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Decarbonization of energy-intensive industries in Poland on the road to climate neutrality – the role of electrification, hydrogen, and synthetic fuels

Abstract: Energy-intensive industry plays a key role in the structure of greenhouse gas emissions in Poland and is one of the most difficult sectors to decarbonize in the energy transition process. The aim of this article is to identify and organize the main paths for decarbonizing energy-intensive industries in Poland in the context of striving for climate neutrality by 2050, with particular emphasis on the role of electrification, low- and zero-emission hydrogen, and synthetic fuels.

The article is based on a review of current scientific literature, reports from international institutions, and strategic documents from the European Union and Poland. The first part presents the characteristics of energy-intensive industry in Poland compared to the European Union and the main structural conditions affecting the pace and scope of decarbonization. It then discusses the potential, limitations, and interrelationships of three key transformation pathways: direct electrification of industrial processes, the use of hydrogen as an energy carrier and raw material, and the development of synthetic fuels within the Power-to-X technology.

The article shows that effective decarbonization of energy-intensive industries requires a portfolio approach, combining different technologies depending on the specific nature of the processes and sectors, as well as close coordination of energy and industrial policies.

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The results indicate that electrification will play a dominant role in low- and medium-temperature processes, while hydrogen and synthetic fuels will be indispensable in high-temperature applications and in processes where fossil fuels are used as feedstock.

Keywords: decarbonization, energy-intensive industry, electrification, green hydrogen, synthetic fuels, climate neutrality

Introduction

The decarbonization of the economy is one of the key pillars of contemporary climate and energy policy in the European Union (EU) and is a response to the growing challenges of climate change, energy security, and long-term economic competitiveness. The framework for this transformation was set out in the European Green Deal (European Commission 2019), a document which, for the first time, systematically linked climate targets with industrial, innovation, and social policy. These provisions are further developed in the Fit for 55 legislative package (European Commission 2021), which aims to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and achieve climate neutrality by 2050 in EU countries.

In Poland, the implementation of the targets set by the European Commission is particularly challenging. Given the historically shaped structure of the economy and the energy mix, which over the years has been largely based on fossil fuels, climate neutrality may pose a significant challenge. In 2024, the emissions intensity of the national electricity system was approximately 666 g CO_2e/kWh, while the EU average was 251 g CO_2e/kWh (Świercz et al. 2025). This means that the decarbonization of end-use energy sectors, including the industrial sector, faces significant structural constraints, and electrification often leads to a shift of emissions from end use to the energy generation sector in the short term.

Energy-intensive industries (EII), which include sectors such as metallurgy, cement, chemicals, refining, and coking, play a special role in the process of decarbonizing the economy. According to data from the industrial emissions database compiled by the Instrat Foundation, CO_2 emissions from industrial activities in Poland in 2024 amounted to approximately 60 million tonnes, which represents nearly 20% of national greenhouse gas emissions, and these emissions are highly concentrated; just ten of the largest companies account for more than half of industrial emissions (Instrat 2025). This structure means that the technological and investment decisions of individual entities are of systemic importance for the achievement of national climate targets. The high share of fossil fuels in the energy mix further increases the emissions intensity of industrial production compared to the European Union average.

The transformation process of energy-intensive industries is closely linked to the transformation of the coal sector. Despite a decline in hard coal production from 82 million Mg in 2010 to 69.6 million Mg in 2021 and a decrease in mining employment from 120,000 to 74,000 people, the sector continues to play an important economic and social role, especially in mining regions (Pepłowska 2025a). Despite the proposed schedule for the gradual phasing out of mines by 2049, which is the result of the 2021 Social Agreement, this process generates not only social and fiscal challenges, but also technological ones. At the same time, there is an opportunity to treat CO_2 not only as a by-product of industrial processes, but also as a raw material for conversion technologies within Power-to-X, which could reduce the costs of the transition during the transition period (Pfennig et al. 2023; Müller et al. 2025; Oyewo et al. 2024; Pepłowska 2025b).

The literature on the subject emphasizes that the decarbonization of economies with a high share of energy-intensive industries is not possible using a single technology or a single transformation pathway (IEA 2023; CATF 2025). A complementary approach and diversification of transformation pathways are necessary.

This article analyses three key pathways for decarbonizing energy-intensive industries: the electrification of industrial processes, the use of low- and zero-emission hydrogen, and the development of synthetic fuels.

Electrification is the fundamental and most technologically mature pathway for reducing emissions in low- and medium-temperature processes, where it is possible to replace fossil fuel combustion with electricity from low-carbon sources (IEA 2023). However, in energy-intensive industries, a significant proportion of emissions is associated with high-temperature processes and the need for continuous energy supply, which limit the possibilities for full electrification.

