Review

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Review

Transitioning towards Net Zero Emissions in the Chemical and Process Industries: A Holistic Perspective

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Abstract: Transitioning towards net zero emissions is a critical endeavor in the chemical and process industries to combat climate change and ensure environmental sustainability. Key focus areas of this review include the reduction of carbon emissions, the efficient utilization of energy resources, and the adoption of sustainable practices. Cutting-edge technologies such as biomass utilization, biotechnology applications, and waste management strategies play a crucial role in achieving this transition. Industries, including cement production, encounter unique challenges in their quest for sustainability and must actively seek innovative solutions to mitigate their carbon footprint effectively. The role of hydrogen as a clean fuel and its potential to revolutionize the chemical and process sectors is also discussed. The European Green Deal and Sustainable Development Goals (SDGs) hold immense significance for the chemical industry. They provide a clear roadmap and framework for promoting sustainability, driving innovation, and reducing the industry's environmental impact. By aligning with these initiatives, the chemical industry can enhance its competitiveness, contribute to societal well-being, and foster collaboration across sectors to achieve shared sustainability objectives.

Keywords: net zero; energy; process industries; emissions; climate; chemicals; biomass; waste; cement; metals

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) member countries have committed in the Paris Agreement to limiting global temperature increase to well below 2 °C above the pre-industrial level and to aim to limit the increase to 1.5 °C. Without drastic cuts in global greenhouse gas emissions (GHG), even the 2 °C limit will already be exceeded before 2050. Global mean near-surface temperature between 2012 and 2021 was 1.11–1.14 °C warmer than the pre-industrial level, which makes it the warmest decade on record. European land temperatures have increased faster over the same period by 1.94–1.99 °C, depending on the dataset used [1].

The annual mean global near-surface temperature for each year between 2023 and 2027 is predicted to be between 1.1 °C and 1.8 °C higher than the average over the years 1850–1900 [2]. In 2018, an Intergovernmental Panel on Climate Change (IPCC) special report on 1.5 °C of warming estimated that the world would probably hit the 1.5 °C threshold at some stage between 2030 and 2052 [3]. In 2021 outlook, using a different methodology, has been pinned down to the early 2030s – therefore, global greenhouse gas (GHG) emissions need to peak before 2025.

Global energy-related CO_2 emissions grew by 0.9 % or 321 Mt in 2022, reaching a new high of over 36.8 Gt [4]. CO_2 growth in 2022 was well below global GDP growth of 3.2 %, reverting to a decade-long trend of decoupling emissions and economic growth that was broken by 2021's sharp rebound in emissions. Emissions shrank by more than 5 % in 2020, as the Covid-19 pandemic cut energy demand. In 2021, emissions rebounded past pre-pandemic levels, growing more than 6 %. Emissions from energy combustion increased by 423 Mt, while emissions from industrial processes decreased by 102 Mt.

Process industries include pulp and paper, chemicals and pharmaceuticals, biobased solutions and biorefining, mining and metals, food and beverage, glass, textile fibers, etc. Overall, the 'materials' industry is responsible for 27 % of global CO_2 emissions (including energy-related emissions) [5]. The global cement industry is causing about 8 % of planet-warming CO_2 emissions, the iron and steel branch about 7 %, and the chemical industry around 2 % of total global emissions. The food and beverage industry with 36 % of global emissions, and the textile industry, causing about 10 % of global GHG emissions will not be dealt with due to their complex (processing and manufacturing) and long supply chains and energy intensive productions.

Direct CO_2 emissions from primary chemical production amounted to 925 Mt in 2021, a 5 % increase with respect to the previous year, resulting from a production increase to levels above those in 2019 [4]. This is in tandem with a relatively stable primary chemicals CO_2 intensity over recent years, at around 1.3 (CO_2 intensity is the mass ratio of CO_2 emitted to primary chemicals produced with the unit t/t = 1). The global chemical industry makes up around 4 % of global GHG emissions.

