processes

Review

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

Peter Glavič *, Zorka Novak Pintarič, Helena Levičnik, Vesna Dragojlović and Miloš Bogataj

Department of Chemistry and Chemical Engineering, University of Maribor, 2000 Maribor, Slovenia; zorka.novak@um.si (Z.N.P.); helena.levicnik1@um.si (H.L.); vesna.dragojlovic@um.si (V.D.); milos.bogataj@um.si (M.B.)

* Correspondence: peter.glavic@um.si; Tel.: +386-41409611

Abstract: Given the urgency to combat climate change and ensure environmental sustainability, this review examines the transition to net-zero emissions in chemical and process industries. It addresses the core areas of carbon emissions reduction, efficient energy use, and sustainable practices. What is new, however, is that it focuses on cutting-edge technologies such as biomass utilization, biotechnology applications, and waste management strategies that are key drivers of this transition. In particular, the study addresses the unique challenges faced by industries such as cement manufacturing and highlights the need for innovative solutions to effectively reduce their carbon footprint. In particular, the role of hydrogen as a clean fuel is at the heart of revolutionizing the chemical and process sectors, pointing the way to cleaner and greener operations. In addition, the manuscript explores the immense importance of the European Green Deal and the Sustainable Development Goals (SDGs) for the chemical industry. These initiatives provide a clear roadmap and framework for advancing sustainability, driving innovation, and reducing the industry's environmental impact, and are a notable contribution to the existing body of knowledge. Ultimately, alignment with the European Green Deal and the SDGs can bring numerous benefits to the chemical industry, increasing its competitiveness, promoting societal well-being, and supporting cross-sector collaboration to achieve shared sustainability goals. By highlighting the novelty of integrating cutting-edge technologies, addressing unique industrial challenges, and positioning global initiatives, this report offers valuable insights to guide the chemical and process industries on their transformative path to a sustainable future.

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

Citation: Glavič, P.; Pintarič, Z.N.; Levičnik, H.; Dragojlović, V.; Bogataj, M. Transitioning towards Net-Zero Emissions in Chemical and Process Industries: A Holistic Perspective. *Processes* **2023**, *11*, 2647. https://doi.org/10.3390/pr11092647

Academic Editors: Farooq Sher and Francesca Raganati

Received: 30 June 2023
Revised: 8 August 2023
Accepted: 18 August 2023
Published: 4 September 2023

1. Introduction

The transition to net-zero emissions is a critical undertaking for the chemical and process industries, given their role in combating climate change and ensuring environmental sustainability. Member countries of the United Nations Framework Convention on Climate Change (UNFCCC) committed in the Paris Agreement to limit the global temperature increase to well below 2 °C above pre-industrial levels and to aim for a limit of 1.5 °C. However, without drastic reductions in global greenhouse gas (GHG) emissions, even the 2 °C target could be exceeded before 2050. Recent data suggest that the global mean temperature near the surface between 2012 and 2021 was already 1.11–1.14 °C warmer than before industrialization, making it the warmest decade since records began. In Europe in particular, land temperature rose even faster during the same period: 1.94–1.99 °C [1].

Projections indicate that the annual average temperature near the surface between 2023 and 2027 could be 1.1–1.8 °C higher than the 1850–1900 average [2]. The Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C Warming predicts that the world could reach the 1.5 °C threshold sometime between 2030 and 2052 [3]. A 2021 projection using a different methodology narrowed this timeframe to the early 2030s, underscoring the urgency of reaching the peak of global greenhouse gas emissions before 2025.

Within the industrial landscape, global energy-related CO_2 emissions continue to rise, reaching a new peak of over 36.8 Gt (gigatons) in 2022, with a growth rate of 0.9%, or 321 Mt/a (megatons per year) [4]. Most of the emissions growth was from energy combustion, which increased by 423 Mt, while emissions from industrial processes decreased by 102 Mt.

The materials industry, which includes process industries such as pulp and paper, chemicals, bio-based solutions, mining and metals, and more, contributes to 27% of global CO_2 emissions, including energy-related emissions [5]. Certain sectors such as cement, iron and steel, chemicals, and oil refining contribute significantly and account for about 7%, 6%, 2.6%, and 2% of total global emissions, respectively [6]. Given the complexity and energy-intensive production of certain industries, the food and beverage industry (responsible for 36% of global emissions) and the textile industry (responsible for about 10% of global GHG emissions) are not covered in this report.

The findings underscore the urgent need for further efforts to reduce emissions and shift to sustainable practices in the chemical and process industries. While significant progress has already been made, it is critical to align the trajectory of industrial growth with global climate goals to pave the way to a more sustainable and environmentally friendly future. Achieving net-zero emissions and contributing to a greener world will require collective and innovative action across all sectors to ultimately preserve the planet for future generations.

2. Literature Review

The chemical industry holds a pivotal position in the global economy, generating numerous jobs and making significant contributions to the GDP. By prioritizing emissions reduction, this industry can achieve substantial growth, which is projected to reach 2.5 times current levels by 2050. It also has the potential to play a crucial role in facilitating the transition to net-zero emissions across other sectors. Aligning with the Paris Climate Agreement, the chemical industry can effectively manage its own greenhouse gas emissions (Scope 1–3) while pursuing remarkable growth [7]. To realize these advantages, the European Commission has outlined a transition pathway specifically tailored to the chemical industry [8].

To explore the relevance of research in approaching net-zero emissions in the chemical and process industries, a literature search was conducted in Web of Science, Science Direct, and Google Scholar for the following keywords: 'Chemical Industry', 'Chemical Industries', 'Process Industry', 'Process Industries', 'Net Zero', 'Net-Zero', and 'Emissions'. The period under consideration ranged from 2013 to half of the year 2023. The queries are listed in Table 1. According to Google Scholar results, about 5670 articles on net-zero emissions have been published in the last ten years, of which about 75% were published in the last three years. In contrast, searches on Web of Science and Science Direct yielded a total of only 39 and 12 articles, respectively. The search results shown in Figure 1 clearly indicate that the urgency of addressing global climate change challenges has led the scientific community and the chemical industry to work together to develop sustainable solutions over the past decade. Although it is sometimes difficult to judge whether an article is aimed at a solution to reduce emissions or whether "net zero" is just being used as a buzzword, it is safe to say that awareness of the need for such solutions is deeply rooted in both academia and industry.

Table 1. Search queries.

Keyword	Keyword No.	Query A	Query B	Query C
Chemical Industry	1			
Chemical Industries	2	$(1 \vee 2)$	$(3 \vee 4)$	$(1 \vee 2) \wedge (3 \vee 4)$
Process Industry	3	$\wedge$	$\wedge$	$\wedge$
Process Industries	4	$(5 \vee 6)$	$(5 \vee 6)$	$(5 \vee 6)$
Net Zero	5	$\wedge$	$\wedge$	$\wedge$
Net Zero	6	7	7	7
Emissions	7			

Logical operators : $\wedge$ −AND; $\vee$ −OR;.

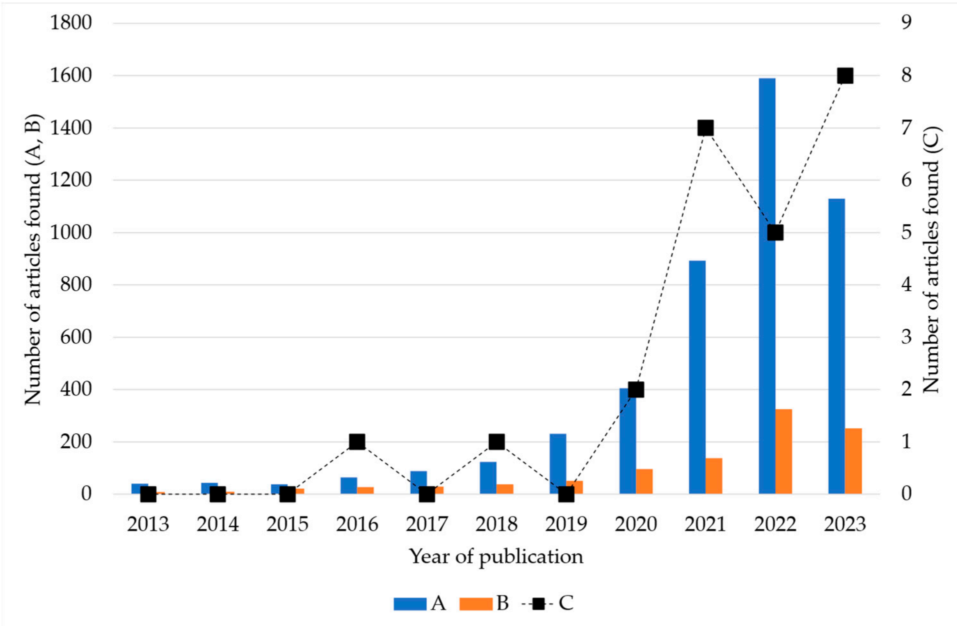

Figure 1. Google Scholar search results (2023: 1st January to 25th July).

Having established the significance of research and the growing awareness of net-zero emissions in the chemical and process industries, we now turn to innovative approaches and transformative actions. These integrate principles of the circular economy and climate action, essential for a sustainable and low-carbon future [7]. Urgently limiting anthropogenic CO_2 release to levels absorbable by natural sinks becomes imperative [9]. Critical processes such as hydrogen production, ammonia synthesis, CO_2 reduction, and novel aspects of acetylene chemistry are vital for creating a sustainable chemical sector [10]. Innovative approaches play a crucial role in waste reduction and the discovery of new utilization methods [11]. A notable example is the direct incineration of brewer's grains and coffee grounds, effectively removing biomass waste from urban solid waste streams, which is a commendable waste recovery method [12]. Another example is the addition of calcined canal sediments, otherwise considered waste, as an artificial pozzolanic material, which can improve strength and significantly reduce energy consumption and greenhouse gas emissions [13].

In addition to developing innovative technologies, the chemical industry needs a comprehensive and coordinated strategy that incorporates its interconnected supply chains to effectively achieve the goal of net-zero GHG emissions [14]. Even what was considered innovation some time ago must keep pace with a new paradigm. For example, conducting a thorough life cycle assessment (LCA) prior to establishing a biorefinery and its entire supply chain is essential to comprehensively assess environmental impacts [15]. Recently, circular design strategies, including the design-for-disassembly (DfD), have been promoted to address waste production, raw material consumption, and lack of reuse; however, their environmental impacts are not always measured [16]. Digital transformation is also important for decarbonization. Several computer-based tools facilitate design and allow more rapid assessment of the environmental impacts of chemical processes [17], as traditional LCA can take weeks to complete. One prominent avenue is the use of artificial intelligence (AI) as a valuable tool for mitigating CO_2 emissions in the chemical industry [18]. It is possible to integrate AI data and methods to estimate sustainability metrics and design for more sustainable chemical processes [19]. One example is the development of a sustainable closed-loop supply chain (SCLSC) incorporating a non-dominated sorting genetic algorithm that considers multiple subsystems and enables the optimization of concrete production to reduce carbon intensity while considering the complexity of customers, suppliers, production, and recycling stations [20]. In contrast to large-scale management systems, new technologies such as lab-on-a-chip are becoming increasingly popular [21].Computer-assisted engineering approaches are also important for integrating and optimizing existing processes with the aim of reducing emissions, as shown for example in the oxidative dehydrogenation of propane using CO_2 (CO_2-ODP) [22,23], a coal gasification system integrating a commercially available coal gasifier with the Allam Cycle [24], or optimizing carbon and energy flows in ethylene production [25].

System engineering approaches are relevant to the chemical and process industries, as well as to individual sectors with specific characteristics. 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 a 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 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].