Hydrogen plays a key role in these areas, being seen in the literature as a systemic carrier of energy transition, enabling the decarbonization of processes that are difficult to electrify and the integration of the electricity sector with industry and transport (Komorowska et al. 2023; CATF 2025). Hydrogen acts as a bridge between direct electrification and more advanced forms of energy conversion.

Synthetic fuels, developed as part of Power-to-X technology, complement the above paths in sectors where both electrification and the direct use of hydrogen face significant technical or infrastructural constraints. The literature indicates that e-fuels play a particularly important role in sectors on the margins of the transition, such as aviation, shipping, and heavy transport, where high energy density and compatibility with existing infrastructure are crucial (Wilson and Styring 2017; Müller et al. 2025).

Other technologies, such as improving energy efficiency, carbon capture and storage (CCS/CCUS), and biomass use, are treated in the article as complementary solutions or boundary conditions for the transition, rather than as separate decarbonization pathways. This is because, although important, these technologies do not in themselves lead to the elimination of fossil fuels in energy-intensive industries in the long term and are not the main pillars of EU climate policy (IEA 2023; European Commission 2021).

However, it is worth noting that the literature on the subject points to a much broader spectrum of possible decarbonization pathways for energy-intensive industries. Carmona-Martínez et al. (2023) identify seven main groups of technological solutions, including: direct electrification of low- and high-temperature processes, the use of green hydrogen and ammonia, synthetic fuels (e-fuels), carbon capture, utilization, and storage technologies, biomass and biofuels, as well as advanced thermochemical and electrothermal processes. The authors emphasize that effective decarbonization of energy-intensive industries requires combining different technologies in a way that is tailored to the specific processes and energy needs of individual sectors.

The rest of this article will focus on the characteristics of energy-intensive industries in Poland compared to the European Union, as it is the structure of this sector, its emissions, and its links to the national energy system that determine the range of possible decarbonization pathways and the pace of their implementation.

1. Characteristics of energy-intensive industries in Poland compared to the European Union

In the literature on the subject, the term energy-intensive industries (EII) is understood as a group of industrial sectors characterized by high energy consumption per unit of production, a significant share of energy in operating costs, and a large share of technological processes requiring high temperatures or a continuous supply of energy. Energy-intensive industries include, in particular, the following sectors: metallurgy, cement, chemicals, refining, coking, paper, and glass and ceramics production (IEA 2023; Skoczkowski et al. 2025).

According to the International Energy Agency, energy-intensive industries account for about one-third of global final energy consumption in industry and a significant share of greenhouse gas emissions (IEA 2023). A similar approach is presented in the English-language literature, where EIIs are defined as sectors particularly vulnerable to rising energy costs and emissions in the context of increasingly stringent climate policy, yet crucial to the functioning of economic value chains (European Commission 2021; Beckmann et al. 2025).

Poland's energy-intensive industry is characterized by higher unit emissions than the EU average, which is due to both the dominance of fossil fuels in the energy mix and the high share of high-temperature processes and raw material processes generating process emissions. In 2024, the EII sector accounted for about a quarter of domestic greenhouse gas emissions, with the refining and chemical sector remaining the largest emitter (Instrat 2025).

Compared to other European Union countries, Poland is characterized by a relatively large share of energy-intensive industries in its gross domestic product. This means that a significant part of the country's economic activity is based on sectors with high energy demand and high emission intensity, which, in the context of increasingly stringent climate policy, increases the sensitivity of the Polish economy to the rising costs resulting from the emissions trading system and the border adjustment mechanism. Between 2019 and 2024, the rate of emission reductions in industry was around 6%, while in the electricity sector it exceeded 20%, indicating a clear delay in the transformation of industry (Instrat 2025). According to analyses contained in government strategic documents, further reductions in process emissions in industry by 2030 are assumed in transformation scenarios, but their implementation requires acceleration of decarbonization measures (Ministry of Climate and Environment 2024).

The characteristics of energy-intensive industry in Poland presented above indicate that its decarbonization faces simultaneous technological, infrastructural, and economic constraints. The high share of high-temperature processes, the significant concentration of emissions in a small number of entities, and the strong links with the coal sector mean that classic climate policy instruments, based solely on improving energy efficiency and increasing emission prices, will not ensure climate neutrality by 2050.