The EU chemical industry has already made significant progress. Despite the increase in production of more than 43 % since 1990, GHG emissions from EU-27 chemical production have decreased by 55 % in comparison to 1990 levels [6]. Over the same period, energy consumption in the EU-27's chemical industry has fallen by 22 %. EU27 chemical waste fell by nearly one third since 2007. The products of industrial biotechnology (biofuels, biobased chemicals, and bioplastics) must be demonstrated to produce less GHG emissions than their non-biological counterparts, whilst maintaining product performance [7].

2. Literature review

The chemical industry plays a crucial role in the global economy, providing millions of jobs and contributing significantly to GDP. With a focus on emissions reduction, the industry can experience growth of 2.5 times by 2050 but also facilitate the transition to net-zero emissions in other sectors, while effectively managing its own Scope 1-3 greenhouse gas emissions in accordance with the Paris Climate Agreement, substantial growth while aligning with climate goals [8]. To yield these advantages, the European Commission published the transition pathway for the chemical industry [9].

Web of Science literature search for 'chemical and process industries (CPI), net zero emissions' yielded 38 articles. The urgency of addressing global challenges related to climate change has brought academia and the chemical industry together in a collaborative effort to develop sustainable solutions. With the aim of achieving net-zero greenhouse gas emissions and ensuring a low-carbon future, it is imperative to explore innovative approaches that integrate circularity principles and climate action.

Restriction of the release of anthropogenic CO_2 into the atmosphere to a level that can be effectively absorbed by natural sinks is urgent [10], together with the pursuit of innovative approaches that combine circularity principles and climate action [11], and focus on critical processes such as hydrogen production, ammonia synthesis, and CO_2 reduction, along with new aspects of acetylene chemistry are crucial to creating sustainable chemistry sector [12].

Innovative approaches play a crucial role in waste reduction and discovering novel utilization methods. A notable example is the direct combustion of brewery spent grains and spent coffee grounds, which effectively diverts biomass waste from urban solid waste streams, demonstrating a commendable method for waste valorization [7]. Otherwise considered waste, the addition of calcined canal sediments as an artificial pozzolanic material could improve strength and save significant production of energy or greenhouse gas emissions [13].

To effectively attain the goal of net-zero GHG emissions, the chemical industry necessitates a comprehensive and coordinated strategy that encompasses its intricate supply chains [14].

Furthermore, even what was considered innovation a time ago, must catch up with new technology, for example conducting a thorough life cycle assessment (LCA) prior to the establishment of a biorefinery is essential to comprehensively evaluate its environmental impacts [15]. Lately, circular design strategies, including design-for-disassembly (DfD), are promoted to address waste

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production, raw material usage and lack of reuse; however, their environmental impacts are not always measured [16].

There is also a growing need to rapidly assess the impact of environmental impacts on chemical processes, as LCA analysis takes weeks to complete [17]. A prominent pathway is the use of artificial intelligence (AI) as a valuable tool in mitigating CO_2 emissions from the chemical industry [18]. The integration of data and artificial intelligence (AI) methodologies for the estimation of sustainability metrics and the design of more sustainable chemical processes can be done [19]. An example was made with the development of a sustainable closed-loop supply chain (SCLSC), incorporating a non-dominated sorting genetic algorithm that considers multiple subsystems, enables the optimization of concrete production to reduce carbon intensity while addressing the complexities of customers, suppliers, and manufacturing and recycling stations [20]. Also, new technologies such as lab-on-a-chip are becoming increasingly popular [21].

Existing chemical processes can be optimized, e.g., oxidative dehydrogenation of propane using CO_2 (CO_2-ODP) [22,23], integrating a commercially available coal gasifier with the Allam Cycle [24], or optimizing carbon and energy flows in ethylene production was made [25].