All of the above-mentioned process industries are large consumers of energy; thus, developing renewable energy sources is crucial to get rid of coal-fired power plants (CFPPs), which cause significant harm 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 effort to achieve net-zero greenhouse gas emissions, the use of CO_2 as a feedstock plays an important role [35,36]. Carbon capture and storage (CCS route, [37]) can be conducted 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 through the electrochemical reduction method has attracted much attention [39], along with the improvement of existing process intensification technologies for CO_2 capture applications [40].

The sequestration and reduction of CO_2 require the development of a portfolio of technologies [41]. In addition, the integration of various renewable energy sources with CO_2 capture processes [42] and carbon-neutral processes to replace current industrial processes is urgently needed. Studies have been conducted on the sustainable synthesis of ammonia and iron with high value nanocarbon products by electrolysis in molten salt(s) with the introduction of the Solar Thermal Electrochemical Process (STEP) [41]. There is also potential for closing the carbon cycle (C-3) for the nation's carbon-intensive industries, such as the production of olefins by reducing lignite for power generation in Germany and the need to increase carbonaceous waste recycling [43].

There is a critical need to further develop cost-effective technologies related to the use of 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 thermo-catalytic CO_2 conversions to clean fuels, the core-shell catalysts for thermo-catalytic CO_2 conversion to syngas and fuels have recently received much attention [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. Integrating innovative technologies such as carbon capture and utilization, renewable energy sources, and process optimization is critical to reducing greenhouse gas emissions and minimizing environmental impact. In addition, accelerating digital transformation, applying circular economy principles, and conducting life cycle assessments can guide decision making toward more sustainable practices. To achieve a low-carbon and environmentally sustainable chemical industry, further research, collaboration, and policy support are essential.

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. The United Nations has organized a growing coalition of countries, cities, businesses, and other institutions that are pledging to work towards 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. 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.

4.1. Sustainable Development Goals

The 17 SDGs with 169 targets are the main action plan of the Paris Agreement [49]. The chemical and process industries play an essential role in achieving the SDGs by addressing environmental, social, and economic challenges and making an important contribution to the global economy by providing critical products and services to various industries. The pursuit of the SDGs is consistent with promoting clean production methods, optimizing resource efficiency, and minimizing environmental impact. Industry efforts to reduce GHG emissions and adopt CCUS techniques are an essential part of global climate action. In addition to environmental aspects, the chemical and process industries also impact the social and economic dimensions of sustainable development. By promoting innovation in materials science, process engineering, and sustainable technologies, the chemical process industry contributes to inclusive economic growth and job creation.

The World Business Council for Sustainable Development (WBCSD) has coordinated an SDG roadmap for the chemical sector proposed by leading chemical companies and industry associations [50]. Ten goals were identified as a priority of the sector: 2—Zero hunger, 3—Good health and well-being, 6—Clean water and sanitation, 7—Affordable and clean energy, 8—Decent work and economic growth, 9—Industry, innovation, and infrastructure, 11—Sustainable cities and communities, 12—Responsible consumption and production, 13—Climate action, and 14—Life below water. The roadmap outlines 18 impact opportunities that can contribute to the 10 priority SDGs. They are grouped into five key themes: food, water, people and health, energy, infrastructure, and cities. To reach the goals by 2030, innovation will be needed across products and processes, in cooperation with partners.

The International Council of Chemical Associations (ICCA) published six themes cross-referenced to specific SDG indicators: health and well-being; sustainable consumption and production; energy, environment, and sustainable cities; sustainable economies; learning and education; and public-private partnerships [51]. The article presented some other links to several trade associations, and examples of several chemical companies' approaches.

American Chemical Society (ACS) has identified seven priority SDGs and five additional SDGs that are foundational to the work of the chemistry community [52]. The ACS Green Chemistry Institute organized various principles of green chemistry and engineering and presented them in three groups: (1) maximize resource efficiency; (2) eliminate and minimize hazards and pollution; (3) design systems holistically and using life cycle thinking—requiring chemists and chemical engineers to design, measure, be efficient, and be sustainable [53]. The European Chemical Industry Council (CEFIC) published a report focusing on four areas of impact: the low-carbon economy, resource efficiency, the circular economy, and for people and the planet [54].

Concrete and other materials based on cement are the most widely used construction materials due to their ease of use, flexibility, durability, and low cost [55]. Sustainable Development Report 2023 mentions cement only in connection with SDG 13-CO_2 emissions from fossil fuel combustion [56]. The high-volume fraction of annual CO_2 emissions (7–8%) is due to the large mass of cement-based materials produced—around 30 Gt/a [57]. Moreover, the cement industry has lowered specific emissions of CO_2 per mass of cementitious material by 19.2% since 1990 [58]. They knew this was not enough, and the GCCA committed to supporting its members in achieving carbon-neutral concrete by 2050. They are also significantly reducing emissions of airborne pollutants, such as dust and NO_X, that directly impact human health [57]. Alternative fuels are a key area in which the cement industry can significantly contribute to the wider communities in which it operates, as a sustainable solution to waste management. The use of refuse-derived fuels (RDF) has reached substitution rates well over 50% in Europe, and companies are pushing them to hit 100%. Cement will be a critical resource in achieving many SDGs.

UN have declared 2022 the »International Year of Glass« (IYOG) to raise awareness of the significant contribution this material has made over several millennia of human history, and the important role it will continue to play in the future. In the description of glass achievements, they mentioned that "Glass melting is being de-carbonized and glassy products are being safely recycled)" [59]. The aim of the IYOG was to highlight the important role of the glass in achieving the 17 SDGs [60]. The most important goals will be SDG 3 (bioactive glasses), 6 (porous and coated glass filters), 7 (covers and reflective mirrors for photovoltaic systems, glass photobioreactors, glass-reinforced composite materials for wind turbines), 9 (optical fibers, doped glass, ultra-thin glasses, spherical lenses, prisms, and beam splitters), 11 (chemically reinforced glass and coated windowpanes), and 12 (high recycling rates, energy-efficient melting technologies, and optimized glass compositions).

Intensity of association between 10 metal (steel, copper, aluminum, nickel, zinc, gold, silver, platinum group metals, silicon, and rare-earth elements) producing companies, estimated from their corporate social responsibility (CSR) reports, sustainability reports, and integrated reports, was the largest with the SDG 8, followed by SDG 3, SDG 12, and

SDG 9 [61]. The metals industry review with 152 metal companies places the most focus on SDGs 8, 3, and 12, but its activities are less associated with SDGs 14, 2, and 1 [62]. The steel sector is the most important sector in the European process industry. The steel industry places great weight on SDG 12 and less on SDGs 1 and 2, whereas the copper industry recognizes the relevance to SDGs 1 and 2.

Worldsteel is focusing on climate action, responsible value chain, life cycle thinking, circular economy, water management, and air quality [63]. In the area of climate action, e.g., they are proposing three groups of policy goals and development initiatives:

1. Breakthrough technologies: (a) Using carbon as a reductant while preventing the emission of fossil CO_2, for example using CCUS and/or sustainable biomass, e.g., bio-charcoal; (b) Using electricity through an electrolysis-based process; (c) Substituting hydrogen for carbon as a reducing agent, generating H_2O instead of CO_2.
2. Efficiency and circular economy: (a) Optimal raw material selection and use, (b) Increasing energy efficiency and minimizing waste, (c) Improving yield, (d) Improving process reliability, and (e) Circular economy with four Rs: Reduce, Reuse, Remanufacture, and Recycle.
3. Developing advanced steel products to enable societal transformations: (a) Developing and manufacturing the advanced steel products necessary to facilitate the required transformation and adaptation of society and reach carbon neutrality through zero-energy buildings, renewable energy infrastructures, electrification, etc. (b) Assisting customers in delivering innovative solutions using steel and introducing new, advanced steel products.

Environmental standards, e.g., ISO 14000 series on Environmental Management Systems, Environmental Auditing, Environmental Labeling, Environmental performance, Life Cycle Assessment, etc. [64], ISO 26000 on social responsibility [65], and EU Eco-labeling system, e.g., Environmental Product Declaration (EPD) [66] are upholding their importance.

The pulp and paper industry must align its sustainability strategy with the SDGs as well. In Canada, Resolute Forest Products, committing to ESG principles, identified eight SDGs that align with its sustainability strategy [67]: SDG 6 (Water management), SDG 7 (Energy), SDG 8 (Employees' health, safety and wellness), SDG 9 (Economic performance and infrastructure investments), SDG 12 (Waste management), SDG 13 (Climate change), SDG 15 (Forest management, fiber sourcing practices, and biodiversity), and SDG 16 (Environmental compliance). In 2021, they surpassed their 2025 GHG emission reduction target ahead of schedule, and in 2022, the Science-Based Targets initiative (SBTi) validated their new reduction goals, which include the 41.5% reduction in absolute scope 1 and 2 emissions by 2026 from a 2015 base year, and a 16.5% reduction in scope 3 emissions within the same timeframe [68]. Over the past two decades, their carbon-reduction initiatives have cut more than 7.3 Mt/a of GHG, comparable to taking close to 1.6 million cars off the road.

Asia Pulp & Paper (AP&P) prepared a new Sustainability Roadmap Vision 2030 guiding them in fulfilling their commitment to protect forests, support communities, conserve biodiversity and work towards achieving carbon neutrality across their operations [69]. The earlier Vision 2020 set out ten key impact areas relevant to stakeholders across their business and wider supply chain: climate change, emissions, solid waste, reforestation, conservation and biodiversity, human rights and indigenous people, community empowerment, employee welfare, fiber sourcing, and water management. AP&P have met most of the targets set out in the Sustainability Roadmap Vision 2020, e.g., protection and restoration of national forest, 40% fiber was from recycled sources, carbon intensity decreased 29% compared to a 2012 baseline, energy intensity decreased 14%, water intensity decreased 30%, and solid waste reduction was 47%, etc. Vision 2030 focuses on three main areas:

1. Production—30% reduction of carbon footprint by (a) increased share of renewables in the energy mix, (b) reduced energy consumption, (c) reduced water consumption, (d) zero waste to landfill, (e) increase recycled fiber composition, and (f) increased product biodegradability and resource efficiency.

2. Forest—over 0.5 Mha of natural forests area conserved by (a) sustainable forest management, protection, and restoration (of APP property and supplier concessions), (b) increased fiber productivity. (c) Protecting and conserving the forests, peatlands and biodiversity that sustain their business; (d) maintain the area impacted by fires at under 2%.
3. People (improving the lives of millions) by (a) reduction of land conversion for agricultural purposes through the use of fire, (b) improve the welfare of local communities through capacity building and enhance community access to markets, (c) respect the rights of local communities and indigenous people thorough increased multistakeholder engagement, (d) increase the number of women in management positions, (e) strengthen organizational agility, (f) best practices for fraud reporting and whistleblower management, and (g) best practices for ensuring adherence to their Code of Conduct.

4.2. European Green Deal

EGD plans to transform the EU into a modern, resource-efficient, and competitive economy, ensuring: (1) no net emissions of greenhouse gases by 2050 (at least 55% reduction by 2030), (2) economic growth decoupled from resource use, and (3) no person and no place left behind [70]. The European Green Deal shall improve the well-being and health of citizens and future generations by providing: (1) fresh air, clean water, healthy soil, and biodiversity; (2) renovated, energy-efficient buildings; (3) healthy and affordable food; (4) more public transport; (5) cleaner energy and cutting-edge clean technological innovation; (6) longer lasting products that can be repaired, recycled, and re-used; (7) future-proof jobs and skills training for the transition; (8) a globally competitive and resilient industry. In 2023, the Commission presented an EGD Industrial Plan to enhance the competitiveness of Europe's net-zero industry and support the fast transition to climate neutrality [71]. It is based on four pillars: (1) a predictable and simplified regulatory environment, (2) speeding up the access to finance, (3) enhancing skills, and (4) open trade for resilient supply chains.