When analyzing energy-intensive industries, it can be observed that there is no single universal decarbonization path that can be applied across the entire sector. The diversity of technological processes, temperature requirements, and energy functions makes it necessary to adopt a portfolio approach, combining different technological solutions depending on the nature of the industry in question. In particular, low- and medium-temperature processes, which dominate part of the manufacturing industry, can be significantly decarbonized through direct electrification, provided that the electricity sector is decarbonized in parallel. On the other hand, high-temperature processes and applications where electrification is technically or economically limited require the use of alternative energy carriers, such as low- and zero-emission hydrogen. In addition, sectors related to energy-intensive industries, in particular heavy transport, aviation, and shipping, require energy carriers with high density and compatibility with existing infrastructure, which justifies the development of synthetic fuels based on Power-to-X technologies. From the point of view of Polish structural conditions, the possibility of using existing infrastructure and material flows during the transition period is also important. This applies in particular to the potential use of carbon dioxide from industrial installations and the coal sector as a raw material in fuel synthesis processes. Such action could reduce the costs of the transition and support the process of a just transition for mining regions.

The identified structural conditions of energy-intensive industries indicate that a significant part of the emission reduction potential can be achieved through changes in the way energy is supplied to technological processes. In this context, the first and most direct path to transformation is the electrification of industrial processes.

2. The role of electrification in the decarbonization of energy-intensive industries

The electrification of end-use energy sectors is one of the key directions for decarbonization identified in the European Union's climate and energy policy. It is recognized as a cost-effective path to reducing greenhouse gas emissions, provided that the electricity generation sector is decarbonized in parallel. EU strategy documents identify electrification as a key mechanism for reducing fossil fuel consumption in industry, transport, and construction, and its importance is growing as the share of renewable energy sources in the energy mix increases (European Commission 2021; IEA 2023).

From a systemic perspective, electrification enables the replacement of processes based on direct combustion of fossil fuels with technologies with higher end efficiency, such as electric motors, heat pumps, induction furnaces, and electric process heating systems. The literature emphasizes that these technologies reduce energy conversion losses and improve end-use energy efficiency compared to conventional thermal solutions, which helps to reduce primary energy demand and end-use emissions (IEA 2023). At the same time, electrification plays a key role in creating conditions for the development of further decarbonization pathways, in particular the production of renewable hydrogen and synthetic fuels within the Power-to-X technology. This means that the pace of electrification of industrial processes and the pace of development of renewable energy sources are closely linked, and access to low-carbon electricity is a prerequisite for the deep decarbonization of energy-intensive industries (Müller et al. 2025; Beckmann et al. 2025).

In Poland, the potential for electrification of energy-intensive industries is significant but varies greatly between sectors. The greatest opportunities for electrification are in low- and medium-temperature processes, typically up to around 500°C, which dominate many branches of the processing industry. This applies in particular to the food, paper, wood, speciality chemicals industries, and selected refining and metallurgical processes (Instrat 2025). Key technologies enabling the electrification of industrial processes include high-efficiency electric motors and drive systems, industrial heat pumps, electric and induction furnaces, and electric drying and process heating systems.

Instead of clear-cut percentages, the literature points to significant potential for reducing emissions in these processes, depending on the nature of the installation, the structure of energy consumption, and the emission intensity of the electricity used in the process (Instrat 2025). It is emphasized that the potential for electrification is not evenly distributed across industries, and its effective implementation requires an individual approach to specific plants and installations. According to national analyses, in some sectors, such as chemicals and cement, electrification may be a viable path to decarbonization, but in many cases, it will require further pilot studies and demonstration projects by 2040 (Reform Institute 2025).

A significant limitation to the effectiveness of electrification in Poland remains the high emissions of the national power system. In 2024, more than half of the electricity was generated from coal, which means that some of the potential climate benefits of industrial electrification are currently offset by emissions from energy generation (Świercz et al. 2025). In the short term, electrification may therefore lead to a shift in emissions within the energy system rather than their complete elimination.

Industry analyses predict that the ongoing electrification of the economy, including industry and transport, will contribute to a significant increase in electricity demand in Poland, from approximately 154 TWh in 2024 to a projected 210–230 TWh in 2040 in transformation scenarios (Świercz et al. 2025; Zero Carbon Analytics 2025). This means that parallel investments are needed in new generation capacity, particularly renewable energy sources, and in the modernization and expansion of network infrastructure.

The increase in electricity demand in energy-intensive industries increases the importance of the flexibility of the power system. For electrification to be both climate- and economically effective, it is necessary to develop energy storage, demand-side response mechanisms, and sector coupling. The absence of these elements can lead to infrastructure and operational constraints, increased system balancing costs, and a decline in the competitiveness of electrification as a path to decarbonization (Khalili et al. 2025).

