Strategies and key factors to achieve carbon neutrality for an industrial company: a systematic literature review

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Abstract: The industrial sector is one of the most significant greenhouse gas emitters, accounting for about 20% of total CO_2 emissions. The challenging objectives imposed by the European community require companies operating in the industrial sector to implement necessary and timely actions to achieve Paris Agreement targets. If the goal is clear, the strategies and actions that companies must undertake are in the process of being outlined. Through a Systematic Literature Review (SRL), this work aims to identify the key factors to be considered for a company operating in the industrial sector to implement a decarbonization strategy. The SLR allowed us to analyze the state-of-the-art technologies and processes currently used in the industrial scenario and the most innovative and promising enabling technologies such as heat pumps, CO_2 capture technology, and hydrogen production. Furthermore, other relevant aspects such as continuous research to improve energy performance, responsible energy management, and waste management like waste heat recovery also emerged. These topics will play a fundamental role in achieving carbon neutrality, along with technological innovation. The results are collected in a comprehensive database to provide examples for implementing strategies to become carbon neutral through concepts and empirical evidence available in the scientific literature.

Keywords: carbon neutrality, decarbonization, energy transition strategies, industry, energy efficiency.

I. INTRODUCTION

The industrial sector accounts for about 30% of total final energy consumption worldwide. In 2018, industries reported about 20% of global CO_2 emissions, corresponding to 6.2 billion tons of CO_2 [1]. Energy-intensive industries such as iron & steel, chemical and petrochemical, cement, ceramics, glass, paper & pulp, and food & drinks are the most CO_2 intensive subsectors. They account for about 64% of the total industrial emissions in the European Union (EU). These significant emissions are mainly due to the high-temperature processes required [2].

As part of the European Green Deal, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the EU by 2050, including the intermediate target of at least 55% net reduction in greenhouse gas (GHG) emissions by 2030 below 1990 levels. These proposals cover a wide range of policy areas, including climate, energy, transport, and taxation. All sectors will contribute to achieving the emissions reduction target by improving energy efficiency and increasing renewables.

This vision covers most EU policies and is in line with the Paris Agreement's objective to keep the global temperature increase below 2.0 °C and pursue efforts to keep it to 1.5°C [3].

Given the high energy consumption and CO_2 emissions that characterize industries, the ambitious goal of achieving carbon neutrality is closely linked to the decarbonization of the industrial sector by making it more sustainable.

In response to the EU Roadmap 2050, there has been a great deal of effort in recent years by the scientific community to seek viable solutions and strategies to achieve the challenging goals. Renewable energy production, energy storage, production and use of hydrogen, Carbon Capture and Storage (CCS), electrolysis, and biomass are configured as the leading "enabling" technologies for achieving carbon neutrality, mainly in the medium and long term [4].

Together with other factors such as the continuous improvement of energy efficiency and waste management, these technologies constitute a wide range of opportunities that the energy transition can offer.

On the other hand, if the goals are clear and there is an awareness of numerous technologies, differing views about their maturity and applicability generate a high degree of inconsistency and uncertainty in the expected pathways and technologies for achieving industry-wide decarbonization.

This work aims to carry out a systematic literature review (SLR) to identify which enabling factors are the most relevant for the industrial sector and their short, medium, and long-term prospects. Another essential purpose is to analyze and delineate the base strategy elements that a single company can undertake to become carbon neutral.

The paper is organized as follows: Section 2 illustrates the methodology used to carry out the literature review; Section 3 contains the description of the results and thematic synthesis of their content; Section 4 contains a discussion of the results. Finally, Section 5 provides the conclusions of the study.

II. Research Methodology

A. *Research question*

The relevance and actuality of Carbon Neutrality lead it to be widely discussed in different contexts, from the political to the social, with different levels of depth. The first step was to direct our research to investigate in detail the current relationship between decarbonization and the industrial scenario, defining appropriate research questions:

- What key factors must an industrial company consider in becoming carbon neutral?
- What are the strategies that can be undertaken in this energy transition process?

