −346 Electr.: +102	7.5	11.8	19.3
HT heat pumps	Process heat < 200 °C	−38	Fossil: −209 Electr.: +69	3.6	8.0	11.6
Electric engines	Motive power	−13	Fossil: −47 Electr.: +22	0.1	2.5	2.6
Use of CO_2-neutral gases and solid biomass combustion						
Bio-CH_4	Space heating	−72	Fossil: −346 Bio-CH_4: +346	12.6 Bio-CH_4 1.7 Furnace	11.4	25.8
	Process heat < 200 °C	−42	Fossil: −209 Bio-CH_4: +209	7.6 Bio-CH_4 1.0 Furnace	6.9	15.6
	Process heat > 200 °C	−1672	Fossil: −6813 Bio-CH_4: +6813	249.1 Bio-CH_4 34.2 Furnace	224.5	507.8

Table 11. *Cont.*

Technology	Application	TCNP [$ktCO_2e$]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Bio-SNG	Space heating	−72	Fossil: −346 Bio-SNG: +346	9.4 Bio-SNG 1.7 Furnace	19.6	30.7
	Process heat < 200 °C	−42	Fossil: −209 Bio-SNG: +209	5.7 Bio-SNG 1.0 Furnace	11.8	18.5
	Process heat > 200 °C	−1672	Fossil: −6813 Bio-SNG: +6813	184.5 Bio-SNG 34.2 Furnace	385.6	604.3
H_2 from electrolysis	Space heating	−47	Fossil: −346 H_2: +311 *Electr.: +436*	6.9 H_2 1.6 Furnace	15.6	24.1
	Process heat < 200 °C	−27	Fossil: −209 H_2: +188 *Electr.: +263*	4.2 H_2 0.9 Furnace	9.4	14.5
	Process heat > 200 °C	−1192	Fossil: −6813 H_2: +6131 *Electr.: +8584*	136.8 H_2 30.7 Furnace	307.3	474.9
H_2 from pyrolysis	Space heating	−67	Fossil: −346 H_2: +312 *CH_4: +582* *Electr.: +89*	4.6 H_2 1.6 Furnace	27.0	33.2
	Process heat < 200 °C	−39	Fossil: −209 H_2: +188 *CH_4: +352* *Electr.: +54*	2.8 H_2 0.9 Furnace	16.4	20.1
	Process heat > 200 °C	−1574	Fossil: −6813 H_2: +6131 *CH_4: +11,466* *Electr.: +1749*	90.1 H_2 30.7 Furnace	532.6	653.5
Solid biomass	Space heating	−72	Fossil: −346 Biomass: +346	2.1	19.3	21.4
	Process heat < 200 °C	−42	Fossil: −209 Biomass: +209	1.3	11.7	12.9

Table 12. Technologies and respective TCNP, change in energy consumption, and cost structure values for process-related emissions in non-metallic minerals.

Technology	Application	TCNP [ktCO_2e]	Energy Balance [GWh/a]	A_{CAPEX} [MEUR/a]	C_{OPEX} [MEUR/a]	Total Costs [MEUR/a]
Carbon Capture						
Oxyfuel-combustion	Sector-spec. processes	−2771	Electr.: +676	70.4	78.1	148.6
Amine scrubbing	Sector-spec. processes	−2729	Electr.: +1421	37.5	164.3	201.8
Circular economy						
Bio-CH_4	Recycling of concrete	−827	Bio-CH_4: +1466	56.4 Bio-CH4 7.4 Furnace	46.9	110.7
Bio-SNG	Recycling of concrete	−827	Bio-SNG: +1466	42.5 Bio-SNG 7.4 Furnace	81.7	131.5
H_2 from electrolysis	Recycling of concrete	−712	H_2: +1466 *Electr.: +2052*	35.5 H_2 7.4 Furnace	71.8	114.7
H_2 from pyrolysis	Recycling of concrete	−804	H_2: +1466 *CH_4: +2741* *Electr.: +418*	24.4 H_2 7.4 Furnace	126.1	157.8

3.3.1. Energy-Related Emissions

Electrification: The supply of space heating and process heat below 200 °C through heat pumps can contribute to a GHG reduction of approximately 100 kt CO_2e. Due to the small shares of space heating and low-temperature process heat necessary in the subsector, this consequently corresponds to only a small share of total emissions. The technical climate neutrality potential attainable through the electrification of stationary engines, on the other hand, amounts to even less—13 kt CO_2e/a. In comparison to the above-described conventional fossil-based technologies, the electrical alternatives provide total yearly cost advantages of ~27 MEUR. The highest relative savings can be generated within applications for space heating (56%) and process heat below 200 °C (58%).

CO_2-neutral gases and biomass combustion: With 97% of process heat above 500 °C, biomass combustion only shows a TCNP of 114 kt CO_2e/a. On the other hand, the TCNP for energy-related emissions of CO_2-neutral gases can reach up to 1786 kt CO_2e/a, as shown for the cases of bio-CH_4 and bio-SNG due to the higher available temperature ranges in the case of gaseous energy carriers. The cost structure of these CO_2-neutral gases mirrors the discussion presented for iron and steel; in the case of bio-CH_4, the A_{CAPEX} and C_{OPEX} are approximately evenly distributed and sum up to 550 MEUR/a, while the C_{OPEX} for bio-SNG are double the amount of necessary capital expenditures due to the more expensive feedstock (totalling 654 MEUR/a). The costs for electrolysis-derived hydrogen range below all other gaseous energy carriers at approximately 514 MEUR/a. Due to the upstream electricity demand and its underlying CO_2 intensity, the TCNP is reduced to 1266 kt/a. H_2 from pyrolysis, on the other hand, causes only small electricity-related TCNP reductions (−106 kt in comparison to biobased gases to a total of 1680 kt CO_2e/a) but is found to be the most costly option of employing CO_2-neutral gases for reducing energy-related emissions in the non-metallic mineral subsector. Pyrolysis-derived hydrogen exhibits projected costs of 707 MEUR/a. Still, even as the most expensive technology in this climate neutrality pathway, it stays slightly below the projected costs for conventional technologies, which are calculated to amount to 728 MEUR/a for the application cases of space heating and process heat below and above 200 °C when costs for process-related geogenous emissions are not considered.

3.3.2. Process-Related Emissions

Carbon capture: At up to 654 MEUR/a, the above-described annual costs for the abatement of energy-related emissions for temperature levels above 200 °C surpass the projected annual costs for carbon capture technologies for the mitigation of geogenous process emissions shown in Table 12 (a maximum of 202 MEUR/a in the case of oxyfuel). However, in the non-metallic mineral subsector, the use of such technologies exhibits by far the biggest TCNP of a single technology, with more than 2700 kt CO_2e/a. Most carbon capture technologies feature sequestration rates of 90 to 95%, with the ability to include energy-related emissions in the sequestration process [66]. More relevant differences exist in system integration and energy intensities, among others. For example, end-of-pipe amine scrubbing requires more than twice the amount of electrical energy than oxyfuel technology, which offers additional efficiency options regarding oxygen production on site. Because of this gap, the resulting TCNP is reduced by approximately 40 kt when using amine scrubbing. While it exhibits advantages in the A_{CAPEX} of approximately 30 MEUR/a, operational expenditures are much higher than for carbon capture with oxyfuel. Annually, ~50 MEUR will be saved by 2040 when deploying oxyfuel carbon capture instead of amine scrubbing.

Circular economy: In contrast to the iron and steel industry, the deployment of an increasing circular economy using waste concrete offers both primary resource savings *and* GHG reductions. Studies on the availability of waste concrete in 2040 suggest the use of primary cement can be reduced by up to 28% [64]. Additional energy is needed, especially for the pre-processing of recycled concrete before admixture in cement production. By using sustainable gases for the energy-intensive treatment of waste concrete, savings of up to 827 kt CO_2e in the case of bio-CH_4 and bio-SNG can be realised. The relation between technology-specific A_{CAPEX} and C_{OPEX} follows already identified trends. While for bio-CH_4, this relation is very even and the technology is the cheapest (111 MEUR/a), together with hydrogen from electrolysis (115 MEUR/a), pyrolysis-derived hydrogen in particular is very C_{OPEX}-intensive and costly. Costs for bio-SNG range above electrolysis-derived hydrogen and bio-CH_4 but are considerably lower than hydrogen from methane pyrolysis at approximately 132 MEUR/a.

3.4. Pulp and Paper

In the pulp and paper industry, the energy demand is dominated by medium temperature levels ranging between 100 °C and 500 °C [26]. The conventional technologies used are given in Table 13. In the fossil-based route, process heat is mostly supplied by gas furnaces with a total of approximately 10 TWh/a of energy demand and annual costs of ~1000 MEUR. In comparison, the energy demand and costs for space heating and stationary engines are relatively minor, with a total of approximately 770 GWh/a and costs amounting to ~75 MEUR/a.

Table 13. Conventional routes in the pulp and paper industry per application case and the respective energy demand, GHG emission, and yearly cost values.

		Energy Demand	Emissions	A_{CAPEX}	C_{OPEX}	Total Costs
		[GWh/a]	[kt CO_2e/a]	[MEUR/a]	[MEUR/a]	[MEUR/a]
Space heating	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	18.8	5.5	0.0	2.5	2.5
	Gas furnace	393.2	78.4	2.0	35.7	37.7
Stationary engines	Diesel engine	0.0	0.0	0.0	0.0	0.0
	Gas engine	363.0	72.4	0.9	32.9	33.8
Process heat < 200 °C	Coal furnace	475.0	158.0	2.1	45.2	47.3
	Oil furnace	22.4	6.6	0.0	3.0	3.0
	Gas furnace	3467.6	691.6	17.4	314.7	332.1
Process heat > 200 °C	Coal furnace	0.0	0.0	0.0	0.0	0.0
	Oil furnace	3.9	1.1	0.0	0.5	0.5
	Gas furnace	7184.1	1432.8	36.0	652.1	688.1

In the pulp and paper industry, no process-related emissions are relevant. Therefore, the investigation of the TCNP must be focused on the abatement of energy-related GHG emissions (Table 14). Because of the dispersed GHG sources in the Austrian case study, carbon capture technologies were excluded from further consideration. A total of 2 Mt of virgin pulp and approximately 5 Mt of paper in a multitude of qualities are produced annually [26]. With a recycling rate of more than 77%, the Austrian paper industry's use of secondary fibre in paper production is considered to range close to technical limitations for the current product portfolio [67]. Therefore, we also consider no further expansion of circular economy measures in this work.

Table 14. Considered alternative technology options in pulp and paper.

Climate Neutrality Pathway	Source of Emission	Technology	Application
Electrification	Energy-related	Use of heat pumps	Space heating Process heat < 200 °C
	Energy-related	Electric engines	Stationary engines
Use of CO_2-neutral gases and solid biomass combustion	Energy-related	Bio-CH_4	Space heating Process heat </> 200 °C
	Energy-related	H_2 from electrolysis	Space heating Process heat </> 200 °C
	Energy-related	H_2 from pyrolysis	Space heating Process heat </> 200 °C
	Energy-related	Solid biomass comb.	Space heating Process heat </> 200 °C
Carbon capture Circular economy			

Energy-Related Emissions

Table 15 below presents the results for the mitigation of energy-related emissions in the pulp and paper industry. It follows the established format used for the previous subsectors.

<u>Electrification:</u> The electrification of space heating and stationary engines offers a TCNP of approximately 60 to 70 kt CO_2e/a each. While investment costs for engines are negligible due to small volumes, the total annual costs for the aforementioned applications are similar at approximately 20 MEUR/a. In contrast, the use of high-temperature heat pumps up to 200 °C provides a TCNP of close to 800 kt CO_2e/a at an annual cost of 222 MEUR. Due to the distribution of different temperature levels, this technology pathway offers greater TCNP and cost advantages in comparison to the two subsectors above. In contrast to conventional fossil-based technologies, the electrical alternatives in pulp and paper provide a total yearly cost advantage of ~190 MEUR/a. Due to the higher shares of medium-temperature process heat application, the climate neutrality impact and cost reduction are also considerably higher. The relative savings per application category in relation to conventional technologies reach 40 to 43% per technology.

<u>CO_2-neutral gases and biomass combustion:</u> In the pulp and paper industry, the highest TCNP can also be found in the provision of process heat above 200 °C, especially in the form of steam. For the temperature range between 200 and 500 °C, only CO_2-neutral gases and solid biomass are considered. In contrast to the iron and steel and the non-metallic mineral industries, biomass combustion in the pulp and paper industry shows a TCNP of 2468 kt CO_2e/a, 61% of which is with regards to the provision of process heat and steam between 200 and 500 °C. The total costs for all temperature levels in this case reach 715 MEUR/a, the majority of which stems from operational expenditures, mainly fuel costs. The investigated biobased gases match this TCNP; however, they do so at considerably higher costs. Exhibiting higher shares of annual C_{OPEX}, bio-SNG has annual costs of 1026 MEUR. Lower costs are calculated for the deployment of the more capital-intensive bio-CH_4 route, but with 862 MEUR/a, it is still roughly 150 MEUR/a more expensive than the combustion of solid biomass. Costs for electrolysis-derived hydrogen are approximately even with bio-CH_4 with 858 MEUR/a, but this route provides a lower TCNP due to indirect

emissions from the electricity supply (1670 kt CO_2e/a). H_2 from methane pyrolysis, on the other hand, offers a TCNP of 2228 kt CO_2e/a but exhibits the highest annual costs by far at 1172 MEUR/a—a cost difference to the cheapest option of solid biomass of roughly 460 MEUR/a. In comparison to the investigated conventional routes outlined above, the most expensive alternative pathway with a very high TCNP—pyrolysis-derived hydrogen—exhibits approximately the same annual costs (1144 MEUR/a in the case of conventional technologies).

Table 15. Technologies and the respective TCNP, change in energy consumption, and cost structure values for energy-related emissions in pulp and paper.

Technology	Application	TCNP	Energy Balance	A_{CAPEX}	C_{OPEX}	Total Costs
		[ktCO_2e]	[GWh/a]	[MEUR/a]	[MEUR/a]	[MEUR/a]
			Electrification			
LT heat pumps	Space heating	−75	Fossil: −412 Electr.: +122	8.9	14.1	23.1
HT heat pumps	Process heat < 200 °C	−789	Fossil: −3965 Electr.: +123	68.3	154.1	222.3
Electric engines	Motive power	−62	Fossil: −363 Electr.: +171	0.0	19.8	19.8
		Use of CO_2-neutral gases and solid biomass combustion				
Bio-CH_4	Space heating	−82	Fossil: −412 Bio-CH_4: +412	15.1 Bio-CH_4 2.1 Furnace	13.6	30.7
	Process heat < 200 °C	−863	Fossil: −3965 Bio-CH_4: +3965	145.0 Bio-CH_4 19.9 Furnace	130.7	295.5
	Process heat > 200 °C	−1523	Fossil: −7188 Bio-CH_4: +7188	262.8 Bio-CH_4 36.0 Furnace	236.9	535.7
Bio-SNG	Space heating	−82	Fossil: −412 Bio-SNG: +412	11.2 Bio-SNG 2.1 Furnace	23.3	36.5
	Process heat < 200 °C	−863	Fossil: −3965 Bio-SNG: +3965	107.4 Bio-SNG 19.9 Furnace	224.4	351.7
	Process heat > 200 °C	−1523	Fossil: −7188 Bio-SNG: +7188	194.7 Bio-SNG 36.0 Furnace	406.9	637.6

Table 15. *Cont.*

Technology	Application	TCNP	Energy Balance	A_{CAPEX}	C_{OPEX}	Total Costs
		[ktCO_2e]	[GWh/a]	[MEUR/a]	[MEUR/a]	[MEUR/a]
			Electrification			
	Space heating	−82	Fossil: −412 H_2: +372 *Electr.: +520*	8.3 H_2 1.9 Furnace	18.6	28.8
H_2 from electrolysis	Process heat < 200 °C	−583	Fossil: −3965 H_2: +3569 *Electr.: +4996*	79.6 H_2 17.9 Furnace	178.8	276.4
	Process heat > 200 °C	−1005	Fossil: −7188 H_2: +7188 *Electr.: +10,063*	160.4 H_2 32.5 Furnace	360.1	553.0
	Space heating	−73	Fossil: −412 H_2: +372 *CH_4: +694* *Electr.: +106*	5.5 H_2 1.9 Furnace	32.2	39.6
H_2 from pyrolysis	Process heat < 200 °C	−778	Fossil: −3965 H_2: +3569 *CH_4: +6674* *Electr.: +1018*	52.5 H_2 17.9 Furnace	310.0	380.4
	Process heat > 200 °C	−1377	Fossil: −7188 H_2: +5170 *CH_4: +13,443* *Electr.: +2051*	95.4 H_2 32.5 Furnace	623.9	751.9
	Space heating	−82	Fossil: −412 Biomass: +412	2.5	23.0	25.5
Solid biomass	Process heat < 200 °C	−863	Fossil: −3965 Biomass: +3965	23.9	221.3	245.2
	Process heat > 200 °C	−1523	Fossil: −7188 Biomass: +7188	43.3	401.2	444.5

4. Discussion

Given the current exceptionally high uncertainty in international energy markets, the global economic outlook, and geopolitical developments, the discussion of the results is accompanied by a sensitivity analysis of the impact of fuel and feedstock costs, respectively, on total annual technology deployment costs. In Section 4.1, an exemplary sensitivity analysis for space heating, process heat below and above 200 °C, and primary steel production for changes in fuel and feedstock costs is presented. Thereafter, the results of the case study and sensitivity analysis are further discussed in Section 4.2.