The production of cement is a significant contributor to global CO_2 emissions, accounting for more than 7 % of the total which can be reduced in many ways. Firstly, carbon emissions in Ordinary Portland Cement (OPC) can be brought down with the use of alkali-activated materials (AAM), which are traditional binders [26]. Secondly, the proposed option for reducing CO_2 emissions in the cement industry is the use of CO_2-containing flue gas and cement kiln dust (CKD) for producing mineral carbonates that serve as non-reactive fillers for blending cement [27]. Thirdly, the use of alternative supplementary cementitious material (SCM), such as biochar, obtained by pyrolyzing rice husks at a temperature of 550 °C can be performed [28].

In addition to concrete production, the manufacturing of zeolites calls for more sustainable production due to high energy consumption and substantial CO_2 footprint [29]. Similarly, achieving the production of high-quality iron at low temperatures is preferred [30].

Steel production, however, is responsible for another 7 % of CO_2 emissions globally and for 5 % of emissions in the EU, which is why the EU steel industry is moving forward with hydrogen-based steelmaking as a decarbonization strategy [31].

The development of renewable energy sources is crucial to get rid of coal-fired power plants (CFPPs), which impose substantial damage to human health, the environment, and climate change [32]. The industry of synthetic ammonia is the largest energy consumer and CO_2 emitter in China's chemical industry, and the process was reviewed from the viewpoint of deep emission reduction in terms of energy-saving and emission reduction potential [33]. However, the portfolio of low-carbon energy sources also includes hybrid energy systems (HESs) that provide heat and electricity to industrial processes [34].

In the pursuit of achieving net-zero greenhouse gas emissions, the use of CO_2 as feedstock is playing a significant role [35,36]. CO_2 utilization of carbon capture and storage (CCS route, [37]) can be done with various mechanisms such as pre-combustion, post-combustion, oxy-fuel technologies, direct air capture, chemical looping combustion and gasification, ionic liquids, biological CO_2 fixation, and geological CO_2 capture [38]. Furthermore, the utilization of CO_2 in value-added chemical products by the electrochemical reduction method has attracted great attention [39], together with improving existing process intensification technologies for CO_2 capture applications [40].

Sequestration and diminution of CO_2 require the development of a portfolio of technologies [41]. Integration of various renewable energy sources with CO_2 capture processes [42], as well as carbon-neutral processes to replace current industrial processes, such as iron and ammonia production, are much needed [41]. Studies on the sustainable synthesis of ammonia and iron with high value nanocarbon products via electrolysis in molten salt(s) with the introduction of the Solar Thermal Electrochemical Process (STEP) were made. There is also potential for closing the carbon cycle (C-3) for the nation's carbon-intensive industries, such as olefins production from a reduction in lignite for electricity production in Germany and the need to increase carbonaceous waste recycling [43].

There is a critical demand for the advancement of low-cost technologies in the context of utilizing CO_2 as a feedstock valuable chemical, and material for fuels [41]. A carbon-neutral fuel is characterized by the utilization of the atmosphere as the primary source of hydrocarbons, followed by combustion that releases CO_2 as a byproduct [44]. In the area of thermos-catalytic CO_2 conversions into clean fuels, the core-shell catalysts for thermo-catalytic CO_2 conversion into syngas and fuels are receiving much attention lately [45]. The U.S. Department of Energy (DOE) aims to reduce the cost of clean hydrogen to 1 USD/kg in one decade [46].

In conclusion, addressing the challenges of climate change and creating a sustainable future for the chemical industry requires a comprehensive and coordinated approach. The integration of innovative technologies, such as carbon capture and utilization, renewable energy sources, and process optimization, is crucial for reducing greenhouse gas emissions and minimizing environmental impact. Additionally, the adoption of circular economy principles and the implementation of life cycle assessments can guide decision-making towards more sustainable practices. Moving forward, continued research, collaboration, and policy support are vital in achieving a low-carbon and environmentally responsible chemical industry.