Despite significant technical potential, the pace of electrification in Poland is limited by economic and regulatory barriers. High electricity prices for industrial consumers, which are among the highest in the European Union and have been growing at one of the fastest rates in recent years, constitute a significant investment barrier, especially for energy-intensive industries covered by the EU ETS (Eurostat 2024; PAP 2025). In addition, the lack of a coherent and dedicated strategy for the electrification of industry in national documents causes regulatory uncertainty. Other key barriers include the long time it takes to obtain connection conditions, the lack of dedicated investment support instruments, and the limited availability of dynamic tariffs (Reform Institute 2025).

In the long term, electrification remains a necessary but insufficient condition for achieving climate neutrality in energy-intensive industries. Its importance will grow with the decarbonization of the electricity mix, but in high-temperature sectors and in applications requiring high-density energy carriers, it must be complemented by hydrogen and Power-to-X technologies (IRENA 2023; UN Global Compact 2024). Electrification should therefore be treated as part of the decarbonization technology portfolio, playing a key role in the short and medium term.

In addition to its direct environmental effects, the electrification of industrial processes also has an important competitive dimension. With rising emission allowance prices in the EU ETS and the introduction of the CBAM mechanism, companies that reduce their consumption of fossil fuels in technological processes more quickly may gain a cost advantage in the long term over those that maintain traditional combustion-based solutions. The literature indicates that electrification, especially when combined with long-term PPAs for renewable energy, can stabilize energy costs and reduce exposure to the volatility of fossil fuel and emission allowance prices (IEA 2023; Zero Carbon Analytics 2025).

In the context of energy-intensive industries, the possibility of gradual, phased electrification of selected technological lines is of particular importance. Instead of one-off, capital-intensive upgrades of entire installations, modular approaches are increasingly being considered, involving the replacement of individual devices or process nodes with electrical solutions. This approach reduces investment risk, enables testing of technologies in real-world conditions, and promotes organizational learning (learning-by-doing).

Another important aspect is the impact of electrification on the structure of energy demand over time. Energy-intensive industries are characterized by relatively predictable load profiles, which, combined with appropriate price incentives, can encourage the adjustment of energy consumption to periods of high-RES production. The literature emphasizes that integrating electrification with demand flexibility mechanisms can reduce system balancing costs and increase the use of domestic renewable energy potential (Khalili et al. 2025).

From a public policy perspective, this means that instruments supporting the electrification of industry need to be linked to RES development and grid modernization policies. Effective electrification cannot be treated as a separate sectoral objective, but as part of a broader strategy for the transformation of the energy and industrial systems. The lack of such coordination may lead to a situation where the technological potential of electrification remains untapped, despite the availability of technical solutions.

At the same time, an analysis of the potential for electrification shows that not all industrial processes can be fully decarbonized through the direct use of electricity. This applies in particular to high-temperature processes and applications in which fossil fuels also serve as raw materials. In these areas, low- and zero-emission hydrogen is beginning to play a key role.

3. The role of hydrogen in the transformation of energy-intensive industries

Hydrogen is widely identified in European Union literature and strategic documents as one of the key pillars of decarbonization in sectors that are difficult to electrify, in particular heavy industry, refining, chemicals, and parts of long-distance transport. Unlike direct electrification, which is mainly used in low- and medium-temperature processes, hydrogen enables emissions to be reduced in high-temperature processes and where fossil fuels serve as both an energy carrier and a process feedstock (IEA 2023).

EU strategies attach particular importance to renewable hydrogen (RFNBO), produced by electrolysis of water using electricity from renewable sources. In line with the Fit for 55 package and the RED III directive, the development of renewable hydrogen is intended to support both the reduction of emissions in industry and the creation of new value chains based on low-carbon technologies (European Parliament & Council 2023a; European Commission 2021). In this context, hydrogen acts as an energy carrier, a chemical feedstock, and an element integrating energy sectors (sector coupling).

Currently, hydrogen production in Poland is based almost exclusively on fossil fuels, primarily steam reforming of methane and gasification of coal fuels. This results in a high carbon footprint of so-called grey and brown hydrogen, the use of which generates significant CO_2 emissions. According to analyses by the Clean Air Task Force (2025), Poland is one of the largest producers of hydrogen from fossil fuels in the European Union, and decarbonizing this stream is one of the most cost-effective points of intervention in the short and medium term.

The Polish Hydrogen Strategy envisages a gradual transition towards low- and zero-emission hydrogen, including the development of domestic electrolyzer capacity, the use of hydrogen in industry, and the construction of basic transmission and distribution infrastructure. Analyses by Komorowska and co-authors indicate that the scale of potential demand for hydrogen in Poland will grow as climate targets become more stringent, with energy-intensive industries and the fuel and chemical sectors remaining the main drivers of demand (Komorowska 2025).