CEFIC sees the transformation to a climate-neutral and circular economy as a key driver of European jobs and economic growth [72]. The European chemical industry has the ambition to become climate neutral by 2050. To reach it, decarbonized and circular economy solutions shall be developed by the chemical industry. Access to abundant and competitive low-carbon energy, development of relevant infrastructure, as well as new market opportunities related to sustainable products, are key conditions to ensure that the industry stays globally competitive during the transition [73]. Costs and opportunities of the EGD for the chemical industry for core equipment and the design, construction and modification of facilities have been estimated to be 400–600 GEUR by Accenture [74]. Chemicals for the EGD are foreseen to be used in (1) Renewable energy, (2) Clean Road transport, (3) Circular economy, (4) Public health, (5) Electronics, (6) Aerospace, etc.. The chemical industry is indispensable to Europe's strong and sustainable economy of the future, as chemicals are present in almost every strategic value chain [75].

Other sectors of process industries have also been active. The European Cement Association Cembureau published the Carbon neutrality roadmap to demonstrate that reaching net-zero emissions along the cement and concrete value chain is achievable by 2050 in key areas: (1) CCUS (42% of the CO_2 emissions reduction), (2) Replacement of fossil fuels by non-recyclable and biomass waste (15% of the emissions reduction), and (3) Providing low carbon-cements products (13% emissions reduction), etc. [76].

The EU is the world's biggest glass producer, with a market share of around one-third of the total world production. Glass production in the EU reached 36.8 Mt in 2020 according to Glass Alliance Europe. It comprises five subsectors: 60.4%—Container glass, 29.2%—Flat glass, 3.2%—Domestic glass, 5.3%—Fibers (reinforcement and insulation), and 2.1%—Special glass [77].

The pulp and paper industry (P&PI) is the fourth most energy-intensive industry in Europe. Since 2005, CO_2 emissions of the pulp and paper sector have been reduced by 36%. By substituting fossil-based products, the European forest-based industries lowered the EU's total emissions by an estimated 410 Mt/a [78]. P&PI is the largest industrial generator and user of renewable energy—60% of the industry's total primary annual energy consumption is biomass-based [79]. In 2019, European P&PI chief executive officers (CEOs) declared their intention to be at the forefront of supporting the 2050 carbon-neutral society. In 2020, Cepi 2030 Industry Manifesto responded to the tightening climate change policy in the EU. Their future is also tackling fiber-based packaging circularity, biorefineries, emerging bio-based products (e.g., human-made cellulosic fibers), and a shift towards a low-carbon circular bioeconomy.

In 2024, the EU Corporate Sustainability Reporting Directive (CSRD) will strengthen the rules concerning the environmental, social, and governance (ESG) information that large companies with more than 250 employees and 40 MEUR in net turnover or 20 MEUR in assets [80], and listed companies must report [81]. The CSRD is expected to increase the number of companies subject to the EU sustainability, as they reported requirements from 11,700 to approximately 50,000. They will have to report according to the European Sustainability Reporting Standards (ESRS) and will require external auditing.

The 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 [82]. The European Commission published the Transition pathway for the chemical industry [83], 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 [84]. 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 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.

4.3. 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 Commons at the Tokyo University & Systemiq, for example, identified three main strategies: replacing fossil fuels with alternative feedstocks, switching from fossil to renewable energy sources, carbon capture, storage, and utilization [7]. 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 the electrolysis of water, nitrogen from the air, and carbon from biomass, waste, and/or captured CO_2. Also listed are seven major production processes for the 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 [85]. 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 [86]. There is a need to encourage investment in low-carbon technologies and carbon capture and storage/utilization through various financial incentives [87]. 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 [88].

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 [89]. 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 [90]. 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 [84]. It leads to a lower consumption of heat, energy, and materials, and thus lower emissions [91]. The use of process integration is expanding to include greenhouse gas emissions' planning and reduction [92]. It is a mature approach that includes various methods such as pinch analysis, mathematical programming, and P-graphs [93]. 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 [94]. 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 [95].

4.4. Process Industries

The chemical sector is the largest industrial energy consumer and the third largest industry subsector in terms of direct CO_2 emissions [96]. 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 [97]. 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.

4.4.1. Chemical Industry

Direct CO_2 emissions from primary chemical production reached 925 Mt in 2021 [97]. This represents a 5% increase from the previous year, due to higher production levels than in 2019 [4]. However, the CO_2 intensity of primary chemicals has remained relatively stable at around 1.3, indicating the mass ratio of emitted CO_2 to primary chemicals produced. On a global level, the chemical industry is responsible for about 4% of global greenhouse gas emissions.

On a more positive note, the chemical industry in the EU has made remarkable progress in reducing its environmental impact. Despite an increase in the production of more than 43% since 1990, greenhouse gas emissions from chemical production in the EU-27 have decreased by 55% compared to 1990 [98]. Over the same period, energy consumption in the EU-27 chemical industry has fallen by 22%, and chemical waste has decreased by nearly a third since 2007. In addition, the introduction of industrial biotechnology products promises to further reduce greenhouse gas emissions while maintaining product performance [98].

Industrial chemicals, such as ammonia, methanol, and ethylene, are crucial feedstocks for over a dozen different sectors—from healthcare, agriculture, and construction, to packaging, cars, and textiles [99]. 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 [7].

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) [100,101]. 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 [102]. Technologies such as electrochemical conversion [103,104], catalytic hydrogenation [105], and photocatalytic conversion of CO_2 [106] 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. The electrification of processes [107,108], by switching from fossil-powered processes to electricity-powered processes (e.g., electrical furnaces and boilers, heat pumps) and the integration of renewable energy sources [109–112], such as 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 [113,114], e.g., direct, and indirect photolysis, photo-fermentation, or dark fermentation), by thermochemical processes [115], e.g., biomass pyrolysis and gasification, or electrolysis of water [116], by electrolysis, e.g., proton exchange membrane electrolysis, anion exchange membrane electrolysis [117], or solid oxide electrolysis [118].

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 [119], and food wastes [120], can be converted into bio-based chemicals through various processes such as fermentation [121], enzymatic conversion [122], or thermochemical conversion [123].

Process optimization and advanced catalysts. Improving the efficiency of chemical processes and developing advanced catalysts [124,125], 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 [126,127] and heat integration [128], 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 [129]. Developing innovative recycling technologies, such as chemical recycling, enables the recovery of valuable materials and reduces the need for virgin feedstocks [130].

Artificial intelligence (AI) and data analytics. AI and data analytics can be employed to optimize processes [131], predict and detect anomalies [132], 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.

4.4.2. 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 [133], contributing to climate change. The pharmaceutical industry is responsible for an estimated annual direct emission of approximately 52 Mt of CO_2 equivalent worldwide [134]. 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 [135], optimizing chemical processes, and designing more environmentally friendly reactions to reduce waste generation and energy consumption [136,137].

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 [138–141].

Decentralized Energy Generation and Advanced Energy Management Systems. Utilizing waste-to-energy systems [142], 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 the 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 [143,144]. Recycling and repurposing of materials [145], implementing closed-loop systems [146], and developing innovative recycling technologies [147] 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 [148,149], can identify novel and sustainable reaction pathways and thus directly or indirectly optimize processes, improve energy efficiency, and identify opportunities for emission reduction. Advanced modeling and simulation tools [150] can also aid in designing more sustainable and environmentally friendly pharmaceutical manufacturing processes [151,152].

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

4.4.3. Cement Industry

Around 40% of CO_2 emissions from fuel combustion worldwide and 25% of global GHG emissions are attributed to the built environment [153]. Among these figures, cement production stands out as one of the most significant contributors, responsible for 6–10% of global CO_2 emissions [154]. 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 [155]. 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 such as fly ash [156,157], granulated blast furnace slag [158], calcined clays [159] and even red mud, to some extent [160,161].

Reducing energy-related CO_2 emissions. To decrease emissions associated with energy usage, industry participants are actively investigating alternative fuels (biomass and municipal and industrial wastes and their mixtures) [162,163], developing innovative technologies such as kiln electrification [164,165], oxy-combustion [166], and heat generation via plasma technology [167].

Carbon capture, storage, and utilization. The CO_2 emissions captured from production processes [168,169] can be reintegrated into the value chain through various means [170]. For instance, they can be utilized in the production of recycled clinker (mineralization, [171]) or incorporated into fresh concrete (carbon curing, [172]). Moreover, concrete structures can absorb a substantial amount of CO_2 during their lifespan through a process called recarbonation.

4.4.4. Glass Industry

In 2019, the world consumed more than 194 Mt/a of glass, and the demand is forecast to increase to 256 Mt/a by 2027 [173]. Glass is made in furnaces at extremely high temperatures (up to 1700 °C) to melt several minerals, including silica (the main ingredient, in the form of sand), soda ash, and limestone. Producing it causes 95 Mt/a of GHG emissions worldwide [174]. The EU has set a timetable for the reduction of GHG emissions, with a 30% reduction target from 1990 levels by 2030 and 40% by 2040, culminating in net zero by 2050. The main methods forecast are energy efficiency, renewable sources of energy, minerals' selection and composition, and circular economy. Globally, fuel emissions (mass ratio of CO_2 and melted glass) were reduced by 69% between 1960 and 2010 [173].

The UK glass industry has increased energy efficiency by 50% in the last 40 years by using waste heat, Organic Rankine Cycle, or steam turbine to preheat raw materials, fuel, or oxidants [175]. Oxyfuel combustion is using oxygen instead of combustion air, yielding energy savings of 10–15% and reduced emissions. Fossil fuels can be replaced by biofuels with reduced emissions of NOx. All electric furnaces are an established technology in the glass sector and are more efficient than gas-fired furnaces. The latest development is using up to 80% electricity with 20% gas energy (hybrid furnaces) with the future opportunity to consider hydrogen combustion using 100% hydrogen as well as different proportions of hydrogen blended with natural gas for glass melting.

Process emissions can be reduced by using a higher fraction of recycled glass which substitutes the carbonate raw material and reduces CO_2 emissions [175]. Alternative raw materials, such as calcium oxide, mineral slags, waste incineration ashes, etc., can replace carbonate raw material or reduce the melting temperature of the glass and thereby energy requirements. CCUS may be needed as a final stage for decarbonization.

Recycled glass reduces the usage of raw materials and GHG emissions as well as air and water pollution. Saint-Gobain was the first manufacturer in the world to achieve zero carbon flat glass production using 100% recycled glass (cullet) and 100% green energy, produced from biogas and decarbonized electricity [176].

4.5. Biotechnology

Industrial biotechnology, based on renewable resources, can save energy and significantly reduce CO_2 emissions. Bio-based chemicals can replace their fossil-based counterparts with significant GHG emissions reductions [177]. Bio-based 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 bio-based materials and biofuels, public procurement supporting bio-based materials and sustainably produced biofuels [178].

4.6. Metals Production

4.6.1. Iron and Steel

CO_2 emissions and energy use in European steel production have already been halved since 1960 [31]. Presently, 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 the 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.

4.6.2. Aluminum

An aluminum net-zero transition strategy will require [179]:

- 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 (10^{12} USD) of the investment over the next 30 years will be needed to deliver the transition for the primary aluminum sector, with over 70% of the sum required for supporting infrastructure, most of it for power supply.