3. Methods

A literature review, foreseeing the engineering developments from international organizations along with their analyses and syntheses, and personal experience were used as the methodology. The ChatGPT response was used in the literature overview analysis [47].

4. Results

This section reviews the current situation and methods planned for the net zero transition. It is divided into sectors of process industries.

Net zero means cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests, for instance. United Nations has organized a growing coalition of countries, cities, businesses, and other institutions that are pledging to get to net-zero emissions [48]. More than 70 countries, including the biggest polluters – China, the United States, and the European Union – have set a net-zero target, covering about 76 % of global emissions. More than 3000 businesses and financial institutions are working with the Science-Based Targets Initiative to reduce their emissions in line with climate science. And more than 1000 cities, over 1000 educational institutions, and over 400 financial institutions have joined the Race to Zero, pledging to take rigorous, immediate action to halve global emissions by 2030.

EU has accepted a Green Deal Industrial Plan to enhance the competitiveness of Europe's net-zero industry and support the fast transition to climate neutrality. It is based on four pillars: 1) a predictable and simplified regulatory environment, 2) speeding up access to finance, 3) enhancing skills, and 4) opening trade for resilient supply chains [49]. European Commission published the Transition pathway for the chemical industry [50], identifying electrification, hydrogen, biomass, waste, Carbon Capture and Utilization (CCU), Carbon Capture and Storage (CCS), and process efficiency as key technological contributors to the transition pathway.

Bengtsson et al. have studied more than 20 decarbonization projects in the chemical industry in 9 developed EU member states [51]. Their CO_2 emissions could be reduced by pursuing steam generation, utilizing residual heat, changing electricity procurement, and improving energy efficiency. Industrial clusters, also known as “chemical parks”, could reduce their CO_2 emissions by 50–60 % until 2030 in the fields of steam generation (25–30 %), heat integration (10–15 %), electricity procurement (10–15 %), and energy efficiency (1–3 %). In a steam generation, coal can be substituted by seven carbon-free heat-source technologies – biomass, solar thermal, hydrogen, biogas, thermal storage, heat pumps, and e-boilers.

4.1. The role of Chemical Process Systems Engineering

The vision for the chemical industry to achieve net-zero emissions by 2050 exists. The Center for Global and Systemiq, for example, identified three main strategies: replacing fossil fuels with alternative feedstocks, switching from fossil to renewable energy sources, and carbon capture, storage, and utilization [8]. It highlights the main chemicals, namely green hydrogen, ammonia, methanol, olefins, and aromatics, whose synthesis needs to be switched from fossil to non-fossil feedstocks, specifically hydrogen from electrolysis of water, nitrogen from the air, and carbon from biomass, waste, and/or captured CO_2. Also listed are 7 major production processes for carbon-free production of primary chemicals: (i) electrolysis of water to produce green hydrogen, (ii) reforming of methane, (iii) gasification of biomass and waste to produce syngas followed by methanol and ethanol synthesis, (iv) CO_2 capture and conversion to methanol with green hydrogen, (v) steam cracking of biomass and waste to produce olefins and aromatics, (vi) catalyzed conversion of methanol to downstream chemicals (methanol to X), and (vii) dehydration of ethanol to olefins. Since all these processes are very energy intensive, it is important that they use renewable energy to get to a net-zero. The report states that in a certain scenario, it would even be possible for the global chemical industry to become carbon-negative before 2050 by acting as a CO_2 sink and generating economic value from it.

While the vision and strategies for a net-zero chemical industry are well defined, the concrete pathways to achieve these goals are less obvious. The introduction of the above principles will enormously increase the demand for hydrogen, ammonia, and methanol. Therefore, consumption must also decrease, and this requires a much higher level of circularity than today, when the global circularity level is only 7.2 % in 2023 [52]. Does society have the knowledge, motivation, and resources? Are the know-how and skilled professionals available to design net-zero transition technologies? Over the decades, chemical process systems engineering has developed a remarkable methodological portfolio of methods and tools for process design and optimization that are key to achieving net-zero transition, such as efficiency improvement, multi-objective optimization, process integration, and process intensification.

