Decarbonisation of energy-intensive industries in context

instrat

Instrat Policy Paper 05/2023
Jarosław Kopeć
Michał Kulbacki
Stanisław Stefaniak
Michał Hetmański

Decarbonisation of energy-intensive industries in context

Instrat Policy Paper 05/2023
Jarosław Kopeć
Michał Kulbacki
Stanisław Stefaniak
Michał Hetmański

Warsaw, November 2023

Recommended citation:
Kopeć J., Kulbacki M., Stefaniak S., Hetmański M. (2023). *Decarbonisation of energy-intensive industries in context* Instrat Policy Paper 05/2023.

Authorship:
Jarosław Kopeć
Michał Kulbacki
Stanisław Stefaniak
Michał Hetmański

Contact:
Stanisław Stefaniak
stanislaw.stefaniak@instrat.pl

Cover design and typesetting:
Anna Olczak

This publication was produced with the support of the European Climate Foundation (ECF).

The publication is available for download at:
http://www.instrat.pl/en/industry-decarbonisation

The macroeconomic model presented in Chapter 4 is available for download at:
www.link.instrat.pl/model_przemyslowy

Any errors are ours.
The usual disclaimers apply.

Instrat Policy Paper 05/2023

Warsaw, November 2023

ISBN: 978-83-967509-8-3

Fundacja Instrat
ul. Hoża 51
00-681 Warsaw
www.instrat.pl

Table of contents

Key figures and conclusions

47 mln
tonnes of CO_2

The four most important energy-intensive sectors (metals, cement, chemicals and oil refining and coke production) were responsible for this amount of emissions in 2021. They accounted for 81% of all industrial CO2 emissions and 15% of all CO_2 emissions in Poland.

27%

Cement plants, located in the so-called Cement Belt in southern Poland, where cement production is concentrated, are responsible for up to this much of total industrial CO_2 emissions.

50%

This is the approximate share of secondary steel melted from scrap in total steel production in Poland. The other half is produced in the high-carbon smelting process in oxygen furnaces.

3 000
new jobs

This is the number by which employment in energy-intensive sectors could increase by 2050 in a scenario of a green investment shock – increased investment in the energy transition – according to our modelling.

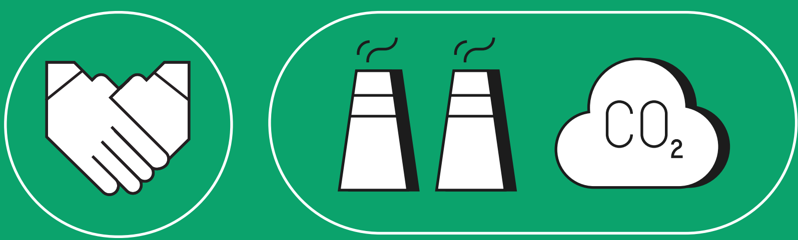
- Decarbonisation poses specific challenges for each energy-intensive industry, and there is a range of diverse technological solutions available to address them (electrification, use of hydrogen, CCS technology or introduction of process changes). Which of the available technological options is optimal for a given sector depends as much on the decisions of investors as on public support schemes for these technologies and an active industrial policy shaping the investment conditions.

- Western countries are currently pursuing an intensive green industrial policy, competing to subsidise the domestic production of key net-zero technologies such as production of wind turbines or battery storage. However, it is also necessary to include traditional energy-intensive industries in such policies. The strategic plans adopted by the Polish government to develop net-zero technologies or to support the decarbonisation of industry in general should be complemented by sectoral strategies addressing the specific challenges and needs of each sector. What is at stake is not only achieving climate neutrality of the economy, but also ensuring its competitiveness.

- The energy transition does not imply an industrial collapse. On the contrary, the results of our economic modelling suggest that, in the scenario of increased transition spending, both employment and value added in energy-intensive sectors remain stable (and employment increases by 1%).

- The decarbonisation of energy-intensive industries may also have negative socio-economic consequences in carbon-intensive regions, due to the relocation of production facilities, currently located mainly in the south of the country, to the north of Poland. It is therefore necessary to include Polish industrial regions in the Just Transition Fund in the next EU budget perspective. The government and local authorities should develop support instruments and programmes to offset the negative social and economic consequences of the industry's relocation analogous to those implemented for post-coal regions.

- The decarbonisation of the industry requires significant investments. Part of this funding, especially for innovative technologies, has come from national and European public funds. However, energy-intensive industries can increase their access to private capital by adopting ambitious decarbonisation strategies that guarantee to the investors that the entity will remain competitive in the new low-carbon economy.



1. Introduction

The transformation of the Polish economy towards climate neutrality will not take place without the decarbonisation of the industry. For this process, the decarbonisation of the four most energy-intensive industries is crucial:

- cement production,
- metal production,
- chemical sector,
- oil refining and coke production.

These four industries were responsible for 81% of emissions from industrial manufacturing and 15% of all CO_2 emissions from the Polish economy, including households in 2021[1]. In addition to their high environmental impact, energy-intensive industries are also of significant economic importance. They account for a significant proportion of the GDP and provide inputs to more complex production processes.

The decarbonisation of energy-intensive industries poses a number of challenges for the Polish economy. Western countries are already pursuing active green industrial policies supporting the development of net-zero technologies, such as hydrogen production, renewable energy generation sources, battery technologies or CO_2 capture and storage. The success of the decarbonisation of energy-intensive industries largely depends on the availability and cost of these technologies and their deployment in the industrial context.

Energy-intensive industries, although not the main target of the new green industrial policy, have also recently become significant beneficiaries of public aid due to rising energy costs. Properly managed decarbonisation of these industries, combined with the development of low-carbon technologies to increase their availability to business, will reduce emissions and ensure long-term competitiveness of Polish industry.

In this report, we aim to show the many contexts in which the decarbonisation of energy-intensive industries should be considered. The policy, technology, regional and financial dimensions of this challenge need to be taken into account.

1 Definitions of energy-intensive industries and information on the sources of their emissions data are described in the Note on terminology and methodology.

Note on terminology and methodology

The terms "industry" and "industrial manufacturing" used in this study refer to activities included in the Polish Classification of Activities (PKD), section C – manufacturing.

Energy-intensive industries correspond to the following divisions of Section C of the PKD:

- **PKD 23 – Manufacture of other non-metallic mineral products.**

Within this division, the production of cement is accounted for together with lime and plaster production, in group 23.5 – Manufacture of cement, lime and plaster.

- **PKD 24 – Manufacture of basic metals.**

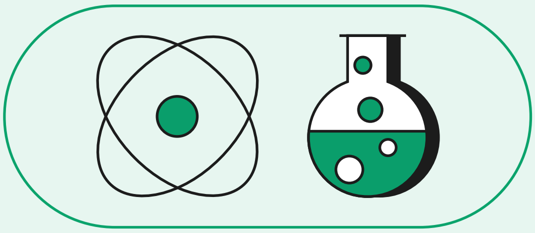
Within this division, the production of steel is included in group 24.1 manufacture of pig iron, ferroalloys, cast iron and steel and steel products.

- **PAC 20 – Manufacture of chemicals and chemical products.**

- **PKD 19 – Manufacture of coke and refined petroleum products.**

In the remainder of the study, the analysis is mostly conducted at the level of the four PKD divisions indicated above (19, 20, 23 and 24). Where justified and where data granularity allows for it, the analysis is conducted at the level of PKD subgroups: in chapter 3.1. at the level of subgroup 23.5 comprising cement production (which also includes the production of lime and plaster, but this does not significantly affect the data presented, as cement is responsible for the majority of emissions in this subgroup) and in chapter 3.2. at the level of subgroup 24.1, which comprises steel and iron production.

Unless stated otherwise, the emission and fuel consumption data for the industries covered in this report are taken from Statistics Poland's (pl. Główny Urząd Statystyczny; GUS) cyclical publication, *Roczniki przemysłu* (Industry Yearbooks). Economy-wide emissions were based on data from the National Centre for Emissions Management (KOBiZE, 2023).



1.1. Policy and regulatory context

1.1.1. THE RETURN OF INDUSTRIAL POLICY WORLDWIDE

In 2022, industrial policy – understood as the active influence of the state on the structure and volume of domestic industrial production – made a comeback in Western countries. This was influenced by several factors. The COVID-19 outbreak in 2020 had already highlighted the vulnerability of international supply chains to economic shocks. It also highlighted the need to increase their resilience through diversification and shortening.

In recent times, geopolitical factors have intensified Western countries' resolve to reduce their economic dependence on Chinese industrial production (*decoupling*) and to relocate production back within their national territories (*reshoring)* or at least to the territories of the allied countries (*friendshoring*). These factors, combined with climate policy objectives, were the main motivations behind the adoption of the *Inflation Reduction Act* (IRA) by the United States in August 2022.

The US Inflation Reduction Act

The IRA introduces a number of support mechanisms for net-zero technologies (zero-emission technologies), mainly through tax credits, both for consumers of these technologies (e.g. a credit for the purchase of electric vehicles for households) and their manufacturers (White House, 2023). These support instruments have the objective of increasing the domestic production of net-zero technologies.

One of the more controversial elements of the IRA are the requirements related to the so-called local content of subsidised products, i.e. the requirement for products to be produced locally to certain extent. These requirements are intended to ensure that clean investments use locally produced intermediates and services in their value chain. Making financial support conditional on an adequate level of local component is supposed to contribute to the retention and even relocation of industrial production to the US.

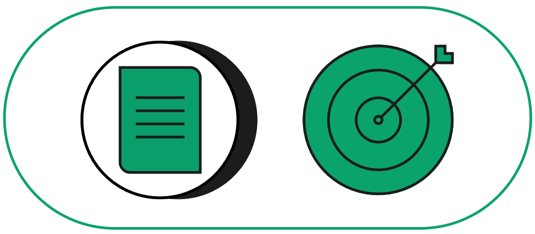
Green Deal Industrial Plan – the EU's response to the IRA

The scale of IRA's subsidies is regarded in the European Union as a potential threat to the competitiveness of European industry. These concerns, coupled with the need to minimise dependence on third countries for the production of key low-carbon technologies, have prompted EU policymakers to take action on climate-related industrial policy. The European Commission has set out an overall action plan in this area in the Green Deal Industrial Plan (GDIP) (European Commission, 2023a), which can be considered the European response to the IRA (Kleimann et al., 2023). In it, the Commission has set out several objectives and actions in the area of green industrial policy:

1. **Improving the regulatory environment for key climate technologies.** This is being pursued through the adoption of the *Net-Zero Industry Act* (NZIA) and the *Critical Minerals Act*, drafts of which were presented by the Commission in March 2023. Regulatory interventions also include electricity market reform to protect industrial consumers from short-term energy price fluctuations by supporting long-term energy contracts such as *Power Purchase Agreements* (PPAs) and contracts for difference (CfDs).