Therefore, our research motivation is to determine the current state of maturity of the enabling technologies for the energy transition and the short and long-term strategies in the development phase. In addition, we will pay special attention to critical issues and future research directions.

B. *Materials and methods*

The SLR was carried out using the SCOPUS online database (www.scopus.com).

The approach followed consists of 5 main steps:

1. Selection: formulate keywords and research boundaries (e.g., research period, type of documents, language).
2. Research: search for articles using the SCOPUS online database according to the criteria.
3. First evaluation: perform articles preliminary screening based on titles and abstracts. Only those papers that meet research purposes must be selected.
4. Final evaluation: analyze the full text of selected papers to determine the final database.
5. Classification: divide the articles into categories based on their content.

We did not consider geographical boundaries for this literature review and limited the research to a period between 2017 and 2022. This period is considered appropriate by the authors to achieve the most innovative aspects of the topic of decarbonization. In addition, only articles, conference papers, and reviews are considered valid document types, and we also limited the results to the English language.

Initially, we considered the results of the following research strings: "Decarbonization" AND "Industrial." From an initial analysis of the resulting papers, many researchers often used the term "Carbon Neutrality" instead of "Decarbonization," and it was therefore introduced as a keyword in combination with the term "Industrial."

This research, done in April 2022, produced 667 results described in the following section.

III. Results

The research produces 667 documents, divided by type in article (519), review (83), and conference paper (65). Figure 1 shows the number of documents for each year of publication. It is interesting to note that the issue of Carbon neutrality is clearly described by an actively growing interest, especially in the last two years.

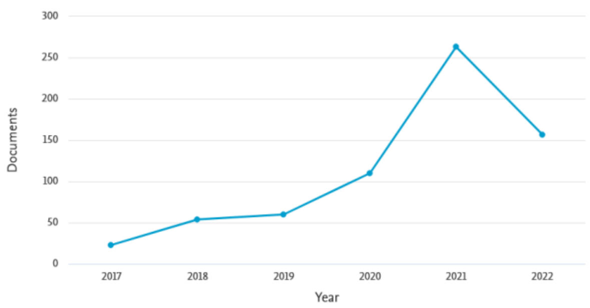

Figure 1: Number of documents per year of publication

Figure 2 shows the geographical distribution of the documents detected by the first phase of the research (top 15 countries). It is essential to note the important contribution of the EU countries represents. The great attention to the issue is due to the challenging targets imposed by the European community regarding reducing CO_2 emissions.

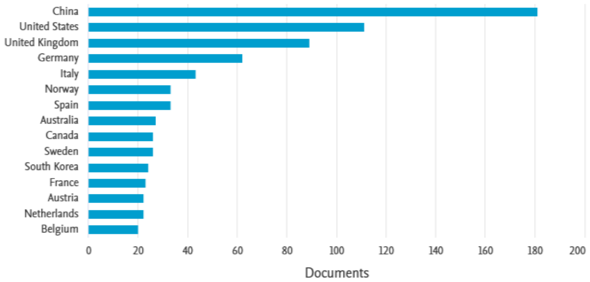

Figure 2: Documents by country or territory

Initial screening was done by matching the detected papers with the project boundaries, particularly the relevance to the industry. This activity identified 118 documents within the boundaries of the research project whose full text was analyzed. The full-text evaluation resulted in the final database consisting of 81 papers that were divided into categories. Table 1 provides a summary of the selection process.

TABLE I
SUMMARY OF THE SLR SELECTION PROCESS

Phase	Documents
Identified documents	667
Documents after title and abstract review	123
Documents after full-text review	81

The main reasons for deleting non-relevant documents can be attributed to several factors. Many documents were eliminated because they proposed a scenario analysis questioning the feasibility of achieving carbon neutrality without detail on technologies or operational aspects. Other documents ask about national policies and strategies, while others focus only on the transport or building sectors.

The last phase of the research involved identifying categories based on which to subdivide the final database. We identified five thematic categories: Technologies, Sector analysis, High-level analysis, Energy efficiency measures, and Methodologies. Table 2 shows the number of documents detected for each category.