Increasing efficiency. To reduce resource consumption, the efficiency of bio-based chemical processes must be increased. The conversion of renewable and alternative resources, e.g., biomass and waste, is often less efficient economically and technologically than the conversion of fossil resources [53]. There is a need to encourage investment in low-carbon technologies and carbon capture and storage/utilization through various financial incentives [54]. On the other hand, fossil-based technologies are still economically attractive in many cases and should be charged accordingly for CO_2 emissions. A higher CO_2 tax in process optimization promotes higher reactant conversion, lowers feedstock consumption, and increases the required investment by encouraging the use of more efficient process units and higher quality feedstocks [55].

Multi-Objective Process Optimization. The introduction of technologies to move the chemical industry closer to net-zero production involves many conflicting criteria. Reductions in greenhouse gas emissions are usually associated with reductions in economic benefits [56]. It was shown by Kasaš et al. that trade-off solutions between economic, operational, and environmental criteria can be achieved if an appropriate objective function is used [57]. This is usually the net present value that promotes a balance between the return on invested funds and the long-term generation of a stable cash flow with moderate environmental impacts and operational efficiency.

Process Integration. Process integration is one of the main methodological approaches that contributes significantly to the decarbonization of the chemical industry [51]. It leads to lower consumption of heat, energy, and materials, and thus lower emissions [58]. The use of process integration is expanding to include greenhouse gas emissions planning and reduction [59]. It is a mature approach that includes various methods such as pinch analysis, mathematical programming, and P-graphs [60]. The most common applications are the integration of hot and cold streams within the process and in total sites which offer the possibility of using the excess process heat in residential areas [61]. With the use of heat pumps, it is possible to recycle even low-temperature waste heat and increase the efficiency of the generated heat and electricity from renewable sources by coupling a heat pump with a CHP unit [62].

4.2. Process industries

The chemical sector is the largest industrial energy consumer and the third largest industry subsector in terms of direct CO_2 emissions [63]. This is largely because around half of the chemical subsector's energy input is consumed as feedstock – fuel used as a raw material input rather than a source of energy. In 2021, direct CO_2 emissions from primary chemical production reached a total of 925 Mt [64]. In the Net Zero Emissions by 2050 Scenario, CO_2 emissions will be reduced by 17 % until 2030 – both the private and public sectors will need to achieve technological innovation, efficiency gains and higher recycling rates. Ammonia production is responsible for the highest fraction of emissions, followed by high-value chemicals (i.e., ethylene, propylene, benzene, toluene, and mixed xylenes) and methanol.

4.2.1. Chemical industry

Industrial chemicals, like ammonia, methanol, and ethylene, are crucial feedstocks for over a dozen different sectors – from healthcare, agriculture, and construction, to packaging, cars, and textiles [65]. However, the chemical industry is also deeply involved in many issues related to Planetary Boundaries, such as greenhouse gas emissions, the discharge of waste plastics into the oceans, deviations from the natural cycle of nitrogen and phosphorus, and the loss of biodiversity [8].

The chemical industry plays a significant role in global emissions due to its energy-intensive processes and reliance on fossil fuels. However, several promising and state-of-the-art technological innovations are emerging to shift the industry towards net-zero emissions.

Carbon Capture, Utilization, and Storage (CCUS) [66,67]. CCUSs capture CO_2 emissions from industrial processes and either store CO_2 underground by injecting it into suitable geological formations or utilize it for other purposes [68]. Technologies such as electrochemical conversion [69,70], catalytic hydrogenation [71], and photocatalytic conversion of CO_2 [72], have the potential to reintegrate captured CO_2 into the value chain by converting it into fuels and chemicals.