4.7. Pulp and Paper

- The pulp and paper industry is among the top five most energy-intensive industries globally and is the fourth largest industrial energy user. This industry accounts for approximately 6% of global industrial energy use and 2% of direct industrial CO_2 emissions [180]. As the paper production will increase, greater efforts must be made to reduce the emissions intensity of production by 2030 by substituting fossil fuels with renewable energy sources, e.g., biofuels, accelerating the energy efficiency improvements, and reducing the energy needed for drying [181].
- Substituting more pulp by recycled wastepaper to over 60% by 2030.
- Installation of high-temperature heat pumps using waste heat sources inside the production process.
- On-site waste heat recovery and co-generation.
- Emerging technologies, e.g., heat recovery from thermomechanical pulping, black liqueur gasification, microwave drying, supercritical CO_2 or deep eutectic solvent.

EU believes that by 2050 the European pulp and paper industry can reduce its energy consumption by 14% and greenhouse gas (GHG) emissions by 62% compared to 2015 levels [182]. Carbon capture and storage (CCS) could further reduce GHG emissions. Biorefinery products from the pulp and paper mills could replace fossil fuels for light duty vehicles, be used as raw materials in the chemical industry, or as fertilizers.

4.8. Key Technologies Related to Net-Zero Emission

Several technologies, directions, and approaches have been identified as important for the transition to a net-zero economy. Some of these are tailored to a specific industry, such as the reduction of the fraction of clinker in cement in the cement industry, while others are across industries, such as carbon capture, electrification, waste reduction, etc. To indirectly assess the activity of the development and interest in respective fields as they pertain to net-zero emissions, a Google search was performed relating some of these to net-zero emissions. The results are shown in Figure 2.

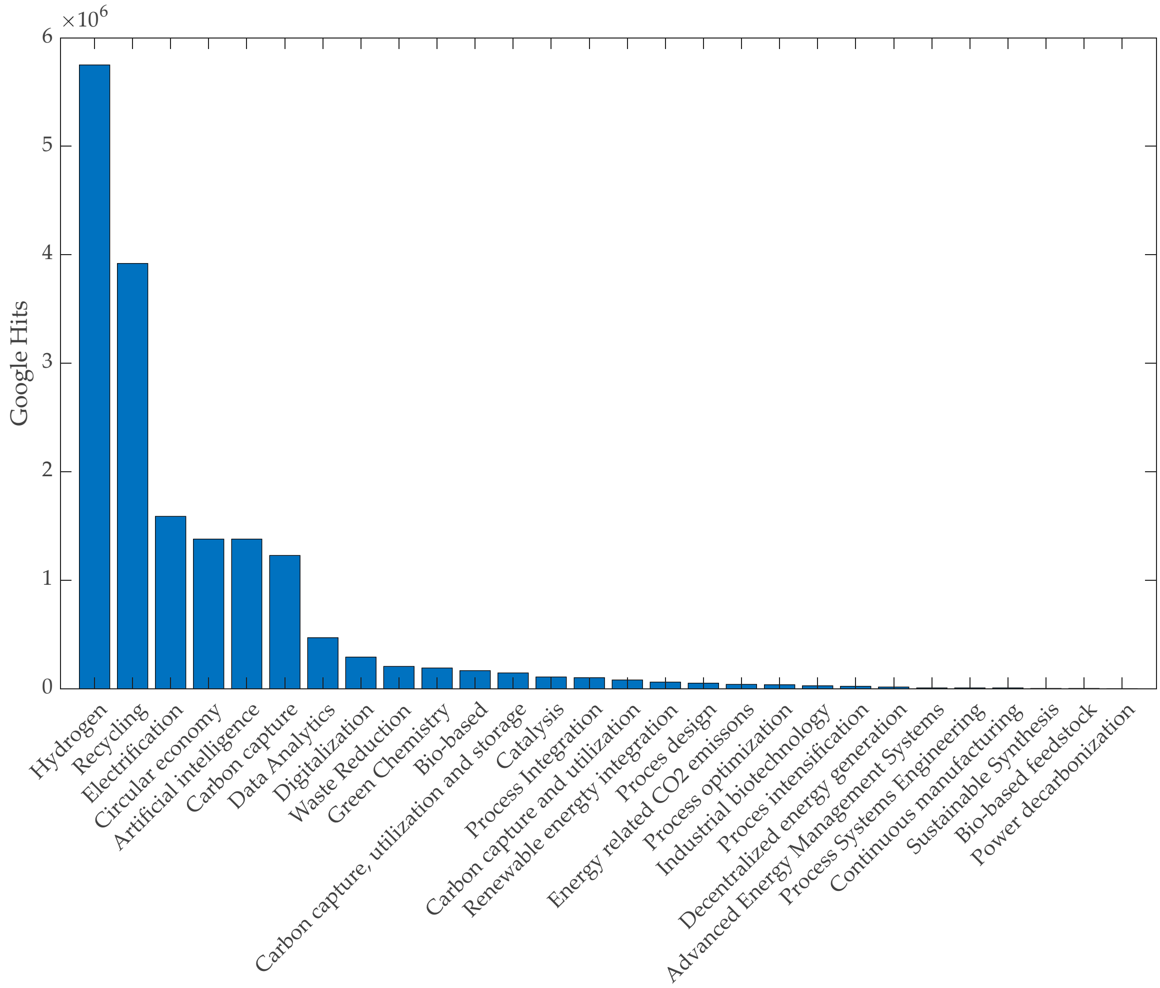

Figure 2. Results of Google search on key technologies related to net-zero emissions.

As can be observed from the bar chart in Figure 2, most of the net-zero activities relate to hydrogen. This is followed by Recycling and Electrification, which are the second and the third most active areas linked to net-zero emissions. Just below the top of the list are Carbon Capture, Circular Economy, Artificial Intelligence, Data Analytics, Digitalization, and Waste Reduction. This representation is by no means conclusive, as it is merely a snapshot of current trends. In addition, it may possibly be skewed by the search algorithm. However, it potentially does reveal that to achieve net-zero emissions, several technological solutions must be developed further and eventually implemented in an integrated framework.

5. Conclusions and Outlook

The review highlights the important concept of achieving net-zero emissions as more than just a singular focus on energy production. While the decarbonization of energy production remains critical, it is imperative to extend this goal to the entire supply and value chain to achieve a sustainable and carbon-neutral future. The discussion highlighted that the advancement of renewable energy technologies is a key pillar in the pursuit of net-zero emissions. We would also like to shed light on the major challenge that fossil-based feedstocks pose to the chemical industry. Switching to sustainable and renewable feedstock sources is critical to reducing emissions associated with chemical production processes. The importance of a comprehensive systems approach to achieve net-zero emissions was highlighted.

Megatrends are presumptive transformations of a 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 [183]. Three megatrends have been observed in the chemical industry [184]:

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

Deloitte has published the following four trends for chemical industry [185]:

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, and 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 [186]. It shall significantly contribute to decarbonization by developing batteries, biogas/biomethane, carbon capture, and sustainable and alternative fuel technologies. The proposal was not accepted by the industry—Cefic (European Chemical Industry Council), described it as a "Zero Industry Act" [187].

Achieving net-zero emissions in the chemical process industries necessitates a holistic approach that combines technological advancements, supplies 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 [188]. Key aspects include:

1. Emission pricing policy instruments;

2. Standards and regulations;
3. Complementary policies to facilitate the reallocation of capital, labor, and innovation towards low-carbon activities and to offset the adverse distributional effects of reducing emissions.

In conclusion, recognizing the complex interlinkages between sectors and understanding that emissions need to be addressed holistically across the value chain are crucial aspects to successfully achieving this ambitious goal. Furthermore, the roadmap toward net-zero emissions must encompass not only net-zero energy production, but also net-zero feedstock production. By ensuring that raw materials are sustainably sourced and do not contribute to net emissions, we can significantly reduce the carbon impact of various industries. In this effort, we emphasize the importance of highly selective conversions and striving for high recycling rates of products and equipment. By optimizing processes and reducing waste, we can minimize emissions throughout the life cycle of products and contribute to a more sustainable economy. However, making the transition to net-zero emissions a reality requires concrete strategies, innovative approaches, and effective policies. Joint efforts by governments, businesses, and consumers will play a crucial role in bringing about meaningful change. The roadmap to achieving net-zero targets requires a comprehensive, collaborative, and multifaceted approach. By considering all aspects of the economy, from energy production to raw materials and the life cycle of products, we can effectively navigate the path towards a sustainable future for generations to come.

Author Contributions: 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.

Funding: The authors thank the Slovenian Research and Innovation Agency for support (Program P2-0414).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Environment Agency. Global and European Temperatures. Available online: https://www.eea.europa.eu/ims/global-and-european-temperatures (accessed on 29 May 2023).
2. World Meteorological Organization. Global Annual to Decadal Climate Update, Target Years: 2023 and 2023–2027. Available online: https://library.wmo.int/doc_num.php?explnum_id=11629 (accessed on 29 May 2023).
3. Jones, N. When will global warming actually hit the landmark 1.5 °C limit? *Nature* **2023**, *618*, 20. [CrossRef] [PubMed]
4. International Energy Agency, IEA. CO_2 Emissions in 2022. Available online: https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf (accessed on 29 May 2023).
5. Ellen MacArthur Foundation. To Reduce CO_2 Emissions, the Materials Industry Needs to Transition to a Circular Economy. Available online: https://medium.com/circulatenews/to-reduce-co2-emissions-the-materials-industry-needs-to-transition-to-a-circular-economy-520d83620283 (accessed on 29 May 2023).
6. Olabi, A.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Maghrabie, H.M.; Abdelkareem, M.A. Large scale application of carbon capture to process industries—A review. *J. Clean. Prod.* **2022**, *362*, 132300. [CrossRef]
7. Center for Global Commons at the University of Tokyo & Systemiq. Planet Positive Chemicals. Available online: https://cgc.ifi.u-tokyo.ac.jp/research/chemistry-industry/planet-positive-chemicals.pdf (accessed on 29 May 2023).
8. European Commission. Transition Pathway for the Chemical Industry. Available online: https://single-market-economy.ec.europa.eu/sectors/chemicals/transition-pathway_en (accessed on 29 May 2023).
9. Marzi, T.; Knappertsbusch, V.; Grevé, A.; Deerberg, G.; Doetsch, C.; Weidner, E. Resources of a New Carbon Economy. *Chem. Ing. Tech.* **2018**, *90*, 1374–1383. [CrossRef]
10. Bowker, M.; DeBeer, S.; Dummer, N.F.; Hutchings, G.J.; Scheffler, M.; Schüth, F.; Taylor, S.H.; Tüysüz, H. Advancing Critical Chemical Processes for a Sustainable Future: Challenges for Industry and the Max Planck–Cardiff Centre on the Fundamentals of Heterogeneous Catalysis (FUNCAT). *Angew. Chem. Int. Ed.* **2022**, *61*, e202209016. [CrossRef]