4.1. Sensitivity Analysis

Following above methodology, for this analysis, annual costs of deployment are calculated, taking into account GHG certificate costs, fuel, and—in the case of CO_2-neutral gases—feedstock costs, as well as a 20-year depreciation period for investments. In each figure below, the cost of conventional fossil technologies for each of the given applications is compared to the costs of alternative technologies. The total annual costs of conventional technologies are visualised with and without GHG certificate costs. Thereby, we can visualise the impact of the chosen cost of 250 EUR/t CO_2 and assess its leverage on the annual costs of conventional and alternative technologies. Some alternative technologies are already cost-comparative with conventional technologies, while others need at least the chosen certificate price to incentivise their uptake through competitive annual costs of deployment. Electricity-based technologies—most notably electrification through heat pumps and hydrogen—also exhibit significant GHG certificate costs due to the consideration of upstream emissions from electricity generation. These costs are included in the shown graphs. The *x*-axis shows the underlying assumed difference in fuel costs, while all other cost factors, e.g., capital expenditures and GHG certificate costs, are kept constant. On the *y*-axis, the resulting total annual costs are plotted.

Figure 3 illustrates the results of the sensitivity analysis of fuel costs for space heating. Except for pyrolysis-derived hydrogen, all investigated pathways stay robustly below the costs of current fossil technologies. Due to the necessary upstream investment for the generation of CO_2-neutral gases, bio-SNG can only sustain fuel cost increases of approximately 20 to 30% before reaching cost parity with the base case of conventional technology. Solid biomass and pyrolysis-derived hydrogen react very strongly to fuel cost increases due to unfavorable energy conversion rates, with the former starting from a relatively low cost level in the base case. Solid biomass, bio-CH_4, and electrolysis-derived hydrogen reach annual costs of the conventional base case at an increase in fuel price of approximately 60 to 70%. On the other hand, for electric heat pumps, this point occurs at over 150%. Conventional technologies exhibit the lowest costs only if no GHG certificate costs are considered, highlighting the large steering effect of GHG taxation. When GHG certificate costs are considered, the sensitivity to changes in fuel costs is reduced accordingly, and the curve flattens.

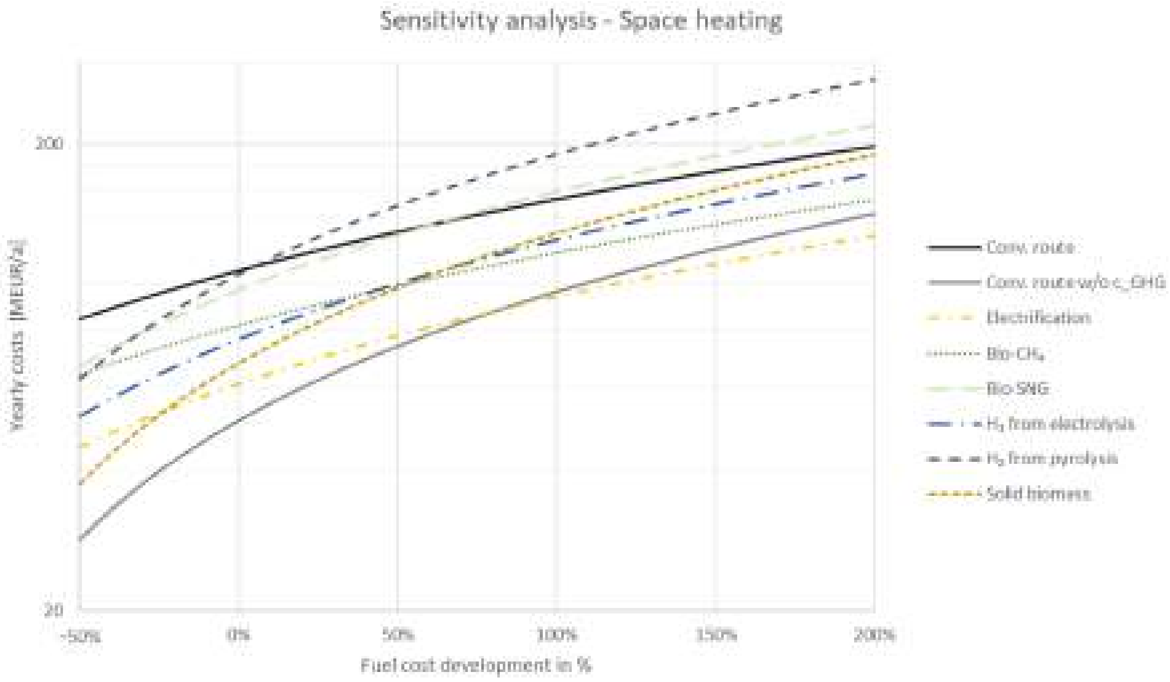

Figure 3. Sensitivity analysis for space heating for changes in fuel/feedstock costs.

Figure 4 presents a sensitivity analysis for fuel costs in applications of process heat below 200 °C. The trend identified in Figure 3 above is confirmed for the higher temperature range. Keeping fuel prices constant for the current production route, only the combustion of hydrogen from methane pyrolysis for process heat below 200 °C reaches fossil reference costs in the base case. Feedstock prices for the use of bio-CH_4 and electrolysis-derived hydrogen could rise by 70% before reaching cost parity with the conventional base case, while heat pumps can sustain an increase in electricity cost of more than 130%. On the other hand, the use of bio-SNG can only withstand price increases of 20% to 30%. Due to the large lever of assumed GHG certificate costs and the resulting flat development curve of conventional technologies, fossil costs would need to reduce by approximately 50% to lie below the base case of bio-SNG. The base case costs of the remaining technologies—heat pumps, biomass, bio-CH_4, and H_2 from electrolysis generation—could only be reached with an even greater than 50% decrease in fuel costs. Without GHG certificate costs, however, in this application category as well, no alternative technology exhibits cost leadership over the conventional base case.

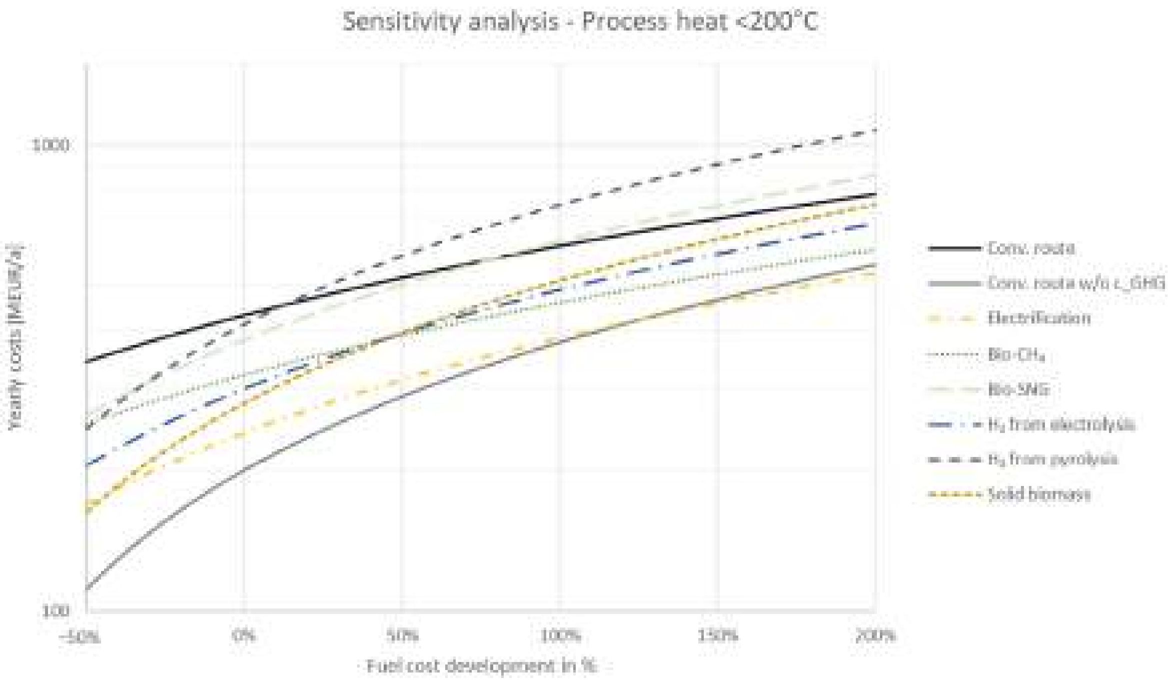

Figure 4. Sensitivity analysis for process heat < 200 °C for changes in fuel/feedstock costs.

Figure 5 presents a sensitivity analysis for fuel costs in applications of process heat above 200 °C. In contrast to the previously discussed diagrams, the gap between costs for conventional and alternative technologies in this application case is smaller. Only CO_2-neutral gases can be applied over the full temperature range above 200 °C, which is the reason why the combustion of solid biomass and electrification is not visualised in the figure. Again, keeping fuel prices constant for conventional technologies, only the combustion of hydrogen from pyrolysis for process heat is above fossil reference costs in the base case. The price of feedstock for bio-SNG can sustain an increase of approximately 15%. Of the four investigated gaseous energy carriers, bio-CH_4 is the most robust against feedstock cost increases—breaking even with the conventional base case at a relative feedstock cost increase of approximately 60%, similar to electrolysis-derived hydrogen. A 50% fuel price decrease in the fossil fuel reference case, including GHG certificate costs, would not bring cost advantages over the two most economical CO_2-neutral gas options, bio-CH_4 and electrolysis-derived H_2. Taking no GHG certificate costs into account for conventional technologies, on the other hand, fossil fuel prices can experience an increase of up to 150% before matching the assumed annual base case costs of alternative technologies for process heat above 200 °C.

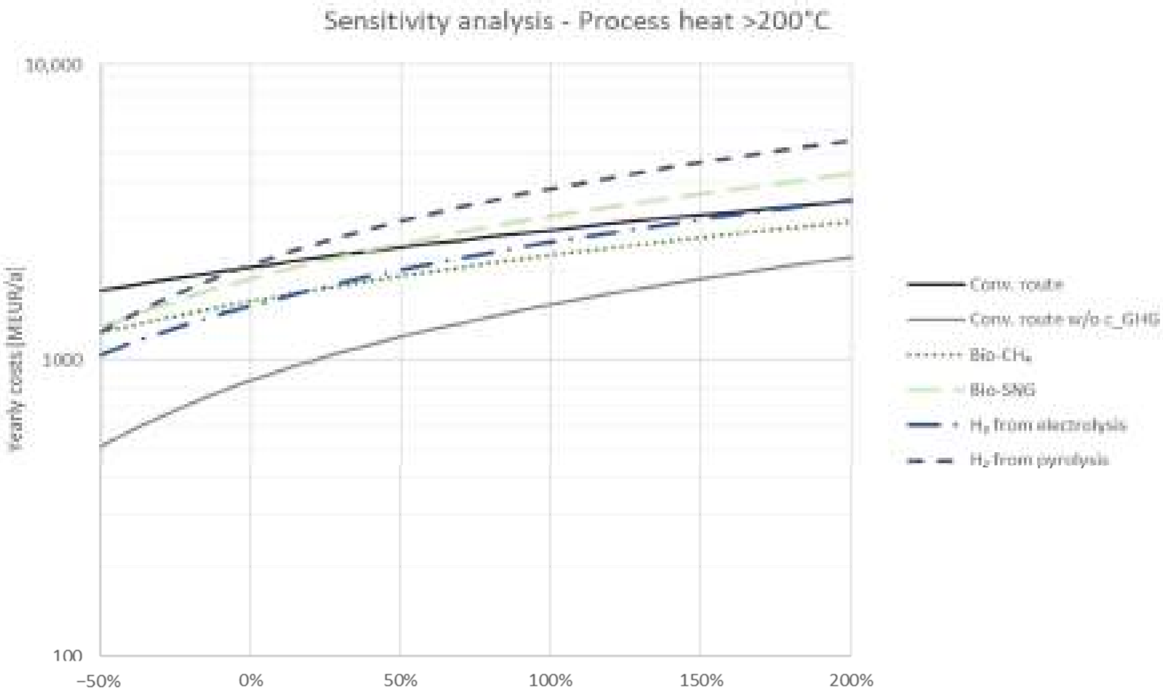

Figure 5. Sensitivity analysis for process heat > 200 °C for changes in fuel/feedstock costs.

While the above figures depict sensitivity analyses for final-energy-consuming applications and therefore the mitigation of energy-related emissions, Figure 6 investigates fuel and feedstock price sensitivity for the mitigation of process-related emissions in primary steelmaking. In general, all four investigated technologies, bio-CH_4, SNG, and hydrogen from electrolysis and pyrolysis, lie below the conventional fossil base case of primary steel production via the BF/BOF route when considering GHG certificate costs and can therefore be considered cost-competitive. Assuming constant prices for fossil energy carriers, the production of bio-CH_4 reaches cost equality only after a 160% price increase in feedstock. On the other hand, this does not apply in the same order of magnitude for bio-SNG and electrolysis-derived hydrogen, whose graphs exhibit greater feedstock cost sensitivity. DR/EAF using H_2 from pyrolysis, as the most expensive alternative option, still sustains a 50% increase in feedstock costs in comparison to the conventional base case. Investigating the impact of decreasing fuel costs, it can be observed that while the reference fossil route is relatively constant, small relative decreases in fuel costs for the alternative technologies already exhibit great absolute savings. If no GHG certificate costs are considered for BF/BOF, alternative technologies would have to find a decrease in feedstock costs of approximately 50% to become cost-competitive, again emphasising the lever of emission taxation for the success of the energy transition identified above.

4.2. *Discussion of Case Study Results*

In total, the subsectors considered in the case study currently emit approximately 19 Mt CO_2e/a via energy- and process-related emissions through several different energy application cases. Figure 7 illustrates the investigated technical climate neutrality potential per climate neutrality pathway. Horizontally, on the bottom, all investigated application cases and applicable alternative technology pathways as well as their respective conventional fossil routes are shown. Moving from top to bottom, the total annual GHG emissions of all investigated subsectors are shown on the left, next to the primary *y*-axis. For each alternative technology pathway and application case, the respective TCNP is shown. From bottom to top, associated costs, both operational and capital expenditures, are presented and assessed on the secondary y-axis on the right. For each pathway, the technology with the best ratio of TCNP to total annual costs is presented. As evident, thorough climate neutrality can only be attained by attending to all energy applications and making use of a combination of available climate neutrality pathways. As shown in the case study, a wide range of potential annual costs and TCNP values for these alternatives can be expected.

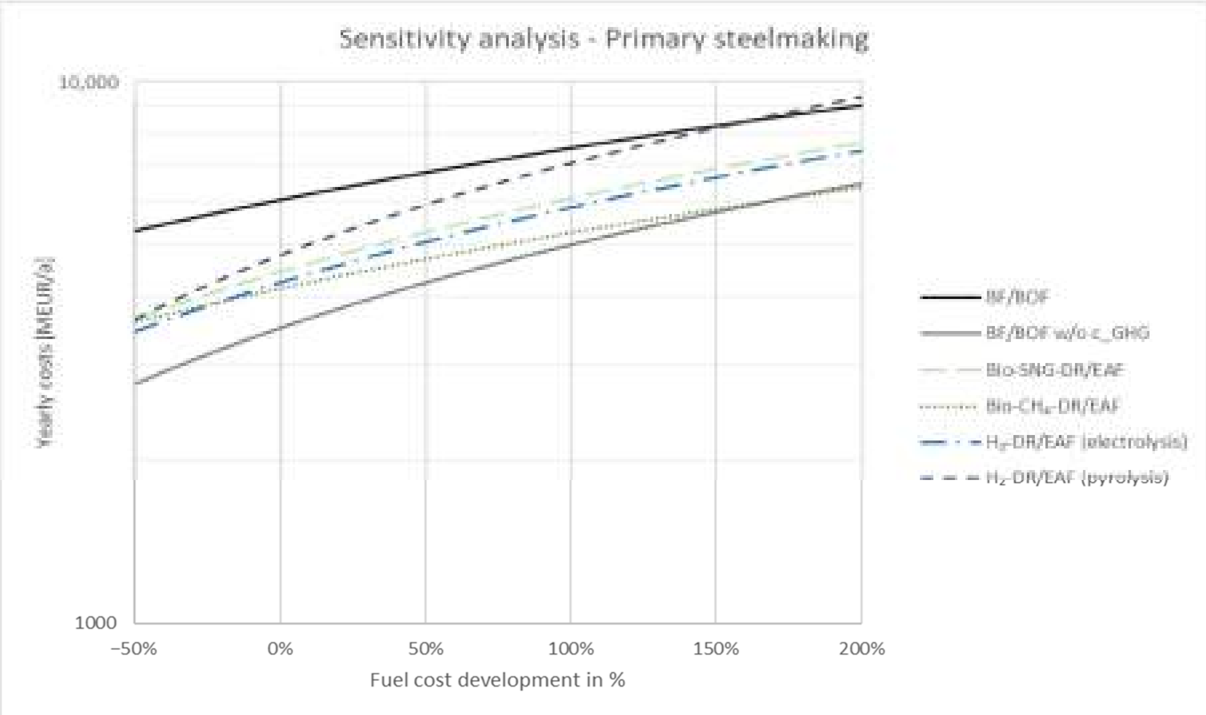

Figure 6. Sensitivity analysis of primary steelmaking for changes in fuel and feedstock costs.