Electrification and renewable energy integration. Shifting from fossil fuel-based energy sources to renewable energy is crucial for decarbonizing the chemical industry. Electrification of processes [73,74], by switching from fossil powered processes to electricity powered processes (e.g., electrical furnaces and boilers, heat pumps) and integration of renewable energy sources [75–78], like solar, wind and biomass can reduce or eliminate the need for fossil fuel combustion.

Hydrogen as a feedstock and energy carrier. Hydrogen produced from renewable sources (green hydrogen) can serve as a clean feedstock and energy carrier in chemical manufacturing processes. It can be produced by biological processes [79,80]. (e.g., direct, and indirect photolysis, photo-fermentation, and dark fermentation), thermochemical processes [81], e.g., biomass pyrolysis and gasification, and electrolysis of water [82], by e.g., proton exchange membrane electrolysis and anion exchange membrane electrolysis [83], and solid oxide electrolysis [84].

Bio-based feedstocks. The utilization of bio-based feedstocks derived from biomass can help reduce the industry's reliance on fossil fuels. Biomass, such as agricultural residues [85], and food wastes [86], can be converted into bio-based chemicals through various processes like fermentation [87], enzymatic conversion [88], or thermochemical conversion [89].

Process optimization and advanced catalysts. Improving the efficiency of chemical processes and developing advanced catalysts [90,91], can reduce energy consumption and emissions through increased conversion and selectivity and milder operating conditions with respect to temperature and pressure. Optimization techniques for example process intensification [92,93], and heat integration [94], enhance the overall energy efficiency and sustainability of chemical production.

Circular economy and recycling. Embracing a circular economy approach within the chemical industry involves designing products for reusability, recycling, or biodegradability [95]. Developing

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innovative recycling technologies, such as chemical recycling, enables the recovery of valuable materials and reduces the need for virgin feedstocks [96].

Artificial intelligence (AI) and data analytics. AI and data analytics can be employed to optimize processes [97], predict and detect anomalies [98], etc. AI and data analytics will play a major role in boosting new product development, increasing the safety and reliability of chemical production processes, and enhancing the sustainability of chemical supply networks.

4.2.2. Pharmaceutical industry

The pharmaceutical industry plays a vital role in advancing human health, but its environmental impact cannot be overlooked. The manufacturing processes involved in pharmaceutical production generate significant GHG emissions [99], contributing to climate change. The pharmaceutical industry is responsible for an estimated annual direct emission of approximately 52 Mt of CO_2 equivalent worldwide [100]. It is important to note that this estimation solely accounts for emissions directly generated by pharmaceutical activities, without taking into consideration the indirect emissions associated with energy use throughout the entire supply chain. Indirect emissions may arise from various sources such as the transportation of medicines, lighting and refrigeration in distribution facilities, and other energy-related processes.

The pharmaceutical industry is exploring various state-of-the-art technological innovations that hold promise for shifting towards net zero emissions. Several key advancements have emerged in recent years:

Green Chemistry and Sustainable Synthesis. The adoption of green chemistry principles and sustainable synthesis methods is gaining traction in pharmaceutical manufacturing. This approach focuses on minimizing the use of hazardous materials [101], optimizing chemical processes, and designing more environmentally friendly reactions to reduce waste generation and energy consumption [102,103].

Process Intensification and Continuous Manufacturing. Process intensification involves optimizing manufacturing processes to improve efficiency, reduce resource consumption, and decrease emissions. Continuous manufacturing, as opposed to batch processing, allows for streamlined operations, reduced waste, and improved energy and material efficiency, thereby lowering the overall carbon footprint [104–107].

Decentralized Energy Generation and Advanced Energy Management Systems. Utilizing waste-to-energy systems [108], solar photovoltaic systems, wind turbines, and biomass energy facilities on-site can significantly reduce reliance on fossil fuels. Advanced energy management systems integrate energy storage, demand response and smart grid technologies. This enables optimization of energy use, real-time monitoring of energy consumption, and identification of opportunities to improve energy efficiency.