11. Nikas, A.; Xexakis, G.; Koasidis, K.; Fernández, J.A.; Arto, I.; Calzadilla, A.; Domenech, T.; Gambhir, A.; Giljum, S.; Eguino, M.G.; et al. Coupling Circularity Performance and Climate Action: From Disciplinary Silos to Transdisciplinary Modelling Science. *Sustain. Prod. Consum.* **2022**, *30*, 269–277. [CrossRef]
12. Idowu, I.A.; Hashim, K.; Shaw, A.; Nunes, L.J.R. Energy recovery from brewery spent grains and spent coffee grounds: A circular economy approach to waste valorization. *Biofuels* **2023**, *14*, 333–342. [CrossRef]
13. Sadok, R.H.; Maherzi, W.; Benzerzour, M.; Lord, R.; Torrance, K.; Zambon, A.; Abriak, N.E. Mechanical Properties and Microstructure of Low Carbon Binders Manufactured from Calcined Canal Sediments and Ground Granulated Blast Furnace Slag (GGBS). *Sustainability* **2021**, *13*, 9057. [CrossRef]
14. Zibunas, C.; Meys, R.; Kätelhön, A.; Bardow, A. Cost-Optimal Pathways towards Net-Zero Chemicals and Plastics Based on a Circular Carbon Economy. *Comput. Chem. Eng.* **2022**, *162*, 107798. [CrossRef]
15. Silva, C.; Moniz, P.; Oliveira, A.; Vercelli, S.; Reis, A.; Silva, T.L. Cascading Crypthecodinium Cohnii Biorefinery: Global Warming Potential and Techno-Economic Assessment. *Energies* **2022**, *15*, 3784. [CrossRef]
16. Roberts, M.; Allen, S.; Clarke, J.; Searle, J.; Coley, D. Understanding the Global Warming Potential of Circular Design Strategies: Life Cycle Assessment of a Design-for-Disassembly Building. *Sustain. Prod. Consum.* **2023**, *37*, 331–343. [CrossRef]
17. Staddon, J.; Smit, J.; Skoufa, Z.; Watson, D. Chemical Networks: A Methodology to Rapidly Assess the Environmental Impact of Chemical Processes: Applying Graph Theory Principles to Chemical Industry Data Enables Early-Stage Decision Making for Optimum Decarbonisation Solutions. *Johns. Matthey Technol. Rev.* **2022**, *66*, 466–478. [CrossRef]
18. Saggar, A.; Nigam, B. Maximising Net Zero in Energy-Intensive Industries: An Overview of AI Applications for Greenhouse Gas Reduction. *J. Clim. Chang.* **2023**, *9*, 13–23. [CrossRef]
19. Toniato, A.; Schilter, O.; Laino, T. The Role of AI in Driving the Sustainability of the Chemical Industry. *CHIMIA* **2023**, *77*, 144. [CrossRef]
20. NoParast, M.; Hematian, M.; Ashrafian, A.; Amiri, M.J.T.; AzariJafari, H. Development of a Non-Dominated Sorting Genetic Algorithm for Implementing Circular Economy Strategies in the Concrete Industry. *Sustain. Prod. Consum.* **2021**, *27*, 933–946. [CrossRef]
21. Datta, S.S.; Battiato, I.; Fernø, M.A.; Juanes, R.; Parsa, S.; Prigiobbe, V.; Carreras, E.S.; Song, W.; Biswal, S.L.; Sinton, D. Lab on a Chip for a Low-Carbon Future. *Lab A Chip* **2023**, *23*, 1358–1375. [CrossRef]
22. Xing, F.; Ma, J.; Shimizu, K.; Furukawa, S. High-Entropy Intermetallics on Ceria as Efficient Catalysts for the Oxidative Dehydrogenation of Propane Using CO_2. *Nat. Commun.* **2022**, *13*, 5065. [CrossRef] [PubMed]
23. Xing, F.; Furukawa, S. Metallic Catalysts for Oxidative Dehydrogenation of Propane Using CO_2. *Chem. A Eur. J.* **2023**, *29*, e202202173. [CrossRef] [PubMed]
24. Lu, X.; Forrest, B.; Martin, S.; Fetvedt, J.; McGroddy, M.; Freed, D. Integration and Optimization of Coal Gasification Systems with a Near-Zero Emissions Supercritical Carbon Dioxide Power Cycle. In Proceedings of the ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, Seoul, Republic of Korea, 13–17 June 2016. [CrossRef]
25. Layritz, L.S.; Dolganova, I.; Finkbeiner, M.; Luderer, G.; Penteado, A.T.; Ueckerdt, F.; Repke, J.U. The Potential of Direct Steam Cracker Electrification and Carbon Capture & Utilization via Oxidative Coupling of Methane as Decarbonization Strategies for Ethylene Production. *Appl. Energy* **2021**, *296*, 117049. [CrossRef]
26. Lanjewar, B.A.; Chippagiri, R.; Dakwale, V.A.; Ralegaonkar, R.V. Application of Alkali-Activated Sustainable Materials: A Step towards Net Zero Binder. *Energies* **2023**, *16*, 969. [CrossRef]
27. Pedraza, J.; Zimmermann, A.; Tobon, J.; Schomäcker, R.; Rojas, N. On the Road to Net Zero-Emission Cement: Integrated Assessment of Mineral Carbonation of Cement Kiln Dust. *Chem. Eng. J.* **2021**, *408*, 127346. [CrossRef]
28. Aneja, A.; Sharma, R.L.; Singh, H. Mechanical and Durability Properties of Biochar Concrete. *Mater. Today Proc.* **2022**, *65*, 3724–3730. [CrossRef]
29. Parvulescu, A.N.; Maurer, S. Toward Sustainability in Zeolite Manufacturing: An Industry Perspective. *Front. Chem.* **2022**, *10*, 1050363. [CrossRef] [PubMed]
30. Santawaja, P.; Kudo, S.; Mori, A.; Tahara, A.; Asano, S.; Hayashi, J. Sustainable Iron-Making Using Oxalic Acid: The Concept, A Brief Review of Key Reactions, and An Experimental Demonstration of the Iron-Making Process. *ACS Sustain. Chem. Eng.* **2020**, *8*, 13292–13301. [CrossRef]
31. European Commission. EU Climate Targets: How to Decarbonise the Steel Industry. Available online: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-climate-targets-how-decarbonise-steel-industry-2022-06-15_en (accessed on 29 May 2023).
32. Gingerich, D.B.; Sun, X.; Behrer, A.P.; Azevedo, I.L.; Mauter, M.S. Spatially Resolved Air-Water Emissions Tradeoffs Improve Regulatory Impact Analyses for Electricity Generation. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 1862–1867. [CrossRef] [PubMed]
33. Zhao, F.; Fan, Y.; Zhang, S.; Eichhammer, W.; Haendel, M.; Yu, S. Exploring Pathways to Deep De-Carbonization and the Associated Environmental Impact in China's Ammonia Industry. *Environ. Res. Lett.* **2022**, *17*, 045029. [CrossRef]
34. Zhao, X.; Huning, A.J.; Burek, J.; Guo, F.; Kropaczek, D.J.; Pointer, W.D. The Pursuit of Net-Positive Sustainability for Industrial Decarbonization with Hybrid Energy Systems. *J. Clean. Prod.* **2022**, *362*, 132349. [CrossRef]
35. Huo, J.; Wang, Z.; Oberschelp, C.; Gosálbez, G.G.; Hellweg, S. Net-Zero Transition of the Global Chemical Industry with CO_2-Feedstock by 2050: Feasible yet Challenging. *Green Chem.* **2023**, *25*, 415–430. [CrossRef]

36. Yu, X.; Catanescu, C.O.; Bird, R.E.; Satagopan, S.; Baum, Z.J.; Diaz, L.M.L.; Zhou, Q.A. Trends in Research and Development for CO 2 Capture and Sequestration. *ACS Omega* **2023**, *8*, 11643–11664. [CrossRef]
37. Gabrielli, P.; Gazzani, M.; Mazzotti, M. The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry. *Ind. Eng. Chem. Res.* **2020**, *59*, 7033–7045. [CrossRef]
38. Podder, J.; Patra, B.R.; Pattnaik, F.; Nanda, S.; Dalai, A.K. A Review of Carbon Capture and Valorization Technologies. *Energies* **2023**, *16*, 2589. [CrossRef]
39. Dongare, S.; Singh, N.; Bhunia, H. Nitrogen-Doped Graphene Supported Copper Nanoparticles for Electrochemical Reduction of CO_2. *J. CO2 Util.* **2021**, *44*, 101382. [CrossRef]
40. Joel, A.S.; Isa, Y.M. Novelty in Fossil Fuel Carbon Abatement Technologies in the 21st Century: Post-combustion Carbon Capture. *J. Chem. Technol. Biotechnol.* **2023**, *98*, 838–855. [CrossRef]
41. Ren, J.; Yu, A.; Peng, P.; Lefler, M.; Li, F.; Licht, S. Recent Advances in Solar Thermal Electrochemical Process (STEP) for Carbon Neutral Products and High Value Nanocarbons. *Acc. Chem. Res.* **2019**, *52*, 3177–3187. [CrossRef]
42. Quang, D.V.; Milani, D.; Zahra, M.A. A Review of Potential Routes to Zero and Negative Emission Technologies via the Integration of Renewable Energies with CO_2 Capture Processes. *Int. J. Greenh. Gas Control* **2023**, *124*, 103862. [CrossRef]
43. Lee, R.P.; Wolfersdorf, C.; Keller, F.; Meyer, B. Towards a Closed Carbon Cycle and Achieving a Circular Economy for Carbonaceous Resources—Net Zero Emissions, Resource Efficiency and Resource Conservation through Coupling of the Energy, Chemical and Recycling Sectors. *Oil Gas Eur. Mag.* **2017**, *43*, 76–77. [CrossRef]
44. Saleh, H.M.; Hassan, A.I. Green Conversion of Carbon Dioxide and Sustainable Fuel Synthesis. *Fire* **2023**, *6*, 128. [CrossRef]
45. Rusdan, N.A.; Timmiati, S.N.; Isahak, W.N.R.W.; Yaakob, Z.; Lim, K.L.; Khaidar, D. Recent Application of Core-Shell Nanostructured Catalysts for CO_2 Thermocatalytic Conversion Processes. *Nanomaterials* **2022**, *12*, 3877. [CrossRef]
46. Alia, S.; Ding, D.; McDaniel, A.; Toma, F.M.; Dinh, H.N. Chalkboard 2—How to Make Clean Hydrogen. *Electrochem. Soc. Interface* **2021**, *30*, 49–56. [CrossRef]
47. OpenAI. ChatGPT. Available online: https://chat.openai.com/ (accessed on 20 May 2023).
48. United Nations. For a Livable Climate: Net-Zero Commitments Must Be Backed by Credible Action. Available online: https://www.un.org/en/climatechange/net-zero-coalition (accessed on 4 June 2023).
49. United Nations. *Sustainable Development Goals*. 2015. Available online: https://www.un.org/sustainabledevelopment/development-agenda/ (accessed on 30 July 2023).
50. World Business Council for Sustainable Development. Chemical Sector SDG Roadmap 2018. Available online: https://www.wbcsd.org/contentwbc/download/5187/69414/1 (accessed on 30 July 2023).
51. Axon, S.; James, D. The UN Sustainable Development Goals: How can sustainable chemistry contribute? A view from the chemical industry. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 140–145. [CrossRef]
52. ACS (American Chemical Society). Chemistry & Sustainable Development Goals. Available online: https://www.acs.org/sustainability/chemistry-sustainable-development-goals.html (accessed on 30 July 2023).
53. The ACS Green Chemistry Institute presents Design Principles for Sustainable Green Chemistry & Engineering. Available online: https://www.acs.org/content/dam/acsorg/greenchemistry/resources/2015-gci-design-principles.pdf (accessed on 30 July 2023).
54. CEFIC, ChemistryCAN. *Report*. 2017. Available online: https://chemistrycan.com/ (accessed on 31 July 2023).
55. Scrivener, K. Building for Climate, SDG Action. 2022. Available online: https://sdg-action.org/building-for-climate/ (accessed on 5 August 2023).
56. Sachs, J.D.; Lafortune, G.; Fuller, G.; Drumm, E. *Sustainable Development Report 2023*; Dublin University Press: Dublin, Ireland, 2023; p. 35.
57. Rowland, J. A Sustainable Cement Industry. 2021. Available online: https://cementproducts.com/2021/07/15/a-sustainable-cement-industry/ (accessed on 5 August 2023).
58. Global Cement and Concrete Association (GCCA). Contribution to Achieving the UN SDGs. Available online: https://gccassociation.org/sustainability-innovation/the-un-sustainable-development-goals/ (accessed on 5 August 2023).
59. Glass Alliance Europe. 2022: The UN International Year of Glass. 2021. Available online: https://www.iyog2022.org/ (accessed on 5 August 2023).
60. Friedrich Schiller University Jena. Glass and Sustainability. Available online: https://www.lichtgedanken.uni-jena.de/en/archive/lichtgedanken-11/feature/iyog (accessed on 5 August 2023).
61. Andreotti, M.; Brondi, C.; Micillo, D.; Zevenhoven, R.; Rieger, J.; Jo, A.; Hettinger, A.L.; Bollen, J.; Malfa, E.; Trevisan, C.; et al. SDGs in the EU Steel Sector: A Critical Review of Sustainability Initiatives and Approaches. *Sustainability* **2023**, *15*, 7521. [CrossRef]
62. Hatayama, H. The metals industry and the Sustainable Development Goals: The relationship explored based on SDG reporting. *Resour. Conserv. Recy.* **2022**, *178*, 106081. [CrossRef]
63. Worldsteel Association. Our Commitment. Available online: https://worldsteel.org/steel-topics/sustainability/sustainability-commitment/ (accessed on 6 August 2023).
64. ASQ (American Society for Quality). What Is the ISO 14000 Standards Series? Available online: https://asq.org/quality-resources/iso-14000 (accessed on 25 August 2023).