TABLE II
DOCUMENTS BY CATEGORY

Categories	Documents
Technologies	34
Sector analysis	26
High-level analysis	10
Energy efficiency measures	7
Methodologies	4
Total	81

The category "Technologies" includes documents dedicated to an in-depth analysis of technologies considered "enabling" in the decarbonization of the industrial sector. In particular, we find CCS (12), hydrogen-based systems (11), heat pumps (5), battery storage (2), biogas (1), and other approaches (2), such as the combination of CCS and hydrogen production to obtain synthetic natural gas (power to gas). [5].

The category "Sector analysis" includes studies dedicated to analyzing opportunities for decarbonization for a specific industrial sector. In particular, there are analyses for iron and steel (6), chemical (5), cement (4), food and beverage (4), pulp and paper (3), ceramic (1), glass (1), industrial laundries (1), oil refining (1) sectors.

The "High-level analysis" category contains papers dedicated to presenting the current state, opportunities, challenges, and perspectives of technologies related to achieving carbon neutrality. In this category, there are mainly literature reviews.

"Energy efficiency measures" is the category that includes papers dedicated to the in-depth study of those factors of CO_2 abatement through the improvement of energy performance, such as the implementation of energy management systems, the use of artificial intelligence techniques, or waste heat recovery.

Finally, although it turns out to be the least populated category, the papers contained in "Methodologies" are interesting and particularly aligned with the goals of this research. These papers are dedicated to developing methodologies for evaluating different measures of CO_2 reduction.

IV. DISCUSSION

The research results show that the most represented category is "Technologies", with 34 results. The CCS, hydrogen, and heat pumps are among the most representative technologies.

Most researchers agree that CCS will play a crucial role in decarbonizing the industrial sector, especially in the medium to long term [6]. Carbon capture and sequestration can be done using natural means or industrial-scale carbon dioxide and other emissions, capture, storage, and burial [7]. In parallel with the development of CO_2-neutral technologies, carbon capture and storage can bridge the gap until other technologies mature [8].

On the other hand, the systemic economic advantage of using CCS is still relatively small. This cost aspect opens the question of whether this cost advantage is high enough to outweigh the risks associated with CCS implementation [9]. In conclusion, carbon capture requires the development of efficient technology and policy measures to make it feasible and attractive [7].

Hydrogen can be used to reduce CO_2 emissions attributable to fossil fuel consumption. Evidence suggests that hydrogen could play an essential role in decarbonization where high-temperature heat is used, such as in furnaces and kilns, as well as in industrial processes where the sources of CO_2 emissions are more distributed, making carbon capture expensive [10].

There are several ways to produce hydrogen: fossil fuels and renewable energy. At present, about 96% of global hydrogen is produced from fossil fuel processing such as steam methane reforming (48%), coal gasification (18%), and the partial oxidation of oil (30%). Only 4% is produced through electrolysis [10].

Large-scale H_2 production from fossil fuels is currently the most economically viable method. In contrast, H_2 production by water electrolysis is the most promising approach using renewable energy, such as solar and wind power [11,12]. Mid-term large-scale commercialization of electrolyzers is possible by developing cost-effective and durable components with improved system efficiency. In the long term, green H_2 production using renewable energy resources is expected to increasingly penetrate the market [13]. In this scenario, power to gas can be a promising option to take advantage of renewable H_2 by converting it, together with the captured CO2, into renewable gases, particularly renewable methane [5,14].

Heat pumps represent an important opportunity for decarbonization. The most innovative high and ultra-high-temperature heat pumps can reach output temperatures above 150°C. These can be equipped with a condenser capable of producing steam without an intermediate circuit, making them applicable for various production processes [15,16]. This technology is sufficiently mature and can be a near-term solution for reducing emissions.

Other technologies, such as battery storage, have not been sufficiently represented in the database, although many works define them as fundamental in this transition process.

