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Climate neutrality strategies for energy-intensive industries: An Austrian case study

Maedeh Rahnama Mobarakeh *, Thomas Kienberger

Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef Straße 18, A- 8700, Leoben, Austria

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A B S T R A C T

The industry is responsible for 24% of anthropogenic emissions and a quarter of total energy consumption worldwide. Accelerating the action plan for climate neutrality for the industry, particularly the energy-intensive industrial subsectors, which are responsible for about 70% of the sector's emissions and energy consumption, is crucial to achieving the climate change goals. Iron and steel, pulp and paper, nonmetallic minerals emphasizing cement and nonferrous metals focusing on aluminum are the four energy-intensive industrial subsectors investigated in this study. We evaluate the benefits and obstacles of various mitigation methods for each subsector over two time horizons: short/medium-term emission reductions and long-term emission reductions. Actions that have already been implemented in some industrial sites and do not require extensive infrastructural upgrades are generally considered in the short/medium term. This group covers boosting energy efficiency by retrofitting plants and adopting the best available or best practice technologies in existing process stages, as well as substituting fossil fuels as energy sources with bioenergy, hydrogen, or electricity (low-emission electricity). This strategy can reduce emissions in the shortest possible timeframe; nevertheless, the reduction is insufficient, and additional efforts are required to transition the industry to a low-carbon economy by 2050. These further efforts are viewed as long-term reductions that broadly address mitigation alternatives connected to process emissions, which are an inherent part of the production processes of industrial subsectors across a more extended period. The frontline technologies studied in this category are fossil fuel feedstock change to non-fossil gases such as hydrogen, carbon capture usage and storage, a higher degree of electrification and increased use of secondary raw material. By evaluating the conditions for each subsector, this study also analyses the industrial landscape along the industrial value chain, showing that all of these four technology groups need to be implemented in a sector-specific approach to close the ambitious net-zero emissions gaps. In this essay, Austrian energy-intensive industrial subsectors are assessed as case studies using a comprehensive approach that includes influencing factors such as the subsector's current energy and emissions intensity, energy infrastructure, future national and international policies, and related decarbonization techniques. Transitioning from fossil fuels to emission-free fuels as raw materials (in the iron and steel subsector) and energy sources, as well as circular economy paths, have more potent effects on decarbonizing the Austrian industry. When these strategies are integrated with CO_2 capture solutions for the cement industry and energy efficiency improvements for relevant subsectors, Austrian industrial emissions can be reduced by more than 65% compared to the current level.

1. Introduction

In terms of climate change mitigation efforts, an overarching goal at the global level is needed to control the temperature intensification due to human activities below 2 °C by mid-century (United Nations, 2015). The main sources of greenhouse gas (GHG) emissions leading to temperature rise are categorized into the energy- (heat and power producer (40%)), building (9%)-, transport (24%)-, and industry (24%) sectors (IEA, 2020f, 2019a). In recent decades, the building-, transport-, and energy sectors have attempted to develop distinct decarbonization pathways (Fischedick et al., 2014). In contrast, as one of the most challenging sectors that significantly impact global warming, the

* Corresponding author.
E-mail addresses: maedeh.rahnama-mobarakeh@unileoben.ac.at (M. Rahnama Mobarakeh), Thomas.kienberger@unileoben.ac.at (T. Kienberger).

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industry needs to make more efforts to clarify its decarbonization roadmap. The industry consumes about a quarter of the world's total primary energy,[1] of which almost 70% comes from fossil fuels (IEA, 2020f). Globally, the industry is also responsible for over 24% of total anthropogenic GHG emissions due to fossil fuel consumption and manufacturing process, without including indirect emissions from purchasing electricity and heat (IEA, 2020i). The difference between the industrial subsectors regarding energy consumption and GHG emissions is noteworthy. While the iron and steel (I & S); chemical and petrochemical; cement; aluminum, and pulp and paper (P&P) industries, as energy-intensive industrial subsectors (EIIs), are responsible for more than two-thirds of industrial energy demand and sectoral emissions; the rest of energy consumption and emissions are accounted by other industrial subsectors such as textiles, food and drink, wood and wood products, machinery, etc. (IEA, 2020f).

To transition the industry to a low-carbon economy, decarbonization of EIIs is critical. However, specific factors such as high-temperature heat demand, process emission results from chemical reactions, and the long life of the industrial plants make it challenging to mitigate emissions from EIIs (IEA, 2020f; Pee et al., 2018). This study, performed within the framework of NEFI- New Energy for Industry (NEFI), a consortium of Austrian companies, research institutes, and public institutions, aims to develop an integrated approach for deep decarbonization of EIIs toward being sustainable, efficient, and a low-carbon economy and examines the Austrian EIIs as a case study.

1.1. State of research

In recent years, studies have started to look at ways to save energy and reduce emissions in the industry. The literature covered within the systematic and comprehensive literature review of this work includes policy documents, roadmaps, technical reports, journals and conference publications, and forecast studies on the transformation and decarbonization of the energy system focusing on the industrial sector, divided into two groups: the integrated industry sector and individual industrial subsectors.

1.1.1. State of research on the Integrated Industry Sector

The first group of references has proposed energy savings and emissions reduction in the industry as an integrated sector. This group is almost top-down in its approach. Their main goals are to find possibilities to reduce GHG emissions and analyze the industry's overall emission reduction strategies at the national and international levels. European Commission studies (European Commission, 2018c) and International Energy Agency (IEA) reports (IEA, 2021c, 2020f) have addressed the transformation of emissions and energy in the industrial sector, likewise the other sectors, such as buildings, transport, and energy in the EU and international contexts.

Some references in this group were more industry-specific, focused on EIIs, and sought to highlight emissions reduction opportunities (Chan et al., 2019) and present decarbonization pathways (Bataille et al., 2018). In addition to providing a compilation of possible key solutions, numerous publications also discussed the barriers and challenges facing the industry. Wesseling and his colleagues (Wesseling et al., 2016) pointed out costs, availability of renewables and electricity, and lack of infrastructure as major bottlenecks to the adoption of new technologies (Wyns and Axelson, 2016). presented the crucial conditions and frameworks. They stated that the exciting or new obstacles like the development and cost of new technologies, energy constraints, circular economy and material efficiency, etc., must be overcome to decarbonize the EIIs. Beyond the reflection on possibilities and obstacles, a group of references provided recommendations for policymakers, such as improving emissions monitoring and benchmarking and converting the existing plan to BAT as fast as possible (Napp et al., 2014), providing stimulus and technical support, and promoting a market for low-carbon technologies (Whitlock et al., 2020), etc.

Although industrial emissions, and EIIs specifically, are hard to abate, industry decarbonization is technically feasible. In the following the options that have been widely discussed in the literature are divided into five pillars:

- **Energy efficiency improvement (I)** is seen as the most technologically mature option (European Commission, 2018b). However, energy efficiency improvement using the Best Available Techniques (BAT) or Best Practice techniques (BPT) cannot reduce emissions by more than 15–30% for the industry sector (Chan and Kantamaneni, 2015; European Commission, 2018c). They are fundamental in the first step for near-term transformation to a low carbon economy (Fischedick et al., 2014). They can immediately and simultaneously reduce emissions and provide additional cost reduction benefits in the next step (IEA, 2021e).
- **Electrification (II)** of industrial processes' heat (steam) demand is one of the key pillars of decarbonizing the industrial energy system (IEA, 2020f). Electrification offers a wide range of opportunities to reduce emissions in the industrial sector. Industrial manufacturing requires fossil fuels for heating at low, medium, and high temperatures, which can be replaced by electrification across a broad spectrum. At low to medium temperatures (up to 400 °C), the heat demand for space heating, cooling, steam generation, and drying can be fully electrified with commercial electric boilers, infrared, microwave and heat pumps (close to ready to use for medium temperatures), etc. (Lechtenböhmer et al., 2016; Madeddu et al., 2020). Such technologies are mature and have adequate capacity for industrial applications (Madeddu et al., 2020). Nonetheless, the main challenges are the high-temperature heat requirements. Electrification of this group is technically feasible, but the technologies are not yet fully developed (e.g., electric furnaces and thermal plasma for the cement sector (Vattenfall, 2019), electrowinning, and electrolysis of hydrogen (H_2) in I&S (Lechtenböhmer et al., 2016)). Electrification of industrial sites usually does not expect a fundamental change in the production process; instead, it requires replacing equipment such as boilers or furnaces. It also has other manufacturing benefits, such as reducing maintenance costs and, in some cases, capital costs (e.g., industrial boilers) compared to traditional equipment (Roelofsen et al., 2020). Electrification diminishes GHG emissions substantially where zero-emission electricity is utilized; otherwise, it boosts GHG emissions. Nevertheless, the availability of sufficient renewable resources for power generation, the electricity price (Lechtenböhmer et al., 2016), and the readiness of the essential technologies in high-temperature demand (Bruyn et al., 2020) are obstacles facing electrification.
- **Fuel switching (III)** by replacing fossil fuels with biofuels (biomass, biogas, H_2, etc.) as an energy source or feedstock is a crucial option that can significantly reduce emissions in EIIs (European Commission, 2018c). The substitution of fossil fuels as feedstocks in the I&S as well as the chemical industry requires converting production processes and adopting alternative technologies (Bruyn et al., 2020; Pfaff et al., 2018). A few industries have started to transition to alternative fuels, although some technological options for moving energy-intensive processes away from current fossil fuels are not yet commercially available and require further optimization to become technically viable (Lyons et al., 2018). The replacement of fossil fuel as an energy source is dependent on the temperature and the direct or indirect purpose of fuel use. Traditional bioenergy sources such as biomass and biogas would be employed at low to medium temperatures, where fossil fuels are indirectly used (Honore, 2019). For high-temperature heat, which is usually direct combustion with

[1] Primary energy based on the IEA Energy Balance boundaries is total final consumption by industry, non-energy uses for chemical feedstock, and energy used in blast furnaces and coke ovens IEA (2020f).

fossil fuels, solid biomass, biomethane, and H_2 can be burned directly instead of fossil fuels (Honore, 2019). H_2 (Dolci, 2019)and biomethane are the most attractive renewable sources and can be used 100% or combined with other fuels (IEA, 2019b). The comparative similarity between H_2 and biomethane with natural gas (NG) means they are likely suitable for many processes currently powered by NG (Lyons et al., 2018). The main obstacle to fuel substitution that must be overcome before any particular technology can be considered a realistic option is the reliability of biomass and H_2 supply in sufficient quantities and the impact on product quality for direct heat applications (Lyons et al., 2018).

- **Carbon Capture and Storage (CCS) or Carbon Capture Utilization and Storage (CCUS) (IV)** are up-and-coming abatement options. They may play an indispensable role in some subsectors such as cement (non-metallic minerals), chemical, and I&S (Pfaff et al., 2018). In these subsectors, the process-based emissions, an inherent part of production processes, can be heavily decreased using CCS/CCUS with no or less modification of existing production processing (Bruyn et al., 2020). The widely used and under considering separation technologies are chemical absorption, physical separation, oxyfuel separation, membrane separation, and calcium looping (IEA, 2021a). The collected carbon dioxide (CO_2) from the exhaust gases, after purification and compression, is transported for permanent storage in an underground storage facility (Alcalde et al., 2018; IPCC, 2005) or used in another industrial subsector as a feedstock (Pee et al., 2018; Pfaff et al., 2018). The chemical industry and fuel manufacturing are interested stakeholders in using captured CO_2 to produce cost-effective, low-carbon products (IEA, 2020c, 2019d). Combining CO_2 capture technology with renewable energy sources - the promised goal for the next decades - will represent a profound transformation towards net-zero emissions (IEA, 2021d). Notwithstanding the benefits of CCS/CCUS in bringing the technology to existing industrial sites, some barriers to deployment need to be addressed. Currently, the high cost of CCS/CCUS techniques, the lack of the enabling infrastructure to transport captured CO_2 to the storage site, and insufficiently available geological reserves for CO_2 capture, which are essential for reducing the risk of carbon leakage and storing carbon for a long time (Alcalde et al., 2018; IPCC, 2005), are obstacles that need to be overcome (IEA, 2020c, 2019c).
- **Circular economy (V)** (Material Economics, 2018) and raw material efficiency (Material Economics, 2019) are also remarkable options for emissions reduction in the future. Track the industry value chain from raw material production to end-use consumption can limit the waste of materials. By improving the waste management system, materials will be able to return to the economic cycle and decrease primary materials production, which is energy and emission-intensive (e.g., primary steel production, primary paper production, etc.) (European Commission, 2018c). The production of recycled materials such as secondary aluminum, secondary steel, paper making by recycling fibers, etc., is considerably less energy and emission-intensive than the extraction of the same tons (t) of new materials. The objective of the circular economy is achieved by minimizing waste throughout the supply chain and optimizing material use (Material Economics, 2018; Sen et al., 2021). Combining the circular economy with a material efficiency strategy-that improves material production and reduces material consumption-provides a great occasion to decarbonize EIIs. However, some hurdles must be overcome in implementing the circular economy strategy than the current system, which uses less recycled material. Lack of knowledge and specific framework conditions to make the industry take a step in this direction, uncertainty about consumer acceptance, technical feasibility, and production costs are some issues that need to be explored (McKinsey & Company and World Steel Association, 2021a; Sen et al., 2021). Furthermore, most of all, this concept requires close collaboration throughout the value chain.

In addition to the technologies and pillars mentioned above, the industrial transition to a low-carbon economy cannot be an isolated affair (Wyns and Axelson, 2016). Instead, it must be coordinated with other important shifts in other sectors, such as transportation and energy, during the coming decades. In particular, in connection of the industry sector with the energy sector, manufacturers face supply and price fluctuations of natural gas (currently imported from Russia to Europe), which could significantly affect the costs transferred through the supply chain, industrial demand, technical problems, and fuel prices. Overall, a sustainable transition will require a concerted effort by the public and private sectors, industrial companies, government, and policymakers (European Commission, 2018b, 2018c).

1.1.2. *State of research on the individual industrial subsector*

The most recently emerging literature in this group has put forward an in-depth analysis of the various technology options in EIIs separately. They usually have taken a bottom-up approach and focused on each subsector's specific information and mitigation options. In addition to the scientific papers, the well-known technical reports published by the European Commission, the Joint Research Center (JRC), and the IEA on I&S (EUROFER, 2013; Pardo et al., 2015), P&P (Moya and Pavel; Suhr et al.) cement (European Cement Research Academy and Cement Sustainability Initiative, 2017; IEA, 2018), and aluminum (Cusano et al., 2017; Moya et al., 2015) subsectors were consulted.

Table 1 shows some cutting-edge technologies (excluding BAT) of the literature considered in Sections 1.1.1. and 1.1.2. categorization by subsectors and technology pillars. The Technology Readiness Level (TRL) is also introduced to characterize the maturity levels of technologies.

The extended description of related technologies is discussed in the other sections.

1.2. *Objective and structure*

To evaluate how future production demands in the EIIs might affect CO_2 emissions and support the net-zero transition, this study aims to close the gap between current climate strategies and the long-term goal of deep decarbonization. This essay examines decarbonization strategies for EIIs globally and analyzes them using the Austrian case study as the primary focus. So the objectives of the present paper, intending to take into account the less mentioned issues in the previous works, are organized as follows:

- Whereas previous research, as cited in Sections 1.1.1 and 1.1.2, employs a top-down approach for the integrated industry sector or a bottom-up approach for individual subsectors, the present work intends to assess the impact of abatement options using a mix of bottom-up and top-down perspectives on individual subsectors. Therefore, prepare an energy flow Sankey diagram for each subsector to identify the source and type of energy consumption and emissions for today's process chain.
- Conduct an extensive inventory of technology options for four EIIs: I&S, P&P, cement, and aluminum, based on the energy-saving and emission abatement potential and maturity of the technology, using valuable knowledge gained from other literature through the process- and energy-system analysis, and divide the important options into two main groups: short/medium-term and long-term reduction.
- Introduce a comprehensive and convenient framework for selecting technology for decarbonization pathways that has received little attention in the literature so far.
- Determine the most important subsector-specific technology pillars and propose broad decarbonization pathways for Austrian EIIs. It is noticeable that in recent years some research has paid attention to Austrian industry (Karl-Heinz Leitner et al., 2014; Sejkora et al., 2018), such as I&S (Dock et al., 2021; Raupenstrauch and Pulm, 2014), cement (Haider and Werner, 2014), P&P (Rahnama

Table 1
Decarbonization Technology from the literature research for the considering EIIS.