The greatest potential for hydrogen use in industry is in iron and steel metallurgy (replacing coke in reduction processes), ammonia and methanol production, refineries, and selected high-temperature processes in the cement and glass industries. The literature indicates that in these sectors, the use of renewable hydrogen can lead to emission reductions of several dozen per cent compared to conventional technologies, provided that low-carbon electricity is available (IEA 2023; CATF 2025). At the same time, it is emphasized that the development of the hydrogen economy is strongly dependent on the pace of expansion of renewable energy sources. The cost of producing hydrogen by electrolysis currently remains significantly higher than the cost of hydrogen produced from fossil fuels, which limits the market competitiveness of the technology without support mechanisms. IRENA (2023) points out that a reduction in the cost of electrolyzers and cheap energy from RES are key conditions for the widespread use of renewable hydrogen on an industrial scale.

Infrastructure also remains a significant challenge. Poland does not currently have a developed transmission network dedicated to hydrogen, and most of the planned applications are based on local production and consumption clusters (so-called hydrogen valleys). The lack of linear infrastructure limits the possibility of scaling projects and integrating the domestic market with the emerging European hydrogen network (European Hydrogen Backbone). For this reason, many analyses indicate that in the short and medium term, the model of hydrogen production close to industrial consumers will dominate (CATF 2025; Komorowska et al. 2023). Hydrogen also serves as a key link between electrification and the development of synthetic fuels. As a basic intermediate product in Power-to-X technologies, it enables the synthesis of e-methanol, e-methane, e-ammonia, and liquid fuels, which extends its scope of application beyond direct energy uses. For this reason, many studies refer to hydrogen as a "platform" energy carrier for the future low-carbon system (IEA 2023; Müller et al. 2025).

In the long term, hydrogen should be seen as a complementary technology to electrification, not a substitute for it. In sectors where direct electrification is possible, it will remain the preferred solution due to its higher energy efficiency. However, in energy-intensive industries with high temperature requirements and in raw material processes, hydrogen will play a key role in achieving deep emission reductions and moving towards climate neutrality by 2050 (IEA 2023; UN Global Compact 2024). Hydrogen is not only an alternative energy carrier for industrial processes, but also a basic intermediate product for more advanced energy conversion technologies. A natural extension of the analysis of the role of hydrogen is therefore a discussion of synthetic fuels, which enable the conversion of electricity and hydrogen into high-energy-density carriers that can be used in sectors on the margins of the transition.

4. The role of synthetic fuels in complementing the decarbonization pathways of industry and transport

The energy transition and the implementation of climate policy objectives require a deep reduction in greenhouse gas emissions, including in sectors that are difficult to electrify directly, such as aviation, shipping, parts of the high-temperature industry, and heavy transport. In recent years, regulatory pressure in this area has been growing significantly, partly due to the revised RED III directive, which raises the EU target for the share of energy from renewable sources to at least 42.5% in 2030 (with an aspiration to reach 45%) (European Parliament & Council 2023a). The answer to these challenges is synthetic fuels, which enable the use of electricity from RES in a high-energy-density chemical form that is compatible with existing logistics infrastructure and end-use energy conversion technologies (engines, turbines, boilers, furnaces) (Wilson & Styring 2017; Müller et al. 2025). For this reason, the starting point for the analysis of synthetic fuels should be to treat them as energy products rather than solely as production technologies, as it is the end product that determines the scope of applications, quality re quirements, logistics costs, and regulatory treatment. There is no single universally accepted classification in the literature, but there are several complementary axes of division that are widely used in technical, economic, and environmental analyses (Müller et al. 2025; Beckmann et al. 2025).

The first criterion often used is the origin of the carbon and energy carrier. Classic synthetic fuels include X-to-Liquids technology pathways, in which the carbon source is fossil fuels or biomass: Coal-to-Liquids (CTL), Gas-to-Liquids (GTL), and Biomass-to-Liquids (BTL). In these processes, the carbon contained in the raw material is converted into synthesis gas (CO/H_2) and then into liquid hydrocarbon fuels (Tuomisalo et al. 2025; Lin and Wu 2025). At the same time, a class of electricity-derived fuels is being developed, in which the main primary energy carrier is electricity (preferably from renewable sources), and the carbon comes from CO_2 captured from industrial processes or from the air, or – in the case of ammonia – nitrogen from the air. This group of fuels is referred to as e-fuels, electrofuels, Power-to-X (PtX), or, in EU regulatory terms, RFNBO (Khalili et al. 2025; Oyewo et al. 2024). The second criterion concerns the technological path. In the case of fossil-based and biomass-based fuels, gasification and Fischer-Tropsch synthesis dominate, leading to the production of synthetic liquid hydrocarbons (diesel, petrol, aviation fuel), as well as methanol synthesis with subsequent conversion to other products (Tuomisalo et al. 2025; Lin and Wu 2025). Electric-derived fuels are characterized by a two-step chain: the production of green hydrogen through electrolysis, followed by its conversion from CO_2(or N_2) into the final fuel (Pfennig et al. 2023; Müller et al. 2025). The third axis of classification refers to the type of product and its function in the energy system. A distinction is made between synthetic gaseous fuels (H_2, e-methane/SNG, NH_3) and synthetic liquid fuels (e-diesel, e-kerosene, e-methanol, DME, OME), as well as synthetic chemical carriers (Power-to-Chemicals), which serve both as fuels and raw materials for the chemical industry (Oyewo et al. 2024; Beckmann et al. 2025).