2. **Temporary loosening of the state aid framework for industries key for EU's decarbonisation.** This action was implemented by extending and modifying the content of *The Temporary Crisis Framework for State Aid measures to support the economy following the aggression against Ukraine by Russia*. This document, adopted in February 2022[2], establishes the conditions under which state aid can be granted in emergency situations. In March 2023, the Commission updated it along the lines of the GDIP[3], by providing more leeway for aid aligned with the objectives of the GDIP, to certain sectors and investments. In a direct response to the IRA, the newly liberalised state aid rules allow the states to match the value of subsidies offered outside of the EU, in order to prevent investment's relocation abroad.

3. **The creation of the Strategic Technologies for Europe Platform** (STEP). The STEP is a mechanism for direct allocation of state aid for investments aligned with the objectives of the GDIP at EU level. It was originally known as the European Sovereignty Fund.



2 European Commission, *Communication from the Commission. Temporary Crisis Framework for State Aid measures to support the economy following the aggression against Ukraine by Russia* (OJ EU, 2022/C 131 I/01, pp. 1-17.).

3 European Commission, *Communication from the Commission. Temporary Crisis and Transition Framework for State Aid measures to support the economy following the aggression against Ukraine by Russia* (OJ EU, 2023/C 101/3, pp. 3-46).

The Net-Zero Industry Act

The main regulatory arrangements to support the achievement of the GDIP's objectives are laid out in the draft Net-Zero Industry Act (NZIA). The draft sets out support measures for what it refers to as 'strategic net-zero technologies'. These include, among others, the production of photovoltaic panels, wind turbines, heat pumps, electric batteries and energy storage, as well as components of these technologies. For these, the act sets a target of 40% of EU production capacity of annual deployment by 2030[4]. Currently, the EU share of production of these technologies ranges from a few per cent of total deployment for PVs, to almost the entire deployment needs for wind turbines (Sgaravatti et al., 2023; PwC, 2023).

The draft NZIA obliges Member States to review administrative and judicial procedures and to give net-zero technologies projects priority status in all proceedings, and to establish a 'one-stop-shop' for obtaining the required permits for investments in these technologies. The range of technologies is broader than the category of strategic net-zero technologies mentioned earlier and also includes, in. al., small modular reactors (SMRs).

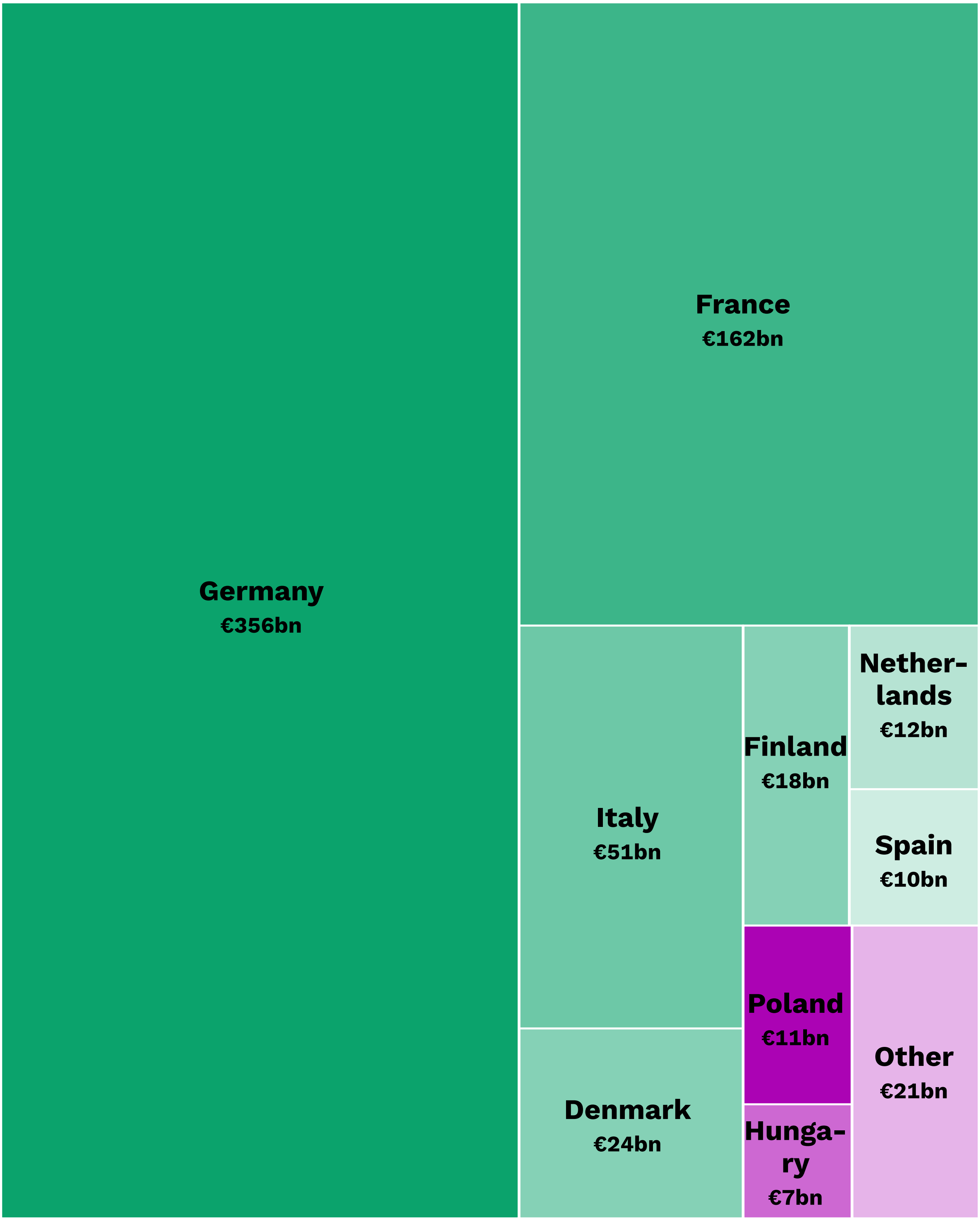
With regard to CCS technologies, the NZIA requires Member States – with the participation of oil and gas companies – to identify both the national demand for the use of CCS technologies and to estimate the national potential for CO_2 storage.

Furthermore, the NZIA proposes solutions to strengthen competencies related to carbon-neutral technologies in the labour market and to ensure prioritisation of locally produced net-zero technologies in public procurement (Kleimann et al., 2023).

Notwithstanding the importance of regulatory relief for net-zero technologies production, state aid remains crucial to the success of EU's response to the IRA and for greening European industry while maintaining its international competitiveness. However, despite enabling EU as a bloc to compete with US and other players in the subsidy race, loosening of the state aid framework may also contribute to distorting competition within the EU, by allowing countries with the largest budgets to support their domestic industrial sectors more intensively, which gives them a competitive advantage on the EU's internal market. This concern is confirmed by the fact that the vast majority of state aid granted since March 2022 under the temporary crisis framework has been granted by Germany (53%) and France (24%) (European Commission, 2023b).

4 The full list of these technologies includes: Solar photovoltaic and solar thermal technologies, onshore wind and offshore renewable technologie, battery/storage, heat pumps and geothermal energy, electrolysers and fuel cells, sustainable biogas/biomethane technologies, carbon capture and storage (CCS), grid technologies.

FIGURE 1. Breakdown of State aid granted under the temporary crisis framework by Member State



Source: Instrat based on Fleming et al. 2023 and European Commission data.

Strategic Technologies for Europe Platform (STEP)

The dominance of EU's largest economies in the provision of state aid is to be offset by the Strategic Technologies for Europe Platform (STEP), tasked with providing public financial support for green industries at the EU level. According to the Commission's plans, the STEP platform is to have €10 billion in funding. However, this money is to come from reallocating funds from other EU programmes, rather than from raising new funds (European Commission, 2023).

Both the regulatory interventions envisaged under the NZIA and the funding from STEP are intended to focus on the production of strategic net-zero technologies listed in the NZIA (clean-tech industry). The traditional energy-intensive industry is of course connected with this budding new industry: first as a supplier of some of the inputs necessary in their production and secondly, and more importantly, as a consumer of these technologies, to decarbonise its own operations. In general, however, the energy-intensive industries are not producers of these technologies – exceptionally though, some actors might decide to produce them for their own needs.