Technology option (pillar)	TRL	Description	application	References
Electrification (II)	4–5	Use of electricity to reduce the iron ore in two ways Electrolysis (ULCOLYSIS) and Electrowinning (ULCOWIN)	Ironmaking	(Moya and Pardo, 2013; Siderwin, 2018; World Steel Association, 2021a; Yan Junjie and Junjie, 2018)
Smelting reduction process (HIsarna) (III)	7	Reduce directly injected iron ore at the top and coal powder at the bottom by using purified oxygen to replace the air in the smelting reduction process. The process will produce CO_2-rich waste gas and is suitable for combination with a CCS plant.	Ironmaking	(Abdul Quader et al., 2016; EUROFER, 2013; IEA, 2021b; Yan Junjie and Junjie, 2018)
Top gas recycling (TGR) (III)	7	recycle the CO and H_2-containing blast furnace exhaust gas (BFG) and utilize it as a reduction agent to replace coke or coal	Ironmaking	(Feiterna et al., 2014; Pardo et al., 2015; Pfaff et al., 2018; Yan Junjie and Junjie, 2018)
Direct reduction with Natural gas (ULCORED) (III)	9	Use of natural gas as a reducing agent in direct reduced iron (DRI) replacing coke. To increase the emission reduction efficiency process can be integrated with CCS.	Ironmaking	(EUROFER, 2013; Keys et al., 2019; Yan Junjie and Junjie, 2018)
H_2 plasma direct reduction (III)	4	Use of H_2 plasma to melt the pre-reduced fine or pelletized iron ore as reductant.	Ironmaking	(IEA, 2020f; Naseri Seftejani et al., 2019; Sabat and Murphy, 2017)
Direct reduction iron with hydrogen (DRI-H_2) (III)	5	Use of H_2 (renewable) instead of coal for the reduction of iron ore pellets in the shaft furnace or fine iron powder in the fluidized bed	Ironmaking	(Bhaskar et al., 2020; Da Ranzani Costa et al., 2013; IEA, 2020f, 2019b; Thyssenkrupp, 2021; Vogl et al., 2018)
CCS/CCUS (IV)	6–7	CO_2 separation of other produced gases (BF gas containing up to 60% CO_2) in the iron-making process and capture it. The captured CO_2 can be used in other industrial processes such as the chemical industry.	Ironmaking	(IEA, 2019d; IEAGHG, 2013; McQueen et al., 2016)
Black Liquor gasification (BLG) (I)	8–9	BLG is a new technology capable of efficiently recovering energy from the black liquor's organic content using a recovery boiler and gasification process.	Pulping	(Bajpai, 2016b; Moya and Pavel; Rogers, 2018)
Direct electric heating (II)	7–8	Fossil fuel emissions could be eliminated by replacing fossil fuels with electricity and using an electric boiler instead of a fossil fuel boiler (natural gas boiler) to generate heat (steam) demand. If the electricity is supplied from renewable sources, net-zero emissions could be reachable.	Papermaking	(Marsidi et al., 2018; van Berkel, 2018)
Heat pump - recovering waste heat (III)	6–7	The heat pump can convert the arising low-temperature waste heat from process to medium temperature by consuming electricity. Reusing the waste heat at an acceptable temperature would drastically reduce fossil fuel emissions and improve energy efficiency.	Papermaking	(Marsidi et al., 2018; van Berkel, 2018)
Deep eutectic solvents (DES) (I)	3	DES are produced naturally by plants and can break down wood and selectively extract cellulose fibers required in the papermaking process. DES has the potential to be used in pulp production using wood and waste paper with minimized energy demand and CO_2 generations.	Pulping	(Cepi, 2013; Rogers, 2018)
Flash Condensing (I)	3–5	The concept of this technology is to produce waterless paper using high turbulent steam combined with dry fibers. The technology can be applied to any pulp (chemical, TMP, RCF) and reduces energy consumption and fossil fuel CO_2 emissions.	Pulping	(Cepi, 2013; WSP Parsons Brinckerhoff, 2015)
Carbon capture and storage or Biomass-based CO_2 CCS (BECCS) (IV)	6	CO_2 emissions from combustion processing, the recovery boiler, and the lime kiln, particularly at the kraft pulp mill, can be captured and stored, allowing the industry to be a negative emissions site.	Pulping	(Jönsson and Berntsson, 2012; Kuparinen et al., 2019; Moya and Pavel; Sagues et al., 2020)
Superheated steam drying (I)	3–5	Replacing the air needed to remove water from the paper in the drying section with superheated steam can improve heat recovery (full recovery) and increase energy efficiency. The recovered steam can be used in the next steps of paper production.	Papermaking	Cepi (2013)
Gas-fired dryers (I)	6–7	Dryers are heated with hot gases from gas combustion (which may occur in the drum) instead of steam. This dryer technology improves energy efficiency by 75–80% compared to the 65% of the usual system.	Papermaking	(Cepi, 2013; Kong et al., 2012, 2016)
Microwave Drying (I)	3–4	Paper is dried by exposure to microwave radiation. This technology increases the drying rate and reduces the total energy consumption.	Papermaking	(Cepi, 2013; Kong et al., 2012, 2016)
Waste heat recovery (I)	8–9	Recovery of waste heat from the kiln and clinker cooler and converted to electricity using available technologies such as Organic Rankine Cycle, Single Flash Steam Cycle, Duel Pressure Steam Cycle.	Clinker making	(Pardo et al., 2011; Wang et al., 2009)
Advanced grinding (I)	6–9	New grinding technologies such as ultrasonic grinding and non-contact grinding are more efficient grinding processes that can be applied to both raw materials and fuel grinding	Cement making	(European Cement Research Academy and Cement Sustainability Initiative, 2017; IEA, 2021b, 2018)
Electrification (II)	4	Instead of fossil fuels, electricity can be used to meet the clinker kiln's high temperature (1400 °C) heat demand. Electrification is achieved by adapting plasma technologies, microwave heating, and induction heating, which are not commercially available.	Clinker making	(Cembureau, 2019b; IEA, 2020f; Lechtenböhmer et al., 2016)

(continued on next page)

Table 1 (*continued*)

Technology option (pillar)	TRL	Description	application	References
New binder- carbonate calcium silicates	7–8	Carbonated calcium silicate is a new alternative clinker with little lime compared to conventional clinker. It can be produced in the same kiln as Portland cement with a lower burning temperature.	Clinker making	(Gartner and Sui, 2018; IEA, 2020f; Lehne and Preston, 2018)
New binder- Magnesium Silicates (MOMs)	3	Magnesium oxide, which is produced by calcining natural magnesite rock, can be used instead of limestone for clinker production and leads to negative emissions in cement production, as the CO_2 produced during the process is returned to the process.	Clinker making	(Gartner and Sui, 2018; IEA, 2020f; Lehne and Preston, 2018; Taylor, 2013)
New binder- Alkali activated binders (geopolymers)	9	the alkali-activated material, a source of soluble base activator (alkali), and aluminum-rich materials produce the cement with lower energy and carbon intensity than Portland cement.	Clinker making	(Gartner and Sui, 2018; IEA, 2020f; Lehne and Preston, 2018; Luukkonen et al., 2018)
CCS- Oxyfuel (IV)	6	Using oxygen instead of air to produce CO_2-rich exhaust gas that can be easily captured after purification.	Cement making	(Jordal et al., 2019; Voldsund et al., 2019)
CCS- Calcium looping (CaL) (IV)	7	In CaL technology, part of the captured CO_2 from production processing is used in a reversible carbonation reaction to produce the CaO. The remaining CO_2 is stored. CaL can be implemented in tail-end or integration configuration.	Cement making	(Lena et al., 2017, 2019; Rodríguez et al., 2012; Voldsund et al., 2019)
Inert anode (I)	5	New electrolytic technology utilizes an inert anode instead of a conventional carbon anode. The inert anode is a non-consumable anode that produces O_2 instead of CO_2 and increases energy efficiency by 25% during the primary AL production.	Primary Aluminum making	(Chan et al., 2019; Elysis, 2021; Solheim, 2018)
New decoating equipment (I)	8–9	Decoating technology removes the contaminated material and cleans the surface of recycled aluminum. This technology improves the process and reduces raw material loss.	Secondary Aluminum production	(Chan et al., 2019; Evans and Guest Graham, 2000; Moya et al., 2015)
Recuperative or regenerative burners (I)	8–9	These burners can be installed in primary and secondary ways and save energy (fuel consumption) by 30–50%.	Primary/secondary Aluminum making	(Chan et al., 2019; Moya et al., 2015)
CCS/CCUS (IV)	4	Application of CCS in primary aluminum smelting process with CCS absorbent.	Primary Aluminum making	(Chan et al., 2019; Mathisen et al., 2014)

Mobarakeh et al., 2021; Steinmüller, 2014), and aluminum (Pulm and Raupenstrauch, 2014) but has mainly focused on improving energy efficiency and less focus has been given to emissions reduction. Consequently, the primary intention of the present work is to compensate for this.

The following qualitative structure provides the following subjects throughout this study: Section 2 presents a systematic methodology used in the framework for identifying and categorizing relevant technology options. Section 3 gives a broad overview of the Austrian industry, concentrating on EIIs. Section 4 provides a global perspective of each subsector's manufacturing processes, energy consumption, and carbon footprint. The investigation of the current situation for the Austrian case study is then continued by giving an energy flow Sankey diagram for each subsector. This section also analyzes emission reduction technologies for each subsector in two groups: short/medium-term and long-term, based on the literature review results. Eventually, the qualitative bottom-up method examines the Austrian case's possible decarbonization pathways. Section 5 discusses the potential decarbonization pathways for Austrian EIIs, including opportunities and barriers. Finally, the key findings are summarized in Section 6. This groundbreaking study helps policymakers, industry analysts, and especially energy modelers better understand the climate change policy gap and take a step toward making a sustainable transition to a zero-emissions economy.

2. Methodology

In this paper, we apply a mixed top-down and bottom-up approach with the following steps (Fig. 1):

- A top-down approach was used to identify key industrial subsectors based on energy consumption, emissions footprint, and economic data in the first step. This was done using available national and international statistical data. The latest Austrian statistical information is used for the subsectors.
- In the second step, a bottom-up approach was applied to evaluate technology pathways for decarbonization. This approach starts with the analysis of the individual industrial subsectors. The production process and energy consumption are assessed using an energy flow Sankey diagram. Analysis of the Sankey diagram helps determine the type of energy source, distinguishes between total energy (TWh): Eq. (1) and final energy (F_e, TWh) consumption, and leads to an understanding of the source of GHG emissions in each subsector.

$$Total\ energy\ consumption = Final\ energy\ (F_e) + Energy\ sector (E_s) + +Transformation\ input - Transformation\ output + non - energy\ use \tag{1}$$

Where total energy consumption[2] includes all energy carriers (fossil fuels, biofuels, electricity and district heating) consumed as final energy by the end-user, fossil fuels for transformation (e.g., coking coal to coke, fuel oil to electricity), energy purchased to the subsector, and fuels for non-energy uses (primarily relevant to the chemical and petrochemical industry) (United Nations, 2018).

- In the third step, an extensive literature review was conducted to identify technology options to enhance energy efficiency and reduce emissions. Various resources such as the latest scientific papers, reports, books, conference proceedings, and web materials have been studied. Each industrial subsector has created a list of related technologies to the respective BAT and IT. This technology database (only a part of the database is presented in this essay- Table 1) collects the data on energy-saving potential, emission reduction potential, investment cost (CAPEX), operating cost (OPEX), market entry, and TRL of each technology. In this step, the technology options were benchmarked on the technical indicators, and a shortlist of the most relevant technologies was selected. The selected technologies are out of the emerging technology listed. Mainly, technologies that will have a massive impact on energy savings and emission reduction in the subsector by 2050 and are the most promising according to EU, and worldwide benchmarks will be assessed in two approaches: short/medium-term and long-term. This study's short/medium-term vision focuses on routes and

[2] Energy is always a matter of conservation and can neither be destroyed nor generated. All known guidelines for energy statistics (e.g. United Nations (2018)) use the terminus technicus "energy consumption", and so do we in this paper.

technologies that are ready to deploy or have already been deployed at an industrial scale and will have an immediate mitigating effect by 2030. They may not significantly influence deep decarbonization but are necessary to pave the way for long-term goals. In contrast, the long-term strategy prioritizes complete decarbonization in the second phase. It addresses technologies and methods that are not yet commercially accessible but have the potential to be proven beyond 2030. Various Key Performance Indicators (KPIs), such as Specific Energy Consumption ($SEC, \frac{MWh}{tProduct}$): Eq. (2), and Specific CO_2 emissions ($SCe, \frac{tCO_2}{tProduct}$): Eq. (3) served to select the technologies in each subsector.

$$SEC = \frac{Total\ Energy\ consumption\ in\ year}{Total\ production\ in\ year} \tag{2}$$

$$SCe = \frac{Total\ CO_2\ emission\ in\ year}{Total\ production\ in\ year} \tag{3}$$

Total energy consumption (TWh) is based on Eq. (1), and total CO_2 emission (Kt) is the sum of direct emissions from fossil fuel burning (CO_{2Fu}, Kt) and process emissions (CO_{2p}, Kt): Eq. (4) . However, there is another source of emission (indirect emission) from electricity supplied to the industrial subsector (CO_{2El}, Kt). This emission is computed upon the amount of electricity (TWh) purchased for the subsector and the electricity grid emission factor ($\frac{tCO_2}{MWh}$). Due to some restrictions and uncertainty, such as the future share of renewable sources for electricity production, import or export policies, and emission reduction strategies in the energy and electricity sector that are beyond the control of industry, a detailed analysis of indirect emissions (based on the type of fuel used for electricity production in Austria) is outside the scope of this study's system boundaries. Nevertheless, for a more precise analysis of the emission reduction target, the indirect emission is calculated using the electricity demand for each subsector and the European electricity grid emission factors ($0.253 \frac{tCO_2}{MWh}$) in the base year 2019 (European Environment Agency, 2020), ($0.093 \frac{tCO_2}{MWh}$) in the short/medium term in 2030, and ($0.019 \frac{tCO_2}{MWh}$) for the long-term approach in 2050[3] (European Commission, 2020)

$$Total\ CO_2\ emission = CO_{2\ Fu} + CO_{2\ P} + (CO_{2\ El}) \tag{4}$$

These indicators are used particularly for Austrian industrial subsectors to aid in analyzing each subsector's current energy performance and emissions footprint compared to EU benchmarking data, as well as to determine the next step and opportunities for energy improvements and emission reductions.

- Finally, for the Austrian case study, this work proposes a decarbonization technology mapping for each subsector based on two short/medium- and long-term approaches that comprise important alternatives and technologies and estimate a technological demonstration rate. This technology mapping is crucial as input for energy system modeling and assessing the future performance of various technologies and routes for scenario creation in order to accomplish the Austrian industrial transition to a low carbon economy in the 2030 and 2050 timeframes.

However, selecting the most promising technology-based decarbonization option for each subsector requires close collaboration between energy policy, the research community, and the industry. This collaboration can be accomplished by direct interviews with industry representatives and discussing the technology list with experts. This approach ensures that both industry and researchers take advantage of the same possibilities.

[3] The electricity grid emission factor for 2030 and 2050 is based on the EU Mix scenario European Commission (2020).

3. Overview of Austrian energy-intensive industry

In Austria, industry accounts for about 35% of total energy consumption (Sejkora et al., 2018) and 28% of final energy consumption (Statistik Austria, 2019a), with more than 66% of this energy consumed by EIIs (Fig. 2). The required energy is drawn from various sources, renewable and mainly fossil fuels resources (Table 2), to provide the necessary thermal energy (heat and steam) and electrical energy (for pumps, motors, dryers, etc.) or to be used as a reducing agent in the chemical reaction of the production process.

Based on Austrian national CO_2 inventory data, industrial processes and their product uses are responsible for about 34% of total national emissions (Umweltbundesamt GmbH, 2021), of which 38% are from direct fossil fuel use, and 62% are from production processing. As is shown in Fig. 3, more than 60% of direct fossil fuel emissions and 75% of process emissions are due to energy-intensive subsectors' activities (Mandl et al., 2021).

In recent decades especially from 1990 onwards, the Austrian industry has caused to improve the process through measures such as energy efficiency enhancement, use of BAT and BPT, replacement of fossil fuels with renewable and alternative fuels, and the setup of internal combined heat and power plants (CHP) (Umweltbundesamt GmbH, 2021). These activities influenced in some subsectoral emission reductions, such as chemicals - 45% and minerals by - 9.2% compared to 1990 (Umweltbundesamt GmbH, 2021). In contrast, the overall GHG emission trend has risen by 21% since 1990, mainly due to the production of metal (I&S) (Umweltbundesamt GmbH, 2021). Consequently, fundamental changes in emissions reduction must be made to achieve the Paris Agreement target and be in line with Europe's ambitions for deep decarbonization by 2050.

To reduce emissions and lead the industry to a zero-emissions economy, this study has identified the source of emission contribution and determined the reason for fossil fuel consumption for each subsector by using a top-down approach. The outcome of this analysis is used together with the sectoral Sankey diagram developed in the next step to identify sector-specific decarbonization options. As outlined in Table 3, fossil fuels are classified into three categories: Fossil fuel use as a reducing agent, heat demand in industrial furnaces and space heating, and medium temperature demand (steam production). The CO_2 emissions (Eq. (4)) are also divided into process-related emissions, an inherent part of production processing for some subsectors such as I&S and cement, and fuel-related emissions due to the direct combustion of fossil substant in industrial furnaces or their use to generate steam in boilers or CHP. However, the CHP units currently being used at the industrial site contribute to reducing fuel-related emissions by generating

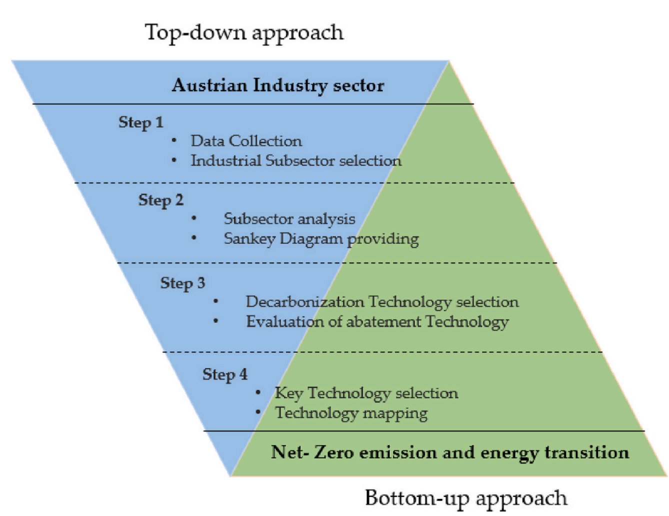

Fig. 1. Review of the methodology employed in the study.

heat and electricity from high-pressure steam.