Against this background, the PtX analysis in this article focuses on a set comprising hydrogen, methane, methanol, Fischer-Tropsch fuels, and ammonia, assuming that all products are made from hydrogen produced in electrolyzers powered by renewable energy sources (Pfennig et al. 2023; Müller et al. 2025). The most basic form of electro-derived fuel is green hydrogen, which can be used directly or as an intermediate for further synthesis. The literature emphasizes its "platform" nature; the entire PtX chain depends on its availability (Müller et al. 2025; Oyewo et al. 2024). Demand for hydrogen is generated both directly (industry, transport) and indirectly –

through the demand for RFNBO and e-fuels. The key demand driver for e-fuels in Poland is the RED III targets. Member States should implement measures by 2030 to ensure that RFNBO accounts for at least 1% of energy consumption in transport, while meeting the combined target of 5.5% for RFNBO and advanced biofuels (IEA 2025). In addition, the FuelEU Maritime and ReFuelEU Aviation regulations set increasing requirements for shipping and aviation, reaching 80% GHG intensity reduction by 2050 and 35% share of e-fuels in aviation fuels, respectively (European Parliament & Council 2023b; 2023c). From Poland's perspective, this means the creation of a stable segment of regulatory demand, which may favor the development of domestic e-fuel production capacity. However, access to large volumes of cheap, low-carbon electricity and the acceleration of RES development are prerequisites.

Literature forecasts indicate that demand for hydrogen as an energy carrier will grow between 2030 and 2050, both in industrial and transport applications, which means that Power-to-X technologies may become an important element of the energy system, rather than just a technological niche (Komorowska et al. 2023; IEA 2023). However, the main barrier to the development of the sector remains economics, as the costs of e-fuels are currently several times higher than those of fossil fuels. In the long term, synthetic fuels should therefore be seen as a complementary element of the decarbonization technology portfolio, crucial for sectors where electrification and direct use of hydrogen are limited.

Summary and conclusions

The decarbonization of energy-intensive industries is one of the most difficult and, at the same time, key elements of the energy transition in Poland on the road to achieving climate neutrality by 2050. The high share of fossil fuels in the national energy mix, the significant concentration of emissions in a limited number of entities, and the dominance of high-temperature processes mean that the transformation of this sector requires the use of a diverse and complementary set of technologies. The three decarbonization pathways presented: electrification, hydrogen, and synthetic fuels form a coherent set of technologies that complement each other and address the different needs of energy-intensive industries. Their combined analysis provides a basis for formulating conclusions on public policy directions and investment priorities in Poland.

The analysis confirms that there is no single universal decarbonization path that could be effectively applied across the entire energy-intensive industry. The diversity of technological processes and the functions that fossil fuels perform in industry (energy carrier, process raw material, reducing agent) necessitates a portfolio approach, combining different solutions depending on the nature of the industry in question.

The electrification of industrial processes remains the fundamental and most technologically mature path to reducing emissions, especially in low- and medium-temperature processes.

However, its climate effectiveness is directly dependent on the pace of decarbonization of the electricity sector and the development of grid and storage infrastructure. Without accelerating investment in renewable energy sources, electrification may only lead to a shift in emissions within the energy system in the short term, rather than their permanent elimination.