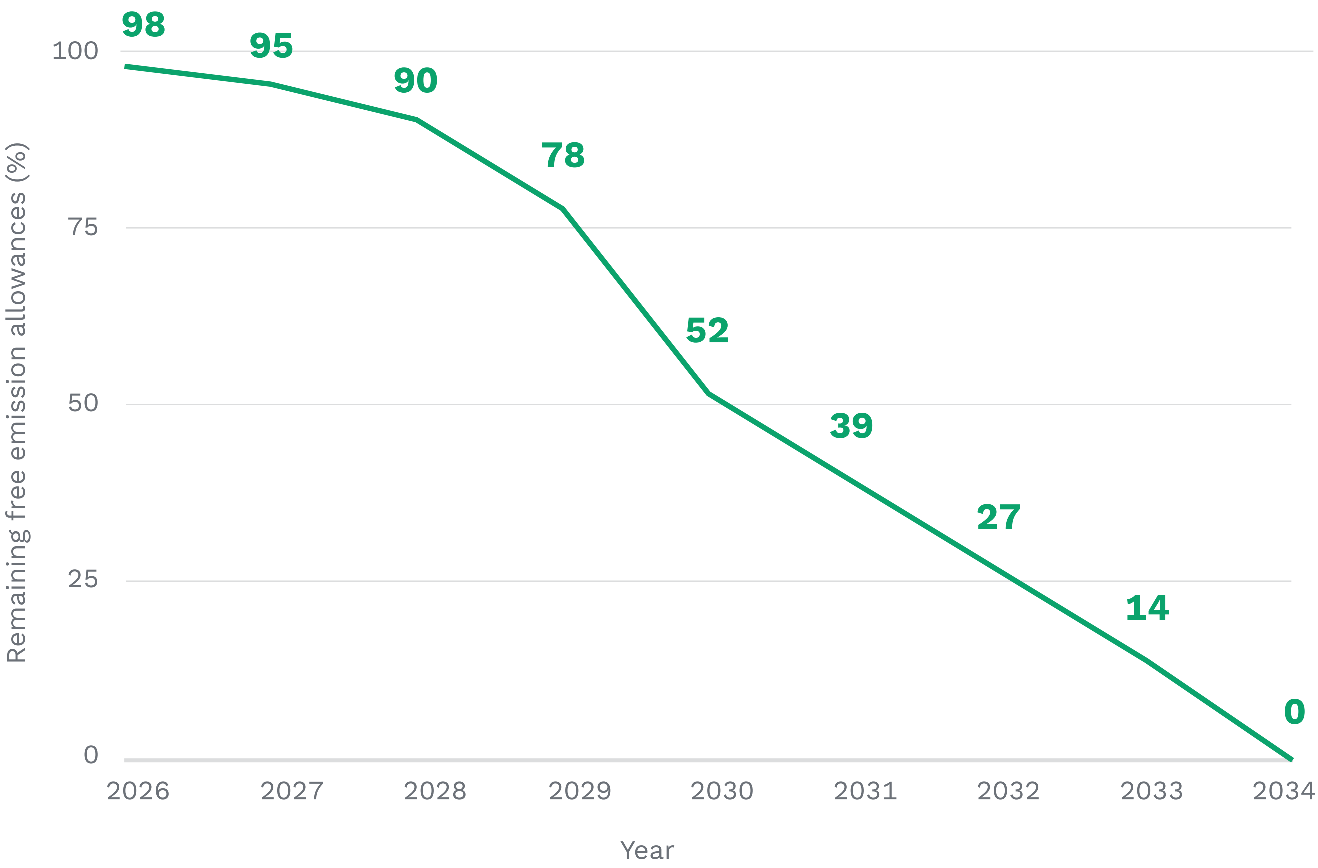
The solutions envisaged in the GDIP are therefore dedicated to building and expanding new industrial sectors in the EU (e.g. the production of photovoltaic panels or electric batteries) rather than supporting the decarbonisation of traditional energy-intensive industries. Although it should be noted that in this area, Member States are keen to make use of the liberalised state aid framework, to provide support to their established energy-intensive industries.

EU ETS

The EU's Emissions Trading Scheme (ETS) is another important mechanism to support decarbonisation of industry, rather in the form of a stick than a carrot. The ETS affects the industrial sector in two ways. Firstly, as the third most emitting sector in the EU (after energy and transport), the industrial sector is itself subject to ETS carbon pricing mechanism, i.e. it has to cover the emissions it generates with emission allowances. For the time being, it obtains the vast majority of emission allowances for free. However, this is about to change – the number of free allowances for industry is to be halved by 2030, and they will disappear completely by 2034. As in the energy sector, the prospect of rising costs of emission allowances is expected to mobilise the industry to decarbonise.

An important complement to the ETS is the Carbon Border Adjustment Mechanism (CBAM). While ETS operates within the EU, the CBAM imposes a carbon levy on the goods imported from outside of the EU. This leads to a level playing field between EU producers selling on the internal market and producers from third countries wishing to export their products to the EU. However, the markets for most industrial products are global and EU producers export a large part of their production outside the EU. CBAM does not improve the competitiveness of EU industrial production on the international market.

FIGURE 2. Planned annual reduction in free EU ETS allowances for industry



Source: Instrat based on: European Parliament, 2022.

On the other hand, energy-intensive industries are important consumers of electricity. Due to the large share of coal in the Polish energy mix, resulting in high emissions and high costs of emission allowances, as the low efficiency of the Polish ageing fleet of coal-fired power plants, the cost of electricity for industry in Poland is one of the highest in Europe. In addition, the industry is itself a significant consumer of fossil fuels, accounting for 42% of domestic gas consumption and 24% of coal consumption in 2021 (GUS, 2022). The industry's dependence on fossil fuels exposes it to shocks from increases in their prices.

Taking into account the fact that the cost of emission charges is ultimately borne by energy consumers, the ETS provides for indirect cost compensations for consumers in energy-intensive sectors. These compensations are intended to partially offset the effects of the ETS in the form of higher energy costs. At the same time, their award is conditional on part of the compensation being spent on measures to reduce the carbon and energy footprint of their beneficiaries, stimulating industry to reduce its own carbon footprint.

1.1.2. INDUSTRIAL POLICY IN POLAND?

Poland should pursue its own green industrial policy, irrespective of the measures taken at the EU level, albeit taking them into account. This is all the more important in the view of the large subsidies offered to their domestic industries by Member States with far greater fiscal capacity. Unable to compete with the scale of subsidies, Poland should ensure that the regulatory environment for decarbonising industry is as friendly as possible and that the legal and policy frameworks are predictable. This is crucial to create favourable conditions for both currently operating industrial companies and new investors.

The Polish government has developed or is currently working on a number of documents relating to specific key technologies for the decarbonisation of industry. These include:

- *the Polish Hydrogen Strategy to 2030 with an Outlook to 2040* (Ministry of the Economy and Labour, 2021), adopted in 2021.

- Ministry of Development and Technology's *Strategy for the Development of CO_2 capture, transport, utilisation and storage technologies in Poland and the pilot of the Polish CCUS Cluster* project, currently ongoing.

Recently there were also several regulatory changes related to industrial access to energy, already implemented or announced. These include the announcement of the plans for creation of special energy zones in which large industrial plants will be able to count on lower electricity bills and easier connection conditions (PSE, 2023), as well as legal changes enabling direct line and cable pooling solutions for bilateral provision of renewable energy, already in force (Elżbieciak, Skłodowska, 2023).

However, there is a lack of government strategies addressing sectoral needs and industry-specific decarbonisation pathways, which vary from industry to industry. The most recent document accentuating this perspective is the *Industrial Policy of Poland* (MRiT, 2021), developed by Economic Development and Technology (Ministerstwo Rozwoju i Technologii, MRiT) in 2021, although never officially adopted by the government. This document places considerable emphasis on identifying needs and challenges specific to the main industrial sectors, and contemplates introducing ‚industry contracts', i.e. strategic documents developed during bilateral talks between the government and representatives of individual industrial sectors, setting out policy interventions to respond to their needs.

Another relevant strategic document issued by the MRiT is the *Productivity Strategy 2030*, adopted by the government in July 2022. Although the strategy refers to the concept of industry contracts (MRiT, 2022, p. 45), it mainly addresses the general needs of the wider industry, such as access to adequate human capital or a business-friendly institutional environment. Thus, at present, despite more than two years having passed since the declaration of the intent of their implementation, industry contracts have not been introduced, although in May 2023, the MRiT revisited the idea (MRiT, 2023).

The priority given to industry decarbonisation in broader policy documents is also low. Industry is barely mentioned in the *National Energy and Climate Plan* (MAP, 2019), or *the National Recovery Plan*, in which – if we do not count support for hydrogen technologies – only a few planned actions refer to industry decarbonisation.

1.2. Technological context

Industrial processes are characterised by high complexity and variability, not only between sectors, as the technologies for production of the same product in one sector also vary considerably, depending on the technological solutions adopted. For this reason, solutions to decarbonise the industry will also strongly depend on the shape of the local production process and the technologies used. Despite this, it is possible to identify some key technologies for industry decarbonisation.

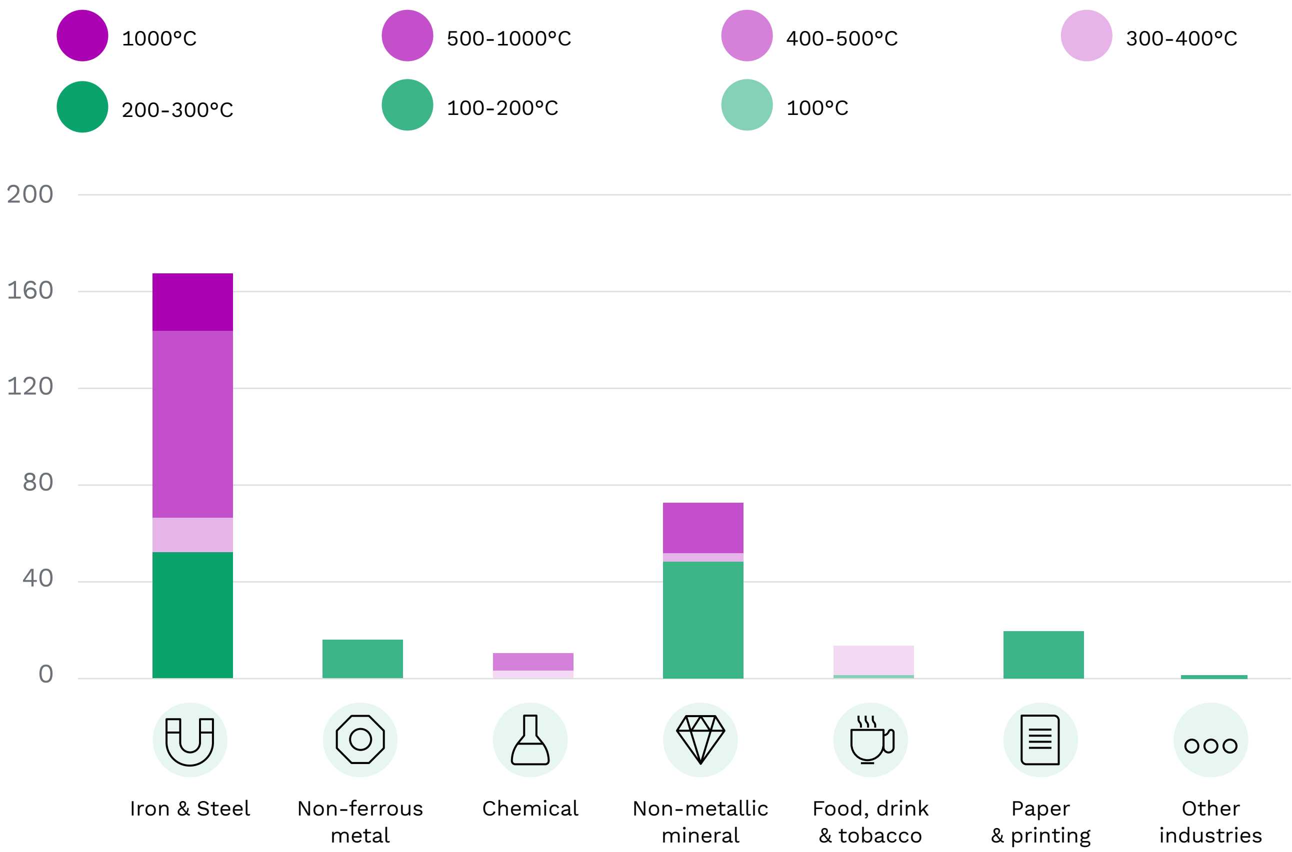
Electrification

One of the main sources of emissions in industry is the generation of heat energy needed for industrial processes requiring high temperatures. As much as 95% of the heat used in high-temperature processes comes from the direct combustion of gas, coal or oil (IEA, 2019, p. 117), although some industrial processes in energy-intensive industries already obtain heat from electricity (e.g. steel production using electric arc technology).