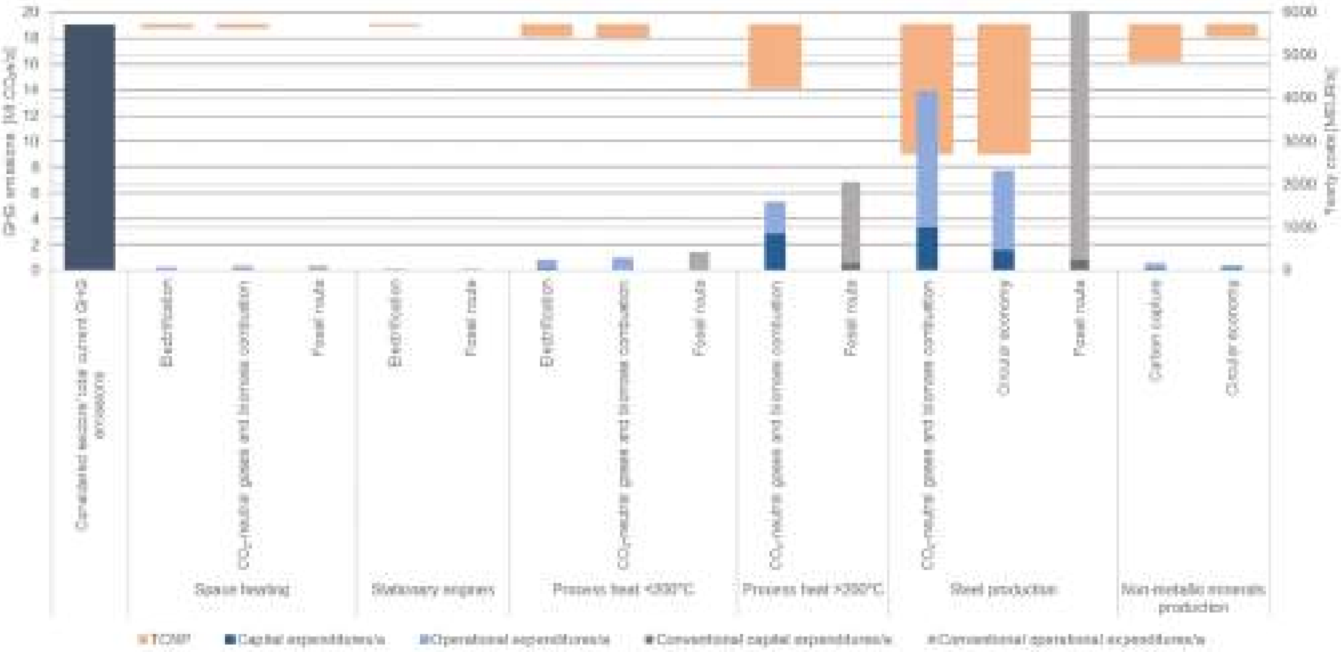

Figure 7. Comparison of investigated alternative technologies' TCNP values and associated total annual costs. The technology with the best TCNP-to-cost ratio is visualised in each climate neutrality pathway.

For space heating and process heat below 200 °C, especially electrification through heat pumps but also the use of solid biomass and bio-CH_4, costs lie well below the prices of their conventional fossil-based counterparts when taking into account GHG certificate costs—even in consideration of significant fuel price increases. However, relative to the other discussed application cases, both their costs and absolute TCNP values are low in the investigated EIIs.

The electrification of motive power applications may be relatively easy to realise and offers cost advantages over conventional technologies. However, only a marginal TCNP of less than 100 kt CO_2e/a across all discussed subsectors can be attained.

Due to its limited temperature range [25], biomass combustion can only be deployed for parts of process heat ranging up to 500 °C;—among the investigated subsectors of energy-intensive industries, this is a temperature range only widely used in the pulp and paper industry. The total TCNP of biomass combustion in the example subsectors amounts to 2675 kt CO_2e/a. Going down further in applicable temperature ranges, the electrification of the heat supply via the use of heat pumps can mitigate approximately 1054 kt CO_2e/a.

For high-temperature applications, in addition to bio-CH_4, bio-SNG and H_2 from electrolysis are also in a cost-competitive range. On the other hand, the use of pyrolysis to produce sustainable hydrogen is faced with large investment as well as feedstock costs that approximately match the costs of conventional technologies under the assumed boundary conditions. By using bio-CH_4—a CO_2-neutral gas with the highest TCNP-to-cost ratio—up to 4870 kt CO_2e/a can be mitigated, resulting in yearly costs of 1576 MEUR. Thereby, the annual costs lie well below the projected fuel and GHG costs of the conventional fossil-based route (2056 MEUR/a). This discrepancy is especially driven by assumed GHG certificate costs of 1204 MEUR/a, without which fossil technologies would result in significantly lower annual costs than their sustainable counterparts.

For the mitigation of process-related emissions in the non-metallic mineral subsector, carbon capture technologies are necessary to reduce geogenous emissions. The considered technologies can attain a sequestration efficiency of approximately 90% but vary greatly in their energy efficiency and cost structure. Because of the significantly higher electricity demand for amine scrubbing, approximately 700 kt of CO_2 emissions can be reduced by this technology in comparison to the alternative oxyfuel route due to the assumed GHG intensity of electricity consumption. While exhibiting considerable advantages in capital expenditures, this also drives fuel and GHG costs to 202 MEUR/a (in comparison to 146 MEUR/a for oxyfuel). The implementation of carbon capture enables additional emission mitigation through the sequestration of energy-related emissions from the calcinator as a side effect of the mitigation of process-related emissions. Approximately half of all energy-related emissions from the subsector could be sequestrated. In comparison to CO_2-neutral gases, carbon capture measures provide a significantly advantageous TCNP-to-cost ratio. In addition, a combination of the two climate neutrality pathways could enable significant opportunities for the realisation of negative emissions. The integration of circular economy aspects reduces resource depletion and mitigates geogenous emissions. While additional energy is needed for pre-processing, the associated benefits regarding the previously mentioned geogenous emission mitigation of approximately 800 kt in cement production alone prove to outweigh the costs. Therefore, a circular economy can provide a meaningful supplement to carbon capture measures for non-metallic minerals.

The already significant impact of the use of CO_2-neutral gases in GHG mitigation for high-temperature process heat is even surpassed by their use in steelmaking via the DR/EAF route. The costs of all four investigated gases lie well below the conventional technology of BF/BOF (6053 MEUR/a), as visualised with 4149 MEUR/a for bio-CH_4. They promise a TCNP between 86% in the case of electrolysis-derived hydrogen and 98% in the case of bio-CH_4 and bio-SNG. The use of a circular economy in steel production can reduce the need for geogenous resources as well as energy. However, the additional effect on the TCNP is negligible in comparison to the investigated DR/EAF-route. Most importantly, both sustainable primary steel production and increasing shares of secondary metallurgy rely on newly built electric arc furnaces.

In total, CO_2-neutral gases can achieve a TCNP of up to 16 Mt CO_2e/a thanks to their broad area-of-application possibilities for both process-related and energy-related emission mitigation. Among these energy carriers, bio-CH_4 can be considered the most economical and efficient under the given assumptions. While bio-CH_4 shows a cost structure balanced between capital and operational expenditures, bio-SNG and the similarly cost-intensive electrolysis-derived hydrogen are more susceptible to high fuel and feedstock costs. The most expensive gaseous energy carrier, pyrolysis-derived hydrogen, follows this trend but suffers from poor energy conversion factors and therefore even higher C_{OPEX} rates.

5. Conclusions

In conclusion, the successful mitigation of greenhouse gas emissions in energy-intensive industries will have to rely on a mix of technological measures. We summarised in our introduction from the existing literature that until now, studies on EIIs' transition to climate neutrality have lacked a sector-comprehensive yet detailed outline of available options per industrial subsector in the context of their conventional fossil-based counterparts. This work, therefore, moves into this gap by presenting a set of indicators that allows the reader to compare—subsector by subsector and application by application—the impact on GHG emission mitigation, energy demand, and costs of every considered technology. Thereby, it bundles efforts across industrial subsectors as greater overarching complexities of the energy system are kept within sight from an energetic point of view but also with regards to ecology and economy. Furthermore, clustering along four climate neutrality pathways enables us to compare general angles of approach to climate neutrality across subsector boundaries that can directly inform researchers and decision makers when contemplating focal points regarding the transition phase for EIIs. The focus on the maximum attainable CO_2-mitigation impact for each technology also sets our proposed approach apart from common scenario analyses as we do not investigate transitional pathways. Rather, progressing from the level of technologies up to subsectors and climate neutrality pathways, we investigate each route by itself at maximum possible applicability without interference from another technology option. In turn, however, at the initial stage of the process of scenario development, the methodology presented herein allows for an insightful pre-examination of the maximum deployment states of the technology pathways.

The presented case study of three energy-intensive subsectors of Austrian manufacturing industries allows the following exemplary conclusions to be reached by applying the proposed approach. In further planning the energy transition for EIIs in Austria, these conclusions can constitute cornerstones of future research on the period of transition to climate neutrality and policy development. Due to the low requirements regarding necessary energy statistics, similar analyses can be extended to other national and international entities, using or even expanding the economic parameters compiled in this work or making use of collections of application-oriented energy and emission balances (e.g., Guminski et al. [68]).

- The use of CO_2-neutral gases can provide significant GHG reductions over a wide variety of applications and features the most significant total technical climate neutrality potential. Due to energy-intensive production routes for H_2, significantly more energy is needed than when considering current fossil-based industrial processes or the alternative bio-CH_4 route.
- At lower temperature levels (up to 200 °C), electrification through heat pumps can positively impact absolute energy efficiency and provides a sustainable setup that is robust against volatile energy prices.
- The impact of intensified circular economy measures is most notable regarding energy and resource efficiency. In the case of steel production, only the already sustainable but energy-intensive EAF-based production route allows for additional recycling capacities. Similarly, in cement production, circular economy measures reduce the especially hard-to-abate geogenous emissions.
- Several technologies for the successful sequestration of CO_2 exist. However, they differ significantly in energy intensity as well as investment requirements. For example,

end-of-pipe solutions like the investigated amine scrubber feature easy application and comparatively low capital expenditures but show significant drawbacks regarding energy efficiency, operational expenditures, and price robustness. Oxyfuel carbon capture requires larger capital expenditures but provides significantly lower total costs of deployment annually—an already existing advantage that may well increase in consideration of expectable learning curves for this technology.

- Prices of GHG certificates are shown to constitute the most essential leveliser of the costs of fossil fuels when comparing conventional fossil-based annual costs for 2040 with those of alternative technologies. For necessary steering effects to take place across all investigated application cases, their prices should lie between 200 and 300 EUR/t CO_2. This resulting span corresponds to price ranges identified in a study by the German climate neutrality research initiative ARIADNE, which investigated necessary CO_2 certificate costs for reaching the 2030 GHG reduction goals of the "Fit for 55" policy programme [69].
- Our exemplary case study in Austria shows that alternative technologies in four main climate neutrality pathways can operate at total annual costs comparable to their conventional fossil-based equivalents. Their implementation timeline will be guided by the timeline of decisions for future replacement investments, which has to be an essential focal point for future studies.

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Abbreviations

BF/BOF	Blast furnace/basic oxygen furnace
CAPEX	Capital expenditures
CH_4	Methane
CHP	Combined heat and power
CS	Crude steel
DR	Direct reduction
EAF	Electric arc furnace
EII	Energy-intensive industry
EU	European Union
GHG	Greenhouse gas
IEA	International energy agency
LCOE	Levelised cost of electricity
MRL	Market readiness level
OPEX	Operational expenditures
RTD	Research and technological development
SNG	Substitute natural gas
TCNP	Technical climate neutrality potential
TRL	Technology readiness level
UK	United Kingdom

Appendix A

Table A1. Considered technologies by climate neutrality pathway and application case.

	Application	Full Load Hours	CAPEX in EUR_{2020}	c_{inst} in $\%_{CAPEX}$	c_{rel} in $\%_{CAPEX}$	Reference for Costs
			Electrification			
LT heat pumps (COP 3.0)	Space heating	2200	400 EUR/kW_{th}	67	0.5	[48]; own assumption for c_{rel}
HT heat pumps (COP 2.5)	Process heat < 200 °C	4000	520 EUR/kW_{th}	100	2.0	[48]; own assumption for c_{rel}
Electric engines	Stationary engines	4000	100 EUR/kW_{el}	20	0.5	[70]; own assumption for c_{inst} and c_{rel}
			Use of CO_2-neutral gases and biomass combustion [a]			
Gas furnace (CH_4, H_2)	Space heating, process heat </> 200 °C; subsector-specific processes	4000	250 EUR/kW_{th}	Included in CAPEX	4.0	[48,49]
Generation of bio-CH_4		8000	2700 EUR/kW_{CH4}	35	2.0	Own assumptions based on [34,71]
Generation of bio-SNG		8000	2000 EUR/kW_{SNG}	35	2.0	[34]
Generation of H_2 through electrolysis		3500	515 EUR/kW_{el}	35	4.0	[34,61]
Generation of H_2 through methane pyrolysis		3500	475 EUR/kW_{H2}	35	4.0	[61]; own assumption for c_{inst} and c_{rel}
Solid biomass combustion		8000	600 EUR/kW_{th}	35	2.0	[59]; own assumption for c_{inst} and c_{rel}
CH_4-DR/EAF [b]	Primary steelmaking	-	400 EUR/t_{CS}	Included in CAPEX	71.0 [c]	[51,52,61]
H_2-DR/EAF [b]		-				
			Carbon capture			
Oxyfuel combustion	Non-metallic mineral production	-	220 EUR/t_{CO2}	40	2.0	[63]; own assumption for c_{inst} and c_{rel}
Amine scrubbing		-	131 EUR/t_{CO2}	25	2.0	
			Circular economy			
Increased use of scrap metal in EAF [d]	Steel production	-	-	-	-	-
Recycling of concrete	Cement production	-	1 $EUR/t_{concrete}$	-	-	[61,64]

[a] for the combustion of CO_2-neutral gases in this climate neutrality pathway, it is assumed that no substitution of current combustion equipment is necessary. Investment costs correspond to the costs for generating CO_2-neutral gases. [b] the use of EAF in primary steelmaking is always in combination with direct reduction using GHG-neutral gases. Below, DR/EAF-routes are therefore allocated to the climate neutrality pathway the "use of CO_2-neutral gases." [c] includes iron ore and fluxes. [d] no additional investment costs for the increased use of scrap metal in steelmaking are assumed.

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Third Journal Article

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Table A 3. Author statement to the third journal article

Activity	Contributing authors (the first-mentioned is the main author)
Conceptualisation	P. Nagovnak, C. Schützenhofer, T. Kienberger
Methodology	P. Nagovnak, R. Cvetkovska, A. Hainoun, T. Kienberger
Data curation	P. Nagovnak, S. Stortecky, A. Hainoun, V. Alton
Investigation and analysis	P. Nagovnak, M. Rahnama Mobarakeh, S. Stortecky, A. Hainoun
Visualisation	P. Nagovnak
Writing (original draft)	P. Nagovnak, C. Schützenhofer
Writing (review and editing)	P. Nagovnak, T. Kienberger, C. Schützenhofer
Funding acquisition	T. Kienberger
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Research article

Assessment of technology-based options for climate neutrality in Austrian manufacturing industry

P. Nagovnak [a,*], C. Schützenhofer [b], M. Rahnama Mobarakeh [a], R. Cvetkovska [a], S. Stortecky [b], A. Hainoun [b], V. Alton [b], T. Kienberger [a]

[a] *Chair of Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef Straße 18, A-8700, Leoben, Austria*
[b] *Austrian Institute of Technology, Giefinggasse 4, A-1210, Vienna, Austria*

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ABSTRACT

The goals set forth by the European Green Deal require extensive preparation and coordination of all stakeholders. As a valuable tool, energy scenarios can generate the necessary information for stakeholders to envision the right steps in preparing this transition. The manufacturing industries represent an especially important sector to investigate. They are responsible for both high energy consumption and GHG emission figures on the one hand side and provide great economic value for member countries on the other. We aim to provide a close investigation of all thirteen industrial subsectors that can be used as a solid information basis both for stakeholders within the manufacturing industries and policymakers. Our approach includes *all* industrial production processes. We achieve this by considering both transformation processes, such as blast furnaces or industrial power plants, and final energy-application. In addition, both scope 1 and 2 emissions of manufacturing industry are assessed in an effort to transparently indicate the interdependencies of industrial decarbonisation efforts with the overall energy system. We propose the integration of a novel stakeholder-based scenario, that puts special emphasis on first-hand information on mid to long-term planning of key industrial representatives, thereby going beyond existing scenario narratives (e.g., scenarios according to the European Monitoring Mechanism). Thus, a balanced deep decarbonisation scenario using best-available technologies can be compared with existing industry plans. To address these points, we have chosen Austria as a case study. Results indicate that industry stakeholders are in general agreement on their subsector-specific technology deployment and already envision investments towards a low-carbon pathway for their respective subsectors. While today's manufacturing industries rely at large on a great diversity of (mostly fossil) energy carrier supply, deeply decarbonised manufacturing industries of the future may be based on the following main energy carriers; electricity, CO_2-neutral gases, and biomass. To mitigate emissions from geogenic sources, carbon capture technologies are needed. On the other hand, the synthesis of olefins in the chemical industry may provide a sink for CO_2 assuming long-term use after production. In addition to the option of using it across subsectors, captured CO_2 will have to be stored or sold to other economies. Comparison of the developed scenarios allows the identification of no-regret measures to enable climate neutrality by 2050 that should be deployed as soon as possible by push and pull incentives. The model results of the two transition scenarios show the need for technology promotion as well as infrastructure development needs and allow the identification of possible corridors, focal points, and fuel shifts – on the subsector level as well as in energy policy. Among others, the modelled magnitude of renewable energy

* Corresponding author.
E-mail address: p.nagovnak@solah.at (P. Nagovnak).

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consumption shows the need for swift expansion of existing national renewable energy potentials and energy infrastructure, especially for energy intensive industry regions. In light of the current energy consumption in other economic sectors (most notably in buildings or transport) and limited renewable potentials, large import shares of national gross domestic energy consumption are likely for Austria in the future.