Circular Economy and Waste Reduction. Implementing circular economy practices within the pharmaceutical industry can minimize waste generation and resource depletion [109,110]. Recycling and repurposing of materials [111], implementing closed-loop systems [112], and developing innovative recycling technologies [113], enable the recovery of valuable resources, reducing the reliance on virgin materials and reducing emissions associated with raw material extraction and production.

Digitalization and Data Analytics. Leveraging digital technologies, such as artificial intelligence (AI), machine learning, and data analytics [114,115], can identify novel, sustainable reaction pathways and thus directly or indirectly optimize processes, improve energy efficiency, and identify opportunities for emissions reduction. Advanced modeling and simulation tools [116], can also aid in designing more sustainable and environmentally friendly pharmaceutical manufacturing processes [117,118].

It is important to note that while these technological innovations hold significant promise, their widespread adoption requires collaboration between industry stakeholders, policymakers, and research institutions. Continued research, development, and investment in these areas are crucial for

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achieving the pharmaceutical industry's goal of net zero emissions and contributing to global sustainability efforts.

4.2.3. Cement industry

Around 40 % of CO_2 emissions from fuel combustion worldwide and 25 % of global GHG emissions are attributed to the built environment [119]. Among these figures, cement production stands out as one of the most significant contributors, responsible for 6–10 % of global CO_2 emissions [120]. Achieving net-zero emissions by 2050 will necessitate the swift decarbonization of the cement and concrete sector.

The cement and concrete industry can utilize the following strategies to accomplish their decarbonization objectives.

Reducing the fraction of clinker in cement. The emission from cement production is predominantly caused by clinker, accounting for roughly 90 % of the total [121]. This makes it imperative for industry stakeholders to prioritize finding solutions for clinker-related emissions. To decarbonize the industry, cement manufacturers can explore the possibility of replacing clinker with alternative materials like fly ash [122,123], granulated blast furnace slag [124], calcined clays [125] and even red mud to some extent [126,127].

Reducing the energy related CO_2 emissions. In order to decrease emissions associated with energy usage, industry participants are actively investigating alternative fuels (biomass, municipal and industrial wastes and their mixtures) [128,129], developing innovative technologies like kiln electrification [130,131], oxy-combustion [132], and heat generation via plasma technology [133].

Carbon capture, storage, and utilization. The CO_2 emissions captured from production processes [134,135] can be reintegrated into the value chain through various means [136]. For instance, they can be utilized in the production of recycled clinker (mineralization, [137]) or incorporated into fresh concrete (carbon curing, [138]). Moreover, concrete structures can absorb a substantial amount of CO_2 during their lifespan through a process called recarbonation.

4.3. Biotechnology

Industrial biotechnology, based on renewable resources, can save energy, and significantly reduce CO_2 emissions. Biobased chemicals can replace their fossil-based counterparts with significant GHG emissions reductions [7]. Biobased plastics are potentially attractive in terms of specific emissions and energy savings. Governmental intervention can play a significant role in the effort to advance the industrial biotechnology sector toward lower GHG emissions, e.g., Emissions trading systems (ETS) or tax for transportation emissions, pollution costs charged to petrol-based materials, labeling systems for biobased materials and biofuels, public procurement supporting biobased materials and sustainably produced biofuels [139].

4.4. Metals production

4.4.1. Iron and steel

CO_2 emissions and energy use in European steel production have already been halved since 1960 [31]. Now, the EU steel industry is mainly focusing on hydrogen-based steelmaking as a decarbonization strategy. Carbon capture and utilization technologies will be developed in partnership with the chemical industry. Recycled iron and steel waste, and electrolytic reduction of iron ore will be used for iron and steel production. Renewable electricity and transmission networks, hydrogen related infrastructure or CO_2 transport, and storage infrastructures will be built.