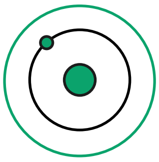
Industrial processes using low (up to 200°C) and medium (up to 500°C) temperatures can be electrified relatively easily by replacing gas and coal furnaces with industrial heat pumps or electric boilers (Agora Industry, FutureCamp, 2022). However, the electrification of these processes must be accompanied by the provision of energy from carbon-free sources, both by increasing their share in the national electricity grid and by facilitating industrial companies to procure green energy individually, through PPAs or investments in their own RES and energy storage.

Electrification of processes requiring higher temperatures (e.g. clinker firing in cement production) is also possible, but often technically more difficult due to the need for significant interventions in existing installations. This entails additional costs that are not required when replacing fossil fuels with low-carbon fuels such as green hydrogen (Friedman et al., 2019, p. 50).

FIGURE 3. Temperature ranges in industrial processes by industry



Source: Papapetrou et al, 2018.



Zero-emission hydrogen

Hydrogen is currently used as a raw material or reactant in many industrial processes in the chemical and refining sectors to produce substances such as ammonia (the basis of most fertilisers) or methanol, and in oil refining processes (hydrocracking). Currently, hydrogen used in these processes is derived from natural gas (less often from coal), and its production generates greenhouse gas emissions. Zero-emission hydrogen, on the other hand, is produced by electrolysis of water using zero-emission electricity. Moreover, many industrial processes use gaseous fuels such as natural gas to generate heat.

Decarbonising industrial processes with hydrogen thus means:

1. Replacing the hydrogen currently used with emission-free hydrogen.
2. Converting processes that currently use gaseous fossil fuels (natural gas) to processes based on emission-free hydrogen.

This requires an adequate supply of emission-free hydrogen, with a number of technological and economic challenges. First and foremost, the electrolysis process involves energy losses of around 35% (IEA 2019a, p. 44). Hydrogen in a gaseous form also has a low energy density. To obtain a volume that allows it to be transported efficiently, the gas must be compressed at high pressure (around 700 atmospheres), liquefied or incorporated into another chemical compound (e.g. ammonia). Each of these conversion processes means further energy losses in the range of 20-45% (IEA 2022, p. 140).

Hydrogen transportation itself is also challenging. The most efficient method, at least for distances of up to a few hundred kilometres, is through pipelines. However, this requires the development and maintenance of an appropriate infrastructure to which industrial consumers can be connected. Finally, the use of hydrogen for energy production at the final location implies an additional energy loss, the scale of which varies depending on the efficiency of the installations used.

Another challenge to increasing the supply of zero-emission hydrogen is its uncompetitive price. Producing 1 kilogram of emission-free hydrogen currently costs an average of €5-6, compared to €2 for gas-derived hydrogen (Energy Institute, 2023, pp. 7-8). However, the falling costs of RES-E generation and investment in electrolysis plants, in parallel with the tightening of EU climate policy manifested in the increase in the price of CO_2, could lead to a significant decrease in the cost of zero-emission hydrogen and price parity even before 2030 (IEA 2023, p. 81).

Due to these technical and economic issues with green hydrogen production, it is unlikely to find wider application in those areas where decarbonisation can be achieved through electrification, based on grid power or with the use of batteries. However, in the industry, due to the key role of hydrogen as a feedstock or reactant in many chemical processes and the possibility of using it as an emission-free fuel in hard to electrify heating processes, the use of hydrogen will be inevitable.

Capture, utilisation and storage of CO_2 (CCUS/CCS)

This is another key technology for the decarbonisation of industry. It refers to the capture of CO_2 under controlled conditions, i.e. in the installations where the gas is produced and needs to be distinguished from the technology of direct CO_2 capture from the atmosphere (*Direct Air Capture*). The captured gas is then to be transported – in the most cost-effective scenario – via pipelines to underground storage sites, such as offshore wells left over from oil production.

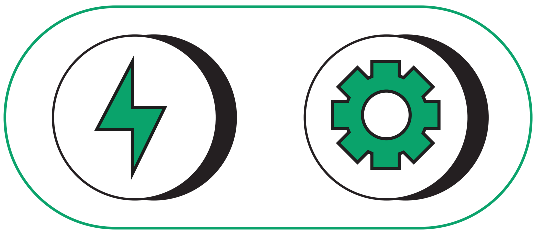
CCS technology has the potential to find widespread use in industry due to the hard-to-abate nature of emissions from many industrial processes. It will be crucial for industries with a high proportion of process emissions for which zero-emission alternatives are lacking. Cement production in particular is such an industry, where more than 60% of emissions are generated by limestone processing (IEA, 2019b), a process to which there are currently not many alternatives.

CCS technology may also find limited application in the chemical or refining sector. It can also contribute to reducing emissions from the combustion of fossil fuels for heat generation in those few processes where electrification or the use of hydrogen as an emission-free fuel will not be possible.

CCS, however, even more than hydrogen technologies, depends on the availability of infrastructure to transfer and store the captured CO_2. Part of the captured CO_2 can be reused in other industrial processes, such as plastics production, in the food industry or in agriculture. However, the demand for CO_2 is not high enough for all the carbon dioxide produced in industry today to be utilised in this way.

Substitution of industrial products in end uses

Manufacturers of more complex products, downstream in the value chain, wishing to decarbonise their own operations, may seek alternatives to previously used materials supplied by energy-intensive industries. For example, the construction sector may make greater use of recycled rubble or use wood for construction, reducing the use of steel or cement. However, the possibilities for such substitution depend on the specific end product and will not always be available. They also necessitate far-reaching changes to the production processes used to date, which is a barrier to their competitiveness. However, the very fact that actors in the downstream industrial value chain might be looking for alternatives to existing solutions should be a motivating factor for energy-intensive industries to decarbonise.

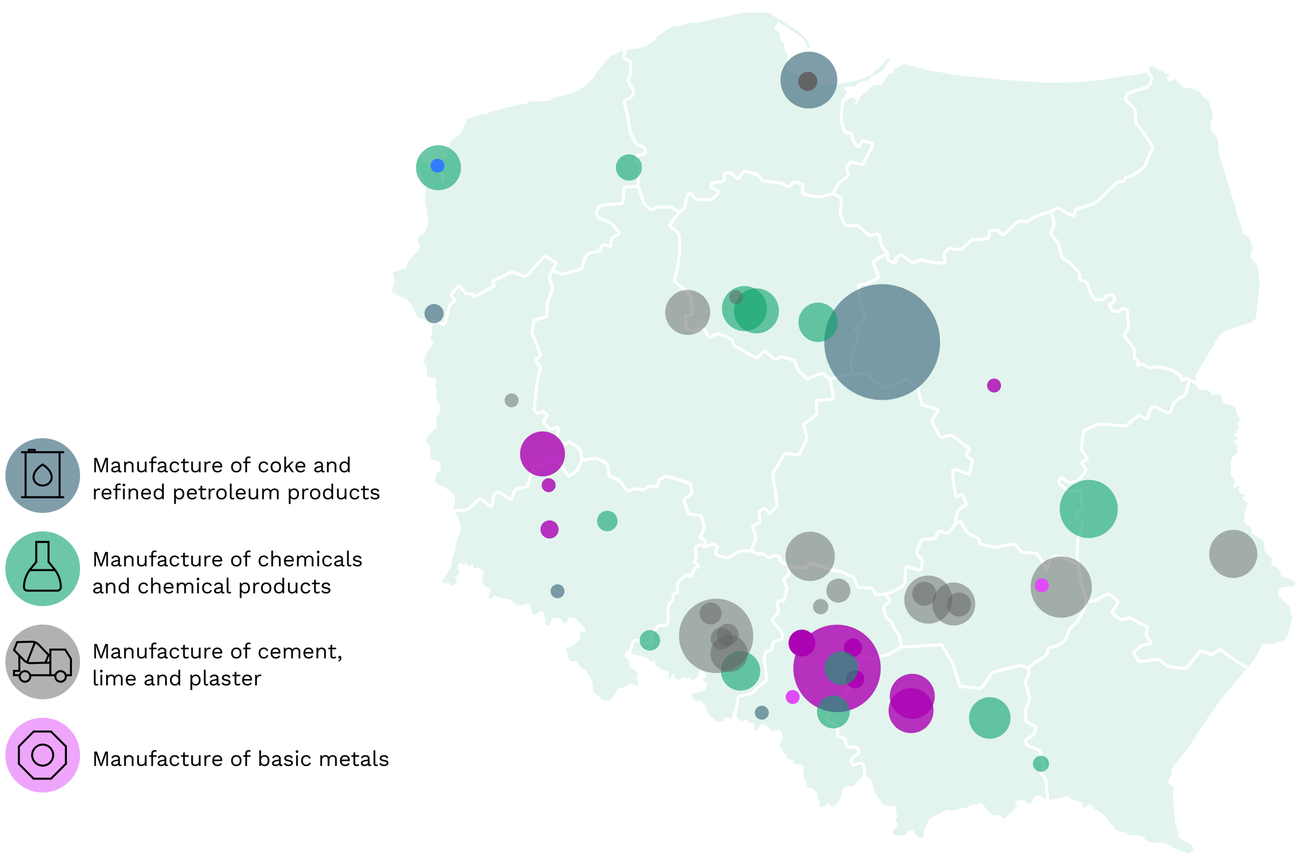


1.3. Regional context

Economic geography

The role of economic geography in the debate on the decarbonising industry is growing (Zachman, McWilliams, 2021). Therefore, it should be taken into account in Poland's current industrial policy. The decarbonisation of technological processes, regardless of the technologies used in the process, will almost always be linked to the need for access to carbon-free energy. The current locations of industrial installations in Europe and Poland were chosen largely because of their proximity to coal-fired power plants, coal mines and coking plants. In Poland, they are mostly located in the south of the country. The map below, created on the basis of Instrat's Industrial Emissions Database, shows the location of industrial plants emitting the most CO_2.