Abbreviations

AWF	Alternative waste fuels
BF/BOF	Blast furnace/basic oxygen furnace
BAT	Best available technologies
BAU	Business as usual
BEP	Break-even point
BTT	Breakthrough technologies
Bio-CH_4	Biogenic methane
CH_4-DR-EAF	Methane-based direct reduction and electric arc furnace
CHP	Combined heat and power
DR	Direct reduction
EAF	Electric arc furnace
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
H-DR-EAF	Hydrogen-based direct reduction and electric arc furnace
HFC	Hydrofluorocarbons
IT	Information technology
PFC	Perfluorocarbons
POI	Pathway of industry
RES	Renewable energy sources
Syn-CH_4	Synthetically produced methane
UBA	*german:* Umweltbundesamt – the Austrian environmental agency
UN	United Nations
ZEM	Zero emission

1. Introduction

With the Green Deal, the European Union and its member states have set the goal of achieving climate neutrality by 2050 [1]. This requires extensive preparation and coordination of all stakeholders due to the high level of complexity arising from the multitude of involved levels in the economic system. Chiodi et al. [2] review four case studies on the national and supranational level where energy systems models' scenario output was able to directly help in overcoming barriers in acceptance, fostering understanding of key areas of action and subsequently leading into long-term energy and emission strategy development and impact appraisal thereof. In the European Union, the European Commission names the EU reference scenario one of its "key analysis tools in the areas of energy, transport and climate action" [3]. Together with the array of progress reports on national energy and climate plans filed in line with the "Regulation on the Governance of the Energy Union" [4] and additional national scenario analyses the member states can bring into the policy delivery process, the scenario has also been used as a baseline for the policy initiatives in the "European Green Deal" package. These examples show that the development of energy scenarios is a powerful and proven tool for identifying potentials, envisioning transformation pathways and appraise the success of already adopted measures that needs to be further expanded and continuously adapted to the evolving realities of technological and economic development.

In 2021, manufacturing industries including construction were responsible for 23 % of energy and process-related European greenhouse gas (GHG) emissions, due to the sector's large dependency on fossil energy for energy-intensive production processes [5]. The total impact of the sector on GHG emissions of the EU are even greater due to upstream electricity and heat generation. On the other hand, the manufacturing industries is an important part of the Union's economy, directly accounting for approximately 15 % of value added and employing 16 % of its workforce [6,7]. Therefore, finding sustainable transition pathways for the manufacturing industry is a key for long-term European prosperity in light of the climate crisis [8].

Following the above-described importance of energy systems modelling for policymaking, energy consumption and accompanying GHG emission scenarios of manufacturing industries can help to envision successful pathways to climate neutrality and identify important fields of action. The comparison of meaningful scenario results indicates the bandwidth of possible pathways towards industrial climate neutrality and allows for the identification of technology and non-technology related no-regret measures on this journey. These measures are necessary to transform the manufacturing industry under the assumption that production activities are maintained and not moved abroad.

Due to their important role in understanding the complex challenges of industrial climate neutrality and their potential for providing visionary guidelines, a great diversity of scenario publications on industrial development exists.

Several academic publications focus only on industrial final energy consumption in total energy system analyses. Exemplary for this group, the works of Saddler et al. [9] and Gaur et al. [10] provide energy scenarios for deep decarbonisation of the Australian and Irish energy system. While taking into account industrial final energy consumption and resulting energy-related emissions, energy consumption of industrial energy transformation units and process-related emissions, e.g., from primary steel or cement production, are not considered. Wiese et al. [11] summarise this problem in their meta-analysis of German energy scenarios, noting significant differences in the observed studies "regarding [...] process emissions in the industry sector". This is the case especially for economies with a considerable share of primary production in the energy intensive subsectors.

Other publications, often also in grey literature, remain specific to one industrial subsector or product. This includes roadmaps and technology reports, e.g., by industrial interest groups. For example, in the chemical and petrochemical industry, DECHEMA [12] for Germany and Windsperger et al. [13] for Austria have provided stakeholder roadmaps for the sector's future development. Griffin et al. [14] have contributed scientific investigations for the chemicals sector in the United Kingdom. For iron and steel, the EU Commission has outlined a "future for steel in Europe", highlighting technology options necessary for the transformation towards climate neutrality [15]. Scientifically, great attention has been given to the question of decarbonising primary steel production through the use of hydrogen direct reduction in combination with electric arc furnaces (H-DR-EAF) as reviewed by Wang et al. [16]. While providing the necessary industrial subsectoral level of detail, these studies lack the possibility to be connected to a greater picture regarding the challenges of attaining industrial climate neutrality because their methodologies and applied balance borders are limited to the specific subsector under investigation and therefore differ greatly.

Some studies on the transformation towards climate neutrality investigate and discuss the role of a single specialised or very limited number of technology pathways, e.g. electrification [17,18], the use of biomass [19,20] or hydrogen [21]. However, due to the much wider range of process technologies actually available to manufacturing industries, these studies cannot depict a holistic transition pathway for entire subsectors or the overall sector.

In comparison to the aforementioned publications, studies focused on several or all subsectors of manufacturing industry considering a large array of technology pathways can present a broader, more holistic overview of transformational options in manufacturing industries. In many cases, due to their large lever towards climate neutrality, the energy-intensive industries iron and steel, chemicals and non-metallic minerals are investigated more deeply by also taking into account process-related energy consumption and emissions. For example, Sánchez Diéguez et al. [22] provide four distinct technology-driven scenarios for the total of Dutch manufacturing industries. Similarly, Fleiter et al. [23] and Schneider et al. [24] use bottom-up modelling tools to calculate transition scenarios for the German industry, taking into account stakeholder information on process peculiarities in the modelling phase based on preliminary results. These and subsequent analyses for Germany are generally embedded in an analysis of the overall energy system making use of a combination of modelling tools [25,26]. This approach merits the big advantage of providing a one-stop-shop for policymakers and a bird's eye view of the energy system under the given scenario narratives – something that is extremely useful in times of uncertainty and demand for quick action. These studies can further be aided by stand-alone publications that are able to underline the lever of technologies and energy carriers of one specific economic sector, in this case the manufacturing industries. This enables a broader stakeholder community – besides policymakers also industrial decision makers and technology officers – to investigate the impact of technology choices in their specific subsectors also when they are not part of the energy intensive industries.

Regarding the formulation of scenario narratives, to the best of our knowledge, industrial stakeholder integration into scenario development has never gone beyond the stage of consultations based on preliminary results of already determined scenario narratives. In above-mentioned group of publications, scenario narratives are focused on emphases on the deployment or sourcing of specific energy carriers (e.g., import/export, electrification, e-fuels), target states (e.g., climate neutrality or GHG reduction by target year) or a combination of these target narratives.

Stakeholder interaction has been recognised as an established and essential tool in all these modelling projects to ensure applicability, understanding and acceptance. However, stakeholder interaction, especially with regards to the manufacturing industries, has not been extended to find reflection in the form of a scenario focus. Under the impression of increasing national and international legislature with regards to GHG mitigation and energy efficiency, many industrial stakeholders already have transition plans on their tables. Their application into scenario modelling and subsequent unioning into subsectorspecific or subsector-overarching scenario results can reduce the risk of developing visions of a climate-neutral future that significantly differ from the industrial realities. In addition, comparison of the resulting pathway of industrial stakeholders with the desired climate neutrality scenarios can enable identification of manufacturing industries' needs to ensure successful transition.

Because of the apparent large lever of action in the industrial sector, reflected by the multitude of studies and approaches mentioned above, it is important to gain a maximum of subsectoral detail while at the same time preserving the possibility for a broader systemic analysis. Therefore, we deduce that the development of innovative and need-orientated industry pathways with a maximum of information content for decision makers must include the following.

- A subsector-resolved analysis of the whole manufacturing industries sector. Homogenous subsectors – e.g., the iron and steel or the chemical and petrochemical industries – must be investigated on the level of their most dominant industrial production processes considering both transformation processes and final energy-application.
- An indication of resulting energy-related and process-related GHG emissions per subsector, both directly within industrial production and the upstream energy supply sector.
- A methodological integration of industrial stakeholders by means of an "industry scenario" which reflects first-hand industrial development expectations. The aim is to guarantee applicability of results in all subsectors both for industrial and political decisionmakers and prepare the basis for the subsequent implementation of developed pathways towards climate neutrality. By considering first-hand information on already planned transformations, this approach significantly differs from a business-as-usual scenario or "with existing or additional measures" - scenario approaches which have already been often used in literature to assess the changes brought about by the planned policy measures.

To address these points, we have chosen Austria as a case study. With industries' contribution to national GDP of approximately 25 % well above the European average and high shares of energy intensive primary industries, Austria is a prime example for a highly industrialised economy. In Austria, total manufacturing industry 2019 accounted for approximately 27 % (133 TWh/a) of national gross domestic energy consumption when adding transformation input to combined heat and power plants (CHPs), blast furnaces (BF), coke ovens, and for chemical production to final energy consumption [27]. At the same time, the sector directly contributed approximately 34 % (27 Mt CO_2e) of national GHG emissions [28].

In section 2, we present and explain in detail the applied methodology of devising energy consumption scenarios and calculating associated GHG emissions for the case study. Subsequently, in section 3, the results of our scenarios for the total of Austrian manufacturing industries are shown and comparatively discussed before we discuss current limitations and necessary future work in the field of manufacturing industries and finally conclude this work in section 4.

2. Methodology

For the definition of our subject of investigation we have used the 13 subsectors of manufacturing industries as classified by the United Nations and shown in Table 1 [29].

In this section, the general scenario development methodology is discussed, and important aspects are highlighted specifically. In section 2.1, the chosen balance border is presented to account for the overall energy demand in connection with manufacturing activity. The calculation of energy and GHG emission scenarios follows a two-step process. First, in section 2.2, the chosen scenario storylines are discussed which set the basis for the calculation of the technology-resolved energy consumption results. The resulting energy demands by subsector represent only demands – without consideration of limiting factors such as infrastructure or energy resource availability which are considered in the discussion of results in section 3. Due to the close interlinkage of the manufacturing industries' energy sector with the overall energy system, it is necessary to apply assumptions on the GHG intensity of the electricity and gas grids in a subsequent step. The applied methodology and results for this step are presented in section 2.3.

Further details are available in the report of the corresponding project NEFI – New Energy for Industry [30], in the course of which this work was carried out.

2.1. Application of an integrative balance border

The investigations within this work are based on a balance border around the industrial sub-sectors (cf. Fig. 1). This allows the examination of both total energy consumption and emissions in each of the industrial subsectors *and* the total of manufacturing industries per reference year. To be able to devise subsector-specific pathways towards climate neutrality, a thorough understanding of their process route related challenges and opportunities is essential. This can only be achieved when the investigated balance border is clearly defined and includes the whole manufacturing activity including both final energy applications and transformation units. Fig. 1

Table 1
Applied division of manufacturing industries into subsectors [29].

Subsector
Iron and steel
Chemical and petrochemical
Non-ferrous metals
Non-metallic minerals
Transport equipment
Machinery
Mining and quarrying
Food and tobacco
Paper, pulp and print
Wood and wood products
Textile and leather
Construction
Industries not elsewhere specified

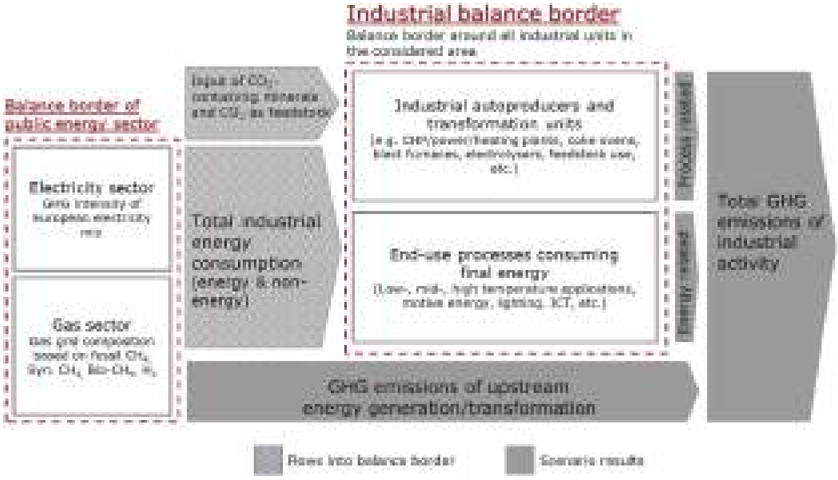

Fig. 1. Considered balance border of manufacturing industries and relevant upstream processes.

depicts the relevant processes for industrial energy consumption and GHG emissions. Herein, for the first time, industry scenarios are prepared following the proposed improvements to international standards of energy balances proposed by the authors in Ref. [31].

Total industrial energy consumption is, as mentioned, determined in situ by two general consumer categories located inside the balance border surrounding all industrially owned final 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. For their application, we have defined five energy application categories – low, medium, and high temperature thermal demand, motive power demand and energy demand for lighting and information technology. On the other side, industries utilise energy for their energy transformation units, e.g., CHP or power plants, blast furnaces, coke ovens, or electrolysers, and as a non-energy use feedstock, e.g., methane or hydrogen for the production of chemicals [30]. Due to the large synergies and future deepening integration into industrial processes, these energy conversion facilities must be included in an industrial energy system model. However, many of these units (e.g., electrolysers) may in the future be operated either inside the presented industrial balance border or inside the energy sector. Therefore, in the results section, we present this energy consumption in the case of electrolysis for hydrogen production in shaded bars as it is directly affecting the magnitude of industrial decarbonisation efforts.

Investigated GHG emissions comprise energy-related and process-related emissions. Energy-related emissions stem from the combustion of fossil energy carriers. Process-related emissions are caused by industrial energy transformation processes (e.g. blast furnace or chemical production (especially CH_4 and N_2O) in line with official methodology of the Austrian national GHG emission inventory report [28]) or by carbonaceous minerals in the production processes (e.g. $CaCO_3$ for cement production). Additional emission sources (e.g., from product use, for example hydrofluorocarbons (HFC), or minor emissions of perfluorocarbons (PFC), SF_6, or NF_3) are not investigated in this study. Besides alternative production technologies and energy carriers, also carbon capture technologies can reduce the GHG intensity of a subsector (e.g., non-metallic minerals). In the chemical industry, CO_2 may be used as an alternative carbon source in the future in which case we count this CO_2 as negative emissions in the chemical subsector. Special care must be taken when calculating the aggregate CO_2 emissions of manufacturing industries. In this case, captured CO_2 from a subsector employing carbon capture but not directly using this CO_2 within its own balance border and instead passing it on within the balance border of manufacturing industries must not be double counted.

As pointed out in the NEFI project report [30], upstream production of energy carriers in the public energy sector, for example

Table 2
Overview of applied investigation level by industrial subsectors.

Industry subsector	Bottom-up modelled manufacturing units	Top-down modelled energy application
Iron and steel	Primary and secondary steelmaking including downstream processing	
Chemical and petrochemical	Ammonia Nitric acid, urea, fertiliser Methanol Olefins	
Non-metallic minerals	Cement production Magnesia production	Clay, glass, lime, ceramics, and auxiliary energy application
Paper, pulp and print	Paper/pulp production, including CHP deployment at integrated plant sites	
Remaining subsectors (non-energy intensive, heterogenous)		Fully modelled top-down based on energy application categories

through the combustion of gas for electricity generation, may add to the GHG intensity of industrial production. We have followed internationally established practice of companies reporting these *scope 2* emissions under energy audit regulations [32]. Therefore, while not directly inside the industrial balance border, these emissions are included in the investigation of industry transformation to avoid moving the challenge of decarbonisation from one sector to another.

Based on the above-described balance border, each subsector is analysed for its current energy consumption, the supplied useful energy categories and transformation processes as well as related GHG emissions. While all subsectors are investigated separately, the homogenous and energy-intensive subsectors iron and steel, chemical and petrochemical industry, the non-metallic minerals and paper, pulp and print are investigated in addition on the level of deployed production processes (e.g. blast furnaces, steam reformers, CHP plants, etc.) Table 2 provides an overview of the considered processes in these sectors. The change in modelled production activity, which is an essential factor for these investigations and has therefore been included in the stakeholder consultation process, are given in Figure A 6 and Table A 1 in the appendix, respectively. Circular economy measures, on the other hand, are not considered in the herein presented investigation.

The employed analysis is based on statistical information available from the Austrian statistics authority Statistik Austria and subsector-specific reports, e.g., from subsector interest groups. In addition, scientific literature on best available (BAT) and breakthrough technologies (BTT) is consulted which has been investigated by the authors in previous works [33,34]. Investigation of the status quo is further strengthened with extensive desk research and expert interviews regarding technological options for GHG mitigation and climate neutrality. The compiled subsector briefings can be found in the project report [30]. The obtained picture of industry subsectors serves as the basis for the subsequent scenario development.

In the iron and steel subsector, two different steelmaking technologies are currently used in Austria: primary steelmaking using the blast furnace/basic oxygen furnace route (BF/BOF) and secondary steelmaking using EAFs. Between 2017 and 2019, the Austrian steel industry produced between 6.9 Mt (2018) and 8.1 Mt (2017) of crude steel per year, of which 90 % was manufactured via the BF/BOF and 10 % via the EAF route [35]. For scenario modelling in this subsector, the total steel production as well as the share of secondary steelmaking by way of EAF through to 2050 is kept constant throughout the modelled timeline to the value of 2017 production in accordance with the communicated plans of the only Austrian company in primary steel production (cf. subsector details in the appendix).

The production of ammonia, urea, fertiliser, nitric acid, methanol and olefins is modelled bottom-up to account for the non-energy consumption of approximately 44 % of the subsector's total energy consumption with activity rates taken from Windsperger et al. [13]. From its total energy carrier consumption of 30 TWh in 2019 over 95 % is currently fossil, mostly naphtha and natural gas. The subsector's production output is set to increase annually by 1.3 % on average in the model. Concordant standard statistical classification, we do not include refineries in the chemical and petrochemical industry as it is accounted for in the energy industries [29].

The Austrian non-metallic minerals subsector represents the second-highest subsector emissions in Austria and can be divided into several areas of production. The production of cement and magnesia specifically accounts for more than 70 % of the total subsector's emissions [28]. Due to their high share of geogenic emissions from mineral resources, these manufacturing units are modelled bottom-up while the remaining energy areas of production are investigated based on their areas of energy application. In general, under consideration of stakeholder feedback on expected activity, production output was kept constant at the levels of the recent past (2017–2019) as published in the Austrian national GHG inventory report [28].