The category related to sector analyses is important regarding the number of documents analyzed. These papers seek to contextualize "enabling" technologies within the processes characteristic of the specific sector under consideration. Among the sectors considered, highly energy-intensive industries, like cement production, are responsible for approximately 8% of global CO_2 emissions [17]. Although we believe that this type of document can significantly contribute to the individual sector, they are often too general and lack operational aspects. In addition, some relevant sectors are not sufficiently covered, such as wood, machinery, non-ferrous metals, textiles, and non-metallic minerals, which many researchers consider crucial [8,18].

Interesting are the contributions in the category "Energy efficiency measures" dedicated to studying those factors of CO_2 abatement through the improvement of energy performance. Among these factors, thanks to the increasing availability of data, we find artificial intelligence techniques, such as machine learning models, to predict and control energy consumption [19]. Other contributions, such as the one proposed by [20], emphasize the importance of introducing energy management systems according to the ISO50001 standard. Absolutely to be taken into account is the issue of waste heat recovery, which is attracting increasing interest from the scientific community. In this regard, technologies such as organic Rankine cycles and heat pumps for converting waste heat into electricity and high-temperature heat are increasingly mature and promising [21,22]. In conclusion, the contributions contained in this category are particularly relevant because these types of solutions are often characterized by low payback times, and they are one of the few short-term solutions for reducing CO_2 emissions.

Finally, the last category, the least populated, is "Methodologies." The article proposed by [23] describes a framework containing energy, economic and environmental analysis methods to discuss the roadmap to achieving a carbon-neutral industrial park. The model combines photovoltaic power generation and electrolysis hydrogen production in various scenarios. Similarly, the work proposed by [24] aims to quantify the effects of three combined measures for CO2 emission reduction in industry, i.e., fuel switching, electrification, and adoption of CCS, and simulate plausible scenarios with a focus on iron and steel sector.

These studies focus on top-down approaches using explorative scenarios that do not fully answer our research questions.

Other works, such as the one presented by [25], propose a different strategy. This work proposes a bottom-up methodology for the single plant that consists of several steps, starting from the description of existing systems to arrive at the technical and economic evaluation of the proposed solutions, including process integration aspects and system consequences as well as the impacts on overall energy efficiency.

Although the methodology is considered valid, it does not go into detail on technological aspects, limiting itself to general considerations.

Finally, interesting but not particularly aligned with the objectives of this research is the work of [26] which provides a conceptual model for evaluating energy efficiency policy programs ex-ante with a focus on the industrial sector.

In conclusion, many emerging technologies are under development to completely decarbonize the industrial sector. For commercial usability of these technologies in time to meet the Paris Agreement goals, we need a wide range of rigorous innovation and market uptake policies from production to end-use [27].

Another aspect that needs more investigation is decarbonization's effect on energy use and optimization, such as important changes in planning and energy-aware scheduling [28].

The biggest problem we have found is the lack of studies that take a bottom-up perspective to investigate decarbonization options at existing industrial sites, including practical implementation. The research has focused on analyzing the overall system while leaving out reasoning about what the way forward might be from the individual's perspective, identifying both ways and timescales for action.

This lack suggests a future research direction to develop roadmaps and pathways to provide a clear vision of how the individual company can achieve the required emission reductions in the decades ahead.

V. Conclusion

In this paper, we carried out a Systematic Literature Review to identify the key factors that a company operating in the industrial sector must consider to define a decarbonization strategy.

The final database obtained contains 81 documents divided into five categories: Technologies (34), Sector analysis (26), High-level analysis (10), Energy efficiency measures (7), and Methodologies (4).

Technologies such as Carbon Capture and Storage, Hydrogen production, and heat pumps are up-and-coming. Together with other key factors, such as the continuous improvement of energy efficiency, they will strongly contribute to achieving carbon neutrality according to the objectives imposed by the EU. For these reasons, these factors will need to be carefully monitored by the industry.

On the other hand, this literature review has identified non-technological barriers to implementing these technologies: scientific research must focus on developing operational methodologies capable of concretely supporting industrial companies in developing suitable strategies for decarbonization.