MAP 1. Largest CO_2 emitters from four energy-intensive industries in Poland in 2019



Source: Instrat, based on the database of energy-intensive industries 2010-2020 (Kościółek et al., 2023).

The size of the circles on the map corresponds to the amount of CO_2. The map only includes plants emitting more than 100,000 tonnes of CO_2 into the atmosphere, according to the E-PRTR register. Emission range includes emissions from the combustion of fuels as part of the generation of electricity and heat for the industrial plant (range 1).

As offshore wind and nuclear power capacities develop, an increasing share of the electricity generating sources will move to the north of the country. It will therefore make sense to locate industrial plants in these regions of Poland. For investors, locating in the vicinity of power generation sources is associated with lower grid fees (transmission fee and quality fee). Such a solution is also beneficial from a systemic point of view, as it limits the need for the north-south power grid buildout.

For these reasons, the government, together with the electricity and gas transmission network operators, including PSE, announced the creation of Special Energy Zones in the north of the country. These will enable large industrial plants to benefit from lower electricity bills and easier connection conditions (PSE, 2023).

Investment – in existing or new locations?

The incentive relocation of industry from the south to the north of Poland suggests a move towards greenfield investments (in new locations) and raises questions about feasibility of investments in the transformation of production in existing industrial centres (brownfield investments). Pursuing greenfield investments in new locations will often be reasonable from the point of view of companies' financial interests as well as from the view of the electricity system in general, but will have a large regional social impact.

Industrial plants, together with their supply chains, are an important source of direct and indirect employment in local labour markets. As the largest regional employers and payers of local taxes and fees (including environmental taxes), they are a source of local prosperity. Thus, the potential closure or reduction of their activities raises the risk of declining tax revenues, increasing unemployment and deepening economic and territorialinequalities[5].

The potential relocation or reduction of activities as a result of competitive pressure from less carbon intensive industries – including those in northern Poland – raises the risk of regional marginalisation of current industrial centres. Even if the decarbonisation of industry at the national level results in a net gain of new jobs, the current industrial regions could be severely affected.

5 For further analysis of the risks and benefits of the transition and how to prepare for it, see the Instrat Foundation's publications on Eastern Greater Poland (Hetmanski et al., 2021) and the tax revenues of coal municipalities (Swoczyna, 2023).

Just transition of industrial regions, not just coal regions

Given the above, the decarbonisation of industrial regions in Poland should be integrated into the planning and monitoring of the just transition of mining regions, as in other EU countries. The similarities in terms of challenges and potential instruments between mining and coal energy (phased-out sectors) and hard-to-decarbonise energy-intensive industries (transition sectors) provide an opportunity to change the approach to a just transition also in Poland[6].

Support for the transition of post-industrial regions

Polish industrial regions and energy-intensive enterprises should become beneficiaries of relevant support instruments, e.g. the Just Transition Fund and Mechanism. Although the planning of interventions within the financial perspective of the EU budget (2021-2027) is already over, there are still opportunities for adaptation of current regional programmes (within regional operational plans) and national programmes (NFOŚiGW – Modernisation Fund). At the same time, there is a discussion at EU level about the potential continuation of the JTF and JTM in the next budget perspective after 2027 (European Commission, 2023c).

Analogous to the priorities of the so-called mining JTF, industrial regions should also receive financial support and technical assistance for **mitigating the negative social effects of the climate transition**. In contrast to mining and coal-fired power generation, the transition of energy-intensive industries (e.g. in a brownfield investment model) does not necessarily mean that jobs are lost or reduced.

Currently, the geographical scope of the Just Transition Fund in Poland covers only five regions – Silesia, Western Lesser Poland, Eastern Greater Poland, Bełchatów and Wałbrzych. Outside its scope are Turów and Lubelszczyzna, which, due to the lack of a credible declaration to move away from coal, have not received support (MFiPR, 2023).

---

[6] Led by the European Commission, the *Coal Regions in Transition* Platform initiative has over time been integrated into the wider *Just Transition Platform* initiative. The synchronisation of regional and energy and industrial policy activities between the relevant directorates (REGIO, ENER) has led to a stronger inclusion of industrial regions as beneficiaries of the Just Transition Fund and Mechanism in the other EU countries (mainly Western Europe) (European Commission, 2023c). Unfortunately, Poland and other EU enlargement countries decided not to submit industrial regions to participate in the call for FST funds and the writing of territorial just transformation plans.

Extension of the scope of instruments supporting just transition in Poland to energy-intensive industries should include an update of the Silesian Just Transition Territorial Plan (taking into account the participation of the Małopolskie Voivodeship), due the steel industry being mainly concentrated in that region. Secondly, it should take into account the challenges of the so-called Cement Belt regions (see section 3.1.), which stretches from the Lubelskie and Świętokrzyskie Voivodeships to the Opolskie Voivodeship. Kujawsko-Pomorskie Voivodeship with its chemical and cement industries is also a potential candidate. Last, but not least, „island" industrial centres, dominated not by clusters but rather by large individual plants (e.g. refineries in Płock and Gdańsk), but with no less influence on the regional economy, should be considered.

1.4. Financial context

Given the scale of investments required for decarbonisation of industry, access to both commercial funding and public sector financial support is crucial.

In the case of private sector financing, industrial companies need to reassure their actual and potential investors that they have well-developed decarbonisation plans and strategies in place. Rising energy prices and changing consumer preferences may cause these companies to lose competitiveness and their carbon-intensive assets to become 'stranded'. To avoid this risk, investors will expect industrial companies to prove that they have plans to remain competitive in the long term. This is confirmed by sectoral standards for decarbonisation plans published by international initiatives. Guidelines for decarbonisation plans of companies operating in the steel or cement sectors have been adopted by, among others, Science-Based Targets (SBTi 2022, 2023), an independent organisation that verifies the compatibility of corporate climate targets with science, and the Institutional Investors Group on Climate Change (IIGCC, 2021).

However, it can be difficult for industrial sectors to plan for significant capital expenditure in a situation where rising energy costs are squeezing their margins and reducing the profitability of current operations. In addition, the application of many low-carbon technologies is still associated with high risks as a result of their low maturity. Fiscal support from the public sector can be a response to these problems. At the EU level, funding for the implementation of innovative decarbonisation solutions can come from the Innovation Fund. In Poland, four projects are currently receiving funds from this source (Table 1).

TABLE 1. List of ongoing projects in Poland funded by the Innovation Fund

Name of the project	Sector	Beneficiary	Amount of support
Kujawy Go4ECOPlanet	Cement	Lafarge Cement	EUR 228.2 million
NORTHSTOR+ Industrialising Green Optimized Li-ion Battery Systems for ESS	Energy storage facilities	NVS Poland, NV Systems AB	EUR 75.5 million
Small scale green hydrogen production facility	Hydrogen	Lotos Green H2	EUR 4.5 million
5 MW green hydrogen production facility in Konin	Hydrogen	BiW, Exion, ZE PAK	EUR 4.5 million

Source: Instrat based on data from the European Commission.

Another important source of funding for industry decarbonisation is the Modernisation Fund. The National Fund for Environmental Protection and Water Management is the national distributor of funding from this programme. The national pool includes a priority programme ‚Energy-intensive industry – RES', within which companies can apply for funding to set-up their own RES installations under preferential conditions[7].

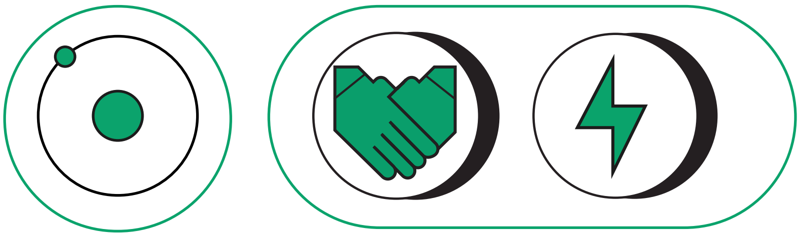
Following the energy price shocks in 2022, the Polish government launched – based on the EU Temporary Crisis Framework for State Aid – a state aid programme to mitigate the effects of rising electricity and gas costs. In 2022, the budget for the programme was around PLN 5 billion. In the end, applications for aid of PLN 3.6 billion were submitted, of which only PLN 2.4 billion was granted.

[7] An overview of the 2023 submissions was presented on WysokieNapiecie.pl (Skłodowska, 2023).

The call for applications for the second edition of the programme for subsidies for costs incurred in 2023 was launched in August this year. The amount of support for all applicants includes 50% of the value of energy costs above 150% of the average price paid in 2021, up to €4 million. Entrepreneurs who have additionally experienced a decline in operating margins and from industries at risk of losing competitiveness can receive higher support. To do so, however, they must present a plan to reduce the energy intensity of their enterprise. The programme has a budget of PLN 5.5 billion, but is still awaiting approval from the European Commission (Elżbieciak, Zasuń 2023).

Support for the production of low-carbon technologies is envisaged in the proposed MRiT regulation on support for investment projects of strategic importance for the transition to a net-zero-emission economy[8]. This is a Polish programme to support net-zero technologies (the same ones on which the GDIP focuses) adopted on the basis of the EU Temporary Crisis Framework for State Aid.

The project envisages financial assistance for new investments in low-carbon technologies worth at least EUR 110 million and creating at least 50 new jobs. The support provided can range from 35% (up to €350 million) to 15% (up to €150 million) of the investment costs, depending on the investment's location. The total budget of the programme is around PLN 5 billion. However, companies from the energy-intensive industry will benefit from this programme only indirectly (as users of low-emission technologies), or in exceptional cases, if they themselves produce low-emission technologies (e.g. hydrogen) for their own needs.