Low- and zero-emission hydrogen is a key tool for decarbonizing high-temperature processes and sectors where fossil fuels are used as raw materials. Its role as a system carrier also involves integrating the electricity sector with industry and laying the foundations for the development of Power-to-X technologies. However, the development of the hydrogen economy in Poland will require significant investment, a stable regulatory framework, and the coordination of hydrogen policy with renewable energy development policy. Synthetic fuels should be seen as a complementary element of the decarbonization technology portfolio, crucial primarily for sectors that are difficult to electrify and use hydrogen directly, such as aviation, shipping, and some heavy transport. Their importance will grow as regulatory requirements in the European Union become more stringent, and the market for renewable non-biological fuels develops. At the same time, the high cost of PtX technologies means that their widespread adoption will be heavily dependent on a decline in the cost of electricity from renewable energy sources and the availability of cheap renewable hydrogen. From Poland's perspective, the possibility of a phased transformation of energy-intensive industries, based on the gradual implementation of electrification, the development of hydrogen clusters and pilot PtX installations, while utilizing existing infrastructure and material flows during the transition period, is of particular importance. This approach can reduce the costs of the transition and mitigate socio-economic risks, especially in regions strongly linked to the coal sector. In light of the analyses carried out, it can be concluded that achieving climate neutrality in energy-intensive industries in Poland is technically feasible, but requires coordinated energy, industrial, and innovation policies, a stable regulatory framework, and a significant acceleration in the development of renewable energy sources. The key challenge remains ensuring the competitiveness of the domestic industry in the face of rising emission costs and global technological competition. Ultimately, the success of the energy-intensive industry's transformation will depend not on the choice of a single dominant technology, but on the ability to integrate electrification, hydrogen, and synthetic fuels in a manner tailored to the specific characteristics of individual sectors and long-term climate goals.

An important direction for further research remains the analysis of the marginal costs of individual technologies in Polish conditions and the assessment of their impact on the competitiveness of energy-intensive sectors.

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References

Beckmann et al. 2025 – Beckmann, J., Klockner, K. and Letmathe, P. 2025. The role of power-to-X and domestic eFuel production for energy transition and energy independence in Europe. *Journal of Cleaner Production* 492, https://doi.org/10.1016/j.jclepro.2025.144807.

Carmona-Martínez et al. 2023 – Carmona-Martínez, A.A., Fresneda-Cruz, A., Rueda, A., Birgi, O., Khawaja, C., Janssen, R. and Jarauta-Córdoba, C. 2023. Renewable power and heat for the decarbonisation of energy-intensive industries. *Processes* 11(1), https://doi.org/10.3390/pr11010018.

Clean Air Task Force (CATF) 2025. Getting hydrogen right: Poland's industrial decarbonisation. [Online:] https://www.catf.us/resource/getting-hydrogen-right-for-polands-industrial-decarbonisation/ [Accessed: 2026-02-01].

European Commission 2019. The European Green Deal. [Online:] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en [Accessed: 2026-02-01].

European Commission 2021. Fit for 55: Delivering the EU's 2030 Climate Target. [Online:] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-eu-55-climate-target-2030_en [Accessed: 2026-02-01].

European Parliament & Council of the European Union 2023a. Directive (EU) 2023/2413 amending Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED III).

European Parliament & Council of the European Union 2023b. Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime).

European Parliament & Council of the European Union 2023c. Regulation (EU) 2023/2405 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation).

Instrat Foundation 2025. Decarbonisation of industry in Poland – analysis of progress and barriers. [Online:] https://instrat.pl [Accessed: 2026-02-01].

International Energy Agency (IEA) 2023. Industrial decarbonisation and energy transition. [Online:] https://www.iea.org/reports/industrial-decarbonisation-and-energy-transition [Accessed: 2026-02-01].

International Energy Agency (IEA) 2025. Renewable Energy Directive III – GHG threshold. [Online:] https://www.iea.org/policies [Accessed: 2026-02-01].

IRENA 2023. World Energy Transitions Outlook 2023. [Online:] https://www.irena.org [Accessed: 2026-02-01].

Khalili et al. 2025 – Khalili, S., Lopez, G. and Breyer, C. 2025. Role and trends of flexibility options in 100% renewable energy system analyses towards the power-to-X economy. *Renewable and Sustainable Energy Reviews* 212, https://doi.org/10.1016/j.rser.2025.115383.

Komorowska, A. 2025. Hydrogen in Poland's energy transition – integration of renewable energy and transportation (*Wodór w transformacji energetycznej Polski – integracja energetyki odnawialnej i transportu*). *Studia Rozprawy Monografie* 220, Kraków: Wyd. IGSMiE PAN (*in Polish*).

Komorowska et al. 2023 – Komorowska, A., Mokrzycki, E. and Gawlik, L. 2023. Hydrogen production in Poland – the current state and directions of development. *Polityka Energetyczna – Energy Policy Journal* 26(4), pp. 81–98, https://doi.org/10.33223/epj/170913.

Ministry of Climate and Environment 2024. Annex 1 to the update of the National Energy and Climate Plan. [Online:] https://www.gov.pl/attachment/88e4c5a6-dea8-4d16-860b-9a7f7afd53f2 [Accessed: 2026-02-01].