65. ASQ. What Is the ISO 26000–Guidance on Social Responsibility? Available online: https://asq.org/quality-resources/iso-26000 (accessed on 25 August 2023).
66. Fernández, C.F. Basic Concepts on Ecodesign; Unit 10: Introduction to Ecolabelling. ECOSIGN Project. Available online: http://www.ecosign-project.eu/wp-content/uploads/2018/09/BASIC_UNIT10_EN_Lecture.pdf (accessed on 25 August 2023).
67. Pulp and Paper Canada. Resolute Sustainability Strategy Aligned with United Nations' Sustainable Development Goals. Available online: https://www.pulpandpapercanada.com/resolute-sustainability-strategy-aligned-with-united-nations-sustainable-development-goals/# (accessed on 5 August 2023).
68. Resolute Forest Products. Sustainability—Climate Change and Energy. Available online: https://www.resolutefp.com/Sustainability/Climate_Change_and_Energy/ (accessed on 6 August 2023).
69. Asia Pulp & Paper (APP) Sinar Mas. Sustainability Roadmap Vision 2030. Available online: https://asiapulppaper.com/documents/20123/202397/roadmap2030.pdf (accessed on 5 August 2023).
70. European Commission. A European Green Deal. 2019. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 31 July 2023).
71. European Commission. The Green Deal Industrial Plan: Putting Europe's Net-Zero Industry in the Lead. 2023. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_510 (accessed on 31 July 2023).
72. CEFIC. How Can Europe's Chemical Industry Help Deliver on the Green Deal? Available online: https://cefic.org/policy-matters/chemical-industry-green-deal/how-can-europes-chemical-industry-help-deliver-on-the-green-deal/ (accessed on 31 July 2023).
73. Climate Action Network (CAN) Europe, CAN Europe's Transformation Pathway Recommendations for the Chemical Industry. 2022. Available online: https://caneurope.org/content/uploads/2022/06/CAN-Europe_2022_Recommendations_Chemicals_Transforming-the-sector.pdf (accessed on 31 July 2023).
74. Ulbrich, M.; Haddadin Finn, M.; Eschenröder, E.C.; Faísca, N.; Elser, B.; Sleep, R.; Hensman, A. Accenture, and NexantECA. The Chemical Industry's Road to Net Zero. Available online: https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-174/accenture-chemicals-costs-opportunities-eu-green-deal.pdf#zoom%3D40 (accessed on 31 July 2023).
75. CEFIC. Chemicals for the Green Deal. Available online: https://cefic.org/app/uploads/2020/06/Chemicals-for-the-Green-Deal-Brochure.pdf (accessed on 31 July 2023).
76. European Cement Association. Cembureau, Cementing the European Green Deal. Available online: https://cembureau.eu/media/w0lbouva/cembureau-2050-roadmap_executive-summary_final-version_web.pdf (accessed on 2 August 2023).
77. European Economic and Social Committee. The EESC Calls for New EU Policies to Support the Glass Industry. 2021. Available online: https://www.eesc.europa.eu/en/news-media/news/eesc-calls-new-eu-policies-support-glass-industry (accessed on 3 August 2023).
78. Confederation of European Paper Industries (Cepi). Press Release: Pulp and Paper Producers Take Stock of Their Investments in Climate Action, April 26, 2023. Available online: https://www.cepi.org/press-release-pulp-and-paper-producers-take-stock-of-their-investments-in-climate-action/ (accessed on 3 August 2023).
79. Confederation of European Paper Industries (Cepi). European Pulp & Paper Industry's Contribution to EU Green Deal. 2021. Available online: https://www.paperchain.eu/wp-content/uploads/2021/06/2021_06_03-EU-Green-week-2021-paperChain-PulpandFuel-Workshop-Cepi-presentation-Bernard-Lombard.pdf (accessed on 3 August 2023).
80. European Commission. Corporate Sustainability Reporting. 2023. Available online: https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en (accessed on 5 August 2023).
81. European Parliament. Sustainable Economy: Parliament Adopts New Reporting Rules for Multinationals. 2023. Available online: https://www.europarl.europa.eu/news/en/press-room/20221107IPR49611/sustainable-economy-parliament-adopts-new-reporting-rules-for-multinationals (accessed on 7 August 2023).
82. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, A Green Deal Industrial Plan for the Net-Zero Age. Available online: https://commission.europa.eu/system/files/2023-02/COM_2023_62_2_EN_ACT_A%20Green%20Deal%20Industrial%20Plan%20for%20the%20Net-Zero%20Age.pdf (accessed on 8 June 2023).
83. European Commission. Transition Pathway for the Chemical Industry. Available online: https://ec.europa.eu/docsroom/documents/54595/attachments/1/translations/en/renditions/native (accessed on 8 June 2023).
84. McKinsey & Company. Decarbonizing the Chemical Industry. Available online: https://www.mckinsey.com/industries/chemicals/our-insights/decarbonizing-the-chemical-industry#/ (accessed on 8 June 2023).
85. Circle Economy. The Circularity Gap Report 2023. Available online: https://www.circularity-gap.world/2023 (accessed on 4 June 2023).
86. Fiorentino, G.; Zucaro, A.; Ulgiati, S. Towards an energy efficient chemistry. Switching from fossil to bio-based products in a life cycle perspective. *Energy* **2019**, *170*, 720–729. [CrossRef]
87. Maltais, A.; Karltorp, K.; Tekle, H. *Policy Priorities for Mobilizing Investment in Swedish Green Industrial Transitions*; Stockholm Environment Institute: Stockholm, Sweden, 2022. [CrossRef]

88. Zirngast, K.; Kravanja, Z.; Pintarič, Z.N. The influence of variable CO_2 emission tax rate on flexible chemical process synthesis. *Processes* **2021**, *9*, 1720. [CrossRef]
89. Hao, Z.; Barecka, M.H.; Lapkin, A.A. Accelerating net zero from the perspective of optimizing a carbon capture and utilization system. *Energy Environ. Sci.* **2022**, *15*, 2139–2153. [CrossRef]
90. Kasaš, M.; Kravanja, Z.; Pintarič, Z.N. Achieving Profitably, Operationally, and Environmentally Compromise Flow-Sheet Designs by a Single-Criterion Optimization. *AIChE J.* **2011**, *58*, 2131–2141. [CrossRef]
91. Foo, D.C.Y.; Tan, R.R. A Review on Process Integration Techniques for Carbon Emissions and Environmental Footprint Problems. *Process Saf. Environ. Prot.* **2016**, *103*, 291–307. [CrossRef]
92. Manan, Z.A.; Mohd Nawi, W.N.R.; Wan Alwi, S.R.; Klemeš, J.J. Advances in Process Integration research for CO_2 emission reduction—A review. *J. Clean. Prod.* **2017**, *167*, 1–13. [CrossRef]
93. Migo-Sumagang, M.V.; Aviso, K.B.; Foo, D.C.Y.; Short, M.; Nair, P.N.S.B.; Tan, R.R. Optimization and decision support models for deploying negative emissions technologies. *PLoS Sustain. Transform.* **2023**, *2*, e0000059. [CrossRef]
94. Zolbin, M.A.; Tahouni, N.; Panjeshahi, M.H. Total site integration considering wind/solar energy with supply/demand variation. *Energy* **2022**, *252*, 123928. [CrossRef]
95. Drofenik, J.; Urbancl, D.; Goričanec, D.; Kravanja, Z.; Novak-Pintarič, Z. Food Waste to Energy through Innovative Coupling of CHP and Heat Pump. *Energies* **2023**, *16*, 3344. [CrossRef]
96. International Energy Agency, IEA. Chemicals. Available online: https://www.iea.org/reports/chemicals (accessed on 29 May 2023).
97. International Energy Agency, IEA. Chemicals—Fuels & Technologies. Available online: https://www.iea.org/fuels-and-technologies/chemicals (accessed on 29 May 2023).
98. CEFIC. Facts and Figures 2023 of the European Chemical Industry. Available online: https://cefic.org/app/uploads/2023/03/2023-Facts-and-Figures.pdf (accessed on 29 May 2023).
99. Cosmos Weekly. How Can the Global Chemical Industry Get to Net Zero? Available online: https://cosmosmagazine.com/earth/chemical-industry-emissions/ (accessed on 29 May 2023).
100. Bhavsar, A.; Hingar, D.; Ostwal, S.; Thakkar, I.; Jadeja, S.; Shah, M. The Current Scope and Stand of Carbon Capture Storage and Utilization—A Comprehensive Review. *Case Stud. Chem. Environ. Eng.* **2023**, *8*, 100368. [CrossRef]
101. Langie, K.M.G.; Tak, K.; Kim, C.; Lee, H.W.; Park, K.; Kim, D.; Jung, W.; Lee, C.W.; Oh, H.-S.; Lee, D.K.; et al. Toward Economical Application of Carbon Capture and Utilization Technology with Near-Zero Carbon Emission. *Nat. Commun.* **2022**, *13*, 7482. [CrossRef] [PubMed]
102. Kelemen, P.; Benson, S.M.; Pilorgé, H.; Psarras, P.; Wilcox, J. An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. *Front. Clim.* **2019**, *1*, 9. [CrossRef]
103. Sullivan, I.; Goryachev, A.; Digdaya, I.A.; Li, X.; Atwater, H.A.; Vermaas, D.A.; Xiang, C. Coupling Electrochemical CO_2 Conversion with CO_2 Capture. *Nat. Catal.* **2021**, *4*, 952–958. [CrossRef]
104. Tang, C.; Zheng, Y.; Jaroniec, M.; Qiao, S. Electrocatalytic Refinery for Sustainable Production of Fuels and Chemicals. *Angew. Chem. Int. Ed.* **2021**, *60*, 19572–19590. [CrossRef]
105. Ra, E.C.; Kim, K.Y.; Kim, E.H.; Lee, H.; An, K.; Lee, J.S. Recycling Carbon Dioxide through Catalytic Hydrogenation: Recent Key Developments and Perspectives. *ACS Catal.* **2020**, *10*, 11318–11345. [CrossRef]
106. Fu, Z.; Yang, Q.; Liu, Z.; Chen, F.; Yao, F.; Xie, T.; Zhong, Y.; Wang, D.; Li, J.; Li, X.; et al. Photocatalytic Conversion of Carbon Dioxide: From Products to Design the Catalysts. *J. CO2 Util.* **2019**, *34*, 63–73. [CrossRef]
107. Eryazici, I.; Ramesh, N.; Villa, C. Electrification of the Chemical Industry—Materials Innovations for a Lower Carbon Future. *MRS Bull.* **2021**, *46*, 1197–1204. [CrossRef]
108. Van Geem, K.M.; Weckhuysen, B.M. Toward an E-Chemistree: Materials for Electrification of the Chemical Industry. *MRS Bull.* **2021**, *46*, 1187–1196. [CrossRef]
109. Fakayode, O.A.; Wahia, H.; Zhang, L.; Zhou, C.; Ma, H. State-of-the-Art Co-Pyrolysis of Lignocellulosic and Macroalgae Biomass Feedstocks for Improved Bio-Oil Production—A Review. *Fuel* **2023**, *332*, 126071. [CrossRef]
110. Klaas, L.; Guban, D.; Roeb, M.; Sattler, C. Recent Progress towards Solar Energy Integration into Low-Pressure Green Ammonia Production Technologies. *Int. J. Hydrogen Energy* **2021**, *46*, 25121–25136. [CrossRef]
111. Potrč, S.; Čuček, L.; Martin, M.; Kravanja, Z. Sustainable Renewable Energy Supply Networks Optimization—The Gradual Transition to a Renewable Energy System within the European Union by 2050. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111186. [CrossRef]
112. Taqvi, S.; Almansoori, A.; Elkamel, A. Optimal Renewable Energy Integration into the Process Industry Using Multi-Energy Hub Approach with Economic and Environmental Considerations: Refinery-Wide Case Study. *Comput. Chem. Eng.* **2021**, *151*, 107345. [CrossRef]
113. Baeyens, J.; Zhang, H.; Nie, J.; Appels, L.; Dewil, R.; Ansart, R.; Deng, Y. Reviewing the Potential of Bio-Hydrogen Production by Fermentation. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110023. [CrossRef]
114. Ubando, A.T.; Chen, W.-H.; Hurt, D.A.; Conversion, A.; Rajendran, S.; Lin, S.-L. Biohydrogen in a Circular Bioeconomy: A Critical Review. *Bioresour. Technol.* **2022**, *366*, 128168. [CrossRef]
115. Mishra, K.; Singh Siwal, S.; Kumar Saini, A.; Thakur, V.K. Recent Update on Gasification and Pyrolysis Processes of Lignocellulosic and Algal Biomass for Hydrogen Production. *Fuel* **2023**, *332*, 126169. [CrossRef]