8 *Draft Regulation of the Minister of Development and Technology on detailed conditions and procedures for granting support for investment projects of strategic importance for the transition to a net-zero-emission economy*, https://legislacja.rcl.gov.pl/projekt/12376902/katalog/13006244#13006244.

2. Energy consumption, fuels and greenhouse gas emissions in energy-intensive sectors

The decarbonisation of energy-intensive industries requires not only electrification of the energy supply, but often also fundamental changes in the technological processes. However, smaller gains in lowering emissions may be achieved by increasing energy efficiency and fuel substitution with less carbon intensive options. Such gains represent a "low-hanging fruit" on the road to decarbonisation of the industry, although they do not remove the need for a deep decarbonisation of industrial processes.

Between 2015 and 2021, two of the four sectors analysed in this report experienced significant changes in their energy and fuel mix. In the manufacturing of basic metals, the use of coke and semi-coke declined in favour of natural gas, allowing for a decoupling of output and emissions, with the latter falling instead of rising (see section 3.2.2.). At the same time, in the manufacturing of other non-metallic mineral products (mostly cement), data shows that natural gas and waste have partially replaced coal use.

In 2010-2021, emissions in the four energy-intensive sectors oscillated between 44-49 Mt CO_2 per year, which accounted for 15-17% of annual CO_2 emissions from the entire Polish economy. Only in the manufacturing of basic metals sector, emissions exhibited a downward trend over the analysed period, and fell by 20% between 2010 and 2021 (2 Mt CO_2 per year). In other sectors (manufacture of coke and refined petroleum products, other non-metallic mineral products) emissions increased or remained at a steady level (chemicals and chemical products).

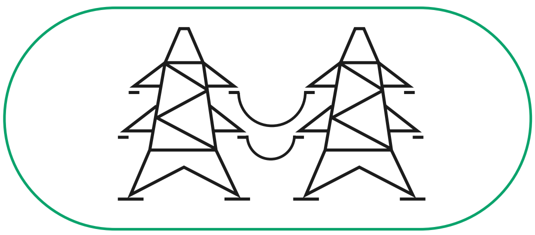
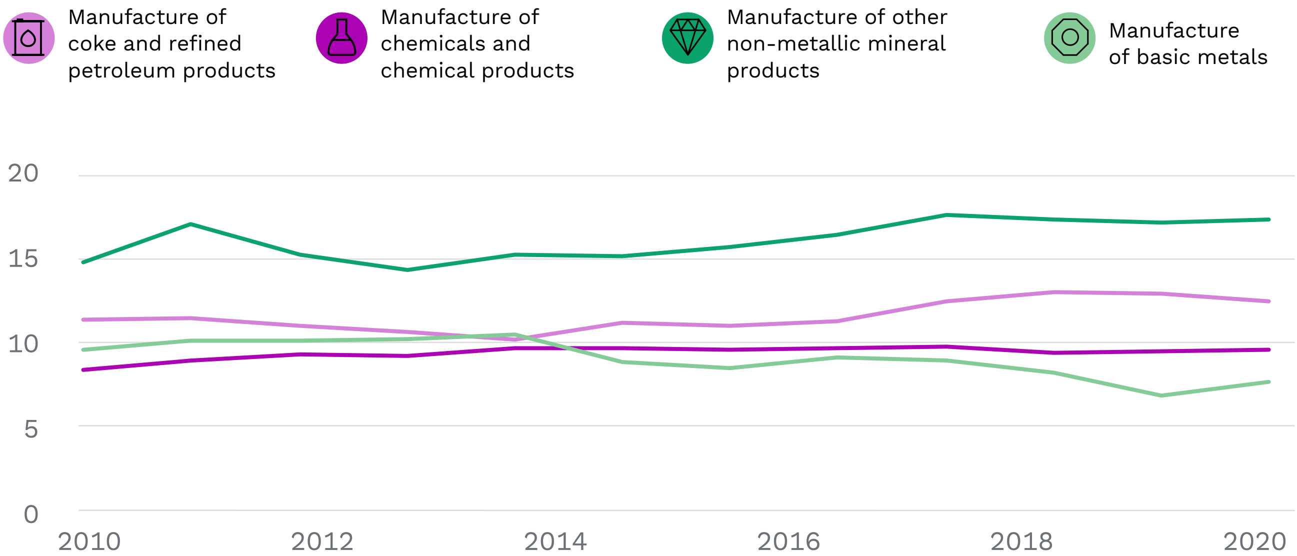


FIGURE 4. CO_2 emissions from energy-intensive manufacturing industries 2012-2022 (Mt CO_2)

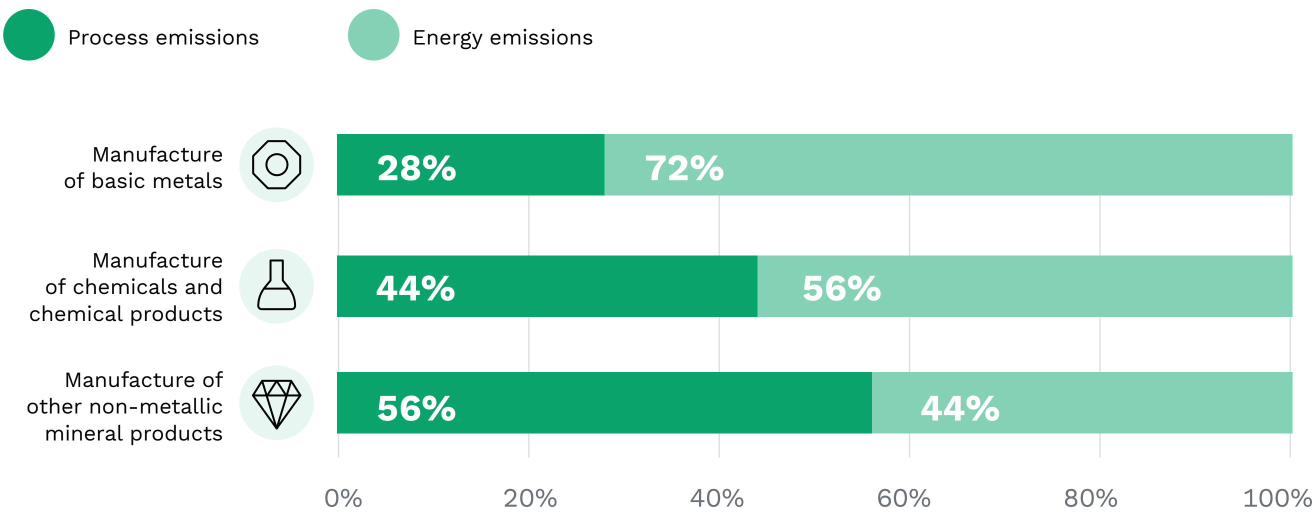


Source: Instrat, based on GUS data.

Emissions from fuel combustion versus process emissions

Emissions from fuel combustion account for 44-72% of greenhouse gase missions, depending on the sector. The remaining emissions are process emissions.

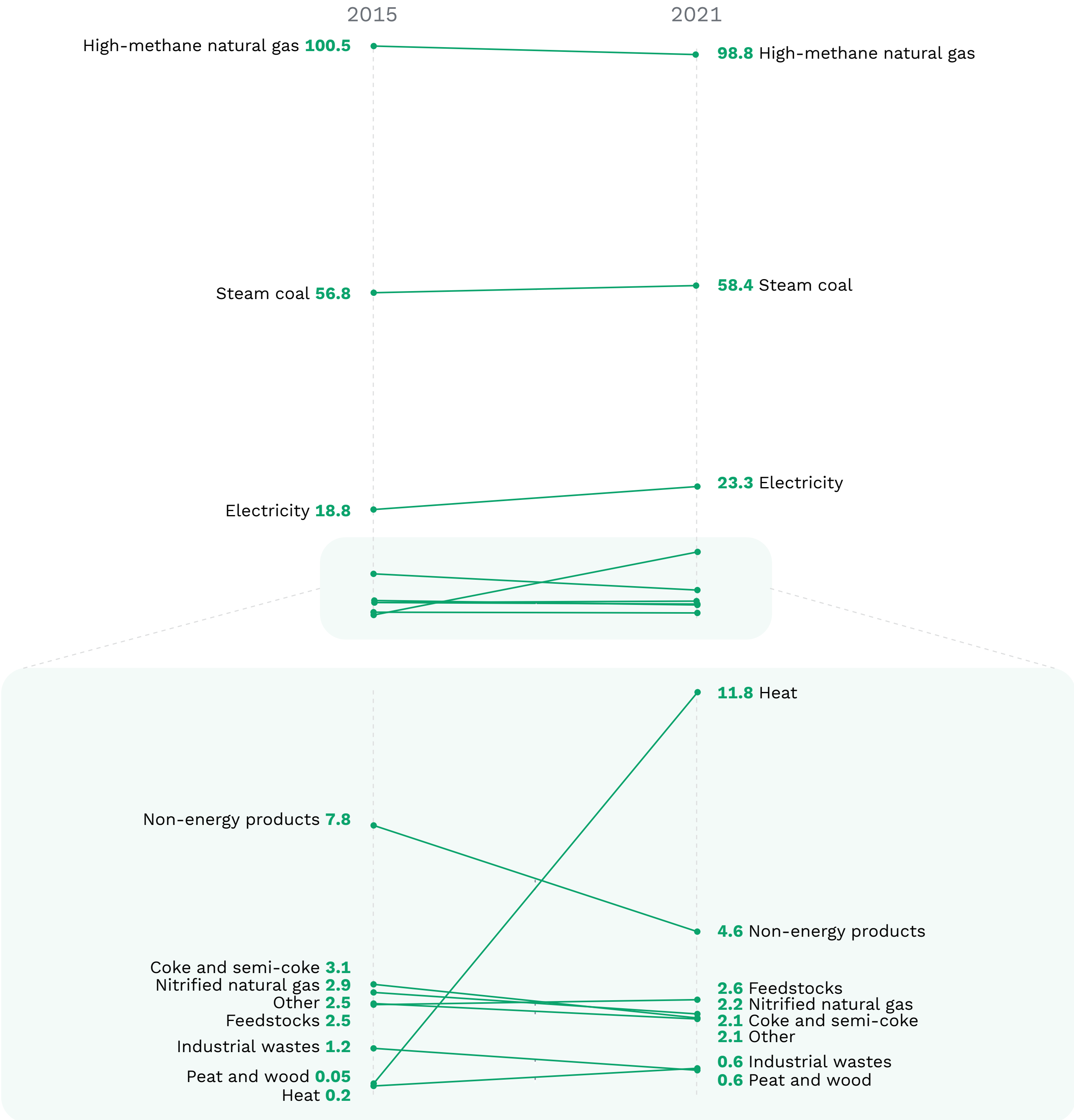
FIGURE 5. Share of greenhouse gas emissions from fuel combustion (energy emissions) and process emissions in total emissions from Polish energy-intensive industries in 2020 (in eCO_2)



Source: Instrat, based on UNFCCC data.