4.4.2. Aluminum

Aluminum net-zero transition strategy will require [140]:

- Power decarbonization is critical: all smelters will need to switch to low carbon power by 2035, equating to approx. 1000 TW h of low-carbon electricity demand.

- Power decarbonization is necessary but not sufficient to decarbonize the sector, new technology for low carbon anodes and new refining technologies need to be commercialized by 2030.
- Recycled aluminum plays a critical role, expanding from 33 % of supply in 2020 to over 50 % by 2050.
- Mobilizing approximately 1 TUSD of investment over the next 30 years will be needed to deliver the transition for the primary aluminum sector, with over 70 % of that required for supporting infrastructure, primarily for power supply.

5. Conclusions and outlook

Megatrends are presumptive transformations of global society, economy, or ecosystem. The most often cited megatrends are climate change with environmental degradation and resource scarcity, growing consumption, acceleration of technological change and digitalization, economic shifts, demographic change, rapid urbanization, and social instability [141]. Three megatrends have been observed in the chemical industry [142]:

1. Sustainability and the circular economy, e.g., bio-based plastics, battery material recycling, improving efficiency of wind turbines.
2. Digitalization, e.g., artificial intelligence (AI) to drive efficiency, sensors and internet of things (IoT) to transform logistics, collaboration with tech giants key to remain ahead of the curve, Machined to perfection.
3. Innovation and accelerated globalization, e.g., novel manufacturing process, making composites affordable, advanced materials for better insulation.

Deloitte has published the following four trends [143]:

1. Sustainability and innovation (integrating innovation and sustainability to move beyond abatement)
2. Portfolio transformation (near-term portfolio action positions the industry for long-term transformation)
3. Supply chains (rearchitecting to balance costs, carbon footprint, and resilience)
4. Digital (emerging technologies drive value chain improvements and sustainability).

Four solutions for fuel switching (green hydrogen, electrification, turquoise hydrogen, and waste heat capture) will be ready in the next decade, but 11 solutions (carbon capture and utilization, industrial bio-based operations, steam cracker electrification, small modular nuclear reactor, electrification) need further development to drive long-term impact.

Net zero activities are addressing the climate and resource problems. Energy and resource efficiency, and simple circular economy are addressing the welcomed low hanging fruits. The European Commission has proposed the Net-Zero Industry Act (NZIA) to promote the production of clean technologies in the EU and prepare for the transition to clean energy [144]. It shall significantly contribute to decarbonization, by developing batteries, biogas/biomethane, carbon capture, and sustainable alternative fuels technologies. The proposal was not accepted by industry – Cefic (European Chemical Industry Council) described it as a "Zero Industry Act" [144].

Achieving net zero emissions in the chemical process industries necessitates a holistic approach that combines technological advancements, supply chain considerations, and societal transformation. While challenges exist, the CPI sector has the potential to significantly contribute to global emission reduction efforts. Collaboration, innovation, and a transition towards sustainable lifestyles are crucial for turning net zero emissions into a tangible reality.

Yet, transitioning towards zero emissions will not be possible unless significant changes in the way human society functions occur. De-growth in developed countries and slower growth in developing ones is needed. OECD published a framework to decarbonize the economy [145]. Key aspects include:

1. emission pricing policy instruments
2. standards and regulations
3. complementary policies to facilitate the reallocation of capital, labour and innovation towards low-carbon activities and to offset the adverse distributional effects of reducing emissions.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, P.G.; methodology, P.G.; validation, P.G., Z.N.P. and M.B.; formal analysis, P.G.; investigation, P.G., Z.N.P. and M.B.; resources, H.L. and V.D.; writing—original draft preparation, P.G., Z.N.P. and M.B.; writing—review and editing, P.G., Z.N.P. and M.B.; supervision, P.G.; project administration, P.G. All authors have read and agreed to the published version of the manuscript."

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