According to the analysis in Table 3, the emission reduction path of each subsector can be determined based on the purpose of fossil fuel consumption and the scope of CO_2 emissions. In general, the following approach seems to be recognizable:

- Innovative technology must be investigated for process-related emission reduction, which is an integrated part of the chemical reaction for material production in I&S, cement, and chemicals. Replacing the current production processing with a new production system, using the recycling-based route, utilizing low carbon resources as, for instance, H_2- based reduction or carbon capture storage or utilization can be seen as solutions for process-related emission reduction.
- To eliminate the emission-related fuel consumption for heat (space heating) and steam generation at low/medium temperatures, possible options for energy efficiency improvement such as waste heat recovery systems and electrification of steam generation by heat pumps (up to 200 °C) or direct electric boilers (200 °C < t < 400 °C) instead of fossil fuels boilers is investigated.
- Abatement of emission-related fossil fuel combustion for high-temperature heat generation (>400 °C in the furnaces) can be achievable by replacing fossil fuels with high calorific value biofuels like bio methane, H_2, biomass, and biogas.

Nonetheless, the influence of material production with a recycling route instead of the primary path (circular economy), which can considerably impact total energy consumption and the associated CO_2 emissions, should not be ignored.

Section 4 defines the process analysis and associated abatement technologies based on this study's approach for four EIIs.

4. Energy-intensive industrial subsector

4.1. Iron and steel industry

4.1.1. Structure of the Iron and steel industry

In the past few years, global steel demand has grown significantly and is forecasted to increase by more than a third by 2050 (IEA, 2020g). Steel is made from iron ore, one of the most common materials in the earth's crust. In the world, there are two main routes to produce steel. The primary route involves steel production from iron ore via blast furnace /basic oxygen furnace (BF/BOF), and a secondary way using recycled scrap in an electric arc furnace (EAF) (Chan and Kantamaneni, 2015).

In primary steelmaking, the raw material contains coke; transferred from coal pyrolysis to coke ovens; sinter/pellets and lump ore are injected into BF/BOF to produce crude steel (CS). During this process, some by-product gases such as coke oven gas (COG), blast furnace gas (BFG), and BOF gas are generated, which are collected and used as energy sources after purification (Chan and Kantamaneni, 2015; Pardo et al., 2015).

The secondary steelmaking process using EAF involves directly melting ferrous materials, usually from scrap and recycled iron, as source material from waste streams. In this process, scrap iron is smelted and upgraded in an electric furnace under a high electric current, producing CS (Chan and Kantamaneni, 2015).

Another commercial method of manufacturing CS from iron ore is Direct Reduction Iron (DRI) (Wörtler et al., 2013). It takes place in a shaft furnace and generates sponge iron. The sponge iron, which has lower carbon content than pig iron (Ecofys, 2009b), and steel scrap are then fed directly into an EAF and melted to produce CS. This process uses natural gas (rich in CO and H_2) as a reducing agent. Therefore, this technology is more feasible for the region with lower NG and electricity prices (Pardo et al., 2015). In 2019, the CS production by BF/BOF was about 71.9%, and by EAF 27.7% worldwide (World Steel Association, 2020).

4.1.2. Energy consumption and carbon footprint of Iron and steel production

Among the EIIs, the I&S subsector accounts for the second-largest share of energy consumption, equivalent to about 8% of the world's final energy and 22% of industrial final energy demand, 75% of this energy is supplied by coal (IEA, 2020f, 2020g). Coal is needed for heat generation and coke production. This is essential in the chemical reactions required to produce steel from iron ore by the primary steelmaking route.

From the point of view of CO_2 emission, the I&S subsector is the largest CO_2 emitter of the industrial segments, representing 7% of global CO_2 emission (including process emission) (IEA, 2020g) and 28% of industrial emission (IEA, 2020f). In I&S, there are two emissions sources: process emissions from coke consumption as a reducing agent and fuel-related emissions from fossil fuels used to supply high-temperature heat to the furnaces (Table 3). Steel production by BF/BOF has an emission intensity of about 1.85 $\frac{tCO_2}{t\ Steel}$ - 1.9 $\frac{tCO_2}{t\ Steel}$ (Material Economics, 2019; World Steel Association, 2021c), which is approximately 68% from the BF and 16% from the coke oven (Material Economics, 2019). EAF steel production is less carbon-intensive and has an emission factor of roughly 0.4 $\frac{tCO_2}{t\ Steel}$ (Material Economics, 2019).

In the BF/BOF steel mill, the interrelationship between primary energy sources as raw materials and energy use leads to a rather complex energy balance (Sun et al., 2020). First, the use of coal in the coke oven produces coke (coke oven coke (COC)), the primary reducing agent of iron ore and coke oven gas. COG, which is generated by the carburization of coal (i.e., high-temperature heating in the absence of oxygen), has the highest heating value of any process gas. COG is typically purified and used as an energy resource in high-temperature processes such as BF and hot mill reheat furnaces (Remus et al., 2013).

COC is applied for iron ore reduction in the BF at temperatures 1400–1500 °C, producing hot metal and BFG, which has the lowest calorific value and is usually utilized in low-temperature processes (Ruth, 2004). The remaining BFG can be used in the CHP plant to process steam and electricity. Finally, the BOF produces CS and BOF gas during the hot metal oxidation process. BOF gas (also known as Linz-Donawitz gas (LDG) (Voestalpine AG, 2013)), which contains a large amount of carbon monoxide (CO), is used as enrichment gas and can be mixed with BFG to improve its heating value (Remus et al., 2013; Ruth, 2004).

The application and quality of these three manufacturing gases as fuel depends on the plant specifications, the technology used, etc., and ultimately affects the amount of external fuel needed to meet the steel mills' primary energy requirements (Chan and Kantamaneni, 2015; Pardo et al., 2015). In general, about 70% of the total energy consumption is used in iron production - cock oven, sinter plant, and BF - and the rest is used in secondary metallurgy, hot rolling, casting, and power plants (W.Griffin and P.Hammond, 2019). The current total energy consumption worldwide for primary I&S productions is estimated at 5.55 (4.7 to 6.4) $\frac{MWh}{t\ Steel}$ (European Commission, 2010; Pardo et al., 2015; World Steel Association, 2019, 2020).

For the secondary steel production route (EAF route), which consumes less energy (10–15% of the required for the primary steel production route (Material Economics, 2019)) and the main energy carrier is electricity, a reference value of 0.97 $\frac{MWh}{t\ Steel}$ is assumed (the average value within the EU-27 is 1.25 $\frac{MWh}{t\ Steel}$ (European Commission, 2010)).

4.1.3. Austrian Iron and steel industry

Austria is the sixth-largest steel producer in Europe, with almost 5% of the steel production within EU-27 (World Steel Association, 2020). In Austria, two different steel production technologies are currently used: primary steel making with BF/BOF and secondary steel manufacturing with EAF. The Austrian annual CS production in 2019 was about 7.4 Mt,

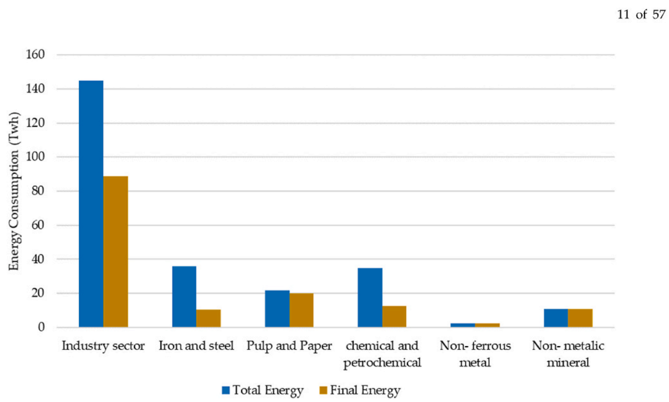

Fig. 2. Total and Final energy consumption by EIIs compared to energy consumption by industry sector in Austria (Statistik Austria, 2019a; 2019b).

90% by BF/BOF route and 10% by EAF route (World Steel Association, 2020). Austria has five BF/BOF located at two sites (Linz and Donawitz) and three EAF (Bürgler and Rummer, 2019; Raupenstrauch and Pulm, 2014).

I&S manufacturing consumes approx. 35.1 TWh of total energy (primary energy), accounting for 10% of total national energy consumption (Eurostat, 2021; Statistik Austria, 2019b). Approximately 88% of this energy comes from fossil fuels such as coal, coke, natural gas, and bituminous coke (Statistik Austria, 2019b). Fossil fuel is mainly used for two purposes: feedstock; 54% and energy source; 46% for energy demand (Table 3) (Statistik Austria, 2019b). As mentioned in Section 4.1.2, the energy balance in the I&S industry is more complex. Fig. 4 depicts the Austrian I&S industry's energy flow Sankey diagram to represent this complexity.

Due to the high share of fossil fuel demand, the I&S industry is Austria's most enormous industrial CO_2 emitter, corresponding to 12.9% of total national GHG in 2019 (Umweltbundesamt GmbH, 2021). Nonetheless, the overall SCe of BF/BOF has decreased from 2.15 $\frac{tCO_2}{t\ Steel}$ in 1990 to 1.7 $\frac{tCO_2}{t\ Steel}$ in 2019 through energy efficiency improvements, and the SCe for EAF 0.1 $\frac{tCO_2}{t\ Steel}$ has remained slightly constant (Umweltbundesamt GmbH, 2021).

4.1.4. Decarbonization opportunities for the Iron and Steel industry

This Section 4.1.4 looks at the potential and challenges of decreasing energy consumption and CO_2 emissions in the I&S subsector and the technical paths for short/medium-term and long-term reductions - deep decarbonization. The broad information regarding the specified technology and approach is first supplied on a global level. An overview of the Austrian I&S industry's technology choices is then offered. As indicated in the Sankey diagram (Fig. 4), the bulk of the emissions come from fossil fuels as feedstock and for energy use. Consequently, according to the pillars outlined in Section 1.1.1 and the pathway approach in Section 3, the top technological solutions for emission reduction are evaluated to reduce fossil fuel usage and CO_2 emissions.

Short/medium-term reduction: this route comprises early-stage technology and strategies for reducing emissions, such as energy efficiency improvement (I) and fossil fuel switching (III) as energy sources. Energy efficiency improvements adopting BAT/BPT cannot lower cumulative CO_2 emissions in the I&S subsector by more than 15–20% compared to current levels (Holappa, 2020). They are, nonetheless, necessary for increasing the efficiency of current manufacturing routes and facilities. BAT (He and Wang, 2017), like waste heat and gas recovery (currently installed in some industrial locations such as Sweden (Fleischanderl et al., 2018) and India (NEDO, 2014)), process integration techniques, system control enhancement, high-performance burners, and other energy-saving options, might save up to 26% of energy by 2050 compared to today's levels (Chan and Kantamaneni, 2015).

In addition to improving energy efficiency, a more significant drop in CO_2 emissions is possible in the short/medium-term by switching to low-carbon energy sources. Coal currently accounts for about 68% of global energy use in the I&S industry (IEA, 2020g). Roughly 75% of coal's energy content is utilized in BF in the form of coke, and the remaining 25% of coal is used in sintering and coking facilities to provide heat (World Steel Association, 2021b). NG and oil, alongside coal, make up nearly 10% of overall energy use in the I&S industry (IEA, 2020g). Electricity and renewable energy account for 11.5% and 9%,

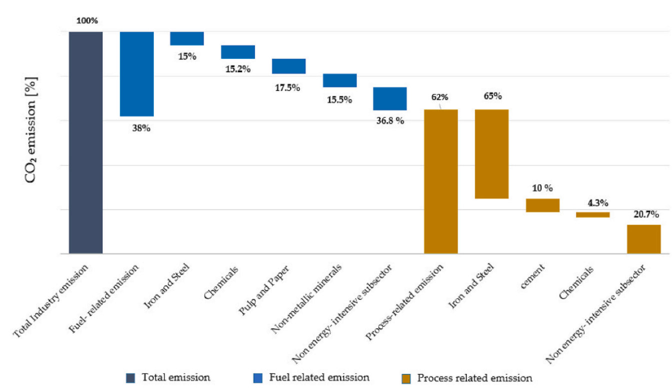

Fig. 3. Share of total CO_2 emission by industrial subsector (Mandl et al., 2021; Umweltbundesamt GmbH, 2021).

Table 2
Overview of material production volume, energy-using, CO_2 emission, SEC, and SCe of the EIIs considered in this study in 2019. yr (AMAG Austria Metall AG, 2020; Austropapier, 2021; Mauschitz, 2021; Statistik Austria, 2019a; 2019b; Umweltbundesamt GmbH, 2021).

industry Sector	Main Production	Production [Mt/yr]	Energy Consumption				CO_2 Emission [Kt]	SEC [MWh/t product]	SCe [t CO_2/t product]
			Total Energy [TWh]	Fossil Fuel [%]	Electricity [%]	Renewable/ alternative fuel [%]			
Iron and Steel	Crude Steel	7.4	35.1	88	11	< 0.05	11,755	4.7	1.58
Pulp and Paper	Paper (graphic, Packaging, Special	5	22.5	30	20	50 [1]	1,943	4.5	0.38
Chemical and Petrochemical	Ammonia	0.508	3.18	97	3	–	469	6.26	0.92
	Olefin	1.286	6.25	96	6	–	1,175	4.86	0.91
Non-Ferrous Metal	Secondary Aluminum	0.788	0.950	70	30	–	138	1.21	0.18
Non-Metalic Mineral	Portland Cement	5.23	4.4	18	14	68 [2]	2,653	0.84	0.51

[1] Renewable sources like: Black liquor, waste wood, biomass, biogas.
[2] Alternative fuels include old tires, plastic waste, waste oil, agricultural residues, and paper fiber residue.

Table 3
Share of fossil fuel consumption and CO_2 emission by categories for Austrian EIIs in 2019. yr (Statistik Austria, 2019a; 2019b; Umweltbundesamt GmbH, 2021).

Industry Sector	Unit	Fossil fuel consumption				Source of CO_2 emission	
		Reducing agent	Steam production [1]	Heat generation [2]		Process-related	Fuel related
				Industrial furnace	Space heating [3]		
Iron & Steel	[%]	54	< 0.01	44	1.5	87.6	12.4
Pulp & Paper	[%]	–	82	9	9	3	97
Aluminum	[%]	–	–	90	10	–	100
Cement	[%]	–	3	90	7	66.7	33.3

[1,2]. Data is generated based on the final energy consumption (except for P&P is based on total energy) (Statistik Austria, 2019a).
[3] A small share is used in stationary engines (Statistik Austria, 2019a).

respectively (IEA, 2020g). As a result, replacing fossil fuel energy sources in the sintering, pelletizing, and downstream forming process, either EAF, with renewable sources such as biogas, biomass, H_2, and electricity for low-to high-temperature demand can minimize fuel-related emissions in the early phases.

Long-term reduction-deep decarbonization: this approach entails alternatives and capabilities that can eliminate CO_2 from I&S manufacturing operations in the long term, bringing the sector closer to the near-zero-emissions economy. The most promising technologies for this approach include transitioning fossil fuels (III) to low carbon fuels as a reducing agent and CCS/CCUS (IV). Through a large infrastructural modification and a considerable transition from BF/BOF to DRI, conventional coal-based reductants can be changed into NG or H_2.

The use of NG as a reducing agent in commercially available DRI-NG produces fewer emissions than the coal-based BF/BOF method, with around a 40% decrease in emissions compared to traditional BF/BOF (Lucas and Di Rossetti Valdalbero, 2018; Material Economics, 2019) DRI-NG can cut emissions, although it is insufficient to achieve substantial reduction. Hence, DRI with H_2 as a reducing agent (DRI-H_2) is considered the most reliable and influential technology for decreasing emissions from the I&S sector; nonetheless, it is still in its immaturity (IEA, 2020f). In the EU, several companies have launched plans to pilot DRI-H_2, such as Salzgitter, 2021) and Thyssenkrupp (Thyssenkrupp, 2021) in Germany, SSAB in Sweden (SSAB, 2021), and Voestalpine in Austria (Voestalpine, 2019). The forecast for commercial-scale operation is predicted after 2030. This technology uses H_2 as a reducing agent to produce sponge iron in a shaft furnace or fluidized bed reactor (Schenk, 2011). The sponge iron is fed to EAF for steel making (Bhaskar et al., 2020; Vogl et al., 2018). It is important to use green H_2 produced with CO_2-free resources (emission-free electricity) in this option. Otherwise, the new emissions would occur outside the system boundaries of the industry. DRI-H_2 can cut emissions by up to 95% compared to the traditional coal-based method by employing green H_2 (Chan et al., 2019).

Electrification (II) of ironmaking via electrolysis (e.g., Ulcolysis) or electrowinning (e.g., Ulcowin) to reduce iron ore with an electrochemical process that uses electricity (World Steel Association, 2021a) might be among the most energy-efficient techniques for steelmaking. Still, the less flexibility compared to DRI and the need for a constant emission-free power source has some drawbacks to this method (Ito et al., 2020; World Steel Association, 2021a).

CCS/CCUS (IV) is another alternative for cutting emissions in steel production (IEAGHG, 2013). However, due to the evident low CO_2 concentration and reduced capture rate in existing BF/BOF attributable to multiple emission sources (coke plant and BF), this is not a feasible option for use on the present BF/BOF route. Despite this, CCS is considering combining BF/BOF modification with other emerging technologies in the Ultra-Low CO_2 Steelmaking (ULCOS) program, such as Top gas recycling, Hisarna, and Ulcored (Abdul Quader et al., 2016; Yan Junjie and Junjie, 2018). CCS adoption in these technologies might increase emission reduction by up to 80% (EUROFER, 2013).