With a total energy demand of over 22 TWh/a, paper, pulp and print is the second most energy-intensive industrial subsector in Austria and responsible for approximately 2 Mt CO_2e GHG emissions. Although all GHG emissions in the paper, pulp and printing sector are energy-related, the sector has a special position in the consideration of GHG emissions because the chemical pulping of wood produces black liquor as waste within the sector boundary. However, subsequently it becomes an energy carrier which is used in companies' own CHP plants to generate electricity and heat. This peculiarity of the sector currently saves considerable amounts of externally purchased energy sources and must be considered in all climate neutrality considerations. Production activity is modelled based on an average annual production increase of 0.2 %/a, both for paper and pulp.

The remaining energy applications in the energy intensive subsectors and the remaining non-energy intensive subsectors are modelled top-down based on the projection of economic activity and the above-mentioned energy application categories – three temperature levels of heat, motive power, and lighting and information technology (IT). To project economic activity into the future, high-level studies on the economic development of Austria are used as a proxy for future production activity. The compound activity growth follows the adopted GDP growth over the study period. For robustness the model starts with historical GDP data from the period 2017 to 2019 with a total value of 360.14 billion $€_{2017}$ in 2017 and growth rates of 2.4 % in 2018 and 1.6 % in 2019 [36,37]. For the following years, growth rates between −6.6 % in 2020 and 1.6 % after that until 2050 over the years and subsectors were used on average, varying only slightly between sectors [38,39]. The subsector-resolved results for the development of economic activity are presented in Fig. 2 (cf. Table A 2 in the appendix for absolute values 2019). Food and beverages, as well as wood and the transport and machinery subsectors are modelled with the highest increase in production activity. Heavy industries, such as construction, mining, or non-ferrous metals, as well as the top-down considered areas of the chemical and petrochemical industries are assumed in the midfield with industries not elsewhere specified trailing with the lowest activity increase.

Subsequently, the respective GDP data is translated into energy demands via sector-specific energy intensities as presented in Table A 3 to Table A 5 in the appendix. This approach takes into account yearly efficiency gains, differed by application category – thermal, motive power, and lighting/IT – and scenario.

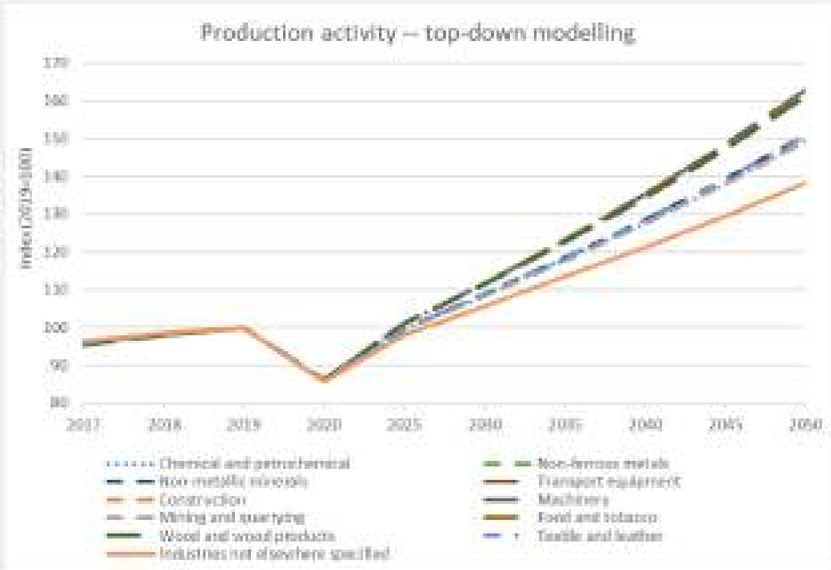

Fig. 2. Assumed development of production activity for top-down modelling.

2.2. Energy consumption scenarios

Three scenarios for future industrial technology deployment and resulting energy consumption are developed and calculated based on three distinct storylines as outlined below and also described in the report of the NEFI – New Energy for Industry project [30]. To guarantee applicability of chosen processes and technologies, respectively, scenario development was performed in a continuous feedback loop with industrial stakeholders. Note that the chosen scenario set differs from the set of above-mentioned existing transformation studies who follow a narrative set within the forcefield between the use of electrons vs. molecules as energy carriers [25]. We choose a different approach. Starting off from a baseline scenario to serve as a statistical reference point into the future, the two transitional scenarios aim to contrast current ambitions by key stakeholders within manufacturing industries against one technologically balanced deep decarbonisation scenario.

The scenario **Business as usual (BAU)** represents a trend scenario in accordance with the methodology put forth for such scenarios by Ducot and Lubben [40]. It serves as a reference scenario, allowing the evaluation of the effectiveness of innovative technologies in the two remaining scenarios. BAU is obtained by extrapolating historic statistical trends on the deployment rate of technologies within manufacturing industries and economic development forecasts. Announced but not yet implemented projects as well as any policy measures that have not already had a significant effect on past energy and emission statistics are not reflected in this approach. This puts the scenario in contrast to a "with existing measures" (WEM) scenario which would include forecasts based on current policies.

The scenario **Pathway of industry (POI)** represents a foresight scenario composed by a methodology as proposed by Martin [41]. It is the result of a close dialogue with technology officers from representative companies from all thirteen investigated subsectors, who have provided their plans and assessments of the technology deployments in their respective subsectors under current and foreseeable boundary conditions through to 2030. Development to 2050 is extrapolated on this basis and considers expected technology readiness. This extrapolation emerges from a tightly knit, workshop-based collaborative process, further involving the above-mentioned stakeholders. Initially, we formulated proposals based on preliminary studies (e.g. Rahnama Mobarakeh and Kienberger [34,42]) assessing the suitability of technologies for achieving climate neutrality. Subsequently, these proposals were synthesised in conjunction with the stakeholders to chart the course of further development up until 2050. The collaborative nature of this process ensures a comprehensive and holistic perspective, incorporating both scientific expertise and stakeholder input. The resulting scenario serves as a valuable framework for understanding and planning the trajectory towards climate neutrality in the coming decades. It is a unique and innovative representation of current industrial transformation plans in Austria and therefore well equipped to identify important areas of policy action in efforts to achieve climate neutrality. It thereby goes well beyond established stakeholder consultations known from existing scenario studies.

The scenario **Zero emission (ZEM)** is obtained by a backcasting approach as proposed by Robinson [43] to reach climate neutrality in 2050. This means that, starting from the target state of widespread adoption of deep decarbonisation technologies identified by Rahnama Mobarakeh and Kienberger [34,42] for the energy intensive industries and BAT-documents for general energy application in non-energy intensive subsectors (e.g., on energy efficiency [44]), a reverse pathway is developed indicating the steps leading to the successful achievement of the goal of far-reaching climate neutrality. Due to the chosen methodology of taking into account emissions of the upstream energy generation for industrial activity, it is important to note that complete industrial climate neutrality may not be achieved just through the modelled technology deployment. Nevertheless, the scenario represents the implementation of extensive and ambitious measures that can transform Austria's industrial energy system. Table 3 presents an overview of a selection of considered

Table 3
Applied BTT by subsector in scenario ZEM.

Industrial subsector	Applied technologies	Current TRL	Start of scenario deployment
Iron and steel	Primary steelmaking by H-DR-EAF	7	2030
Chemical and petrochemical	H_2-based primary production of methanol and olefins	8	2030
	Biomass-based primary production of methanol and olefins	8	2030
	H_2-based ammonia production	8	2030
Non-metallic minerals	Carbon capture of geogenic emissions by oxyfuel technology implementation	6–7	2025
Paper, pulp and print	Extensive heat pump application for temperatures up to 200 °C	7	2025
	Black liquor use in integrated mills with CHP plants	9	Deployed
All subsectors (selected technologies)	Extensive electrification by low (LT) and high temp. (HT) heat pumps	LT: 9	LT: Deployed
	Direct electric heating	HT: 7	HT: 2025
	Electric engines	9	Deployed
		9	Deployed

technologies, their assumed current technology readiness level (TRL) and the point of market entry modelled in scenario ZEM which were chosen from the above-mentioned subsector briefings and technology assessments. Due to the modelling timesteps of 5 years, the earliest possible market entry date for any future technology is 2025. The years in between the considered timesteps where deployment may begin to occur are not depicted. In the case of low temperature heat pumps, direct electric heating, electric engines, and other already existing low-emission technologies (e.g., solar thermal or district heating), deployment is modelled starting with the base year.

It is important to stress here once again, that the resulting scenario demands are not limited by additional framework conditions regarding the availability of energy or enabling infrastructure – except for scenario POI where these are reflected in industrial stakeholders' feedback.

2.3. *Calculation of GHG emissions*

Once energy consumption based on deployed technologies and type of energy carrier (e.g., electricity versus gas) is calculated based on the three scenarios, the energy consumption results are expanded with specific emission factors for energy-related, process-related and upstream emissions. In combination with the industry-focused measures considered for processes (e.g., novel process chains for steelmaking or in the chemical industry) and technologies (e.g., heat pumps or carbon capture technologies, among others) in already existing processes, a widely climate neutral supply side is essential if the manufacturing industries are to decarbonise. This includes, in particular, renewable electricity and gases as infrastructure-bound energy carriers. In the gas sector especially, changes in in-grid gas composition can affect the energy-related emissions intensity of the aforementioned energy consumption results. The applied methodology for the infrastructure-bound energy carriers is presented in 2.3.1 Gas grid and 2.3.2 Electricity grid.

In European industry, approximately 42 %[1] of direct industrial GHG emissions are caused by process-related emissions, e.g. from primary steelmaking in blast furnaces or the use of carbonaceous materials such as $CaCO_3$ in the non-metallic minerals sector [5]. Therefore, in addition to the consideration of energy-related emissions, their consideration is a centrepiece of the here-presented scenario development. For their calculation, specific emission factors per production technology were applied on subsectoral and process level in t CO_2/t of product output. The considered subsectors include iron and steel, the chemical and petrochemical industry, non-metallic minerals, and paper and pulp.

Emissions from the incineration of carbonaceous energy carriers in final energy applications are calculated according to official specific emission coefficients as published by the Austrian environmental agency (UBA) [28]. For emissions from gas combustion, our methodology offers a novel approach to calculation of industrial emissions of the previously calculated demand for chemically stored gaseous energy.

2.3.1. *Gas grid*

Where industries are supplied with energy via the gas grid, the in-grid gas composition varies due to larger developments within the overall energy system in the considered time frame to 2050. Therefore, the current exclusively CH_4-transporting gas grid is gradually transporting a more and more diverse mix of fossil CH_4, bio-CH_4 and hydrogen. We have applied a separate methodology for modelling the in-grid gas composition in the three scenarios as outlined in the corresponding project report [30] and summarised below. Thereafter, the above-mentioned emission intensities are applied to the respective fossil CH_4 content where necessary. Upstream emissions from biomethane are excluded. As Majer et al. [45] point out, the GHG mitigation potential of biomethane in comparison to its fossil counterpart varies depending on the production pathway between 51 % when utilising maize silage and 202 % when production is slurry-based which generates its high mitigation potential from avoiding emissions from untreated slurry.

The evolution of the overall gas supply system's composition is driven by increasing CO_2-costs and decreasing costs for electrolysis production of hydrogen due to learning and scaling effects. To adequately model the available quantities of bio-CH_4, fossil CH_4 and hydrogen, a cost-based methodology to assess the composition of the Austrian gas grid in scenarios POI and ZEM was chosen. While in

[1] including emissions from product use (e.g., HFC) which is not investigated in the present study.

BAU industry-focused technology deployment and therefore also resulting energy consumption follows the statistical extrapolation approach explained in section 2.2, the available in-grid gas composition for final energy consumption is modelled in accordance with current national government targets for 2030 and their linear extrapolation until 2050. In this case 56 % fossil CH_4 (energy share) remains in the overall gas supply system without consideration of costs.

In scenarios POI and ZEM, renewable gases reach cost parity with fossil CH_4 between 2035 (ZEM) and 2045 (POI) and fossil gas is phased out. This means that in contrary to BAU scenario, the overall gas supply system does not contain any fossil CH_4 from these points onwards. The admixture of hydrogen and bio-CH_4 in the gas system from the year 2025 represents a transitional path with focus on reaching climate neutrality of the gas system by the time of the respective break-even point (BEP). It should be noted that the BEPs do not serve as specific input for dedicated H_2-grids, but as an indicator that these become more and more widespread as we reach the BEP.

The considered carbon price development considers the price for carbon emissions which has been charged starting in July 2022 as part of the Austrian eco-social tax reform. As Table 4 visualises, the CO_2 tax is set to be 30 $€_{2017}/CO_2$ in 2022 and 55 $€_{2017}$/t CO_2 in 2025 [46]. The further development of the CO_2 prices corresponds to the assumptions according to the EU commission's guidelines for scenario WEM 2017 (for POI) and scenario Transition 2017 of UBA for ZEM [47].

To calculate the available shares of each gas, *total gas consumption* for Austria is modelled in the first step. For the industrial sector, the herein-modelled industry scenario results – both for bottom-up manufacturing and top-down calculations – are used, while all other sectors (e.g., buildings and transport) are covered using the above-mentioned reports prepared by the Austrian environmental agency.

To merge the gas system modelling with bottom-up industry sector results (e.g., in iron and steel and chemical industry) in the second step, already defined – i.e., technologically required – gas types in these sectors (e.g., H_2 in iron and steel) are subtracted from the overall gas system results. The process to calculate remaining energy amounts per gas type is visualised by eq. (1), with *t* representing each of the three distinct gas types, fossil CH_4, bio-CH_4, and H_2, respectively.

$$E_{t,Gas\ Grid,rem.} = T_{t,Total} - T_{t,Bottom-up} \tag{1}$$

The remaining renewable gases comprise the in-grid gas mix visualised in Fig. 3, available to all users connected to it, i.e., also non-industrial users. This gas grid is a virtual representation of all physical grids that remain after subtraction of dedicated pipelines for the energy-intensive users already considered bottom-up. In scenario BAU, after subtraction of H_2-consumption modelled in the iron and steel industry, extrapolation of government targets results in a 35 % share of renewable gases by 2050, of which 20 % points are provided by hydrogen. In scenario POI, the iron and steel industry and chemical and petrochemical industry rely predominantly on CH_4-based production processes (cf. exemplary subsector results in the appendix). Therefore, by 2045, only hydrogen remains for supply to customers connected to the gas grid. In individual cases, the modelled in-grid gas composition means that if hydrogen from the overall gas grid is not suitable due to flame specifications, (carbonaceous) H_2 derivatives must be produced on-site. In scenario ZEM, processes modelled bottom-up for iron and steel and the chemical and petrochemical industry rely more strongly on H_2. 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.

2.3.2. *Electricity grid*

As mentioned in section 2.1 above and the corresponding project report [30], in our proposed methodology, we include the GHG emission intensity of upstream electricity generation to avoid merely moving the challenge of decarbonisation from one sector to another. Thereby, we are reflecting the interdependencies between industry decarbonisation and the Austrian electricity system as well as Austria's shared dependencies with the ENTSO-E network. To provide an estimate of the actual GHG intensity of industrial transformation, a decarbonisation path for the electricity system formulated by the European Commission for the EU-27 in Scenario MIX is used as basis [48]. Since the GHG-intensity of the Austrian electricity sector has historically been lower than that of the Union, we used the Austrian case as the starting point according to Ref. [49]. Thereafter, the European development as percentage from 2020 onwards is applied. The derived GHG emission development is illustrated in Fig. 4. Starting from 0,19 t CO_2e/MWh of electricity consumed in 2019, the chosen approach results in a reduction of approximately 93 % to just 0.015 t CO_2e/MWh by 2050.

3. Case study results and discussion

While we have modelled the Austrian manufacturing industry based on subsectors and in some cases as explained above on a manufacturing level within these subsectors, in this section only the aggregate of all investigated subsectors is presented and discussed to preserve conciseness. Exemplary subsector results for iron and steel, chemical and petrochemical, and non-metallic minerals where investigations on a manufacturing level are of special importance, as well as machinery as an example for non-energy intensive subsectors can be found in the appendix. The report of the project NEFI – New Energy for Industry in the course of which the

Table 4
Assumed CO_2 prices in €/t CO_2e until 2050 in scenarios POI and ZEM [47].

	2025	2030	2035	2040	2045	2050
POI [€/t CO_2e]	55	76	94	112	155	198
ZEM [€/t CO_2e]	55	85	111	138	203	268

Fig. 3. Considered in-grid gas composition (a) and resulting emission factors (b).

methodology in this paper was developed, provides a collection of all subsectoral results [30].

Development for the aggregate of Austrian manufacturing industry is shown in Fig. 5. As visible, scenario BAU does not achieve meaningful GHG emission reductions compared to the base year. Due to assumed increasing economic activity, total energy consumption is further rising to up to 161 TWh (including 5 TWh of transformation losses for hydrogen production). Only the underlying decarbonisation trend in the electricity and gas grid does have a countereffect on emissions and can account for a reduction of approximately 5 Mt CO_2e/a. In POI and ZEM on the other hand, fossil fuels with high emission intensities, most notably coal, oil, and fossil waste, are phased out and eventually replaced completely by less GHG-intensive or CO_2-neutral alternatives. Emissions already decrease by approximately 35 % in both scenarios in the period between 2025 and 2035.