116. Ehlers, J.C.; Feidenhans'l, A.A.; Therkildsen, K.T.; Larrazábal, G.O. Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective. *ACS Energy Lett.* **2023**, *8*, 1502–1509. [CrossRef]
117. Henkensmeier, D.; Najibah, M.; Harms, C.; Žitka, J.; Hnát, J.; Bouzek, K. Overview: State-of-the Art Commercial Membranes for Anion Exchange Membrane Water Electrolysis. *J. Electrochem. Energy Convers. Storage* **2021**, *18*, 024001. [CrossRef]
118. Min, G.; Choi, S.; Hong, J. A Review of Solid Oxide Steam-Electrolysis Cell Systems: Thermodynamics and Thermal Integration. *Appl. Energy* **2022**, *328*, 120145. [CrossRef]
119. Mahapatra, M.; Pradhan, A.K. Bioethanol Production from Agricultural Wastes with the Aid of Nanotechnology. In *Bio-Nano Interface*; Arakha, M., Pradhan, A.K., Jha, S., Eds.; Springer: Singapore, 2022; pp. 329–337. ISBN 9789811625152.
120. Lee, J.; Chen, W.-H.; Park, Y.-K. Recent Achievements in Platform Chemical Production from Food Waste. *Bioresour. Technol.* **2022**, *366*, 128204. [CrossRef]
121. Ewing, T.A.; Nouse, N.; Van Lint, M.; Van Haveren, J.; Hugenholtz, J.; Van Es, D.S. Fermentation for the Production of Biobased Chemicals in a Circular Economy: A Perspective for the Period 2022–2050. *Green Chem.* **2022**, *24*, 6373–6405. [CrossRef]
122. Gul, B.; Khan, S.; Ahmad, I. Extraction of Phytochemicals from Date Palm (*Phoenix dactylifera* L.) Seeds by Enzymatic Hydrolysis. *Food Process. Preserv.* **2022**, *46*, e17007. [CrossRef]
123. Rahimi, Z.; Anand, A.; Gautam, S. An Overview on Thermochemical Conversion and Potential Evaluation of Biofuels Derived from Agricultural Wastes. *Energy Nexus* **2022**, *7*, 100125. [CrossRef]
124. Bellabarba, R.; Johnston, P.; Moss, S.; Sievers, C.; Subramaniam, B.; Tway, C.; Wang, Z.; Zhu, H. Net Zero Transition: Possible Implications for Catalysis. *ACS Catal.* **2023**, 7917–7928. [CrossRef]
125. Burkart, M.D.; Hazari, N.; Tway, C.L.; Zeitler, E.L. Opportunities and Challenges for Catalysis in Carbon Dioxide Utilization. *ACS Catal.* **2019**, *9*, 7937–7956. [CrossRef]
126. Chit, V.; Tan, L.S.; Kiew, P.L.; Tsuji, T.; Funazukuri, T.; Lock, S.S.M. Advancing Process Intensification with High-Frequency Ultrasound: A Mini-Review of Applications in Biofuel Production and Beyond. *Processes* **2023**, *11*, 1236. [CrossRef]
127. Cholewa, T.; Semmel, M.; Mantei, F.; Güttel, R.; Salem, O. Process Intensification Strategies for Power-to-X Technologies. *ChemEngineering* **2022**, *6*, 13. [CrossRef]
128. Bogataj, M.; Klemeš, J.J.; Kravanja, Z. Fifty Years of Heat Integration. In *Handbook of Process Integration (PI)*, 2nd ed.; Klemeš, J., Ed.; Elsevier: Oxford, UK, 2022; pp. 73–99. ISBN 978-0-12-823850-9.
129. Aurisano, N.; Weber, R.; Fantke, P. Enabling a Circular Economy for Chemicals in Plastics. *Curr. Opin. Green Sustain. Chem.* **2021**, *31*, 100513. [CrossRef]
130. Bogataj, M.; Kravanja, Z.; Nemet, A. Recovery of N-Butanol from a Complex Five-Component Reactive Azeotropic Mixture. *Processes* **2022**, *10*, 364. [CrossRef]
131. He, C.; Zhang, C.; Bian, T.; Jiao, K.; Su, W.; Wu, K.-J.; Su, A. A Review on Artificial Intelligence Enabled Design, Synthesis, and Process Optimization of Chemical Products for Industry 4.0. *Processes* **2023**, *11*, 330. [CrossRef]
132. Al-Anzi, F.S.; Lababidi, H.M.S.; Al-Sharrah, G.; Al-Radwan, S.A.; Seo, H.J. Plant Health Index as an Anomaly Detection Tool for Oil Refinery Processes. *Sci. Rep.* **2022**, *12*, 14477. [CrossRef]
133. Gao, Z.; Geng, Y.; Wu, R.; Chen, W.; Wu, F.; Tian, X. Analysis of Energy-Related CO_2 Emissions in China's Pharmaceutical Industry and Its Driving Forces. *J. Clean. Prod.* **2019**, *223*, 94–108. [CrossRef]
134. Belkhir, L.; Elmeligi, A. Carbon Footprint of the Global Pharmaceutical Industry and Relative Impact of Its Major Players. *J. Clean. Prod.* **2019**, *214*, 185–194. [CrossRef]
135. Silva, A.P.D.S.E.; Pires, F.C.S.; Ferreira, M.C.R.; Da Silva, I.Q.; Aires, G.C.M.; Ribeiro, T.M.; Menezes, E.G.O.; Da Silva Martins, L.H.; De Carvalho, R.N. Case Studies of Green Solvents in the Pharmaceutical Industry. In *Green Sustainable Process for Chemical and Environmental Engineering and Science*, 1st ed.; Inamuddin, Boddula, R., Ahamed, M.I., Asiri, A.M., Eds.; Elsevier: Oxford, UK, 2021; pp. 151–159, ISBN 978-0-12-821885-3.
136. Kar, S.; Sanderson, H.; Roy, K.; Benfenati, E.; Leszczynski, J. Green Chemistry in the Synthesis of Pharmaceuticals. *Chem. Rev.* **2022**, *122*, 3637–3710. [CrossRef] [PubMed]
137. Mishra, M.; Sharma, M.; Dubey, R.; Kumari, P.; Ranjan, V.; Pandey, J. Green Synthesis Interventions of Pharmaceutical Industries for Sustainable Development. *Curr. Res. Green Sustain. Chem.* **2021**, *4*, 100174. [CrossRef]
138. Conway, S.L.; Rosas, J.G.; Overton, P.; Tugby, N.; Cryan, P.; Witulski, F.; Hurley, S.; Wareham, L.; Tantuccio, A.; Ramasamy, M.; et al. Implementation of a Fully Integrated Continuous Manufacturing Line for Direct Compression and Coating at a Commercial Pharmaceutical Facility—Part 1: Operational Considerations and Control Strategy. *Int. J. Pharm.* **2023**, *642*, 122820. [CrossRef] [PubMed]
139. Kerr, M.S.; Cole, K.P. Sustainability Case Studies on the Use of Continuous Manufacturing in Pharmaceutical Production. *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100279. [CrossRef]
140. Testa, C.J.; Shvedova, K.; Hu, C.; Wu, W.; Born, S.C.; Takizawa, B.; Mascia, S. Heterogeneous Crystallization as a Process Intensification Technology in an Integrated Continuous Manufacturing Process for Pharmaceuticals. *Org. Process Res. Dev.* **2021**, *25*, 225–238. [CrossRef]
141. Xiouras, C.; Kuijpers, K.; Fanfair, D.; Dorbec, M.; Gielen, B. Enabling Technologies for Process Intensification in Pharmaceutical Research and Manufacturing. *Curr. Opin. Chem. Eng.* **2023**, *41*, 100920. [CrossRef]
142. Mgharbel, M.; Halawy, L.; Milane, A.; Zeaiter, J.; Saad, W. Pyrolysis of Pharmaceuticals as a Novel Means of Disposal and Material Recovery from Waste for a Circular Economy. *J. Anal. Appl. Pyrolysis* **2023**, *172*, 106014. [CrossRef]