Due to discrepancies in industry categorisation between the Polish PKD and the UNFCCC taxonomy, it is not possible to reliably calculate the share of process emissions for the oil refining and coke production industry, so this sector has been omitted.

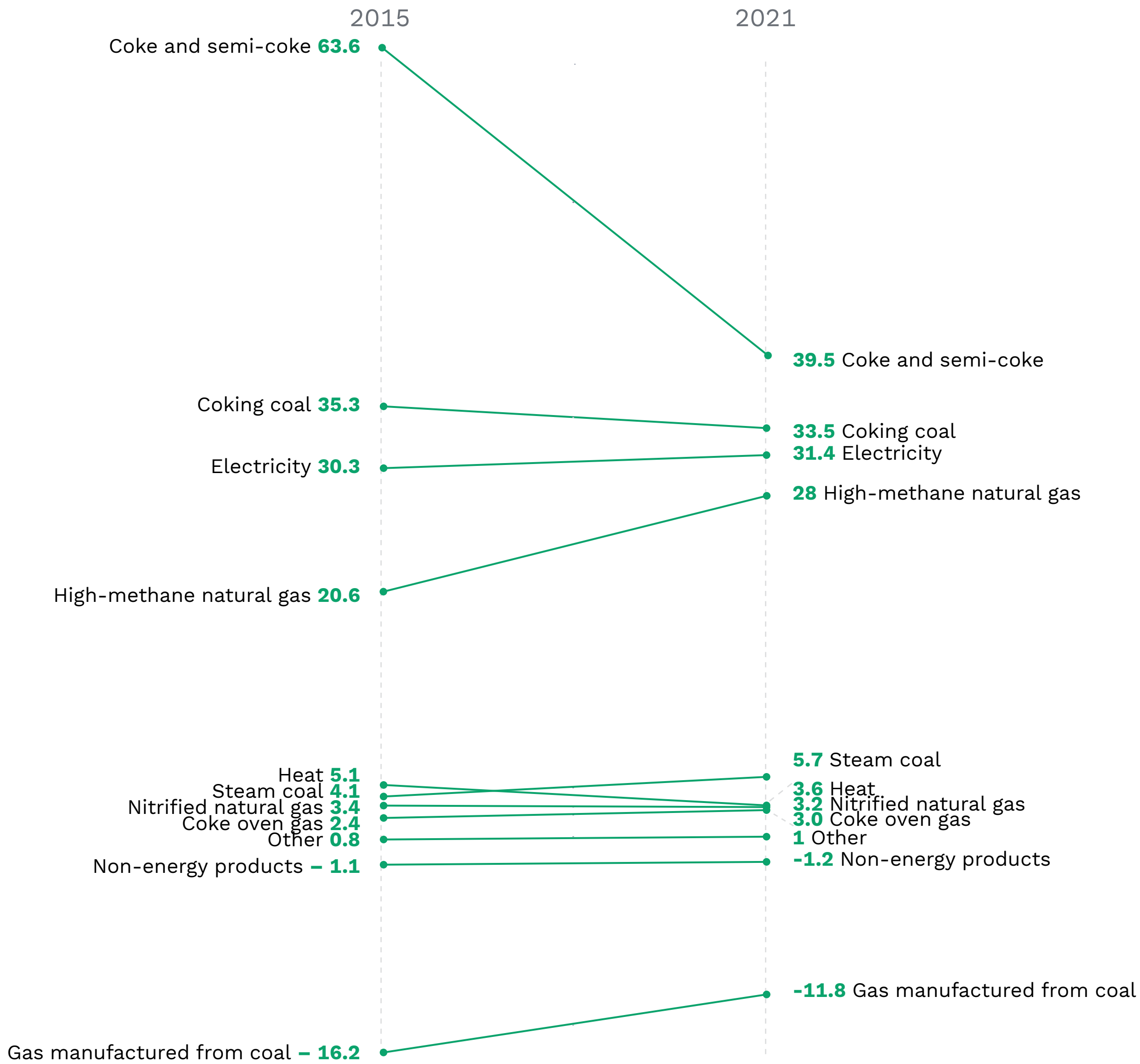
FIGURE 6. Fuel and energy consumption in the manufacturing of chemicals and chemical products industry in Poland 2015-2021 (PJ)



Source: Instrat, based on GUS data.

Between 2015 and 2021, total fuel and energy consumption in the **manufacturing of chemicals and chemical products** sector increased slightly – from 194 PJ to 205 PJ. During this time, output in this sector increased at a much higher rate – from around PLN 61 bln in 2015 to around PLN 95 bln in 2021. (GUS, 2023, p. 71). The increase in energy consumption was particularly evident in the consumption of heat supplied from outside the plants, from 145 TJ in 2015 to 11 822 TJ (11,8 PJ) in 2021.

FIGURE 7. Fuel and energy consumption in the manufacturing of basic metals industry 2015-2021 (PJ)

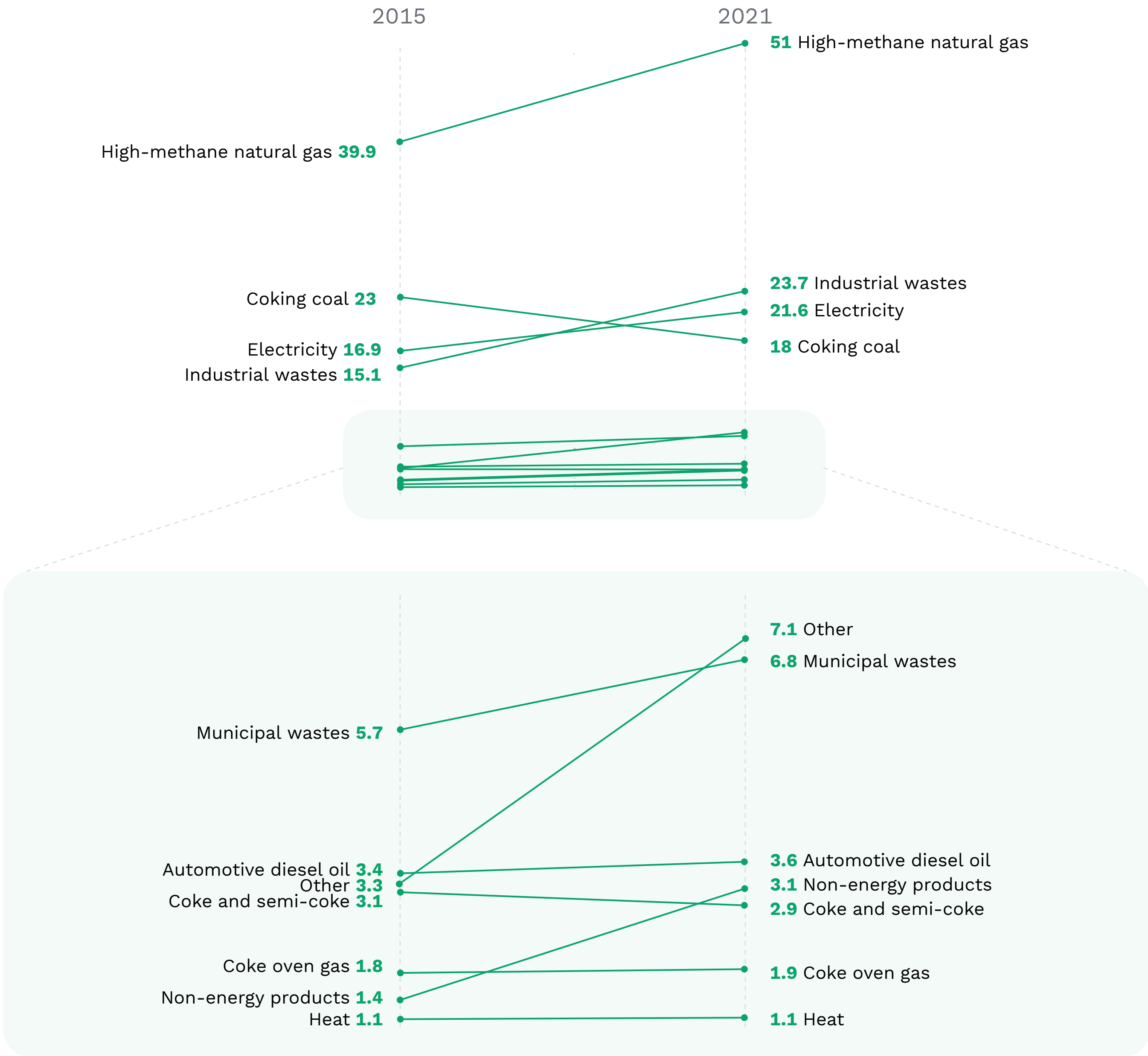


Source: Instrat, based on GUS data.

Changes in fuel use in the **manufacturing of basic metals** sector between 2015 and 2021 reflect the transformation of the steel industry in Poland in this period (Figure 7). In 2020 the oxygen furnace in Kraków (ArcelorMittal, 2020) ceased to operate. Only one steel mill in Poland, in Dąbrowa Górnicza, also owned by ArcelorMittal, is currently operating with this technology[9]. Due to the decommissioning of the furnace in Kraków and the modernisation of production at the Dąbrowa Górnicza site, the consumption of some of the most emission-intensive fuels commonly used in these furnaces – coke and semi-coke – has decreased (from 63.6 PJ in 2015 to 39.5 in 2021). At the same time the use of natural gas increased (at the expense of coke). Export of blast furnace gas, which is produced in coke-fired furnaces, also decreased due to these changes.

[9] We describe steelmaking technologies in more detail in section 3.2.1.