Total results in scenario POI indicate that, based on a technological approach, a GHG emission reduction of Austrian manufacturing industry larger than 92 % compared to 2019 until 2050 is possible if the transformation plans stated by industry representatives are taken into account and enabling conditions – especially in the form of a largely climate neutral energy supply system – are met. In comparison to scenario BAU, this is especially true for the gas grid where close to 60 TWh of largely climate neutral gases are needed by 2050. In the electricity grid on the other hand, further decarbonisation development until 2050 has a smaller impact due to already low emission intensities in the Austrian electricity sector. Most notably, widespread agreement exists among subsector representatives from different companies on the currently envisioned most important technology pathways and energy carriers for their respective subsectors. Total energy consumption in the scenario rises from 135 TWh to 151 TWh (168 TWh when electrolysis losses are included). Solid biomass consumption increases by 18 TWh from 17 TWh today to over 35 TWh by 2050. Approximately 48 TWh of final electricity consumption is projected by 2050 which signifies an increase of more than 22 TWh from 26 TWh in 2019. In the non-metallic minerals sector, over 3.7 Mt CO_2e are captured by 2050. Some of this CO_2 (1.8 Mt) could be utilised in the chemical

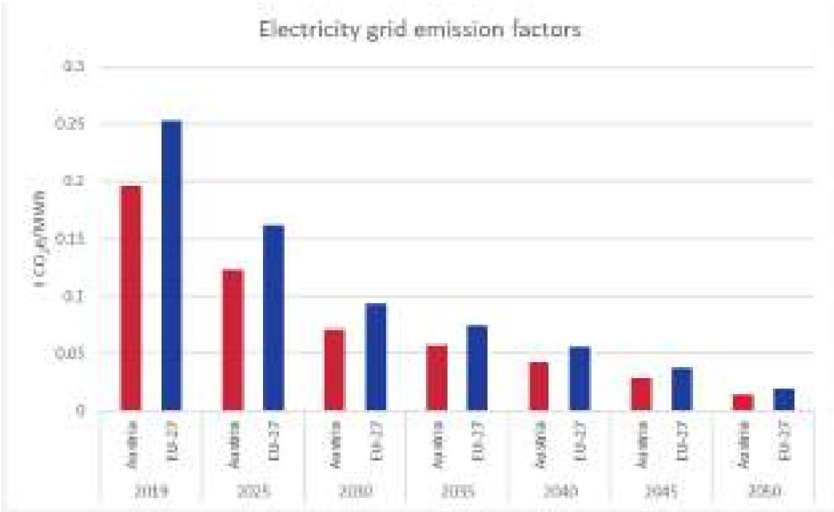

Fig. 4. Assumed electricity grid emission factors development based on data from Ref. [50].

industry to produce methanol and olefins. While this combination has not been further investigated in this study, it is apparent, that due to the resulting gap between CO_2 supply and demand within the manufacturing industry, storage and export strategies for captured CO_2 will be needed.

In scenario ZEM, the modelled technology deployment relies strongly on hydrogen, especially in the energy intensive subsectors iron and steel and chemical and petrochemical industry. By 2050, GHG emission mitigation of 92 % can be realised when including upstream electricity demand and associated emissions for hydrogen generation. Due to the largely decarbonised nature of all other energy carriers, these upstream emissions have a significant effect on the resulting emissions as visualised by the black diamonds in the figure. An especially large decrease of emissions can be observed between 2035 and 2040 due to both hydrogen reaching the BEP with fossil CH_4 and large production volumes in iron and steel being moved from the BF/BOF route to H-DR-EAF. Total energy consumption rises to approximately 172 TWh by 2050, with more than 20 TWh from electrolysis losses already accounted for. Similarly to scenario POI above, solid biomass and electricity consumption both increase by approximately 20 TWh each in comparison to the base year. In comparison to POI, CO_2 uptake by the chemical and petrochemical industry is higher due to the modelled deployment rate of H_2-based methanol synthesis. By 2050, 2.6 Mt of CO_2 are used in chemical production processes. In comparison to 3.70 Mt CO_2 captured in the non-metallic minerals, the annual demand for net storage or export capacities is reduced to approximately 1.1 Mt CO_2.

Fig. 6 presents another angle of investigation by showing the difference in results for scenarios POI and ZEM as a delta in comparison to the baseline scenario BAU. The bottom diagram represents GHG emission deltas, while the top diagram shows resulting deltas for total industrial energy consumption. Until 2025, the total energy consumption and GHG emissions in POI and ZEM scenarios largely follow the BAU scenario. From 2025 onwards, POI and ZEM exhibit differing technological pathways from BAU, resulting in contracting GHG emissions and a differing structure of energy carriers. As evident from comparing the results for scenarios POI and ZEM, Austrian industry representatives by-large already do envision a low emission pathway for their respective subsectors. While relying on different technologies, resulting energy consumption and GHG emissions in the two scenarios over the aggregate of subsectors are actually very similar. However, as exemplary visualised in the appendix, the subsector results for energy carriers can differ significantly between POI and ZEM due to different technology and thus also energy carrier deployment.

In both transition scenarios, energy consumption 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 mostly fossil energy carriers both for energy and non-energy use (e.g., coal, naphtha, oil). To substitute these energy sources, extended production chains are necessary which exhibit greater transformation losses (e.g., H_2 from electrolysis for the non-energy use in the chemical sector, see appendix). Therefore, when considering electrolysis losses, slightly larger total energy consumption can be seen for the POI and ZEM transformation scenarios than for the reference scenario BAU (161 TWh) where upstream energy losses of fossil fuel production are not taken into account. The difference in necessary upstream production chains is also the reason for slightly higher ZEM results for total energy consumption (172 TWh) than can be observed for POI (167 TWh). As ZEM requires greater amounts of hydrogen, more transformation losses for electrolysis occur. This does not only affect the development of energy demand but also that of the associated GHG emissions. Beginning after 2040, when the gas grid in POI has reached the BEP of hydrogen and is thereby largely climate neutral, total GHG mitigation in POI in comparison to BAU is higher than in scenario ZEM. However, if the hatched area of electrolysis losses that may also be situated upstream inside the energy industries, both domestically and abroad, is disregarded, scenario ZEM results in slightly lower energy consumption than POI. The same is true for GHG emissions – without upstream emissions considered, instead of trailing by 0.2 Mt, scenario ZEM leads POI in its mitigation results in comparison to BAU by approximately the same number.

The above-described results, and especially the shown dependencies of manufacturing industries on largely decarbonised upstream energy provision show that large amounts of renewable energy sources (RES) must be made available to Austrian industry. As noted

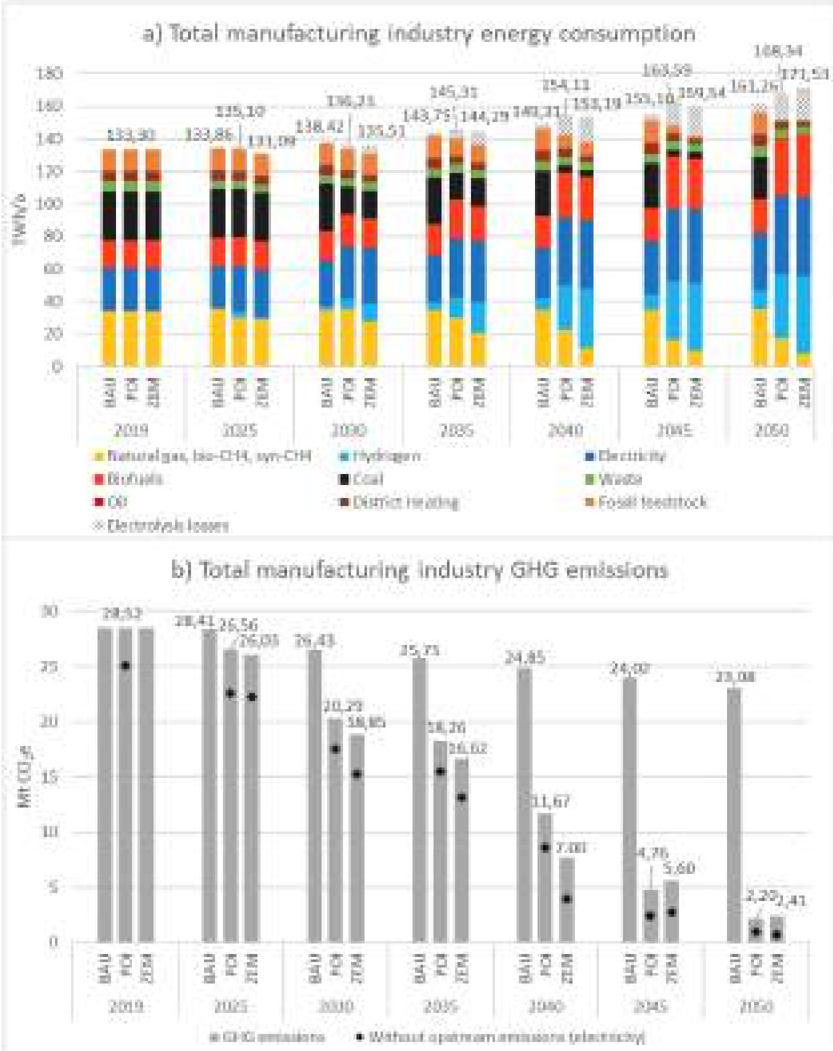

Fig. 5. Total manufacturing industry results for a) energy consumption and b) GHG emissions for scenarios BAU, POI and ZEM.

above, except for scenario POI where industry representatives' assessment of framework conditions implicitly also includes availability of energy sources and infrastructure, no additional limits to energy supply have been considered in the presented demand scenarios. For example, both in scenarios POI and ZEM, 2050 biomass consumption almost doubles in comparison to BAU to up to 38 TWh (ZEM). For electricity applications, approximately 50 TWh of electrical energy for final energy applications is necessary in ZEM; in POI, this category amounts to 35 TWh. Taking into account current total Austrian electricity consumption in 2022 of approximately 64 TWh [27], the magnitude of the challenge of climate neutrality in industry becomes apparent. Current development speed of Austrian RES generation may not be able to fulfil this need. The modelled consumption for 2050 of manufacturing industries alone surpasses the amount Austria has set out to install in renewable electricity generation between 2018 and 2030 (27 TWh), highlighting the need for further efforts in this regard – already now but also beyond 2030 [51]. Besides general electrification efforts, e.g., heat pumps, direct electric heating and for motive power, the electricity consumption is especially driven by the decarbonisation of process-emission intensive subsectors such as iron and steel, the chemical and petrochemical industries, and non-metallic minerals. In these subsectors, the introduction of electric arc furnaces and possibly subsector-overarching carbon capture and utilisation processes signifies an important additional demand. Breakthrough technologies for carbon capture, e.g., oxyfuel, can reduce this amount to a necessary minimum while alternative technologies that are currently more economically viable, have a higher energy demand.

The extensive electrification efforts by use of heat pumps and electric engines also have an important impact on the overall gas consumption. Until 2050, consumption of gases only increases by approximately 10–15 TWh. Most notably, use of gases is shifted from final energy consumption for low or medium temperature and motive power applications to more exergetically-valued deployment as reducing agent and feedstock for non-energy use in basic material production in the chemical and petrochemical industry and primary steelmaking. Overall, approximately 50 TWh (POI) to 64 TWh (ZEM) of climate neutral gases are needed. The applied methodology for the gas grid composition shows cost leadership of renewable gases (mostly H_2) due to rising costs of CO_2 emission certificates and

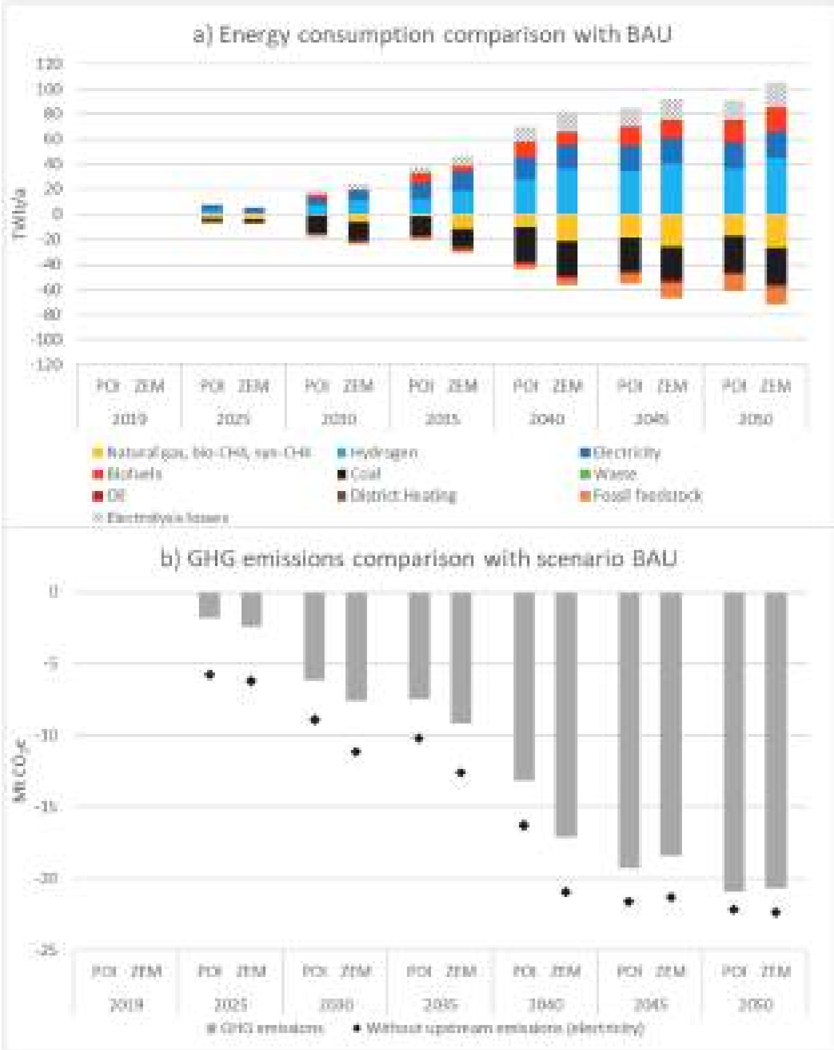

Fig. 6. Total manufacturing industry results for a) energy consumption and b) GHG emissions for scenarios POI and ZEM visualised as difference to scenario BAU.

expectable electrolysis learning and scaling benefits. The combination with the modelled industrial gas consumption exhibits the immense impact and importance of a largely decarbonised gas grid on attaining deep-reaching steps towards climate neutrality in manufacturing industries.

The transition to climate neutrality will rely on the ability of national economies to provide the necessary amounts of energy. Therefore, the industry scenario results developed with energy demand in focus cannot be viewed in isolation but in consideration of the overall energy consumption and supply system. Taking into account the possible additional electricity needs for hydrogen production via electrolysis, total electricity consumption for industrial production in Austria rises from 26 TWh in 2019 to approximately 104 TWh in POI and 116 TWh in ZEM. Sejkora et al. [52] have calculated *technical* potentials of renewable energy sources in Austria to amount to approximately 266 TWh. In contrast, sector-resolved investigation of the most exergetically efficient way of supplying the useful exergy demand in total energy system analyses based on additional investigations by Sejkora et al. [53] reveal up to 41 TWh of electricity consumption and additional 36 TWh of hydrogen demand in the remaining economic sectors (i.e. transport, buildings, agriculture) in Austria. As not all technical potentials can be realised or are economical to use on the path to climate neutrality, a significant import share is highly likely in this case. In light of these limited domestic renewable resources, the consumption scenarios can show decision makers the need to also take into account alternative energy supply, e.g., by means of suitable and reliable import routes and the enabling infrastructure.

The above-discussed developments show that the industrial energy system of the future can operate at almost net zero emissions with the widespread use of three dominating key levers; electrification and general energy efficiency measures, carbon neutral gases and biomass utilisation, and carbon capture and usage as well as storage. Other technology solutions, such as solar thermal, widespread high-temperature electric direct heat, alternative binders for cement production or the deployment of complex bio refinery structures are not necessary according to both industrial stakeholders (scenario POI) and previous scientific investigations modelled by way of scenario ZEM (cf. investigations on industrial climate neutrality by Rahnama Mobarakeh and Kienberger [34,42], Fais et al. [54] and Johannsen et al. [55]).

4. Conclusion

As an especially emission-intensive economic sector but equally important backbone of national wellbeing, the manufacturing industries represent one of the key challenges towards climate neutrality for developed countries. For a successful transition, decision makers both on a political as well as an industrial level, must be able to assess the impact of their measures and actions. Scenario development can play a vital role in this process if able to provide both the necessary level of subsectoral detail *and* a broad understanding of interrelations – among industry subsectors, as well as in relation to the overall energy system where emissions from industrial activity are also dependent on upstream decarbonisation efforts.

When using energy consumption scenarios for long term decision and policymaking regarding technology deployment in manufacturing industries, it is important to link the modelled energy demands with the supply side of energy carriers. As we have seen, while the modelled technologies strongly differ between scenarios POI and ZEM, resulting emissions show much smaller differences – due to the chosen methodology for hydrogen shares in the gas system and the upstream electricity generation. Most strikingly, the results of scenario POI until 2050 show that Austrian manufacturing industries already envision a very progressive technology deployment which comes very close to climate neutrality when assuming a largely climate neutral supply side for gas and electricity. In comparison to the envisioned deep decarbonisation scenario ZEM which is prepared using a balanced deployment of best available and breakthrough technologies, less emphasis is put on energy efficiency in final energy application, and less hydrogen availability is expected. The resulting similarities in aggregate results of the two transition scenarios POI and ZEM underline important areas of action to provide framework conditions to enable far-reaching decarbonisation. Thereby we can raise the relevance of the scenario results for political stakeholders.

4.1. Limitations of current work

Certain areas remain, where this line of research could be further strengthened which we want to highlight. It is of special importance to note that, for successful implementation of the shown methodology, extensive data availability, both from official statistics and industrial stakeholders is key to modelling the investigated industrial system. The presented scenarios incorporate all energy-related units within the thirteen subsectors of manufacturing industries. However, as the approach proposed by the authors in Ref. [31] has not been adopted by official statistics yet, necessary data on subsector level had to be rebuilt from higher aggregation levels, leaving space for uncertainty. Availability of industrial data on consumption aggregates and subsectoral or production plant use of energy transformation units, especially CHP plants, is therefore a current limit and presents great improvement potential for future studies.