CCUS, in contrast to CCS, is a more appealing method for CO_2-free steelmaking that is being researched (IEA, 2019d). One concept for this alternative is to mix the carbon source-containing gases (COG, BFG, and BOF gas) with H_2 to make syngas for chemical activity rather than burning them for energy. Another idea is to store CO_2 and use it in the chemical industry, which is a circular economy and sector coupling concept. In this path, the BF/BOF is still used in steelmaking, but the existing plan needs to complement a principal industrial process (IEA, 2019d; Material Economics, 2019, 2018). Using biomass instead of fossil fuels in the steelmaking process, combined with CCUS, might result in a negative carbon footprint for the sector (Ito et al., 2020).

Although the approaches listed above would minimize a major portion of the emissions, more steps in the I&S manufacturing chain are required. Material efficiency (Material Economics, 2019), material circularity, and circular economy (V) (Material Economics, 2018) are topics that might be regarded as short-to long-term possibilities for reducing CO_2 emissions. Regarding material efficiency, the amount of material utilized for certain goods or constructions might be lowered, while the lifetime could be extended (Material Economics, 2019). End-of-life materials are utilized as inputs to create new raw materials in material circularity. Material efficiency and recycling can greatly lower the long-term need for primary steelmaking and lead to secondary steel production through EAF. Using this plan, secondary steel production with electric steel mills is expected to expand from 40% to nearly double in 2050, notably in the EU (European Commission, 2018c; Material Economics, 2018). However, the availability of sufficiently high-quality iron scraps is a major obstacle due to inadequate separation and treatment techniques (EUROFER, 2020). Consequently, boosting the collection rates of ferrous scrap and efforts to improve collection rate and minimize (coper) contamination of steel scrap should be on the priority list for lowering emissions from steel production (Material Economics, 2019). Emissions can be reduced by up to 20% by implementing a material efficiency and circularity strategy (Material Economics, 2018) (up to 40% by the IEA sustainable development scenario (IEA, 2020f, 2020g)). In combination with the circular economy (product circularity in transport and construction), the reduction can be extended to around 35% (Material Economics, 2018).

The characteristics of dealing with technology options such as emission reduction, energy savings, and TRL are listed in Table 4.

In Austria, the I&S subsector has focused on increasing energy efficiency and process control in order to minimize emissions, particularly from the BF/BOF route. The improvement is confirmed when two KPIs for the BF/BOF route, SCe: 1.7 $\frac{tCO_2}{tSteel}$ and SEC: 5.15 $\frac{MWh}{tSteel}$ are compared to world and EU average specific data of 1.9 $\frac{tCO_2}{tSteel}$ and 5.5 $\frac{MWh}{tSteel}$ for emission and energy, respectively. However, the Austrian BF/BOF route's specific emission factor is higher than BAT's predicted specific emission factor of 1.6 $\frac{tCO_2}{tSteel}$. As a result, there is still the opportunity to cut emissions by improving energy efficiency using BAT/BPT.

Based on the energy flow Sankey diagram (Fig. 4) and the previously mentioned emission reduction opportunities, three main paths and strategies for the decarbonization of the Austrian I&S subsector would be meaningful: fuel switching as an energy source in the short/medium-term, material efficiency and circular economy in the period from now to 2050, mainly with increasing steel production via the EAF route, and process switching from conventional BF/BOF to DRI/EAF.

The state of Austrian energy policy is that the country has a plan to attain CO_2 neutrality by 2040 by phasing out all fossil fuels (IEA, 2020b). They also envision producing electricity from 100% renewable sources by 2030 (Federal Ministry for Sustainability and Tourism, 2019a). In the short/medium-term, eliminating emissions from fuel consumption for low-, medium- and high-temperature level heat demand in furnaces, space heaters, and other appliances, which account for nearly 21% of total energy consumption and 12% of total emissions, according to the Sankey diagram Fig. 4, is predictable.

Regarding the historical development of Austrian steel production, it can be seen that CS has grown at an average annual rate of around 2.8% since 1990 (90% BF/BOF and 10% EAF in 2019) (Umweltbundesamt GmbH, 2021). From the economic point of view, the industry aims to follow the growing production in the future. In direct interview with industry experts, though, it was revealed that the Austrian I&S subsector has no plan to raise ore-based primary steel production capacity beyond the current level. Hence, this research proposes that, on the one hand, material efficiency influences primary steel demand. The balance of steel demand, on the other hand, is met by a scrap-based EAF process, which follows the EU circular economy concept's goal. Consequently, in the Austrian context, the EAF share should grow by at least 40% by 2050, reflecting the target number of 35% (Table 4) reduction through material efficiency and circular economy.

Switching the technology from traditional BF/BOF to DRI-EAF in many phases of penetration rate (not addressed in this study) would be the most appealing choice for the process-related emission, which is the most integral part of the emission. The transition begins with replacing the BF/BOF plant with regular DRI-NG and progresses in steps until DRI-H_2 is fully implemented by 2050.

Fig. 5 depicts the decrease in emissions in two-time steps, short/medium-term and long-term, relative to emissions in 2019 by applying the approach mentioned above for the Austrian I&S subsector.

4.2. Pulp and paper industry

4.2.1. Structure of the pulp and paper industry

Paper production consists of three main stages: raw material preparation, pulp production, and papermaking. All three steps have several sub-processes and can take different routes, making this industry highly complex.

Pulp is the main substance for papermaking and can be made from virgin fibers (wood) or by repulping recycled paper. In the raw material preparation stage, virgin wood is prepared by debarking - removing the bark and wood chipping - reducing the wood logs to small chips. Mechanical or chemical pulping is used to turn the prepared logs or chips into a pulp. The methods varied greatly, resulting in pulp with various qualities suited for diverse types of paper (Ericsson and Nilsson, 2018):

Mechanical pulp is the primary form of pulping and is produced using both wood logs and wood chips. The main kind of mechanical pulping is "groundwood pulping (GW), refiner mechanical pulping (RMP), thermomechanical pulping (TMP), and chemithermomechanical pulping (CTMP)" (Bajpai, 2016a). Typically, the fibers produced with mechanical pulping are short and weak and sometimes need to be combined with strong chemical fibers. They are primarily used for low-grade papers such as newsprint and magazine (Bajpai, 2016a).

Chemical pulping is a more common pulp type responsible for more than 80% of the world's pulp production. Chemical pulp is generated using wood chips in digesters by Kraft or Sulphite types. In both types, cellulose (35–45%), hemicellulose (25–30%), and lignin (20–30%) are separated during the cocking process in the digester. Although almost half of the wood (main-based) is not dissolved in the wood liquor during cooking. As a result, the cooking liquor (called black liquor in Kraft pulp) that includes organic and inorganic substances is sent into a chemical recovery system to recover the cooking chemical and energy (Bajpai, 2016a; Suhr et al.). In most cases, the recoverable black liquor's fuel value is sufficient to make the Kraft pulp mills largely self-sufficient in heat and electrical energy demand. Chemical recovery also offers the mill regeneration of chemical digestion at up to 98%, which significantly reduces the costs of purchasing process chemicals and energy (Bajpai, 2016a; Suhr et al.). This type of pulp is very high quality and is principally used to produce higher grade papers such as office paper.

Another type of pulp production is recycling fibers pulp (RCF), which uses recycled paper instead of raw wood more straightforwardly (Bajpai, 2016a).

The P&P mill can be manufactured at the same site (integrated mill) or in separate locations (non-integrated mill). Integrated mills are generally larger, more cost and energy effective, and have cheaper production than individual mills. The pulp is directly delivered to the paper mill in an integrated mill, whereas in the non-integrated mill, the pulp is dried and shipped to the market pulp. In the paper mill, the pulp, after preparation, is fed into the paper machine through the headbox, wire section, press section, and dryer section. Finally, after the finishing process, namely coating and calendaring, the paper is rolled and stored

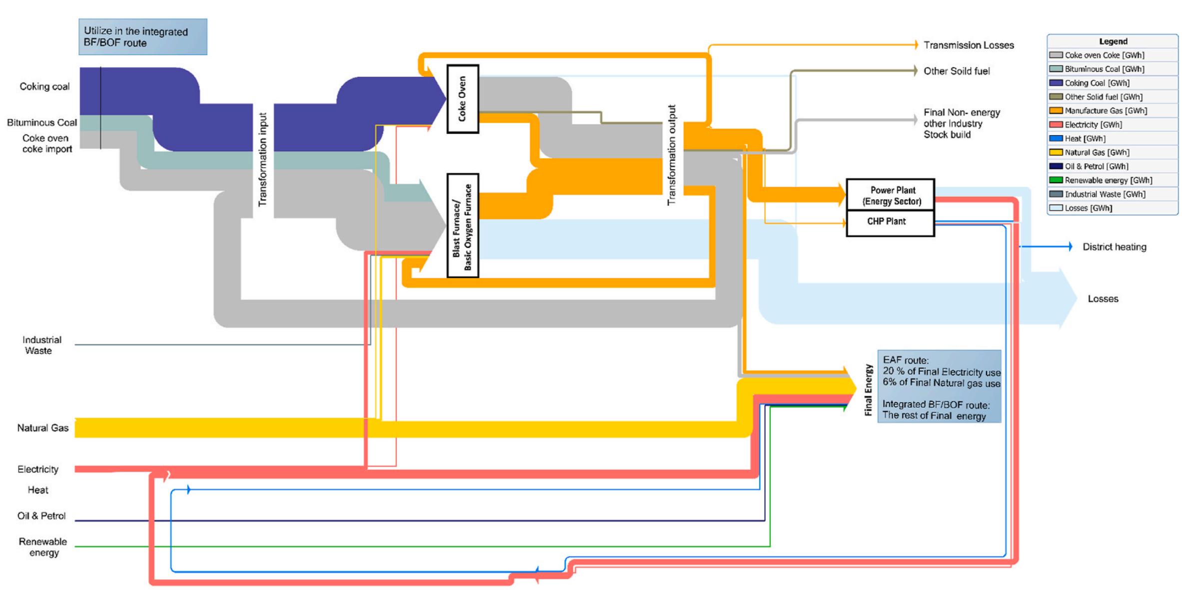

Fig. 4. Austrian Iron and Steel industry energy flow Sankey diagram in 2019 (Eurostat, 2021; Statistik Austria, 2019b).

for market distribution (Bajpai, 2015; Suhr et al.).

4.2.2. Energy consumption and carbon footprint of pulp and paper production

After the I&S and chemical,& petrochemical sectors, the P&P industry was the third-largest industrial energy user worldwide and in the EU-27 in 2019 (Eurostat, 2021). Depending on the pulping process, type of paper output, and the integration or non-integration of production processes, the energy balance and energy consumption characteristics in the P&P sector vary greatly between P&P mills (Ericsson and Nilsson, 2018). In the European P&P sector, thermal power, mainly used to generate pressurized steam, accounts for about 93% of total energy consumption, compared to about 7% of electricity (Moya and Pavel). Pressurized steam (low and medium pressure) is utilized for manufacturing purposes, such as wood chipping, pulp production, cooking liquor in chemical pulping, and evaporating water from pulp and paper sheets in the dryer section. Electric power is employed for motors and electrical equipment, especially in mechanical pulping (Bajpai, 2016a).

P&P processing utilizes approximately 8.5 EJ (Exajoules) of final energy, including 30% from fossil fuels, 42% from biofuels, and 27% from electricity and imported heat globally (IEA, 2020h). Fossil and biofuels are utilized for steam production. The required electricity is usually purchased from the grid to the company or generated by its biofuels (black liquor and waste wood) inside the subsector system boundary. The P&P sector is one of the most prominent consumers of CHP in Europe, accounting for around 10% of installed CHP (Moya and Pavel) and generating more than 50% of its power demand through the internal CHP system (Cepi Statistic, 2020).

Despite the fact that the P&P subsector consumes a lot of energy, it is one of the least CO_2-intensive industrial subsectors in Europe (SCe: 0.33 $\frac{tCO_2}{tpaper}$ (Cepi Statistic, 2020)) and the globe. This is attributable mainly to two factors: on the one hand, unlike the I&S or cement sectors, paper manufacturing does not generate heritable GHG. On the other hand, the P&P manufacturing requires steam at low/medium pressure and temperatures (<200 °C), which are ideal locations for CHP facilities (Rogers, 2018). In the P&P subsector, CHP units utilize more internal bioenergy instead of fossil fuels, lowering the P&P's GHG emission intensity over time. The subsector's emissions are both direct and indirect. Indirect emissions come from the plant's external power supply, and direct emissions are caused by the combustion of fuel and biomass in thermal power plants and the non-process production (process emission from the lime kiln). The Intergovernmental Panel on Climate Change (IPCC) GHG Protocol considers biofuel emissions to be climate neutral, hence only fossil fuel emissions are included in overall CO_2 emissions from the P&P industry (Moya and Pavel).

4.2.3. Austrian Pulp and Paper industry

In Austria, the P&P sector, by producing around 5 Mt of paper, accounted for 5.6% of EU paper production in 2019 (Cepi Statistic, 2020). The sector consists of 21 manufacturing with 24 mills, which produce around 48% paper from raw wood (via 15% mechanical pulp, 63 % kraft and sulphite pulp, and 22% textile pulp), and the rest from RCF pulp using recovered paper (with the paper recycling rate 77.6% in 2019). Paper production comprises 46% graphic paper, 48% packaging and board, and 6% special paper such as sanitary and beverage labels (Austropapier, 2021).

The paper sector consumed 22.5 TWh of total energy (Statistik Austria, 2020; 2019b) and 21.4 TWh of final energy (Statistik Austria, 2019a), corresponding to 24.5% of industrial final energy consumption in 2019. This amount of final energy is applied for steam generation in the drying and separating processes (73.6%), industrial furnaces (3.3%), electric motors (19.6%), and space heating (2.6%) (Statistik Austria, 2019a). The sector also utilized 4.4 TWh electricity and 11.9 TWh steam as useful energy (Austropapier, 2021) for P&P production. About 75% of

Table 4
The reduction potential of considering decarbonization technology options for the I&S subsector, compared to the current level.

Technology option	TRL	emission reduction potential [%] /Emission factor $[\frac{tCO_2}{t\ Steel}]$	energy saving potential [%]
Energy efficiency improvement (using BAT) (I)	8–9	15–20 % (IEA, 2020g) /1.6 (Material Economics, 2019)	26 % (Chan and Kantamaneni, 2015)
Electrification (II)	4	Up to 98% (EUROFER, 2013)	31 % (Siderwin, 2018)
Fuel switching for heat demand to biofuel or electricity (III)	8–9	1.1 (Material Economics, 2018)	–
DRI/EAF NG (III)	9	80% with CCS (EUROFER, 2013) 40% without CCS (Lucas and Di Rossetti Valdalbero, 2018; Material Economics, 2019; Pardo et al., 2015) /1.1 (Material Economics, 2019)	–
DRI/EAF – H_2 (III)	5–7	Up to 95% (Chan et al., 2019)	20% (Chan et al., 2019)
BF/BOF (modifying BF/BOF) with CCS (IV)	5–8	50–90% (EUROFER, 2013; IEAGHG, 2013) /0.9 (Material Economics, 2019)	–
BF/BOF with CCUS (IV)	5–7	0–1 (Material Economics, 2019)	–
Material efficiency, material circularity, circular economy (V)		35 % (Material Economics, 2018)	–

this energy is consumed in papermaking (67% in the drying section (Bajpai, 2016a)), 10% in chemical pulping, and 4% in mechanical pulping processes (Posch et al., 2015). However, the Austrian P&P sector is equipped with local heat and power generators, especially in integrated paper mills and chemical pulping mills. The biofuel obtained from chemical pulping, mainly black liquor, is used in the cogeneration plants (CHP) and generates the central part of the electricity demand, approximately 3.041 TWh, corresponding to 69% of the total electricity demand in 2019, through the use of high-pressure steam in turbines (about 5% of this electricity is produced by on-site hydropower plants) (Austropapier, 2021). Subsequently, the steam output at low/medium -pressure is applied to production processing, making the sector utterly self-sufficient in terms of steam generation. The excess heat and electricity are also fed into the grid (Austropapier, 2021).

To give a general overview of the energy flow in the P&P subsector, Fig. 6 shows an energy flow Sankey diagram of the Austrian P&P manufacturing as a case study.

Approximately 40% of fossil fuels (coal, oil, and NG) are consumed to generate the required energy, emitting 1,943 Kt CO_2 in 2019 as direct emission (including process emission from the lime kiln), with an emission factor of 0.38 $\frac{tCO_2}{tpaper}$ (Mandl et al., 2021). The GHG emission from the 60% biofuel consumption is carbon-neutral and not considered in this scope.

4.2.4. Decarbonization options for pulp and paper industry

In the P&P sector, there are already several opportunities to reduce energy consumption and GHG emissions, which have been pointed out in the literature and are classified into two groups in this Section 4.2.4. As noted in Sections 4.2.1 and 4.2.2, a large amount of the low/medium pressure and temperature (<200 °C) steam is used for the drying section (25–30% of the total energy consumption (Bajpai, 2016a; Moya and Pavel). Hence, the technologies mainly refer to energy saving and emission reduction in the drying step and decarbonization related to steam supply.