143. EFPIA. White Paper on Circular Economy. Available online: https://www.efpia.eu/media/554663/circular-economy.pdf (accessed on 25 May 2023).
144. Sabat, K.C.; Bhattacharyya, S.S.; Krishnamoorthy, B. Circular Economy in Pharmaceutical Industry through the Lens of Stimulus Organism Response Theory. *Eur. Bus. Rev.* **2022**, *34*, 936–964. [CrossRef]
145. Jellali, S.; Khiari, B.; Al-Harrasi, M.; Charabi, Y.; Al-Sabahi, J.; Al-Abri, M.; Usman, M.; Al-Raeesi, A.; Jeguirim, M. Industrial Sludge Conversion into Biochar and Reuse in the Context of Circular Economy: Impact of Pre-Modification Processes on Pharmaceuticals Removal from Aqueous Solutions. *Sustain. Chem. Pharm.* **2023**, *33*, 101114. [CrossRef]
146. Suhandi, V.; Chen, P.-S. Closed-Loop Supply Chain Inventory Model in the Pharmaceutical Industry toward a Circular Economy. *J. Clean. Prod.* **2023**, *383*, 135474. [CrossRef]
147. Singh, S.; Kumar, V.; Anil, A.G.; Kapoor, D.; Khasnabis, S.; Shekar, S.; Pavithra, N.; Samuel, J.; Subramanian, S.; Singh, J.; et al. Adsorption and Detoxification of Pharmaceutical Compounds from Wastewater Using Nanomaterials: A Review on Mechanism, Kinetics, Valorization and Circular Economy. *J. Environ. Manag.* **2021**, *300*, 113569. [CrossRef]
148. Muller, C.; Rabal, O.; Diaz Gonzalez, C. Artificial Intelligence, Machine Learning, and Deep Learning in Real-Life Drug Design Cases. In *Artificial Intelligence in Drug Design*; Heifetz, A., Ed.; Methods in Molecular Biology; Springer: New York, NY, USA, 2022; Volume 2390, pp. 383–407. ISBN 978-1-07-161786-1.
149. Prajapati, B.G.; Philip, A.; Faiyazuddin, M.; Prajapati, D.; Prajapati, J.; Paliwal, H.; Saikia, S. Impact of AI on drug delivery and pharmacokinetics: The present scenario and future prospects. In *A Handbook of Artificial Intelligence in Drug Delivery*, 1st ed.; Philip, A., Shahiwala, A., Rashid, M., Faiyazuddin, M., Eds.; Elsevier: New York, NY, USA, 2023; pp. 443–465. ISBN 978-0-323-89925-3.
150. Jukič, M.; Janežič, D.; Bren, U. Ensemble Docking Coupled to Linear Interaction Energy Calculations for Identification of Coronavirus Main Protease (3CLpro) Non-Covalent Small-Molecule Inhibitors. *Molecules* **2020**, *25*, 5808. [CrossRef] [PubMed]
151. Arden, N.S.; Fisher, A.C.; Tyner, K.; Yu, L.X.; Lee, S.L.; Kopcha, M. Industry 4.0 for Pharmaceutical Manufacturing: Preparing for the Smart Factories of the Future. *Int. J. Pharm.* **2021**, *602*, 120554. [CrossRef]
152. Kim, Y.; Atukeren, E.; Lee, Y. A New Digital Value Chain Model with PLC in Biopharmaceutical Industry: The Implication for Open Innovation. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 63. [CrossRef]
153. McKinsey & Company. Decarbonizing the Built Environment: Takeaways from COP26. Available online: https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/decarbonizing-the-built-environment-takeaways-from-cop26 (accessed on 9 June 2023).
154. Liu, Z.; Ciais, P.; Deng, Z.; Davis, S.J.; Zheng, B.; Wang, Y.; Cui, D.; Zhu, B.; Dou, X.; Ke, P.; et al. Carbon Monitor, a near-Real-Time Daily Dataset of Global CO_2 Emission from Fossil Fuel and Cement Production. *Sci. Data* **2020**, *7*, 392. [CrossRef] [PubMed]
155. McKinsey & Company. Decarbonizing Cement and Concrete Value Chains: Takeaways from Davos. Available online: https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/decarbonizing-cement-and-concrete-value-chains-takeaways-from-davos#/ (accessed on 9 June 2023).
156. Da Silva Magalhães, M.; Cezar, B.F.; Lustosa, P.R. Influence of Brazilian Fly Ash Fineness on the Cementing Efficiency Factor, Compressive Strength and Young's Modulus of Concrete. *Dev. Built Environ.* **2023**, *14*, 100147. [CrossRef]
157. Navarrete, I.; Vargas, F.; Martinez, P.; Paul, A.; Lopez, M. Flue Gas Desulfurization (FGD) Fly Ash as a Sustainable, Safe Alternative for Cement-Based Materials. *J. Clean. Prod.* **2021**, *283*, 124646. [CrossRef]
158. Gao, T.; Dai, T.; Shen, L.; Jiang, L. Benefits of Using Steel Slag in Cement Clinker Production for Environmental Conservation and Economic Revenue Generation. *J. Clean. Prod.* **2021**, *282*, 124538. [CrossRef]
159. Li, X.; Dengler, J.; Hesse, C. Reducing Clinker Factor in Limestone Calcined Clay-Slag Cement Using C-S-H Seeding—A Way towards Sustainable Binder. *Cem. Concr. Res.* **2023**, *168*, 107151. [CrossRef]
160. Ghalehnovi, M.; Roshan, N.; Hakak, E.; Shamsabadi, E.A.; De Brito, J. Effect of Red Mud (Bauxite Residue) as Cement Replacement on the Properties of Self-Compacting Concrete Incorporating Various Fillers. *J. Clean. Prod.* **2019**, *240*, 118213. [CrossRef]
161. Zhang, N.; Liu, X.; Sun, H.; Li, L. Evaluation of Blends Bauxite-Calcination-Method Red Mud with Other Industrial Wastes as a Cementitious Material: Properties and Hydration Characteristics. *J. Hazard. Mater.* **2011**, *185*, 329–335. [CrossRef]
162. Kahawalage, A.C.; Melaaen, M.C.; Tokheim, L.-A. Opportunities and Challenges of Using SRF as an Alternative Fuel in the Cement Industry. *Clean. Waste Syst.* **2023**, *4*, 100072. [CrossRef]
163. Mokrzycki, E.; Uliasz-Bocheńczyk, A. Alternative Fuels for the Cement Industry. *Appl. Energy* **2003**, *74*, 95–100. [CrossRef]
164. Coolbrook. RotoDynamic Heater to Replace Fossil Fuels in Industrial Process Heating. Available online: https://coolbrook.com/technology/rdh/ (accessed on 9 June 2023).
165. Cemnet. The Electrified Commercial Cement Kiln. Available online: https://www.cemnet.com/News/story/174030/the-electrified-commercial-cement-kiln.html (accessed on 9 June 2023).
166. Nhuchhen, D.R.; Sit, S.P.; Layzell, D.B. Decarbonization of Cement Production in a Hydrogen Economy. *Appl. Energy* **2022**, *317*, 119180. [CrossRef]
167. Vattenfall. Vattenfall and Cementa Take the Next Step towards a Climate Neutral Cement. Available online: https://group.vattenfall.com/press-and-media/pressreleases/2019/vattenfall-and-cementa-take-the-next-step-towards-a-climate-neutral-cement (accessed on 9 June 2023).
168. Bacatelo, M.; Capucha, F.; Ferrão, P.; Margarido, F. Selection of a CO_2 Capture Technology for the Cement Industry: An Integrated TEA and LCA Methodological Framework. *J. CO2 Util.* **2023**, *68*, 102375. [CrossRef]

169. Tanzer, S.E.; Blok, K.; Ramírez, A.R. Scoping Cost and Abatement Metrics for Biomass with Carbon Capture and Storage—The Example of BioCCS in Cement. *Int. J. Greenh. Gas Control* **2023**, *125*, 103864. [CrossRef]
170. Ferrario, D.; Stendardo, S.; Verda, V.; Lanzini, A. Solar-Driven Calcium Looping System for Carbon Capture in Cement Plants: Process Modelling and Energy Analysis. *J. Clean. Prod.* **2023**, *394*, 136367. [CrossRef]
171. Strunge, T.; Renforth, P.; Van Der Spek, M. Towards a Business Case for CO_2 Mineralisation in the Cement Industry. *Commun. Earth. Environ.* **2022**, *3*, 59. [CrossRef]
172. Dixit, A.; Du, H.; Pang, S.D. Carbon Capture in Ultra-High Performance Concrete Using Pressurized CO_2 Curing. *Constr. Build. Mater.* **2021**, *288*, 123076. [CrossRef]
173. International Finance Corporation (IFC). Strengthening Sustainability in the Glass Industry. Available online: https://www.ifc.org/content/dam/ifc/doc/mgrt/final-ifc-glass-7-26-21.pdf (accessed on 31 July 2023).
174. European Commission. How LIFE Is Reducing Emissions from Glass Production. Available online: https://cinea.ec.europa.eu/news-events/news/how-life-reducing-emissions-glass-production-2022-03-16_en (accessed on 31 July 2023).
175. British Glass, Glass Sector Net Zero Strategy 2050. Available online: https://www.britglass.org.uk/sites/default/files/British%20Glass%20-%20Net%20Zero%20Strategy.pdf (accessed on 31 July 2023).
176. glassOnline. Saint-Gobain: First Zero-Carbon Production of Flat Glass in the World. Available online: https://www.glassonline.com/saint-gobain-first-zero-carbon-production-of-flat-glass-in-the-world (accessed on 31 July 2023).
177. OECD. Industrial Biotechnology and Climate Change: Opportunities and Challenges. 2011. Available online: https://www.oecd.org/sti/emerging-tech/49024032.pdf (accessed on 3 June 2023).
178. Bang, J.K.; Foller, A.; Buttazzoni, M. *Industrial Biotechnology: More Than Green Fuel in a Dirty Economy? Exploring the Transformational Potential of Industrial Biotechnology on the Way to a Green Economy*; WWF Denmark: Copenhagen, Denmark, 2009; p. 20.
179. International Aluminium. Making Net-Zero Aluminium Possible. Available online: https://international-aluminium.org/resource/mpp-and-iai-release-ambitious-decarbonization-aluminium-sector/ (accessed on 4 June 2023).
180. Furszyfer Del Rio, D.D.; Sovacool, B.K.; Griffiths, S.; Bazilian, M.; Kim, J.; Foley, A.M.; Rooney, D. Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112706. [CrossRef]
181. International Energy Agency (IEA). Paper. Available online: https://www.iea.org/energy-system/industry/paper (accessed on 29 July 2023).
182. European Commission. How EU Pulp and Paper Industry Can Reduce Greenhouse Gas Emissions. Available online: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/how-eu-pulp-and-paper-industry-can-reduce-greenhouse-gas-emissions-2018-09-25_en (accessed on 29 July 2023).
183. Megatrends. Available online: https://www.google.com/search?client=firefox-b-d&q=megatrends (accessed on 24 June 2023).
184. Wadyalkar, S. Market Research. 3 Megatrends in the Chemical Industry. Available online: https://blog.marketresearch.com/3-megatrends-in-the-chemical-industry (accessed on 25 June 2023).
185. Deloitte. 2023 Chemical Industry Outlook. Available online: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-2023-outlook-chemical.pdf (accessed on 27 June 2023).
186. European Commission. Proposal for a Regulation of the European Parliament and of the Council on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act). Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:6448c360-c4dd-11ed-a05c-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed on 27 June 2023).
187. Cefic Statement on the Publication of the European Commission's Net-Zero Industry Act. Available online: https://cefic.org/media-corner/newsroom/cefic-statement-on-the-publication-of-the-european-commissions-net-zero-industry-act/ (accessed on 27 June 2023).
188. D'Arcangelo, F.M.; Levin, I.; Pagani, A.; Pisu, M.; Johansson, Å. A Framework to Decarbonize the Economy. OECD, Economic Policy Paper No. 31. 2022. Available online: https://www.oecd-ilibrary.org/docserver/4e4d973d-en.pdf?expires=1688074583&id=id&accname=guest&checksum=2DC88FA312145ECA9CC65E2FE00131EC (accessed on 28 June 2023).