In addition, several areas of our chosen approach merit additional discussion and could be taken up in subsequent investigations. Firstly, as noted in the introduction, from our point of view, the focus on the manufacturing industries alone – without an overarching energy system modelling to take into account the necessary upstream energy provision – is better suited to direct the focus of industrial stakeholders and policymakers in the area of industrial policies on matters of technology research and enabling framework conditions. On the other hand, one must acknowledge that this approach must make use of less comprehensive upstream energy system analyses than total energy system reports that embed manufacturing industries as one of many economic sectors. The decision on what pathway to choose – focused on industry with more assumptions on the overall energy system or more subsector-resolved industrial energy system analysis – must be made with a deep understanding of the necessities of the target groups and stakeholders as advantages and disadvantages must be weighed against each other. For example, the assumptions we have made on the GHG intensity of the gas and electricity grids may very well be challenged by more holistic analyses. This includes the range of CO_2 prices reflected in the in-grid gas composition, the neglection of (possibly negative) emissions along the biomethane value chain, as well as the single electricity grid model applied to all scenarios uniformly. The significance of these assumptions has been illustrated impressively by comparison of scenarios POI and ZEM by 2050. To remedy this issue within the proposed methodology, future sensitivity analyses will have to investigate the impact of a range of assumptions regarding the upstream energy generation processes.

Further investigations on climate neutrality pathways in manufacturing industries must take up additional technological focus areas, e.g., widespread adoption of circular economy measures, further electrification efforts also in the areas of high temperature heat, production chains that rely more strongly on e-fuels or investigate the possible impact of technologies with a currently lower TRL. Regarding the sequestration and subsequent use or storage of CO_2, the here-presented study supplied only a basic CO_2 balance where we put captured CO_2 from non-metallic minerals side-by-side with possible CO_2 sinks in the chemical industry. Precise analyses of further CO_2 use in chemical production, future consumers' use and eventual disposal must be conducted in future publications. Based on the here-proposed scenario set, additional industrial representatives can further refine the results and expand the current focus which has been dominated by large key representatives to include more small and medium sized companies. It must also be noted here that scenario POI can be a very dynamic scenario as multiple factors can influence industries' current assessment of future technology deployment. In all these cases, as well as for the existing scenario results, techno-economic analyses will help to further assess the need for enabling policymaking (e.g., funding or market regulation) and expanded R&D activities in industrial subsectors.

4.2. Summary and conclusion

The approach presented in this work aims to provide energy demand and GHG emission scenarios for the transformation of the manufacturing industries that can inform both decision making by industrial stakeholders on a subsectoral level *and* policymaking by virtue of the following three aspects.

1. Application of three distinct scenario narratives, taking into account stakeholder decarbonisation plans.

The applied scenarios allow for the investigation of a bandwidth of possible developments, beginning from trend extrapolation, ranging over assessments of already-planned investments and transformations from the point of view of key industrial representatives to the wide-spread use of scientifically identified breakthrough-technologies with the highest available efficiencies.

2. Use of subsectoral resolution for investigation and calculation of all processes related to the respective primary economic activity.

We calculate energy consumption and GHG emissions of all processes related to the respective primary economic activity, including industrial autoproducers, non-energy use and transformation units. This approach tries to find a happy medium between both a holistic view on the energy consumption of any given subsector on the one side and comparability of results between subsectors on the other.

3. Consideration of upstream energy provision and applicable GHG intensity.

We include a cost-driven investigation of the future in-grid gas composition to indicate the GHG intensity of the necessary gas supply. For electricity, Austria's embedding in the European energy market is considered. This inclusion of upstream GHG emission intensities and transformation input (e.g., electrolysis) allows the necessary investigation of industrial dependencies on the overall energy system. As noted above, it allows a compromise between an industry-centred detailed analysis and a more holistic investigation of the overall energy system of a country which we have discussed in the introduction.

Comparison of the developed scenarios allows for the identification of no-regret measures to enable climate neutrality in manufacturing industries' subsectors by 2050 as set forth by the European Commission – not only from a scientific and technological point of view, but very importantly also from the view of industrial stakeholders who already have certain transformation plans in place. We have identified these measures making one basic assumption: We assume these measures increase the attractiveness of the industrial location due to high technological development and an accompanying enabling infrastructure. Thereby, total cost of production via climate neutral energy and technologies remains but one factor in industries' decision making on future locations of activity. To further investigate the framework conditions regarding the choice on future locations of production, the cost structure of herein identified large technological levers of action for climate neutrality in comparison to the currently deployed fossil base case must be assessed in future publications. For the Austrian case study [30], the following no-regret measures can be identified.

- To achieve climate neutrality, energy-intensive and non-intensive industries require different areas of focus as they stand at different stages of their transformation. Energy-intensive industries need to prioritise researching, developing, demonstrating, *and* rolling out their specific technologies to achieve their targets. On the other hand, the non-energy intensive subsectors need to put special emphasis on accelerating the implementation of already-existing cross-sectoral technologies such as heat pumps to maintain their competitive advantage and stay on track towards climate neutrality.
- For the fast implementation of new technologies in manufacturing industries, not only research and development but *also* demonstration is crucial. Therefore, intensified and accelerated efforts are necessary in both these areas.
- Technological, logistical as well as policy related solutions for CO_2 as a feedstock and with regards to storage options need to be found quickly.
- Supply of renewable energy carriers (especially CO_2-neutral gases and electricity) must be secured to enable industrial transition towards climate neutrality. In light of limited resources that we have discussed above, the utilisation of these energy carriers should be prioritised based on technological requirements as well as temperature or exergy levels (e.g., CO_2-neutral gases for high-temperature processes and process demands, heating and cooling by heat pumps).
- Taking into account other economic sectors, Austria's gross domestic energy demand could surpass the technical potential for renewable energy sources in the country. Therefore, it is essential to develop import strategies, particularly for CO_2-neutral gases and their derivatives, to ensure a sustainable and secure energy supply for the future.
- The energy infrastructure must be updated to align with the aforementioned developments. This includes expanding the capacity of domestic and cross-border electricity grids, as well as building infrastructure for hydrogen and its derivatives.

In conclusion, identified measures can relate to all parts of the energy system, ranging from energy generation and supply, over energy infrastructure, to energy use and the deployed process technologies. As seen in the case study, the model results can be used to derive recommendations on technology promotion needs, infrastructure developments and to identify possible corridors, focal points, and fuel shifts. The applied subsectoral focus makes the results relevant both on the level of subsector representatives and for high level policymakers. To identify infrastructural and import requirements, it is important to contrast resulting energy consumptions with existing regional potentials of RES. Thus, the developed energy consumption and GHG emission scenarios contribute to a better understanding of current and future necessities in the energy system and within subsectors.

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Data availability statement

No data associated with the study has been deposited into a publicly available repository.
Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

P. Nagovnak: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **C. Schützenhofer:** Writing – original draft, Conceptualization. **M. Rahnama:** Investigation. **R. Cvetkovska:** Methodology. **S. Stortecky:** Investigation, Data curation. **A. Hainoun:** Methodology, Investigation, Data curation. **V. Alton:** Data curation. **T. Kienberger:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25382.

APPENDIX

Exemplary subsector results

Complementary to section 3, below we present exemplary results from chosen subsectors. As explained above, the report of the NEFI – New Energy for Industry project in the course of which this work has been carried out, includes detailed results of all thirteen investigated subsectors [30]. The first three subsectors – iron and steel, chemical and petrochemical industry, and non-metallic minerals – belong to the energy-intensive industries. As explained in section 2, in these subsectors the manufacturing units given in Table 2 are investigated and both transformation units and final energy consumption are considered. The finally presented subsector – machinery – serves as an exemplary result for the non-energy intensive industries where cross-sectional technologies such as heat pumps and direct electrification were modelled top-down in accordance with the methodology put forth in section 2.

Iron and steel

The Austrian iron and steel industry is the sixth largest steel producer in Europe and in 2021 accounted for 5 % of European Union's (EU-27) steel production [56]. As can be seen in Figure A 1, in the scenarios' base year 2019, the iron and steel industry consumed in total approximately 35 TWh, corresponding to approximately 9 % of Austrian gross domestic energy consumption. Close to 90 % of this energy comes from fossil fuels, including coal, coke, natural gas, and bituminous coke. Fossil fuels are mainly used for two purposes: as a reducing agent (around 54 %) and as a source of energy to cover heating requirements. Approximately 10 TWh/a or ~30 % of total energy consumption is used for final energy applications, primarily to provide high-temperature process heat in furnaces. Approximately 70 % are utilised in transformation processes in primary steelmaking (blast furnaces, coke ovens, etc.) [27]. Total annual CO_2 emissions range between 10.3 Mt (2019) and 12.6 Mt CO_2e (2017) per year, making the subsector an important contributor to Austria's overall emissions (approximately 14 % annually). The visualised increase in energy demand and GHG emissions between 2019 and 2025 results from the chosen production activity of a total of 8.1 Mt of steel (value of 2017, as shown in Table A 1) which as a conservative approach to activity development is kept constant from 2025 onwards in accordance with the communicated plans of the only Austrian company in primary steel production.

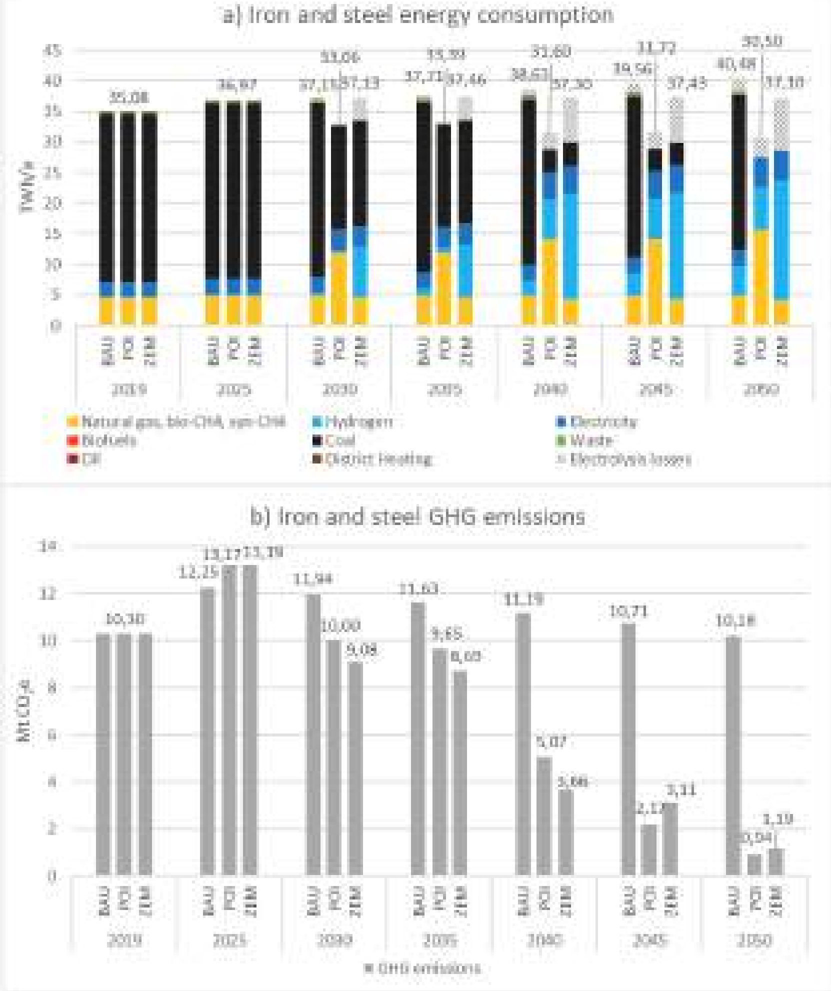

Fig. A 1. Iron and steel results for a) energy consumption and b) GHG emissions for scenarios BAU, POI and ZEM.

Figure A 2 presents an overview of modelled technology shares for steel production in the three scenarios. In all three scenarios, the share of secondary steelmaking via the EAF route has not been varied and remains constant at approximately 0.7 Mt/a, 10 % respectively.

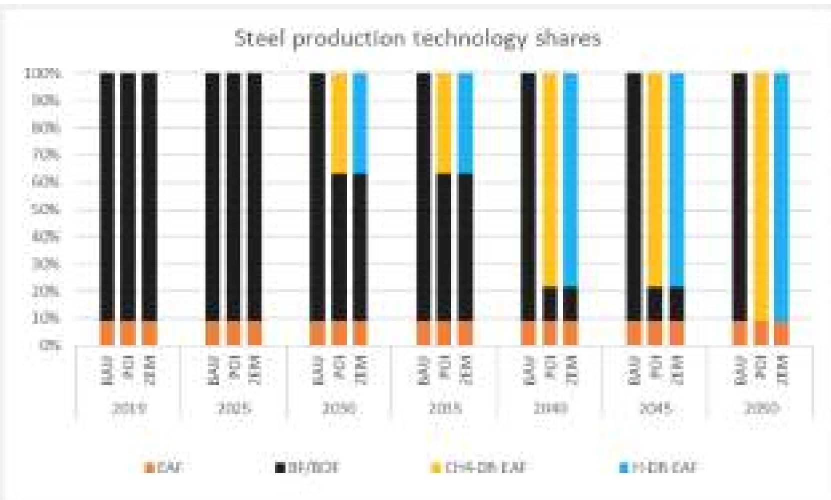

Fig. A 2. Development of technology shares in steel production in scenarios BAU, POI and ZEM.

Scenario BAU does not depict major changes in the mentioned fuel shares of total energy consumption. Reduction of iron ore is supplemented by injection of small shares of hydrogen into the blast furnace beginning in 2025 which are used to decrease the process-related emissions of the currently deployed production route (BF/BOF).[2]

On the other hand, the two transition scenarios POI and ZEM achieve very significant emission reductions of approximately 90 % compared to BAU by2050.[3] The subsector's GHG emission results are most strongly influenced by the scenario-specific technology chosen for primary steelmaking, as well as the upstream emission intensity of electricity and gas supply. POI and ZEM especially differ in applied technology for primary steelmaking. Although CH_4-based direct reduction (CH_4-DR-EAF) is deployed in POI, the difference in GHG emissions remains small due to the modelled decarbonised nature of the gas supply system as described in section 2.3. In addition, hydrogen production through electrolysis drives emissions from the electricity sector's upstream emissions, resulting in higher total emissions in ZEM than in POI. By 2050, approximately 20 TWh of hydrogen are needed in scenario ZEM. This can generate electricity consumption via H_2-electrolysis of more than 28 TWh/a of which transformation losses are presented by the shaded area on top of the bars in Figure A 1. The future location of these upstream energy consumption for hydrogen production may lie either partially or fully in Austria, Europe or, assuming adequate transportation infrastructure, anywhere in the world. In scenario POI on the other hand, the use of biomethane does not result in the same upstream energy losses in our methodology which is advantageous for POI in the shown results.

The greatest decrease in emissions from one 5-year period to the next is caused in the periods 2025–2030 and 2035–2040 by moving approximately 3 Mt of primary steel production each from the BF/BOF route to the DR/EAF technology. In POI, industrial stakeholders envision CH_4-based direct reduction as an already-available technology with an auxiliary share of 30 % H_2 in 2050. On the other hand, in ZEM, BTT by way of H-DR-EAF is deployed.[4] The substitution of traditional BF/BOF production routes in both scenarios starts during the period 2025–2030 and reaches completion after 2045. By 2050, energy consumption in primary steelmaking in both POI and ZEM 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 consumption in POI. The same trend can be observed in scenario ZEM, though slightly stronger due to more progressive electrification efforts.

Chemical and petrochemical industry

Figure A 3 presents the three scenarios' results for the chemical and petrochemical industry. To replace fossil feedstock (naphtha), which is currently non-energy use for producing olefins, in scenarios POI and ZEM, a higher increase in methanol production (for the methanol-to-olefins route) is assumed than in scenario BAU. Therefore, by absorbing up to 4 Mt of CO_2 to produce methanol, the chemical industry becomes a net emission sink with −2 Mt and −4.2 Mt CO_2e in scenarios POI and ZEM, respectively. With reference to the applied balance border discussed in section 2.1, it must be noted that in the case of the subsector investigation of the chemical and petrochemical industries, neither the origin of the captured CO_2 nor the final disposal of products from the subsector are taken into consideration which is why negative emissions can be achieved in the subsector results but not in the overall manufacturing industries shown in section 3.

[2] By injecting up to 20 kg $H_2/t_{pig\ iron}$, the specific process emissions of the BF/BOF route can be reduced from 1.50 t CO_2/t_{steel} to 1.33 t CO_2/t_{steel}.

[3] Approximately 0.75 Mt CO_2e (specific emission intensity 0.08–0.1 t $CO_2/t_{steel)}$ are unavoidable process-related emissions due to EAF deployment, both in POI and ZEM.

[4] Assumed specific energy consumption of H-DR-EAF: 0.58 $MWh_{electricity}/t_{steel}$ and 2.64 MWh_{H2}/t_{steel} [57].