Müller et al. 2025 – Müller, G., Kullmann, F., Linssen, J. and Stolten, D. 2025. The costs of future energy technologies: A comprehensive review of power-to-X processes. *Journal of CO_2 Utilisation* 92, https://doi.org/10.1016/j.jcou.2025.103019.

Oyewo et al. 2024 – Oyewo, A.S., Lopez, G., ElSayed, M., Galimova, T. and Breyer, C. 2024. Power-to-X economy: Green e-hydrogen, e-fuels, e-chemicals, and e-materials opportunities. *Energy Reports* 12, pp. 2026–2048, https://doi.org/10.1016/j.egyr.2024.08.011.

Pfennig et al. 2023 – Pfennig, M., Böttger, D., Häckner, B., Geiger, D. and Zink, C. 2023. Global GIS-based potential analysis and cost assessment of power-to-X fuels in 2050. *Applied Energy* 347, https://doi.org/10.1016/j.apenergy.2023.121289.

Reform Institute 2025. Production under pressure #3: Electrification on the map of zero-emission solutions for energy-intensive industries. [Online:] https://ireform.eu/s/uploads/Produkcja_pod_napieciem_3_Elektryfikacja_na_mapie_zeroemisyjnych_rozwiazan_dla_przemyslu_energochlonnego.pdf [Accessed: 2026-02-01].

Skoczkowski et al. 2025 – Skoczkowski, T., Bielecki, S. and Węglarz, A. 2025. Redefining energy management for carbon-neutral supply chains in energy-intensive industries. *Energies* 18(1), https://doi.org/10.3390/en18010234.

UN Global Compact Poland 2024. *Energy transition in Poland*. [Online:] https://ungc.org.pl/wp-content/uploads/2024/06/Transformacja_energetyczna_w_Polsce.pdf [Accessed: 2026-02-01].

Wilson, I.A.G. and Styring, P. 2017. Why synthetic fuels are necessary in future energy systems. *Frontiers in Energy Research* 5, https://doi.org/10.3389/fenrg.2017.00019.

Zero Carbon Analytics 2025. *Decarbonising industry in Europe*. [Online:] https://zerocarbonanalytics.org [Accessed: 2026-02-01].

Świercz et al. 2025 – Świercz, W., Kaczor, G., Matuszko, M., Moskwik, K. and Ćwiek, P. 2025. *Poland Energy Outlook 2026 & Beyond*. [Online:] https://www.adlittle.com/en/insights/report/poland-energy-outlook-2026-beyond [Accessed: 2026-02-01].

Monika Pepłowska

Dekarbonizacja przemysłu energochłonnego w Polsce na drodze do neutralności klimatycznej – rola elektryfikacji, wodoru i paliw syntetycznych

Streszczenie

Przemysł energochłonny odgrywa kluczową rolę w strukturze emisji gazów cieplarnianych w Polsce i stanowi jeden z najtrudniejszych sektorów do dekarbonizacji w procesie transformacji energetycznej. Celem artykułu jest identyfikacja i uporządkowanie głównych ścieżek dekarbonizacji przemysłu energochłonnego w Polsce w kontekście dążenia do neutralności klimatycznej do 2050 roku, ze szczególnym uwzględnieniem roli elektryfikacji, wodoru nisko- i zeroemisyjnego oraz paliw syntetycznych.

Artykuł opiera się na przeglądzie aktualnej literatury naukowej, raportów instytucji międzynarodowych oraz dokumentów strategicznych Unii Europejskiej i Polski. W pierwszej części przedstawiono charakterystykę przemysłu energochłonnego w Polsce na tle Unii Europejskiej oraz główne uwarunkowania strukturalne wpływające na tempo i zakres dekarbonizacji. Następnie omówiono potencjał, ograniczenia oraz wzajemne powiązania trzech kluczowych ścieżek transformacji: bezpośredniej elektryfikacji procesów przemysłowych, wykorzystania wodoru jako nośnika energii i surowca oraz rozwoju paliw syntetycznych w ramach technologii Power-to-X.

Artykuł pokazuje, że skuteczna dekarbonizacja przemysłu energochłonnego wymaga podejścia portfelowego, łączącego różne technologie w zależności od specyfiki procesów i sektorów, a także ścisłej koordynacji polityki energetycznej i przemysłowej.

Wyniki wskazują, że elektryfikacja będzie odgrywać dominującą rolę w procesach niskotemperaturowych i średniotemperaturowych, natomiast wodór i paliwa syntetyczne będą nieodzowne w zastosowaniach wysokotemperaturowych oraz w procesach, w których jako surowiec wykorzystuje się paliwa kopalne.

Słowa kluczowe: dekarbonizacja, przemysł energochłonny, elektryfikacja, wodór zielony, paliwa syntetyczne, neutralność klimatyczna