In conclusion, the literature review answered the first research question: the key factors correspond to the identified research categories. On the other hand, finding a concrete answer to the second research question regarding the decarbonization strategies to be adopted was more difficult.

The authors' view is that an industrial enterprise's decarbonization strategy can only consist of an optimal combination of the following objectives: reduction of overall energy needs, use of "green" electricity, and reduction of the amount of CO_2 emitted on-site for thermal power generation. From the findings of this research, the objectives may be achieved through a combination of the following actions: energy efficiency measures aimed at reducing consumption, increased use of "green" electricity, and low carbon technologies for self-generation and CO_2 capture and storage. While technological solutions for increasing energy efficiency and less reliance on thermal power generation seem to be available in the short term, the other solutions will be available only in the medium to long term, and their availability will heavily condition the possibility of companies becoming concretely zero-emission.

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Appendix A. DATABASE

TABLE I
SUMMARY OF SOME OF THE RELEVANT ARTICLES INCLUDED IN THE FINAL DATABASE

Title	Category	Subcategory	Ref.	Year
Industrial excess heat recovery in industry-city networks: a technical, environmental and economic assessment of heat flexibility	Energy efficiency measures	Waste heat recovery	[22]	2018
Waste heat recovery technologies and applications	Energy efficiency measures	Waste heat recovery	[21]	2018
Bottom-up methodology for assessing electrification options for deep decarbonisation of industrial processes	Methodologies	-	[25]	2018
A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement	High-level analysis	Literature review	[27]	2018
A review of cross-sector decarbonisation potentials in the European energy intensive industry	High-level analysis	Literature review	[2]	2019
Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries	Technologies	Heat pumps	[16]	2019
Wind and solar energy technologies of hydrogen production – a review of issues	Technologies	Hydrogen	[11]	2019
Production of synthetic natural gas from industrial carbon dioxide	Technologies	Power to gas	[14]	2020
Is the H_2 economy realizable in the foreseeable future? Part I: H_2 production methods	Technologies	Hydrogen	[13]	2020
The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)	High-level analysis	-	[18]	2020
A review of the emission reduction potential of fuel switch towards biomass and electricity in European basic materials industry until 2030	High-level analysis	-	[8]	2020
Long-term development of the industrial sector – Case study about electrification, fuel switching, and CCS in the USA	Methodologies	-	[24]	2020
Industrial Decarbonization by a New Energy-Baseline Methodology. Case Study	Energy efficiency measures	Energy management system	[20]	2020
Decarbonization of industry: Guidelines towards a harmonized energy efficiency policy program impact evaluation methodology	Methodologies	-	[26]	2021
Technologies and perspectives for achieving carbon neutrality	High-level analysis	Literature review	[4]	2021
Towards Deep Decarbonisation of Energy-Intensive Industries: A Review of Current Status, Technologies and Policies	High-level analysis	Literature review	[1]	2021
Techno-Economics Optimization of H_2 and CO_2 Compression for Renewable Energy Storage and Power-to-Gas Applications	Technologies	Power to gas	[5]	2021
Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities	Technologies	CCS	[6]	2021
A 2050 perspective on the role for carbon capture and storage in the European power system and industry sector	Technologies	CCS	[9]	2021
The role of hydrogen in the transition from a petroleum economy to a low-carbon society	Technologies	Hydrogen	[12]	2021
The status of hydrogen technologies in the UK: A multi-disciplinary review	Technologies	Hydrogen	[10]	2021
A Review on the Prediction of Energy Consumption in the Industry Sector Based on Machine Learning Approaches	Energy efficiency measures	Machine learning	[19]	2021
Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply	High-level analysis	-	[7]	2022
A review and perspective on industry high-temperature heat pumps	Technologies	Heat pumps	[15]	2022
Roadmap to carbon emissions neutral industrial parks: Energy, economic and environmental analysis	Energy efficiency measures	Industrial symbiosis	[23]	2022
Decarbonization options for cement production process: A techno-economic and environmental evaluation	Sector analysis	Cement	[17]	2022