Short/medium term reduction: this category is usually associated with energy efficiency (I) and fuel switching (III). The adoption of BAT, operational innovations alongside progressive process control, and an energy management system can all help to increase energy efficiency. BAT includes waste heat recovery, high-efficiency grinding, pulse drying, steam cycle washing, and biological pretreatment are commercially available and have a high TRL (8-9) (Kong et al., 2016; WSP Parsons Brinckerhoff, 2015). By implementing BAT, an energy saving of a maximum of 17% or a minimum of 5.8% is achievable from a technical or economic standpoint (Chan and Kantamaneni, 2015). Emission reductions of up to 22% by 2050, compared to 2015, may be attainable, at least at the European level (Cepi, 2017).

Replacing fossil fuels with locally produced biofuel can occur for steam generation in boilers and also in the lime kiln. However, the availability of local biofuel depends on the processing of mill production. RCF mills do not have on-site biofuel production potential, while chemical pulp mills have access to huge volumes of residuals that can be further processed as fuel (Ericsson and Nilsson, 2018). Biofuels, which currently account for about 40% of total energy consumption in this sector worldwide (IEA, 2020h), generate the required steam in the boiler and, when combined with a CHP plant, provide some of the internally needed electricity, allowing the P&P subsector to reduce total energy consumption (Cepi, 2021; IEA, 2020h; Moya and Pavel). Most P&P firms in the EU, particularly in chemical pulp mills, have internal high-efficiency CHP units (85–92% efficiency) that utilize either biofuels or fossil fuels (NG) and could supply more than half of their energy demands (Moya and Pavel). Other renewable energy sources, such as biomethane and H_2, can also substitute natural gas (the average share of NG in the P&P industry worldwide is about 20% (IEA, 2020h; Mandl et al., 2021). Although H_2 replacement in the P&P industry with steam demand up to 200 °C is not very appealing and relatively low in the "hydrogen value chain" (Cepi, 2021), it can replace the fossil fuel used in the lime kiln. Further transformation of fossil fuels in the subsector to low or free carbon sources might lower emissions by up to 25% compared to 2015 data at the European level (Cepi, 2017).

The preceding methods, which are already in use at some industrial locations, will not be able to meet the aim of reducing CO_2 emissions by 80%. Nonetheless, in short/medium term, they are critical for boosting energy efficiency and lowering energy and emission.

Long-term reduction-deep decarbonization: this technology group contains the breakthrough technologies that contribute to the decrease in energy consumption, notably in the drying step of papermaking and technologies to decarbonize the steam supply chain. CCS/CCUS is also taken into account in this group.

Microwave dryer (TRL 3-4), gas fire dryer (TRL 6-7), boost dryer (TRL 6-7), and other novel drying processes can lower the energy demand of the drying section and enhance energy efficiency (Bajpai, 2016b; Kong et al., 2016). Even so, they may not significantly influence reducing emissions intensity by up to 20%. The Confederation of European Paper Industries (CEPI) has also looked at several technical options for reducing energy consumption and CO_2 emissions, such as deep eutectic solvent (TRL 3, emission reduction up to 20%), dry pulp for curing formed paper (TRL 3, emission reduction up to 55%), and functional surfaces (TRL 6-7, emission reduction up to 35%) (Cepi, 2013). All of these technologies are not yet mature and are under development. Additionally, they have little influence on reducing emissions and conserving energy.

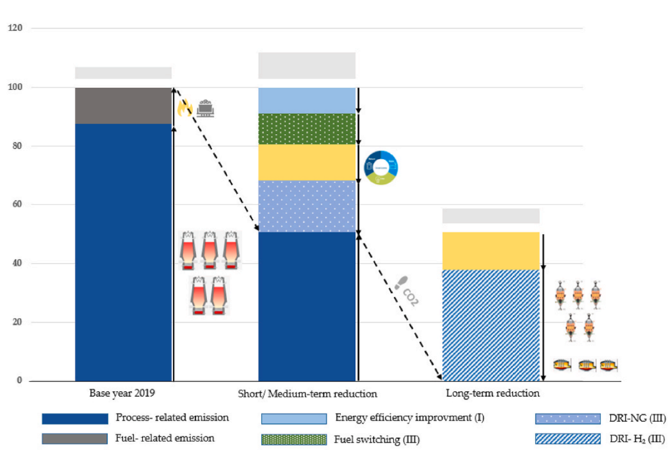

Fig. 5. Effect of the decarbonization pathway on CO_2 emission reduction in the short/medium- and long-term approach on the Austrian I&S industry compared to 2019.

Electrification (II) with an electric boiler and heat pump is frequently explored in association with the decarbonization of the steam supply chain. Electric boilers (Marsidi et al., 2018; van Berkel, 2018) are commercially available and supply heat at low/medium temperatures up to 400 °C, making them a viable alternative to fossil fuel boilers in the P&P industry (Ericsson and Nilsson, 2018). The electric boiler is identical to the current production processing (only fossil fuel boilers are replaced). Electrification in the P&P industry may also be carried out in the dryer section by using the electric dryer. The feasibility of the electrification option is highly dependent on the capacity of the electric grid to meet the high load growth without increasing the use of fossil fuels and the carbon footprint of the grid's electricity mix. With the existing electricity mix, 100% electrification will result in a 20% reduction in emissions. However, increasing the amount of renewables in the electricity grid would raise this technology's decarbonization potential (Cepi, 2013; Roth et al., 2016).

The heat pump (III) is another engaging technology for decarbonizing the steam supply. Industrial heat pumps are active heat recovery systems that consume electrical energy and raise waste heat temperature in an industrial operation. The heat generated can be used in the same or different industrial processes, as well as for heating, cooling, and air conditioning in both commercial and industrial buildings (M. Jakobs et al., 2020). Commercial heat pumps can already deliver heat up to 100 °C, while heat output up to 200 °C for industrial purposes is being studied (M. Jakobs et al., 2020). A heat pump with a coefficient of performance (COP) between 3 and 5 dramatically improves the system's energy efficiency (van Berkel, 2018). Nevertheless, the COP, which depends on the temperature of the waste heat source and the heat demand and plant efficiency, may be lower to 1.6 in the industrial case (Arpagaus et al., 2018). In the P&P sector, waste heat from the drying section with a temperature level of 20–60 °C could be used in heat pumps to generate steam, which would reduce energy consumption in the drying section by up to 80% (Dryficiency, 2021; Jankes et al., 2011). By using heat pumps instead of NG, some publications anticipated a decrease in CO_2 emissions of up to 75% (40–90%) and a total energy savings of 20–80 % for the drying process.

CCS/CCUS (IV) or bioenergy with carbon capture and sequestration (BECCS) (Kuparinen et al., 2019) is another cutting-edge technology for the P&P subsector decarbonization (Klement et al., 2021; Möllersten et al., 2006). This technology can be adopted in the paper mill and combined with an internal CHP plant to reduce biofuel emissions (Möllersten et al., 2006). However, given the current environmental and energy legislation state, the BECCS does not appear to be an encouraging solution. Nevertheless, when negative emissions and the removal of atmospheric CO_2 emissions are taken into account, the P&P industry provides a viable option for BECCS utilization. BECCS adoption is currently costly, and the P&P enterprise must overcome various hurdles to become this alternative more cost-effective. The CCS or BECCS could be more profitable if another industry unit (e.g., I&S or chemical and petrochemical) could be located near the paper mill, and a sector coupling could be used to link the existing transport infrastructure to the collected CO_2 (Cepi, 2021). By combining CCS with increased biomass usage in the energy mix, emissions are expected to be reduced by 98% by 2050 compared to 2015 (European Commission, 2018c).

In parallel to the above-mentioned technological options, the circular economy (V) and increasing the share of RCF paper are necessities alongside the growth in paper demand. Raising the share and quality of recycled paper and producing more paper from recycled fibers would help reduce paper production's specific energy and CO_2 intensity (IEA, 2020h). The total energy required to pulp and make paper from recycled fibers is much lower than that needed for chemical and mechanical pulping. However, the process still needs heat and electricity to dry the final paper products and remove impurities and ink (Moya and Pavel). In 2019, the average European paper recycling rate was 72%, higher than the global average of 59.3% (Cepi Statistic, 2020), but only 54% of total paper production was made from recycled fibers (Cepi Statistic, 2020). Paper production from 100% recycled fibers translates into emission reductions of up to 37% and energy savings of up to 33% (Moya and Pavel). A further reduction in the paper's need would also be achieved through digitization. It is predicted that the increasing use of digital media will decrease the need for print-related paper in the future. Irrespective of this, higher demand for packaging and sanitary paper is expected due to population and economic growth (IEA, 2020h).

Table 5 summarizes the mentioned technologies for the decarbonization of the P&P industry.

In Austria, the P&P sector has started to improve its energy efficiency in recent decades. Implementing the BAT, transitioning from fossil fuels to on-site biofuel production (black liquor), and employing recycled paper have led the industry to reduce absolute CO_2 emissions by roughly 20% and specific CO_2 emissions per ton of paper to 40% in the last twenty years (Austropapier, 2021). Nevertheless, a comparison of the SCe indicator for the Austrian P&P industry, 0.38 $\frac{tCO_2}{tpaper}$ with the EU average number 0.33 $\frac{tCO_2}{tpaper}$ demonstrates that the subsector has to increase its energy efficiency even further in order to meet the Paris Agreement objective. Adopting commercial drying technology, such as gas-fired dryers, impulse dryers, condenbelt dryers, will improve energy efficiency and reduce CO_2 emissions by up to 10% for the Austrian P&P industry (Rahnama Mobarakeh et al., 2021). The additional reduction to 22% based on CEPI assumption by applying various BAT such as more efficient waste heat recovery systems, energy management systems, etc., is also expected for the Austrian P&P sector in short/medium timescale.

From a renewable energy perspective, 60% of the fuel consumption in the Austrian P&P sector comes from biofuel (black liquor, bark, wood waste). Since wood (bioenergy source) is the raw material for paper production, out of the 100% wood energy potential used for paper production, 60% is recovered as bioenergy. The Austrian P&P industry could upgrade its energy efficiency, energy management system, waste heat recovery facility, and biofuel recovery system to raise the share of internal biofuel production. Installing high efficient CHP plans within manufacturing, mainly chemical pulp mills and using onsite produced biofuel to feed the CHP can reduce emissions by up to 25% (based on Table 5), which is also considered for the Austrian P&P sector.

According to Section 4.2.3 and the Sankey diagram of the energy flow (Fig. 6), steam generation accounts for around 90% of the total fossil fuel input in the Austrian P&P industry, while industrial furnaces and space heating contribute 10% (Statistik Austria, 2019a). In the near future, high heating value biofuels in furnaces and commercial heat pumps for space heating can supplant NG, which is the only fossil fuel that accounts for emissions in this section. The remaining fossil fuel consumption for steam generation could be eliminated by replacing the fossil fuel boiler with the electric boiler or biofuel boiler in the short/medium-term and the heat pump (combined with waste heat recovery) in the long-term. The heat pump will improve energy efficiency and bring the sector closer to net-zero emissions by reducing overall energy consumption. Process emissions from the lime kiln represent a minor percentage of total emissions (3%), yet it is anticipated to be phased out through CCS technology.

In parallel with all technological possibilities, more attention should be paid to increasing the share of recycled paper instead of raw wood through the circular economy. In Austria, the paper recycling rate is currently over 70%, but only 50% of paper is produced from recycled paper. Improving the recycled paper system and increasing the use of recycled paper by at least 20% will help reduce emissions up to 10% in 2050 compared to the current level. Fig. 7 depicts the short/medium- and long-term emission reductions compared to 2019 by implementing the above pathways for the Austrian P&P subsector.

4.3. Cement industry

4.3.1. Structure of the cement industry

Cement is one of the significant subsectors in the non-metallic mineral (NMM) group. The NMM is divided into several subproducts: clay products, refractory products, glass and glass products, cement, lime, concrete, ceramics, and gypsum. This production group processes mined or quarried natural raw materials such as sand, stone, clay, and refractory material (magnesia) into semi-finished or finished products such as lime, cement, and concrete (Chan and Kantamaneni, 2015; European Communities, 2008). NMM accounts for around 10% of industrial energy consumption (Srivastava et al., 2011). However, due to the high process-related emissions of cement manufacture, the percentage of CO_2 emissions is substantially larger. Cement manufacturing

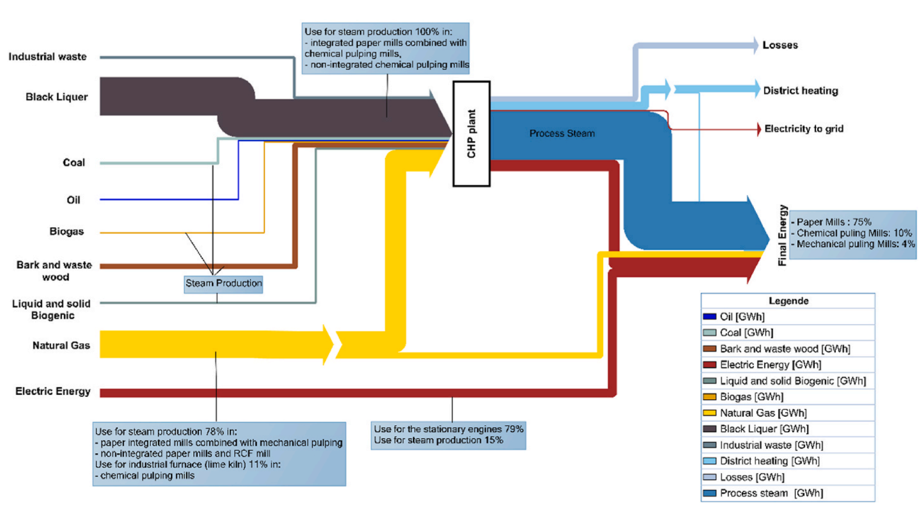

Fig. 6. Energy Flow Sankey diagram of the Austrian Pulp and Paper industry in 2019 yr (Rahnama Mobarakeh et al., 2021; Statistik Austria, 2020; 2019a, 2019b).

accounted for 83% of overall energy consumption and 94% of global CO_2 emissions within the NMM (Srivastava et al., 2011). In 2019, cement manufacturing was responsible for about 7% of global GHG emissions (IEA, 2020f). In Europe, cement manufacturing contributes nearly 45% of total NMM revenues (Chan and Kantamaneni, 2015) and is attributable to almost 60% of energy consumption and 70% of CO_2 emissions during the NMM (Mandl et al., 2021). Due to the high contribution of the cement industry to energy consumption and emission generation during the NMM, the cement subsector is addressed in this Section 4.3.1.

Cement is a crucial material for building and construction products. It produces homogeneously in three main stages: Raw material preparation, clinker production, and cement production. In the first step, the raw materials, consisting of limestone, chalk, and clay as the primary raw material, and other additives such as sand, bauxite, and blast furnace slag (BFS), are extracted in quarries and transported to the kiln (European Commission, 2018a; Schorcht et al., 2013). In order to supply high-quality cement, the raw material must be chemically homogenized and pulverized before being fed into the kiln, which is done during grinding (Schorcht et al., 2013).

In the next step of clinker production, limestone ($CaCO_3$) is heated in the kiln to make lime (CaO). There are different types of clinker kilns, wet, semi-wet, semi-dry, and dry. The wet kiln is more energy-intensive and more expensive than the dry kiln. In Europe, almost all production, over 90%, is based on dry kiln technology due to the availability of dry raw material. A dry kiln requires two steps before the kiln: preheater and precalciner. In the preheater, the raw material is heated to 900 °C with the hot exhaust gas recycling from the kiln to improve the efficiency and reduce the fuel consumption in the kiln (Moya et al., 2010; Schorcht et al., 2013).

In the precalciner, limestone is decomposed into lime by direct fuel combustion, producing lime and CO_2 ($CaCO_3$ + energy → CaO + CO_2 (5)). Then the materials are transferred to the kiln and heated to 1400–1500 °C. In the kiln, the calcination of limestone performed in precalciner is completed, and surface sintering occurs. Next, the produced clinker is rapidly cooled from 1000 °C to 100–200 °C and sent to the cement production stage or storage for later use. Finally, in the cement production step, clinker is mixed with gypsum and other cementitious materials such as slag and fly ash to produce Portland or different types of cement (Moya et al., 2010; Schorcht et al., 2013).

4.3.2. *Energy consumption and carbon footprint of the cement industry*

The cement industry is the fifth largest industrial energy user, with thermal energy accounting for around 80% of consumption and electrical energy contributing for the remaining 20% (IEA, 2020d, 2020e). The central part of the thermal energy consumption is related to the combustion process in the kiln and the precalciner for the chemical reactions required for clinker production. The thermal energy consumption is determined by the kind of kiln technology, number of cyclone stages in the preheater, type of clinker cooler, and the moisture content in the raw materials (Pardo et al., 2011; Schorcht et al., 2013).

To provide thermal energy with direct fuel combustion, mainly fossil fuels with high energy content such as NG, coal, and oil are used. Alternative waste fuels (AWF), such as wood and paper waste, plastics, municipal sewage sludge, waste tiers, and animal feed, have gradually replaced fossil fuels in Europe in recent decades, reaching a level of more than 80% in some cement plants (European Commission, 2018a; Schorcht et al., 2013). The cement industry may help decrease GHG emissions and protect natural resources by using low-carbon AWF such as wood, waste paper, and animal meal. Worldwide, 91% of thermal energy is provided by fossil fuels and 9% by renewable and non-renewable AWF (IEA, 2020d), which for the EU, on average are 52% and 48% from fossil fuel and AWF (Cembureau, 2021c) (with 17% biomass (Cembureau, 2021b)). In general, the specific thermal energy consumption for dry cement kilns with preheaters and precalciner ranges from 0.83 to 1.11 $\frac{MWh}{t\ Clinker}$ (3 to 4 $\frac{GJ}{t\ Clinker}$) (European Cement Research Academy and Cement Sustainability Initiative, 2017; Moya et al., 2010; Schorcht et al., 2013), with a global average value of 0.97 $\frac{MWh}{t\ Clinker}$ (3.5 $\frac{GJ}{t\ Clinker}$) (IEA, 2018). However, various factors, such as plant size and design, moisture content of raw materials and fuels, raw material burnability, and the specific calorific value of fuels, might impact specific thermal energy consumption (Schorcht et al., 2013).