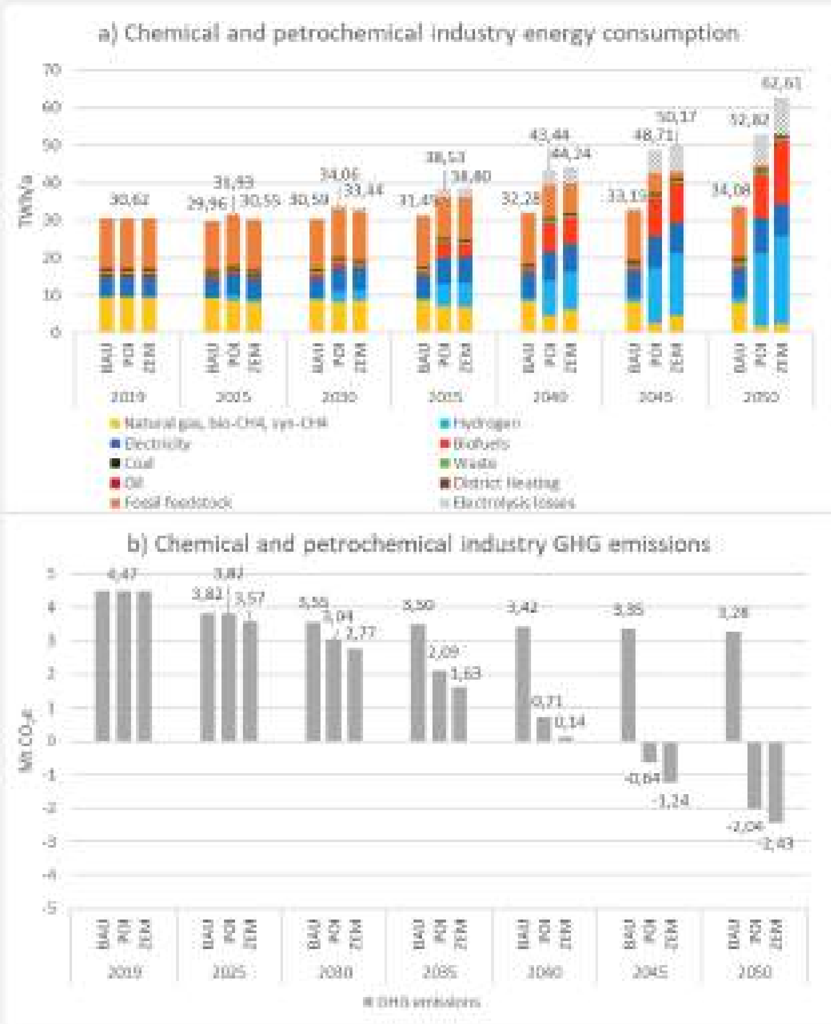

Fig. A 3. Chemical and petrochemical industry results for a) energy consumption and b) GHG emissions for scenarios BAU, POI and ZEM.

The difference of about 2.1 Mt CO_2e in GHG emissions between scenarios POI and ZEM originates from the complete change of the technologies to a hydrogen-based low carbon route of olefin production in ZEM. The effects of replacing the currently imported and energy-dense feedstock naphtha (non-energy use, shown as “fossil feedstock” in the figure above) with methanol by domestically synthesising it from hydrogen and CO_2, increases total energy consumption of the chemical subsector significantly by 73 % in scenario POI and over 100 % in scenario ZEM. The specific emissions change here in the largest product range from 0.91 t $CO_2e/t_{olefins}$ (naphtha sourced) to 0.36 t $CO_2e/t_{olefins}$ when methanol is the feedstock. Transforming methanol production using biomass or hydrogen and CO_2 as feedstock, changes specific emissions from 0.55 t $CO_2e/t_{methanol}$ to −1.37 t $CO_2e/t_{methanol}$. As we have seen for iron and steel above, here too, the large hydrogen consumption generates a strong impact on the upstream energy provision. By 2050, 20 to 23 TWh of H_2 are needed in the subsector alone. This can generate electricity consumption via electrolysis of more than 33 TWh/a. However, the deployment of hydrogen for the production of methanol and its derivatives can offset the occurring upstream emissions from electrolysis which leads to a significant CO_2 sink of 2.6 Mt CO_2 by 2050 in scenario ZEM. This notable resulting forcefield between primary energy demand and emission sink must be taken into account when choosing the future production technologies in the subsector.

Non-metallic minerals

In 2019, the subsector consumed approximately 10.6 TWh of final energy as visualised in Figure A 4. In contrast to the iron and steel or chemical industry, no energy transformation units are deployed in this subsector. The main energy carriers are fossil fuels (51 %) with high shares of natural gas, electricity (24 %) and alternative waste fuels (AWFs, 22 %) [27]. AWFs such as waste tires, and waste oil are currently used especially in the cement production.

In scenario BAU, the challenge of reaching climate neutrality in the subsector remains unsolved, both regarding process-related emissions and deployed fuels. The share of the fossil energy carriers – especially coal and oil – remains high.

Between scenarios POI and ZEM, the deployed technologies for carbon capture present the largest difference.[5] In POI, industry stakeholders report the introduction of carbon capture using readily available amine scrubbing technology, incrementally starting from 2025 onwards. This allows the sector to reduce emissions by up to 83 % in comparison with the base year, sequestrating 3.70 Mt CO_2 by 2050. Due to the deployed carbon capture options' matching CO_2 sequestration rates of 90 %, direct GHG emissions from the subsector do not differ significantly between scenarios POI and ZEM. Staying strictly within the subsector's balance border, after sequestration only storage can be assumed. Additional downstream energy demand for the potentially necessary transport is not accounted for.

In scenario POI, heat consumption of the amine scrubber is supplied by the process' flue gas and the use of heat pumps. The high energy intensity of the chosen technology adds approximately 7 TWh of electrical energy to the subsector's consumption. In comparison, the technology driven ZEM scenario allows for a significantly reduced energy consumption due to deployment of oxyfuel technology instead of the amine scrubbing for carbon capture. For high-temperature applications prevalent in production processes of the subsector, decrease in total gas consumption cannot be observed in either scenario as gas is used as best available technology in accordance with investigations by Rahnama Mobarakeh and Kienberger [42]. In comparison to the base year (10.7 TWh/a), ZEM only shows an increase in energy consumption of 18 %, while scenario POI increases consumption significantly by 55 % to 16.5 TWh/a.

Only upstream emissions in the electricity sector account for a difference between the two transition scenarios. However, by 2050 the total difference amounts to just 2,2 % or 20 kt CO_2e due to the highly decarbonised electricity grid in both scenarios.

[5] Assumed specific energy consumption for carbon capture technologies per scenario: POI – Amine scrubbing (including heat at 130 °C): 1.19 MWh/t CO_2 ZEM – Oxyfuel: 0.27 MWh/t CO_2.

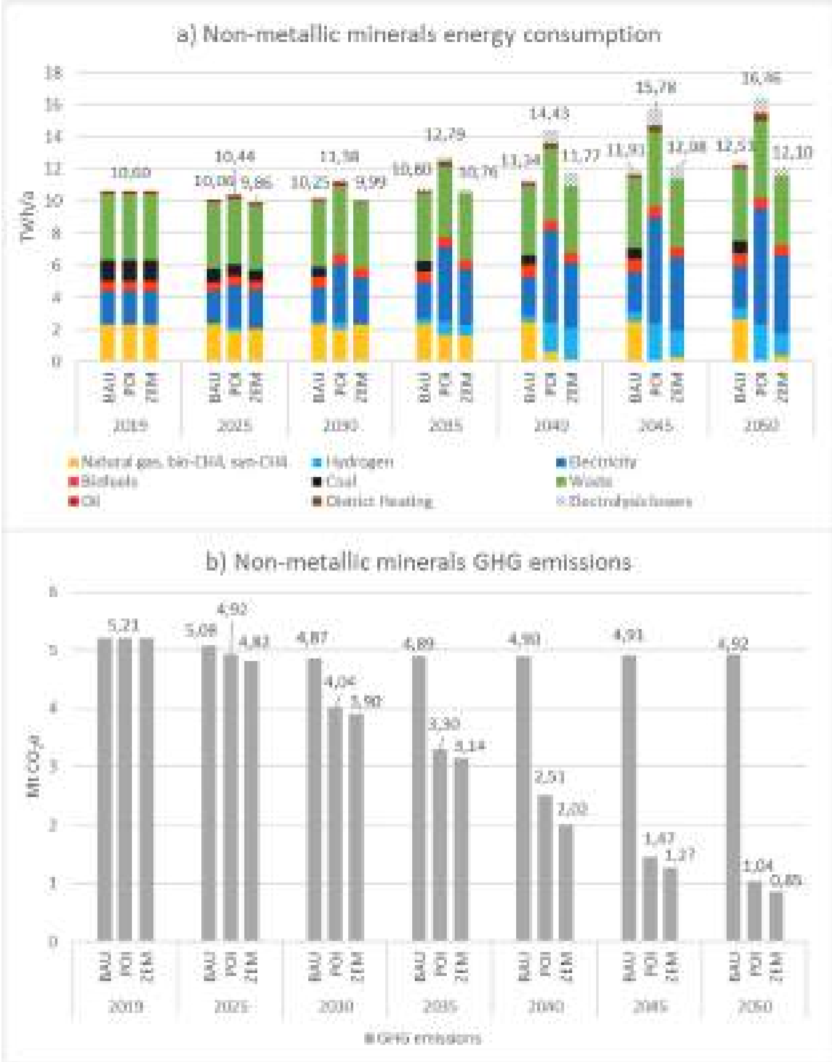

Fig. A 4. Non-metallic minerals results for a) energy consumption and b) GHG emissions for scenarios BAU, POI and ZEM.

Machinery

The machinery subsector belongs to the non-energy intensive industrial subsectors. The subsector consists of a large number of small and medium sized companies and production sites. As it is widely comparable to the other non-energy intensive subsectors in Austria, we present it here as an exemplary case for the subsectors investigated top-down (cf. section 2).

As shown in Figure A 5, total annual energy consumption amounts to approximately 6 TWh. For the machinery subsector, an annual growth rate of 1.6 % is assumed. As visualised by Table A 3 to Table A 5 in the supplementary information section, efficiency gains for motive power, lighting/IT and thermal applications are in the same range as in other industrial subsectors. Hence, the overall energy consumption rises in all scenarios. Space heating together with low temperature process heat (up to 150 °C) represents the major energy application.

The low to medium temperature heat consumption up to 150 °C including for steam is modelled to be supplied by heat pumps with low diffusion rates in scenario BAU starting in 2040, and an accelerated roll out in POI and ZEM serving nearly all technically possible consumption in 2045. Apart from general growth, this trend is the main driver for decreased direct fuel consumptions and a strong rise in electricity consumption. The largest efficiency gains are therefore expected to come from providing space heating with heat pumps. In ZEM, thermal process energy consumption is electrified to a very large extent (above 150 °C using direct electric heating) from 2030 onwards. Hydrogen consumption presented is not process-specific but arises from the gas grid mix.

In the transition scenarios POI and ZEM, the machinery subsector is projected to reduce GHG emissions from a total of 1.3 Mt CO_2e in 2019 to 0.1 Mt or by 92 % until 2050. The two scenarios mainly differ in the rates of technology diffusion in electrifying process heat consumption and the rollout of heat pumps for the medium temperature range, envisioned five to ten years later by industrial stakeholders in POI than modelled in ZEM.

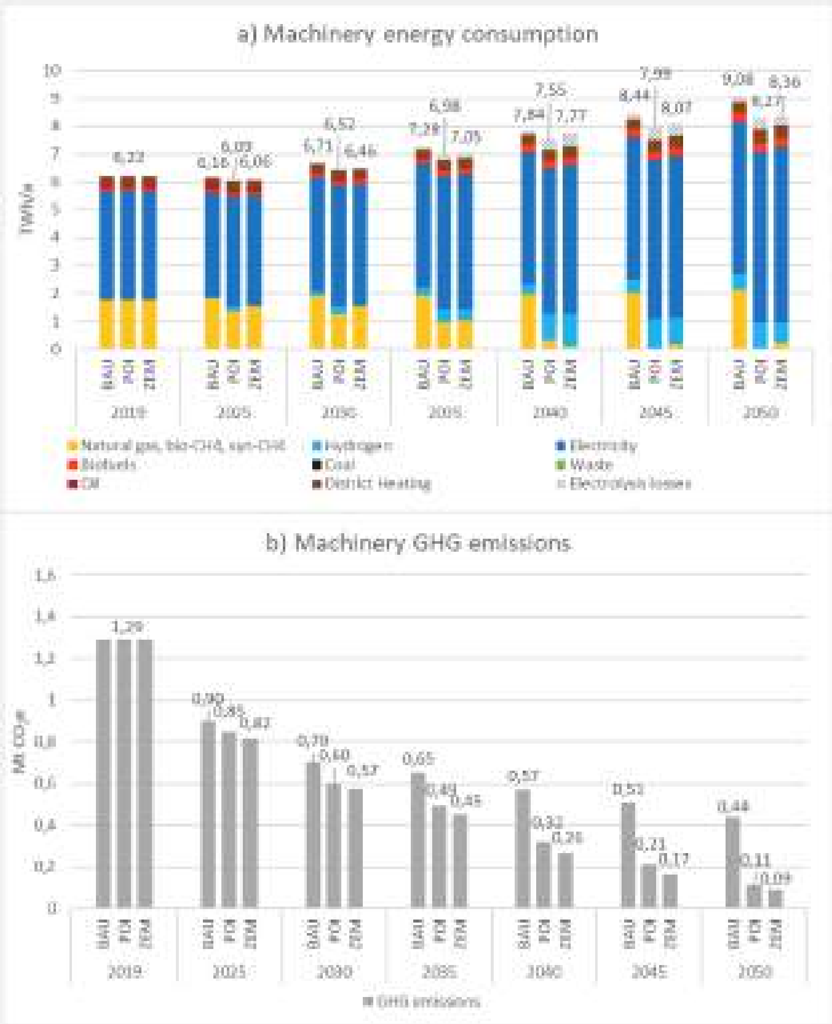

Fig. A 5. Machinery results for a) energy consumption and b) GHG emissions for scenarios BAU, POI and ZEM.

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APPENDIX B: FURTHER SCIENTIFIC PUBLICATIONS

2021

Diendorfer, C., Gahleitner, B., Dachs, B., Kienberger, T., Nagovnak, P., Böhm, H., Moser, S., Thenius, G., & Knaus, K. (2021). *Klimaneutralität Österreichs bis 2040 - Beitrag der österreichischen Industrie*. https://www.bmk.gv.at/themen/klima_umwelt/gruene-industriepolitik/ziele.html

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Kienberger, T., Nagovnak, P., Geyer, R., Hainoun, A., & Binderbauer, P. (2021). Die Industrie als elementarer Baustein der Energiewende für Österreich und darüber hinaus. WING-Business, 54.2021(2). https://issuu.com/beablond/docs/heft_02_2021_end/s/12783119

Nagovnak, P., Kienberger, T., Geyer, R., & Hainoun, A. (2021). Dekarbonisierungsszenarien für das industrielle Energiesystem in Österreich. Elektrotechnik und Informationstechnik, 138.2021(4-5), 258-263. https://doi.org/10.1007/s00502-021-00893-2

2022

Alton, V., Binderbauer, P., Cvetkovska, R., Drexler-Schmid, G., Geyer, R., Hainoun, A., Nagovnak, P., Kienberger, T., Rahnama Mobarakeh, M., Schützenhofer, C., & Stortecky, S. (2022). New Energy for Industry (NEFI) – Pathway to industrial decarbonisation: Scenarios for the development of the industrial sector in Austria.

Cvetkovska, R., Kienberger, T., & Nagovnak, P. (2022). Pathways for ramping-up hydrogen into the natural gas system. Paper presented at 17. Symposium Energieinnovation 2022EnInnov2022, Graz, Austria. https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/738639ca-39a0-4129-b0f0-38b384c12b57/files/lf/Session_D1/411_LF_Cvetkovska.pdf

Kühberger, L., Nagovnak, P., Sejkora, C., & Kienberger, T. (2022). E²GEM - Tool zur Energieanalyse auf kommunaler Ebene. In EnInnov2022 - 17. Symposium Energieinnovation; Kurzfassungsband: FUTURE OF ENERGY - Innovationen für eine klimaneutrale Zukunft; 16.02. – 18.02.2022 TU Graz, Österreich https://doi.org/10.3217/978-3-85125-915-5

Baumann, M., Cvetkovska, R., Felber, B., Kienberger, T., Kühberger, L., & Nagovnak, P. (2022). Entwicklung des Raumwärmebedarfs in Österreich: Szenarien zum künftigen Bedarf an Raumwärme unter der Berücksichtigung der Nutzung von Gas und des Ziels der Klimaneutralität bis 2040.

2023

Nagovnak, P., & Schützenhofer, C. (2023). Industrial energy demand and GHG emission scenarios under changing technologies - an Austrian case study Abstract. Paper presented at IEWT 2023, Wien.

Felber, B., Baumann, M., Cvetkovska, R., & Nagovnak, P. (2023). Entwicklung des Raumwärmebedarfs in Österreich unter der Berücksichtigung der Nutzung von Gas und des Ziels der Klimaneutralität bis 2040.

Binderbauer, P., Wögerbauer, M., Nagovnak, P., & Kienberger, T. (2023). The effect of “energy of scale” on the energy consumption in different industrial sectors. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2023.07.031

Bachhiesl, U., Wogrin, S., Gaugl, R., Konrad, A., Kienberger, T., Nagovnak, P., Wallner, S., Kühberger, L., Vouk, T., Cvetkovska, R., Kettner-Marx, C., Sommer, M., Streicher, G., Wretschitsch, E., & Markytan, S. (2023). InfraTrans2040 – Szenarien und Ausbaupläne für ein nachhaltiges Wirtschaftssystem in Österreich.

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APPENDIX C: SUPPLEMENTARY INFORMATION

Table C 1: Overview of technologies with highest TCNP-to-cost ratio per application category and climate neutrality pathway

Application	**Pathway**	**Technology with best TCNP/cost ratio**	**TCNP/cost ratio [kt CO_2/M€]**
Space heating	Electrification	LT heat pumps	3.8
	CO_2-neutral gases and biomass combustion	Solid biomass	3.3
Stationary engines	Electrification	Electric engines	4.0
Process heat <200°C	Electrification	HT heat pumps	3.8
	CO_2-neutral gases and biomass combustion	Solid biomass	3.3
Process heat >200°C	CO_2-neutral gases and biomass combustion	Bio-CH_4	3.1
Steel production	CO_2-neutral gases and biomass combustion	Bio-CH_4	2.5
	Circular economy	Bio-CH_4	4.5
Non-metallic minerals production	Carbon capture	Oxyfuel-Combustion	15.3
	Circular economy	Bio-CH_4	8.0