Electrical energy is mainly used for raw material extraction and blending (5%), grinding and homogenization of raw materials (30%), clinker production (22%), cement production (38%), and conveying, packaging, and loading equipment (5%) (Hoddinott. P, 2013). Overall, electricity demand ranges from 0.09 to 0.15 $\frac{MWh}{t\ Cement}$ (Schorcht et al., 2013), with an average value of 0.11 $\frac{MWh}{t\ Cement}$at the European level (Cembureau, 2019a) and 0.091 $\frac{MWh}{t\ Cement}$at global level (IEA, 2018).

Concerning the emissions footprint, the cement industry is responsible for 7% of world GHG emissions (IEA, 2020f). The main emission contributor in cement production is the emissions from clinker production in the calcination process. In the precalciner and clinker kiln, the emission drive from the chemical reaction of limestone to lime (Eq. (5)) is referred to as process-related emissions. It accounts for 60–70% of total cement-related emissions. The rest of the emissions are fuel-related and come from fossil fuel combustion for heat requirements with a share of 30–40% (IEA, 2018; Schorcht et al., 2013). The fuel-related emission depends on the fuel type and the carbon content of the calorific value (Schorcht et al., 2013).

The process emission factor of one ton of clinker manufacturing in the European Union ranges from 0.49 $\frac{tCO_2}{t\ Clinker}$ to 0.59 $\frac{tCO_2}{t\ Clinker}$ with an average of 0.53 $\frac{tCO_2}{t\ Clinker}$ (Mandl et al., 2021). The overall emission factor (process and fuel-related emissions) of cement manufacturing is 0.81 $\frac{tCO_2}{t\ Clinker}$ and 0.6 $\frac{tCO_2}{t\ Cement}$ with a clinker to cement ratio of 74% in the European level (Cembureau, 2021d) and 0.54 $\frac{tCO_2}{t\ Cement}$ with a clinker to cement ratio of 65% at the global level (IEA, 2018).

4.3.3. *Austrian cement sector*

There are currently eleven plant locations of the Austrian cement industry, distributed decentrally across the country, mainly in the Limestone Alps. Nine of these sites are cement clinker sites that supply high-grade Austrian cement markets (VÖZ, 2019). With a production

Table 5
Characteristic of considering decarbonization technology option for pulp and paper industry compared to the current level.

Technology option	TRL	emission reduction potential [%] /Emission factor $[\frac{tCO_2}{t\ Paper}]$	energy saving potential [%]
Energy efficiency improvement (using BAT) (I)	8–9	22 % (Cepi, 2017)	17 % (Chan and Kantamaneni, 2015)
Electric Boiler (II)	9	Depending on the power mix emission factor, 20% with the current power mix (Cepi, 2013; Roth et al., 2016)	–
Fuel switching to bio fuel combined with CHP (III)	9	25 % (Cepi, 2017)	–
Heat pump and waste heat recovery (III)	7	75 % (40–90%) (Wilk et al., 2019)	20–80% (Wilk et al., 2019)
CCS with biomass (IV)		Up to 98% (European Commission, 2018c)	
New drying techniques	3–7	20 % (Chan et al., 2019)	10% (Chan et al., 2019)
Paper production by recycling fiber (RCF) (V)	9	37 % (Roth et al., 2016)	33 % (Roth et al., 2016)

capacity of roughly 5.2 Mt, the Austrian cement industry is a massive economic sector with a high degree of regionality that meets local cement demand. In 2019, the cement subsector utilized approximately 4.4 TWh of total (final) energy, of which 86 percent was thermal energy and 14 percent was electrical energy (Mauschitz, 2021). The Austrian cement subsector has substantially replaced fossil fuels with AWF in recent years and is the world's largest AWF user, with a share of 80% (VÖZ, 2019). Fig. 8 illustrates the energy flow Sankey diagram of the Austrian cement subsector.

The Austrian cement industry is fully equipped with dry kilns and the most energy-efficient production plants, according to BAT standards. Its specific thermal and electrical energies were 1.1 $\frac{MWh}{t\ Clinker}$ (3.96 $\frac{GJ}{t\ Clinker}$) and 0.1135 $\frac{MWh}{t\ Cement}$ respectively, in 2019 (Mauschitz, 2021). Nonetheless, compared to the energy intensity of the top cement plants, there is still room for improvement in terms of energy efficiency.

Austria's domestic cement sector is the country's second-largest CO_2 emitter, accounting for 2.3% of total national emissions (Umweltbundesamt GmbH, 2021). Around 67% of these emissions are caused by processes, whereas 33% are caused by fuel (Mauschitz, 2021; Umweltbundesamt GmbH, 2021). With the process emission factor of 0.52 $\frac{tCO_2}{t\ Clinker}$ and overall emission factor 0.51 $\frac{tCO_2}{t\ Cement}$ the Austrian cement subsector has one of the lowest emission factor in the world (Mauschitz, 2021; VÖZ, 2019). It is due to applying energy-efficient equipment and the high proportion of alternative fuels. Furthermore, Austrian cement production has reduced the ratio of clinker to cement to below 69% by using alternative raw materials such as fly ash (a by-product of coal-fired power plants) and granulated BFS (a by-product of the I&S industry) (Mauschitz, 2021; VÖZ, 2019). It has one of Europe's lowest clinker-to-cement ratios, which directly impacts CO_2 emissions and energy use.

4.3.4. Decarbonization options for the cement industry

The decarbonization pathway that emerged from the literature review for the cement subsector is considered in two groups, like other subsectors. Since the major part of emissions comes from the chemical reaction in clinker production, robust solutions should be used to tackle the issues of lowering emissions while simultaneously expanding cement output.

Short/medium-term reduction: in this path to mitigate CO_2 emissions from the cement subsector in the shortest possible time, improve energy efficiency (I), replace fossil fuels with low-carbon fuels (III), lower the clinker-to-cement ratio by promoting material efficiency, and reduce cement demand through both materials efficiency and circular economy (V) can be discussed as crucial elements (European Commission, 2018c; IEA, 2020d). Though, circular economy belongs to both short/medium-term and long-term reduction.

In recent decades, the cement industry's energy efficiency (I) has been improving globally, adopting state-of-the-art technologies. The wet kiln was replaced with a contemporary drying kiln, which resulted in a consistent reduction in energy consumption and emission intensity. Energy consumption and CO_2 emissions will be decreased by 10–12% by improving energy efficiency and using BAT such as advanced grinding, multi-stage preheater, multi-channel burner, and waste heat recovery (have installed in the several cement plants in India (Triveni, 2020)) (Chan and Kantamaneni, 2015; IEA, 2018).

Since directly consumed fossil fuel is responsible for 30–40% of emissions in the cement sector, substituting renewable sources such as H_2, biomass, and renewable AWF in place of fossil fuel (Coal) can reduce partially or fully fuel-related emissions. Regardless, the carbon content of the waste fuel and the proportion of biomass substant for AWF play a role. It is also worth noting that AWF's physical and chemical characteristics differ greatly from traditional fossil fuels (Hoenig and Harrass, 2017). Some characteristics, such as low calorific value and high moisture content, might provide technical issues, necessitating the adaptation of furnaces and other equipment for AWF combustion (Schorcht et al., 2013). The mentioned properties for AWF and the type of fuel mix (share of renewable and non-renewable waste) can influence thermal energy consumption and, in some cases, induce an increase in the specific thermal energy requirement for clinker manufacture (Schorcht et al., 2013). As already discussed, AWF consumption is currently 48% across Europe (Cembureau, 2021b, 2021c). According to the EU's Waste-to-Energy policy, the AWF share in cement production will rise to 60% in the medium term and even to 95% in the future, with a 50% biomass content (Cembureau, 2021b). Direct use of H_2 instead of fossil fuels in the cement plant is associated with technical challenges, such as the corrosiveness of the kiln, which requires a significant change in equipment. Therefore, H_2 application in the cement subsector is less attractive than in other subsectors like the I&S industry (IEA, 2020f). The fuel switching can help reduce up to 35–40% (the share of fuel-related emissions) based on biomass allocation in the fuel mix compared to the current level.

Since clinker is the main ingredient for cement production and all the process emission comes from clinker processing, reducing the clinker to cement ratio can mitigate the process emission (IEA, 2020d). Materials like fly ash, granulated BFS, gypsum, natural volcanic material, and

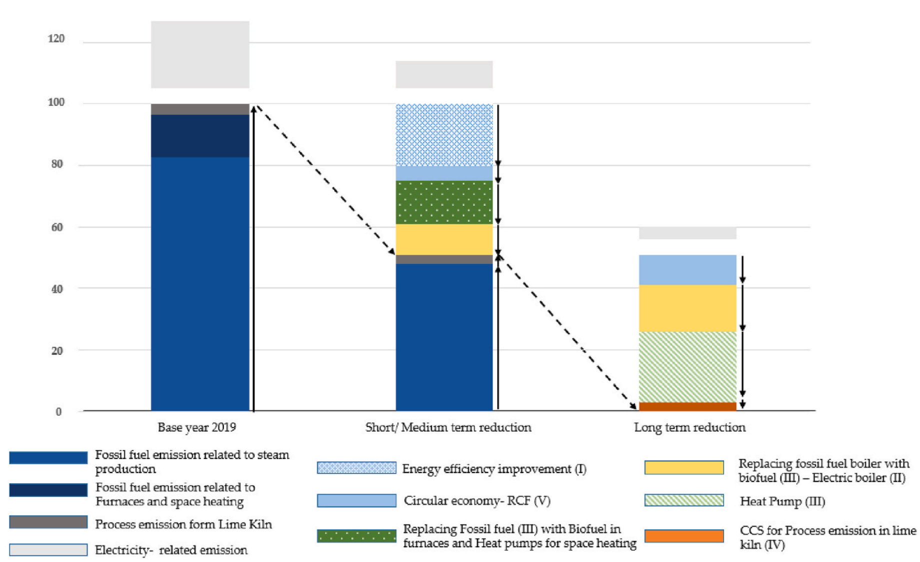

Fig. 7. Effect of the decarbonization pathway in CO_2 emission reduction in the short/medium and long term on the Austrian P&P industry compared to 2019.

calcined clay are used as alternative materials to replace clinker (IEA, 2018; Moya et al., 2010; Schorcht et al., 2013). This alternative material, on the one hand, by reducing the proportion of clinker for cement production, diminishes the process emission intensity (by up to 10% (Material Economics, 2019)-30% (IEA, 2018) by 2050) and, on the other hand, decreases the fuel-related emissions due to the lower thermal energy consumption compared to conventional materials (Schorcht et al., 2013). Currently, the clinker to cement ratio is about 0.7, which is expected to fall to 0.6 in 2050 (IEA, 2020d, 2018). Nevertheless, the regional availability of alternative raw materials, the acceptance by cement markets with a lower clinker content than conventional cement, and cement standards undergoing construction should be considered (IEA, 2018).

Long-term reduction - deep decarbonization: due to the high amount of emissions produced by $CaCO_3$ breakdown in clinker processing, technologies that can significantly reduce process emissions are prioritized and included in this path. CCS/CCUS (IV), electrification combined with CCS (II-IV), and alternative raw materials for producing the new cement were recognized as the main feasible ways to drastically reduce the cement industry's GHG emissions.

CCS/CCUS (IV) is a promising technology for the cement industry. In fact, implementing CCS/CCUS is not just an option; it is a necessity for the cement-making sector to meet climate targets (Plaza et al., 2020). There are three categories of CO_2 captured from cement production (European Cement Research Academy and Cement Sustainability Initiative, 2017): Pre-combustion, post-combustion, and oxyfuel combustion. Pre-combustion is implemented before cement kilns, which can capture only fuel-related emissions. Therefore, this technology has limited mitigation potential and is not evaluated as a well-established option for deep decarbonization of the cement industry (European Cement Research Academy and Cement Sustainability Initiative, 2017; Plaza et al., 2020). Post-combustion CCS is the technological option used to retrofit the existing cement plant without specific modifications. On this route, the kiln exhaust gas with a high CO_2 concentration would be used in post-combustion technologies such as the chemical absorption (e.g., Amine Scrubbing (Laribi et al., 2019), Chilled Ammonia Process), membrane separation, and calcium looping (CaL) (Plaza et al., 2020; Voldsund et al., 2019). CaL (Rodríguez et al., 2012; Romano et al., 2013) is the essential promising technology in this group. CaL is based on the reverse carbonization reaction cycle and can be applied in the plan in two ways: Tail-end (Lena et al., 2017) and integrated configuration (Lena et al., 2019). In this technology, the flue gas released from the cement kiln is transferred to the CaL system and separated into CaO-rich purge and CO_2 using a carbonator and a calciner (two interconnected circulating fluidized beds) (Lena et al., 2019; Plaza et al., 2020). The produced CaO replaces part of the limestone in the raw material, and the CO_2 would save with a 92–94% saving rate by Tail-end and 95% by integrated configuration (Lena et al., 2019; Voldsund et al., 2019). In the CaL circuit, there is sufficient qualitative and quantitative high-temperature waste heat (especially in tail-end configuration) that can be used to generate steam and electricity in the Rankine cycle (Lena et al., 2019; Plaza et al., 2020). Oxyfuel CCS (Jordal et al., 2019; Plaza et al., 2020; Voldsund et al., 2019) is the most likely long-term decarbonization option and offers the opportunity to reduce fuel and process emissions when fully deployed in the cement plant. In oxyfuel technology, pure oxygen is used to burn fuel instead of air. Therefore, fuel efficiency is improved, and more concentrated CO_2 can be captured at a rate of 90%.

Electrification (II) of the kiln with a plasma generator, microwave energy, or through H_2 seems technically feasible to reduce fuel-related emissions in the cement industry (Cembureau, 2021b; IEA, 2020d; Material Economics, 2019; Vattenfall, 2019). Instead of fossil fuels, this option for generating the demanding heat would use electricity (low--emission electricity). The current kiln design mixes two emission streams generated from process and energy, electrification can only reduce fuel emissions, and process emissions are still in place. If these two lines could be separated, almost 100% of the pure CO_2 emissions from processing would be stored by CCS (Material Economics, 2019). As a result, a mix of electrification and CCS would eliminate total emissions from the cement subsector.

The potential to combine clinker with alternative raw materials or even to use new materials in place of clinker to make novel cement instead of Portland cement is an essential enabler to reduce overall emissions from cement manufacturing processing. Traditional clinker, which uses limestone as the primary raw material, can be replaced by alternative materials such as: cementing materials known as geopolymers and alkali-activated binders (Provis, 2018)- produced by reacting solid aluminosilicate materials (e.g., Fly ash, GBFS, clay, volcanic rock) with an alkali activator with the potential of reducing emission 80–90% (Lehne and Preston, 2018); carbonate calcium silicate clinker (CCSC) (Gartner and Sui, 2018) with emission reduction up to 43% (Lehne and Preston, 2018); and magnesium-based cement - magnesium oxides of magnesium silicates (MOMS) (Gartner and Sui, 2018)- with 100% emission reduction (Lehne and Preston, 2018). These materials are not limestone-based and have a comparably high reduction potential. CCSC and MOMS can be hardened by the carbonation process (use of CO_2) rather than hydration (use of H_2O) and absorb more CO_2 instead of releasing it in production processing (Lehne and Preston, 2018). They can produce carbon-negative cement and concrete. However, there are some obstacles to building and using novel cement. Regional availability of appropriate quantitative and qualitative raw materials, especially for geopolymers and alkali-active binders, market availability, production costs, required standards, and customer acceptance make the use of the novel cement uncertain (Gartner and Sui, 2018; Lehne and Preston, 2018).

Material efficiency (Material Economics, 2019) and circular economy (V) (Cembureau, 2016; Material Economics, 2018) with the concept of optimization of cement consumption, efficient use of concrete structure, utilizing old material as input for new material production (recycling concrete/cement (RC) (Carriço et al., 2021; Sousa and Bogas, 2021)), and increasing the lifetime of buildings and infrastructures are other exciting option to decarbonize the cement industry from short to long time scale continuously. Although these options can never reduce emissions to zero, they can help reduce material consumption and the energy required to produce new materials and even reduce new technologies' energy and capital costs. Material efficiency and circular economy can help reduce CO_2 emissions in the cement and concrete value chain by up to 44% (Cembureau, 2016; Material Economics, 2019). It should be noted that the use of waste as a resource, as raw material, or as an energy source (AWF) can also figure as material recycling and circular economy (Cembureau, 2016, 2021b).

Toward deep-cut emissions from the cement subsector, the emission reduction pathways require thinking about breakthrough technology outside the factory gates, in addition to the preceding options. Following the "5C approach" of the European cement industry, concrete, construction, and carbonation also need to be addressed as clinker and cement to promote a collaborative approach along the value chain (Cembureau, 2021a). In this approach, there are some opportunities such as digitization and use of low carbon cement for concrete, less use of concrete in structures, re-carbonization through more recycled concrete, and zero-emission vehicles to transport the material during the value chain given more attention.

Table 6 summarizes the technologies mentioned for decarbonizing the cement industry.

As noted in Section 4.3.3, the Austrian cement industry is a global leader in environmental protection. Using the greatest technology (e.g., dry kiln), substituting fossil fuels with AWF, and reducing the clinker content of cement, the industry has invested in technological techniques and technical equipment to upgrade energy efficiency and emission reduction during the previous decades. These measures have aided in the reduction of carbon emissions. Comparing the SCe of Austrian

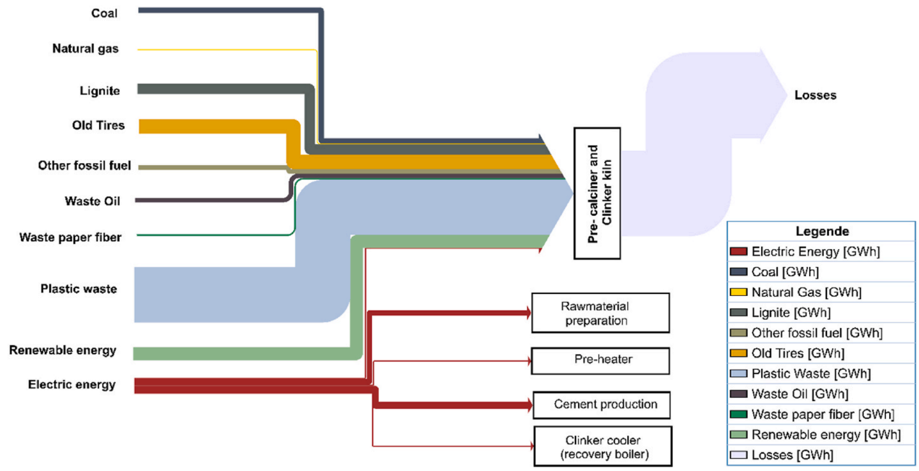

Fig. 8. Energy Flow Sankey diagram of the Austrian Cement Industry in the 2019 yr (Mauschitz, 2021; Statistik Austria, 2019a; 2019b; VÖZ, 2019).

cement production of 0.51 $\frac{tCO_2}{t\ Cement}$ with the global average of 0.54 $\frac{tCO_2}{t\ Cement}$ (IEA, 2018) and the EU average of 0.6 $\frac{tCO_2}{t\ Cement}$ (Cembureau, 2021d) verified this improvement. Still, the SEC of thermal energy and electrical energy demand for the Austrian cement subsector, benchmarking 1.1 $\frac{MWh}{t\ Clinker}$ and 0.1135 $\frac{MWh}{t\ Cement}$ respectively, versus the average global and EU level of 0.97 $\frac{MWh}{t\ Clinker}$ for heat and 0.091-0.104 $\frac{MWh}{t\ Cement}$ for electricity, states there is more room for improvement. Improved energy efficiency (e.g., enhanced waste heat recovery) and the use of AWF with a higher heating value content can help achieve this upgrading.

Despite the Austrian cement industry using AWF for more than 80% of its energy mix infrastructure, most alternative waste fuels contain carbon content, and the biomass content of alternative fuels is relatively low. In the current alternative waste fuel mix, the biogenic carbon content varies from 0% for waste oil and solvents to a maximum of 56% for waste paper (Umweltbundesamt GmbH, 2021). In 2019, the biomass share of total solid waste was only 34%, and the fossil share was 66% (Umweltbundesamt GmbH, 2021). By mid-century, increasing the biomass proportion in AWF until it is entirely replaced by biofuel with high calorific value renewables (e.g., biomethane or H_2) can remove fossil emissions. This would also aid in improving energy consumption performance, particularly in terms of heat demand.

Another technology worth studying for Austrian cement manufacturing is the circular economy and material efficiency, which can effectively reduce the demand for new cement by using more recycled concrete and broken bricks, lowering energy and emissions connected with the manufacture of new material. Based on Table 6, this article assumes that a maximum emission reduction of 44% is possible; however, this is contingent on the availability of recycled material.

As the initial source of emissions is clinker processing, a more robust approach is needed to decarbonate Austrian cement production profoundly. Hence, CCS options (oxyfuel, calcium looking, or amine scrubbing) would be the main, or perhaps the only, way to eliminate process emissions in the long term. CCS application can commence in the near term and fully incorporate all cement plants by 2050. As a result, a reduction of more than 90% is assessable. The impact of various decarbonization pathways on Austrian cement production is depicted in Fig. 9.

4.4. Aluminum industry

4.4.1. Structure of the aluminum industry

The Non-Ferrous Metals (NFM) subsector is divided into several groups: "base metals (aluminum, copper, lead, zinc, nickel, and tin), precious metals (e.g., gold, silver), and so-called technology metals (e.g., molybdenum, cobalt, silicon, selenium, manganese)" (Cusano et al., 2017; European Commission, 2018c). Aluminum (Al) is the most prominent emission contributor and energy consumer in the NFM subsector (European Commission, 2018c). Al plays an essential role in developing low-carbon and energy-efficient applications in modern society. Due to its lightweight, formability, recyclability, and conductivity properties, the demand for Al has increased recently (European Aluminium, 2019b).

Al is produced by two methods: the primary and the secondary Al production routes. The production of primary Al, which is very energy-intensive, is carried out from Al-Oxide (Al_2O_3) in two stages: production of Al-Oxide from bauxite using the Bayer process and primary Al from Al-Oxide using the electrolytic Hall- Héroult process. The Bayer process is a standard process for extracting Al-Oxide from bauxite (a mixture of aluminum hydroxides, oxyhydroxide, and other impurities) at elevated temperatures (250 to 1050 °C) and pressures in digesters. The final products in this stage are Al-Oxide and red mud (a mixture of metal oxides) (European Aluminium, 2019b).

In the next step, the pure alumina is reduced to Al metal by the Hall-Héroult process, where alumina is reduced to liquid Al at about 950 °C in a fluorine bath under a high-intensity electric current with a carbon anode (Cusano et al., 2017). During this process, Al deposits on the cathode while oxygen from Al-Oxide combines with carbon from the anode and produces CO_2 (Moya et al., 2015).

Secondary Al manufacturing makes aluminum from recycled new and old scrap. The new scrap generated during primary Al production, consists of surplus material and is 100% recoverable (Cusano et al., 2017; Moya et al., 2015). The old scrap with lower aluminum content is obtained from Al's old items. The recycled scrap is remelted in a melting furnace (reverberatory furnace) at 700–760 °C and creates molten Al (Chan and Kantamaneni, 2015).

The molten Al produced by the primary or secondary route is then fed to the downstream step to be converted into a final product such as casting, extrusion, and rolling.

4.4.2. Energy consumption and carbon footprint of the aluminum industry

Aluminum is classified as an EIIs due to the high energy requirements of primary Al production. Primary Al manufacturing needs thermal energy of 10.28 $\frac{MWh}{t\ primaryAl}$ (37 $\frac{GJ}{t\ primaryAl}$) (European Aluminium, 2013; Moya et al., 2015) a substantial amount of electrical energy in the range of 14–16 $\frac{MWh}{t\ primaryAl}$ (Ecofys, 2009a) with an average value of 15.141 $\frac{MWh}{t\ primaryAl}$ in Europe and 14.161 $\frac{MWh}{t\ primaryAl}$ globally (IEA, 2020a). The thermal energy is supplied by fossil fuels (coal, oil, NG), and the electricity can be purchased from the grid or generated inside the manufacturing plant (globally, more than 55% of the electricity consumed is self-generated, especially in Asia (International Aluminium

Institute, 2021a)) (IEA, 2020a). The power supply for Al manufacturing is a mix of different energy sources such as coal (61.2%), natural gas (9.4%), and hydropower (25%) on a global scale. In the European region, the Al industry tends to purchase electricity from a low-carbon energy mix, i.e., more than 80% is from hydropower and other renewable sources, around 10% from nuclear power, and the rest from fossil energy (International Aluminium Institute, 2021a).

The important energy-intensive sub-process of primary Al production is refining Al-Oxide and electrolysis, accounting for 21% and 70% of total energy use for Al production, respectively (European Aluminium, 2013). Approximately half of the electricity input in Al production, especially in the Hall- Héroult step, is converted to waste (Moya et al., 2015).

In contrast, secondary Al production is significantly less energy-intensive, requiring as little as 5% of the energy needed for primary production (Moya et al., 2015). The new or old scarp's type and quality can affect the specific energy consumption. For the remelting process using new scarp, the total energy requirement is 1.2 MWh (4.3 GJ) per ton of ingot from clean process scrap, with the thermal energy of 1.1 MWh (3.8 GJ) and electrical energy of 0.124 MWh per ton of Al (European Aluminium, 2013; Moya et al., 2015). Recycling scrap consumes additional energy due to the extra scrap preparation step (e.g., removing coatings such as paint) before remelting. The preparation step requires a higher energy consumption of about 0.4 MWh (1.4 GJ) per ton of Al (Moya et al., 2015).

The Al industry is responsible for 1% of total GHG emissions and about 2% of industrial emissions in the EU and worldwide (European Commission, 2018c). In general, emissions from the extraction and processing of Al come from two scopes. Scope 1 is direct emissions from production processing due to the anode consumption in the electrolysis process of primary Al production and the burning of fossil fuels in both primary and secondary production processes. Scope 2 is indirect emission from electricity demand, calculated based on the amount of electricity consumption and grid intensity (Dietz et al., 2019). Scope 2 associated emissions account for nearly 60–70% of Al's carbon footprint (IEA, 2020a).

Currently, the carbon intensity of primary Al production was 6.3 $\frac{tCO_2}{t\,Al}$ globally (Dietz et al., 2019) and 6.7 $\frac{tCO_2}{t\,Al}$ in Europe (European Aluminium, 2019b). For secondary Al production, emissions vary based on new or old scrap as feed material. The specific emission factor is approximately 0.3 $\frac{tCO_2}{t\,Al}$ for the new scrap remelting process and 0.5 $\frac{tCO_2}{t\,Al}$ for the refining process using old scrap (European Aluminium, 2018).

4.4.3. Austrian Aluminum industry

In Austria, aluminum is an essential part of the NFM industry. About 73% of NFM is accounted for Al (and semi-finished products made from it), followed by 9% lead, zinc, and tin (and their semi-finished products), and 18% copper (U.S. Geological Survey, 2022). The Austrian Al production was carried out on both primary and secondary routes. However, primary production was stopped in 1992, and Al is now only produced via the secondary way (Umweltbundesamt GmbH, 2021). The main part of Austria's Al is consumed in the automotive sector, followed by construction, electrical and machine tools, packaging, and industrial (U.S. Geological Survey, 2022).

The Al subsector consumes about 75–80% end-of-life scrap, and approx. 20% imported virgin scrap to fabricate the secondary Al (AMAG Austria Metall, 2020). It also utilizes roughly 70% natural gas and 30% electricity as an energy carrier to produce high-quality aluminum alloys (Alu-met, 2019; AMAG Austria Metall, 2020). NG is predominantly used in the foundries for melting and tempering, and electricity is used in the rolling mill to drive the rolling stands. By consuming 950 GWh of energy in 2019, the SEC was about 1.21 $\frac{MWh}{t\,Al}$ for the Austrian AL industry.

Regarding the CO_2 footprint, the Austrian NFM sector is responsible for almost 1.5% of industrial emissions (Mandl et al., 2021; Umweltbundesamt GmbH, 2021), while Al with SCe 0.18 $\frac{t\,CO_2}{t\,Al}$ contributes about half of the subsector's emissions (AMAG Austria Metall AG, 2020; Umweltbundesamt GmbH, 2021). In Al production, emissions are mainly due to NG consumption (Scope 1) and electricity purchase (Scope 2). The Austrian Al industry has started purchasing electricity from renewable sources such as hydro- and wind power, reducing scope 2 in particular and overall sectoral emissions (AMAG Austria Metall, 2020).

Table 6
The reduction potential of considering decarbonization technology options for the cement industry, compared to the current level.

Technology option	TRL	emission reduction potential [%] /Emission factor $[\frac{tCO_2}{t\,Cement}]$	energy saving potential [%]
Energy efficiency improvement (using BAT) (I)	8–9	10 %/0.79 (Material Economics, 2019)	10 % (Chan and Kantamaneni, 2015)
Reduce the clinker to cement ratio with low carbon clinker (Decarbonate material) (I)	9	10–30% /0.77 (IEA, 2018; Material Economics, 2019)	33 % (Roth et al., 2016)
Electrification (II)	4	Up to 40%/0.54 (Material Economics, 2019)	–
Fuel switching to alternative fuel (mixed of non-recycled and biomass) (III)	9	Up to 40% (Cembureau, 2021a)	–
Electrification and CCS (II + IV)	3–6	95–100% /0–0.2 (Material Economics, 2019)	–
CCS – oxyfuel (IV)	6–7	90% /0- 0.04 (Material Economics, 2019)	–
CCS- calcium looping (IV)	6–7	Up to 95% (Lena et al., 2019; Voldsund et al., 2019)	–
Circular economy and material efficiency (V)		44% (Material Economics, 2019)	10% (Chan et al., 2019)
New binder material	5–8	43–100% (Lehne and Preston, 2018)	–

4.4.4. Decarbonization options for the aluminum industry

In this Section 4.4.4, based on the literature review, the mitigation options for the Al industry are outlined in two groups. Since more than 90% of the emissions in the Al industry are due to primary production, most decarbonization pathways refer to this production route.

Short/medium-term reduction: in this path, the most relevant issues to consider are energy efficiency improvement (I) and fuel switching (III). The Al industry, alongside other industrial subsectors, has undertaken efforts to increase its energy efficiency and improve the process, which has resulted in a 50% reduction in emissions since 1990 (Chan and Kantamaneni, 2015). It is expected that full implementation of all BAT, such as energy management system, use of prebaked anodes in Hall- Héroult process, installing recuperative or regenerative burners for secondary and primary routes, and improvement of waste heat recovery system can achieve a maximum of 10% emission reduction by 2050 compared to the current level (Moya et al., 2015).

One of the emission sources for Al production is direct fuel-related emissions. Fossil fuels are burned to meet the heat demand in the refinery process, which is responsible for 15–20% of sectoral emissions (International Aluminium Institute, 2021b; World Economic Forum, 2020). Hence, fuel switching (III) to NG with lower emission factors than coal as fast action, electrification, and biofuels with high calorific value fuels such as green H_2 can dispose of these direct fuel-related emissions in the short/medium-term (International Aluminium Institute, 2021b; World Economic Forum, 2020).

Energy efficiency improvements and fuel switching for heat demand are essential for adjusting emission reduction pathways, but they alone cannot decarbonize Al manufacturing. Transition changes are needed, mainly to address process emissions from primary production and indirect emissions from Al electricity demand.

Long-term reduction - deep decarbonization: Processing emissions due to the anode baking process in the primary Al route, which accounted for about 40% of direct Al emissions (or 15% of total Al emissions), is another CO_2 emission source that makes it difficult for the Al industry to reduce (IEA, 2020f; International Aluminium Institute, 2021b). Presently, substantial efforts are being made to develop a new anode design. One new technology for this purpose (non-carbon anodes) is an inert anode (Solheim, 2018). This electrolytic technology involves utilizing non-consumable anodes such as ceramics, cement, or metal alloys instead of a conventional carbon anode (Solheim, 2018). Therefore, the byproduct is oxygen in place of CO_2. Adopting an inert anode combined with an electrolytic cell design (wettable cathode) could have even more outstanding advantages in terms of energy, cost savings, and environmental impact in the smelting process (Solheim, 2018). However, identifying and developing suitable alloys or composites with low corrosion properties is a significant issue (Edwards and Kvande, 2001).

CCS/CCUS (IV) can be adopted to reduce direct emissions from the electrolysis process (Broek and Save, 2016; Mathisen et al., 2014) in the Al industry. CCS/CCUS is applicable in Al manufacturing as an end-of-pipe solution via two methods: Amine-type solvent (monoethanolamine) and ammonia-based adsorbent (chilled ammonia process) (Broek and Save, 2016; Mathisen et al., 2014). Nevertheless, CCS technology is a less exciting technology in the Al industry due to lower CO_2 concentration (close to 1%vol) in the flue gas (Broek and Save, 2016; Mathisen et al., 2014). Although, CCS/CCUS can be used in actual power plants, especially gas-fired CHP plants, for emission-free power generation serving the Al process (Chan et al., 2019).

The Al industry is an energy-intensive and, in particular, electricity-intensive sector (Pfaff et al., 2018); therefore, when extending the system boundary beyond the factory gates, indirect emissions from electricity associated with Al production must be considered. Electricity generation is responsible for about 60–70% of Al's total carbon footprint (including emissions from electricity supplied to the sector and electricity generated within the company by CHP plants) (IEA, 2020a; International Aluminium Institute, 2021b). Accordingly, providing electricity from a renewable power mix is one of the most challenging and effective ways to reduce emissions from the Al industry (International Aluminium Institute, 2021b; World Economic Forum, 2020). However, it ultimately depends on regional strategies and the availability of zero-emission electricity, which can be substituted steadily in the short/medium- and long-term.

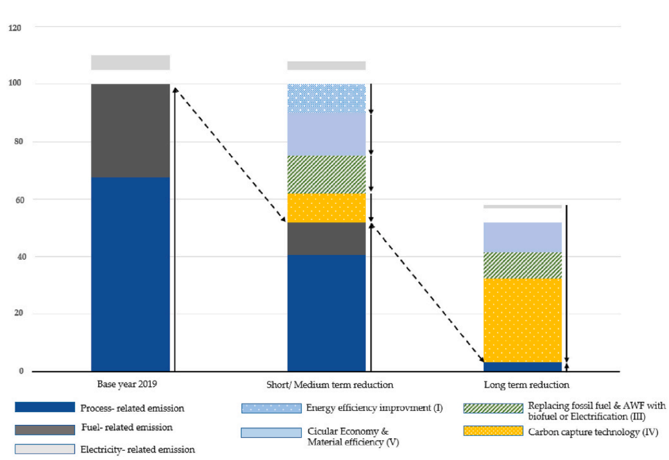

Fig. 9. Effect of the decarbonization pathway in CO_2 emission reduction in the short/medium and long term on the Austrian cement industry compared to 2019.

Except for fuel switching through electrification or biofuels, most of the aforementioned technologies are related to primary Al production. There are some technologies, including " new de-coating equipment (Chan et al., 2019; Evans and Guest Graham, 2000; Moya et al., 2015)," "laser-induced breakdown spectroscopy (LIBS) (Chan et al., 2019; LI et al., 2008; Sabsabi and Cielo, 1995)," and Al minimills (Chan et al., 2019)" are suspected of offering opportunities, such as process improvement, reduction of material losses, ability to adopt a low scrap spectrum, energy savings, and raw material savings for secondary Al fabrication. The LIBS system analyzes quantitative impurities in Al alloys in the air at atmospheric pressure. This technology can potentially improve the material separation system, enabling higher recycled material to be identified for secondary Al manufacture. As higher-quality recycled material requires less energy for secondary manufacturing than lower-quality alloys, energy demand, CO_2 emissions, and production costs will be reduced (Chan et al., 2019; LI et al., 2008). Nowadays, most secondary Al is produced in ingots that should be transported to rolling mills to be processed into finished products. Mini-mills (located in population centers) are integrated designs that eliminate multiple energy-intensive reheating/cooling steps for preparation to shipment. This approach offers 84% energy savings compared to the current production route (Chan et al., 2019).

Global reports project that demand for Al will increase by more than 50% by 2050 due to global population growth, increased urbanization, electric vehicle industry growth, and power grid expansion (International Aluminium Institute, 2021a; World Economic Forum, 2020). Consequently, one of the prerequisites for reducing the sector's overall emissions is to increase the share of Al production in the secondary route towards circular economy strategies. Emission generation in the secondary route is around 95% lower than in the primary route, which today is responsible for 10% of the Al industry's carbon footprint (IEA, 2020a; World Economic Forum, 2020). Nevertheless, it is imperative to increase the collection rate of end-of-life materials and improve the quality of the collection and sorting system, which is not so easy to achieve for some applications, such as the automotive industry, due to the long life of the material. (IEA, 2020a). Today, the collection rate of old scrap is 77% worldwide, and about 25–30% of old and new scraps are lost overall (Material Economics, 2018). Through the circular economy pathway "reducing the losses" and "preventing downcycling" during the manufacturing cycle and producing the high quality of secondary Al, a high percentage (more than 55% recycling production compared to the current level of 30%) of secondary route replacement is achievable (European Aluminium, 2019a; Material Economics, 2018; World Economic Forum, 2020). At the same time, 100% recycling of post-consumer (end-of-life) scrap cannot meet the demand for Al in 2050, and additional primary Al production is required. Based on the International Aluminum Institute (IAI) studies, an emissions reduction of 20% is achievable with a high recycling rate (more than 90%) at the global level in 2050 compared to a pathway without high levels of circularity (International Aluminium Institute, 2021b). In the EU, the emission reduction is projected to be more than 37%, with a high circularity pathway compared to the current level (European Aluminium, 2019a).

The technologies considered for decarbonizing the aluminum sector are summarized in Table 7 below.

Since Al in Austria is only produced via the secondary route, the emission reduction targets are not as ambitious. As mentioned in Section 4.4.3, the Austrian aluminum sector has started importing green electricity and reducing electricity-related emissions. Hence, the main driver of the Austrian aluminum industry is fuel switching, i.e., replacing natural gas with renewable energy sources. This switch would be supported by further strengthening the waste collection and sorting system based on the European Aluminum Action Plan and improving the quality of the material produced (European Aluminium, 2019a). In addition, improving energy efficiency by enhancing waste heat recovery systems and generating electricity will increase the system's overall energy

Table 7
The reduction potential of considering decarbonization technology options for the Al industry, compared to the current level.

Technology option	TRL	emission reduction potential [%] /Emission factor $[\frac{t\,CO_2}{t\,Al}]$	energy saving potential [%]
Energy efficiency improvement (using BAT) (I)	8–9	10 % (International Aluminium Institute, 2021b; Moya et al., 2015)	–
Electrification of furnaces (II)		15–20 % (International Aluminium Institute, 2021b; World Economic Forum, 2020)	–
Zero carbon Electricity (III)	9	60% (International Aluminium Institute, 2021b)	–
Fuel switching to biofuel (III)	9	15–20% (International Aluminium Institute, 2021b; World Economic Forum, 2020)	–
CCS/CCUS (IV)	6–7	Scope 1: up to 35% (International Aluminium Institute, 2021b) Scope 2: up to 50% (International Aluminium Institute, 2021b)	–
Circular economy and material efficiency-secondary Aluminum (V)		20–37% (European Aluminium, 2019a; International Aluminium Institute, 2021b; Material Economics, 2018)	–
Non-Carbon anode	6–7	Up to 15 % (International Aluminium Institute, 2021b; World Economic Forum, 2020)	–

efficiency. In between, the circular economy and material efficiency also play a role in the industry's transition to a low-carbon economy. Increasing the recycling rate of Al, which is currently almost 70% for beverage cans in Austria (European Environment Agency, 2020), by further developing the waste collection and sorting system based on the European Aluminum Action Plan (European Aluminium, 2019a), and improving the quality of the material produced would support this transition.

Considering NFMs are exclusively produced in Austria via the secondary path, the paths for Al can also be utilized for other NFMs, including copper, lead, zinc, and magnesite. Fig. 10 depicts the Austrian aluminum industry's expected decarbonization paths. It is noteworthy that the Austrian Al industry covers its demand entirely with renewable electricity and has no electricity-related emissions. However, to ensure a consistent approach with other industrial subsectors, electricity-related emissions are calculated based on the framework presented in Section 2 on methodology and shown in Fig. 10.

5. Decarbonization strategy for Austrian energy-intensive industrial subsectors

The Austrian government has set an ambitious target to reduce emissions by 2040 according to the Paris Agreement (IEA, 2020b). Achieving CO_2 neutrality by 2040, ten years earlier than the European Union's target, requires significantly accelerated decarbonization measures in all sectors. As in many other countries, decarbonizing the industry and its associated heat demand is a difficult task. On the one hand, industry, especially EIIs, plays a crucial role in Austria's economy. On the other hand, the industry has an essential aspect of national decarbonization initiatives because of its emissions and its influence on enabling GHG reductions along the economic value chain. Based on the observations and analyses in Sections 3 and 4, the following paragraphs explore and summarize possible decarbonization pathways that could be applied to Austrian EIIs.

As shown in Fig. 3, fossil fuel consumption as final energy accounts for around 38% of CO_2 emissions. Fig. 11 indicates that fossil fuels account for over 64% of final energy for heat demand in related Austrian EIIs, whereas electricity accounts for 8% and biofuels for 28%. Process heat is the most prominent fossil fuel user in the manufacturing sector, accounting for 68% of high-temperature heat demand in kilns, ovens, and furnaces and 30% of medium-temperature heat demand (Statistik Austria, 2019a).

As a means of reducing process heat emissions, electrification and bioenergy use are the essential elements. Only 8% of heat demand is generated by electricity, so there is ample scope to use more electricity. Electrification of process heat demand with zero-emission electricity at low and medium temperatures via power-to-heat technologies such as electric boilers and heat pumps can replace fossil fuels used in these segments (Bloess et al., 2018). However, given the high-temperature heat demand of more than 1000 °C in blast furnaces and kilns, electrification is challenging and still under development, so deploying biofuels in place of fossil fuels for high-temperature demand is the most suitable option. In the current situation of the Austrian industry, biofuels are largely used for medium temperatures and only to a small extent for high-temperature heat demand. The leading sector using biofuels in

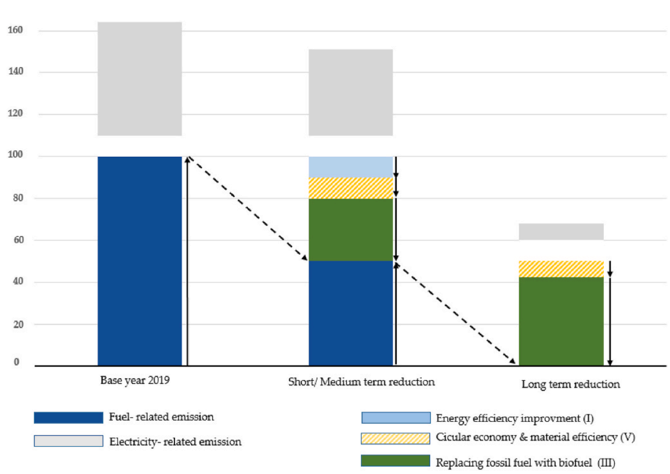

Fig. 10. Effect of the decarbonization pathway in CO_2 emission reduction in the short/medium and long term on the Austrian Aluminum industry compared to 2019.

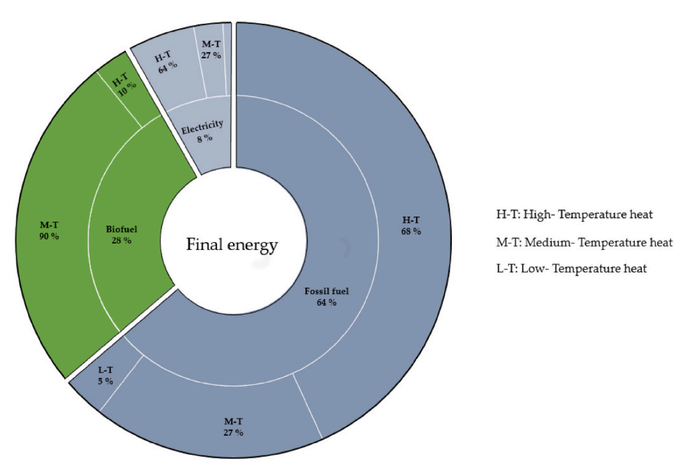

Fig. 11. Final energy consumption for the heat demand of the Austrian subsectors iron and steel, non-ferrous metals, non-metallic minerals, and pulp and paper, based on the type of energy carriers (inner circle) and the target of energy consumption (outer circle) (Statistik Austria, 2019a).

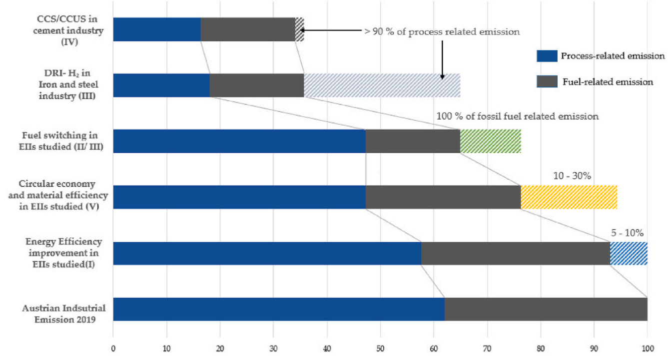

Fig. 12. Technology Options for Austrian industrial Decarbonization.

Austria is the pulp and paper industry, which produces biofuels (black liquor) and consumes them in its cogeneration facilities to provide process heat and electricity. In decarbonizing the industrial energy system, the key biofuels would be biomethane and H_2, which can be used instead of natural gas in high-temperature processing. The other biofuel with lower calorific value can replace fossil fuels in low to medium temperature heat.

Low-carbon energy carriers are undeniably crucial for the decarbonization of EIIs, particularly the P&P and Al subsectors. However, long-term solutions to reduce carbon footprint are still required for the I&S, and cement subsectors account for about 75% of the industry's process-related emissions. Reliance on H_2 (emission-free) instead of fossil fuels to reduce iron ore can reduce emissions from the iron and steel industry, which is currently responsible for more than 40% of overall industrial emissions in Austria. CCS/CCUS is also an undeniable solution technology for cutting the process-related emissions in cement manufacturing or lime kilns in the pulp and paper industry, which other technologies cannot help diminish their emissions.

Energy efficiency improvements, material efficiency, and circular economy are the other relevant factors that should address attentively. Energy efficiency improvement strategies have a slight influence on the decarbonization of Austrian EIIs, according to a benchmarking of the energy efficiency improvement techniques mentioned in Section 4 for each subsector. They can reduce less than 10% of total emissions of considered EIIs. However, they might improve overall system efficiency, reduce the corresponding energy consumption and CO_2 emissions, and reduce the costs associated with OPEX and CAPEX investments for more robust technologies.

Material efficiency and circular economy are the notable pathways that have the potential to close the ambitious decarbonization gap. By accounting for emissions reduction potential through this strategy in the relevant EIIs, the carbon footprint can be reduced by 30%. This pathway is instrumental in reducing the need for primary materials by substituting secondary materials that consume less energy and generate less CO_2 for production processing. Even with 100 percent recycling, raw materials are still required, which must be considered as part of the transition to a low-carbon economy.

The outcomes of the technical debate on the Austrian EIIs' decarbonization pathways are summarized in Fig. 12. The findings are based on a qualitative bottom-up approach that considers the impact of technological emission reduction potential for related technologies in each subsector (as shown in Table 4 to Table 7), as well as the share of each subsector's emission footprint in total industry emissions.

As illustrated in Fig. 12, implementing the decarbonization pathway in the four EIIs studied can reduce total industry emissions by roughly 66%. The remaining emissions are accounted for process and fuel-related emissions from the chemical industry and non-energy intensive subsectors. Overall, for the concrete achievement of Austria's ambitious targets for near-zero emissions by industry, existing barriers need to be identified and removed to create a technically feasible framework.

Such barriers include, for instance, the availability of adequate emission-free electricity and biofuels. Although Austria is already the third-largest renewable energy producer among IEA members, with a share of 77% of total power output, the country plans to grow this contribution to 100% by 2030 (IEA, 2020b). If this goal is met, electrification of energy consumption by industrial end-users would dramatically reduce emissions. To supply the biofuels, strategies like "Greening the Gas" (Gas Connect Austria GmbH, 2021a) and "Power - to - Gas" (Gas Connect Austria GmbH, 2021b) have already been underway to develop the infrastructural setup for utilization and storage of bioenergy such as biomethane and H_2 in the Austrian gas grid in several phases.

In addition, the maturity of new technologies, government acceptance of some technologies, including CCS, which is currently prohibited by law (Federal Ministry for Sustainability and Tourism, 2019b), infrastructure for storing and transporting captured CO_2 for use in other proposed projects, and changing consumer behavior through the circular economy need to be discussed and taken into account by policymakers and experts to plan the best way to close the climate change gap.

6. Conclusion

This study attempted to provide a framework for emissions reductions in the industry sector to be a puzzle-stone to bridge the gap between the current climate action plan and the goals of the Paris Agreement. In the industry sector, energy- and carbon-intensive industrial subsectors pose a major challenge due to the difficulty of reducing emissions from the production process, while demand for basic materials in energy-intensive subsectors is expected to increase. This work commenced with a systematic and comprehensive literature review of four energy-intensive industrial subsectors: iron and steel, pulp and paper, cement, and aluminum, to analyze the current status of each subsector and discuss the opportunities and barriers to reducing the carbon footprint. Following this, the literature review results were categorized into two groups: short/medium-term and long-term emission reduction.

The outcome of the literature review admitted that improving energy efficiency using the best available techniques, expanding the field of bioenergy, especially biomethane and H_2 for high-temperature heat demand, and zero-emission electricity are essential to eliminate fossil fuel consumption and direct emission in the short to medium term. Nonetheless, to make industry a near-zero emissions sector in the long term, additional strategic options are necessary for some specific subsectors where emissions are central to production processing. Innovative technologies such as DRI-H_2 and CCS/CCUS are the most robust and promising technology options to reduce process-related emissions. In parallel, the circular economy and material efficiency are also crucial to filling the ambitious gaps and facilitating the transition by reducing the demand for new materials.

In this paper, the Austrian energy-intensive industrial subsectors were evaluated as case studies using a comprehensive framework that includes influencing factors such as the subsector's current energy and emissions intensity, energy infrastructure, future national and international policies, and corresponding decarbonization techniques.

In a nutshell, switching from fossil fuels to zero-emission fuels as feedstocks (e.g., DRI-H_2 in the iron and steel subsector), as well as energy sources and circular economy pathways, have more substantial impacts on the decarbonization of Austrian industry. Combining the above paths with CCS/CCUS for the cement industry and energy efficiency improvements for relevant subsectors, the carbon footprint of the Austrian industry can be scaled down by more than 65% compared to current levels.

Ultimately, this study concluded that there is no single solution or silver bullet for industrial decarbonization, and a combination of pathways is required. Decarbonization of the EIIs is possible, but a commitment to strong government support and close collaboration among policymakers, experts, energy sectors (especially considering the fluctuating availability and prices of fuels), and industrial subsectors is needed to address these underlying barriers and achieve the goal. By better understanding the challenges and potentials involved, this study can be leveraged to develop a more resilient policy roadmap, especially in the case of Austria.

7. Author contributions

Conceptualization, designed the research, and developed the method M.RM. and T.K.; methodology, M.RM.; writing—original draft preparation, M.RM.; review and editing, T.K. All authors have read and agreed to the published version of the manuscript.

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.

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