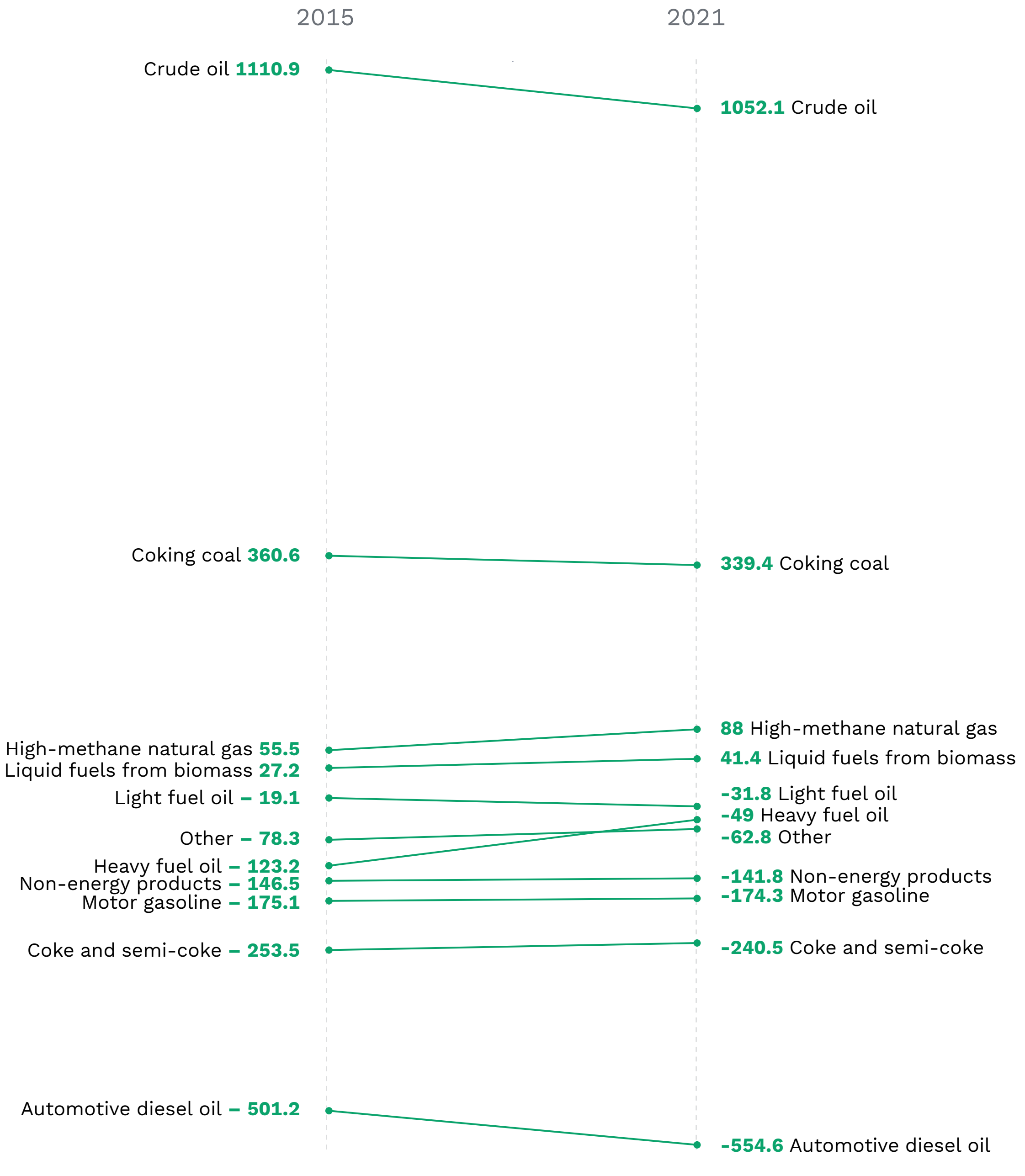
FIGURE 8. Fuel and energy consumption in the manufacturing of other non-metallic mineral products industry 2015-2021 (PJ)



Source: Instrat, based on GUS data.

In the **manufacture of other non-metallic mineral products** industry, the changes in the fuel and energy mix are primarily related to the optimisation of the clinker furnace heating in terms of emissions and costs. Therefore, a decline in the importance of coal and an increase in the role of natural gas can be observed between 2015 and 2021. At the same time, the use of industrial and municipal waste as fuel has also increased, as cement plants have started to play an important role in their disposal.

FIGURE 9. Fuel and energy consumption in the manufacture of coke and refined petroleum products industry 2015-2021 (PJ)



Source: Instrat, based on GUS data.

Between 2015 and 2021, the **manufacturing of coke and refined petroleum products** (including petrochemicals) maintained a steady fuel mix.

Negative values represent the export of fuels outside industrial plants. Polish oil refining and coke production sector exports mainly diesel (555 PJ in 2021), motor gasoline (174 PJ), coke and semi-coke (241 PJ) and non-energy products (142 PJ), which includes mainly petrochemical products.

3. Case studies: decarbonisation of cement and steel production

3.1. The Cement Belt

3.1.1. EMISSIONS FROM THE CEMENT BELT AND ROADS TO ITS DECARBONISATION

Cement, lime and plaster were responsible for 13.5 million tonnes of CO_2 emissions in 2022 (GUS, 2023). GUS, presents aggregate data on emissions from cement plants together with plants producing lime and plaster. However, cement plants are responsible for the vast majority of emissions in this group. The indicated value represents 23.4% of all industrial CO_2 emissions in Poland, and around 6.5% of the total CO_2 emissions from mining, industry, energy and water management sectors[10]. The majority of these emissions came from nine large industrial plants located in the Cement Belt – an area stretching from southern Lubelskie, through Świętokrzyskie, southern Łódzkie, Śląskie and Opolskie provinces (Kopeć, 2023). The share of emissions from the whole Polish economy coming from cement plants in the Cement Belt averaged around 3.4% between 2015 and 2020 (Kopeć, 2023; KOBIZE, 2023).

FIGURE 10. Share of CO_2 emissions from manufacturing of cement, lime and plaster in total industry emissions in 2022.

Source: Instrat, based on GUS data.

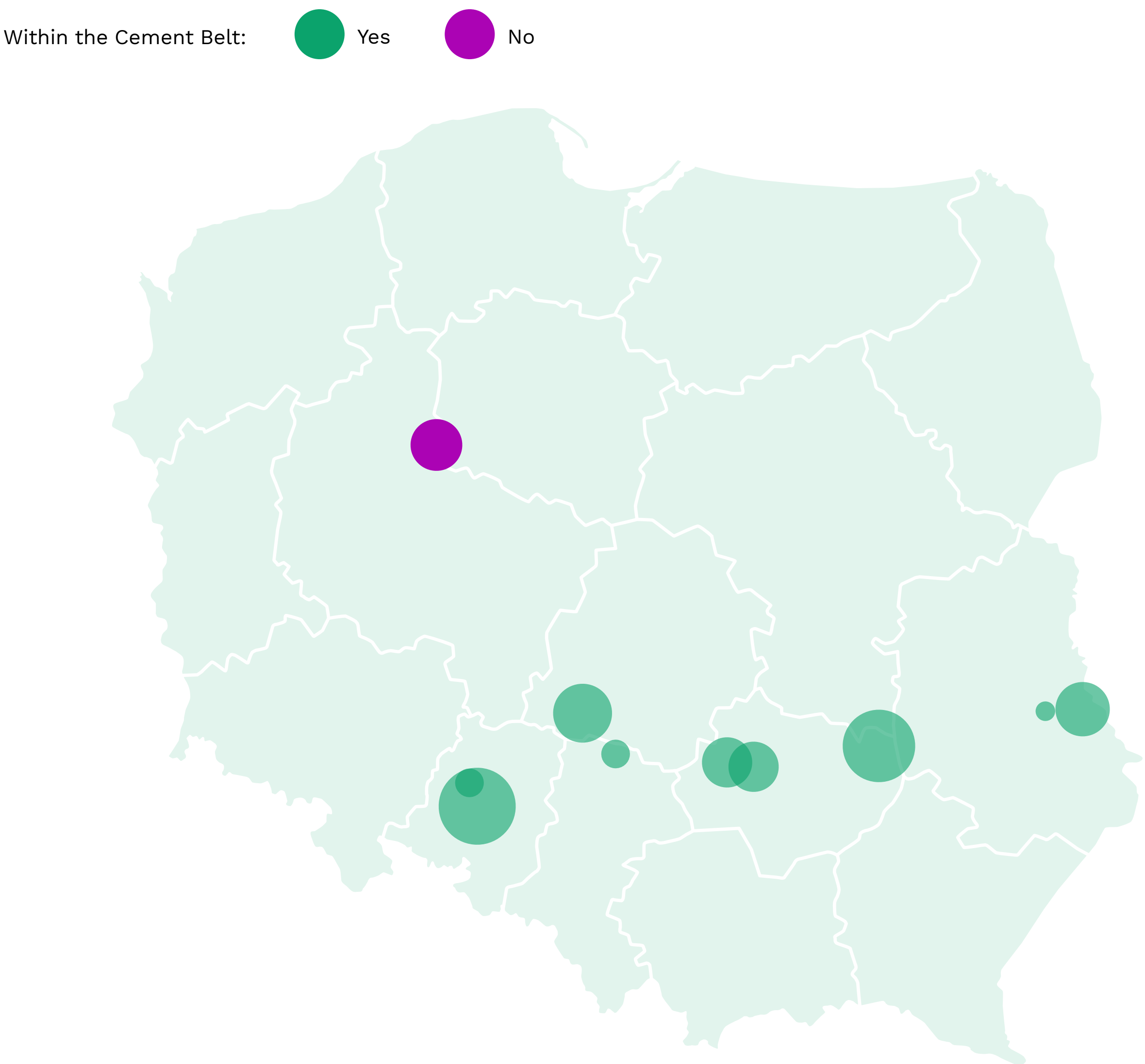
10 According to the PKD, these are sectors B-E. In this report, industry means section C according to the PKD classification.

3.1.2. A DECARBONISATION CLUSTER

The concentration of a large, carbon-intensive industry such as cement production in one geographical part of the country means that its impact on emissions in the region is significant. However, it also opens up the possibility of building a decarbonisation cluster.

In Lubelskie Province, cement plants accounted for 27% of the emissions of all facilities included in the European Pollutant Release and Transfer Register – E-PRTR (Figure 11 and Map 2). This is more than the energy industry located in the province. In addition to the Lubelskie Voivodeship, the share of cement plants in emissions is particularly high in the Opolskie and Świętokrzyskie Voivodeships.

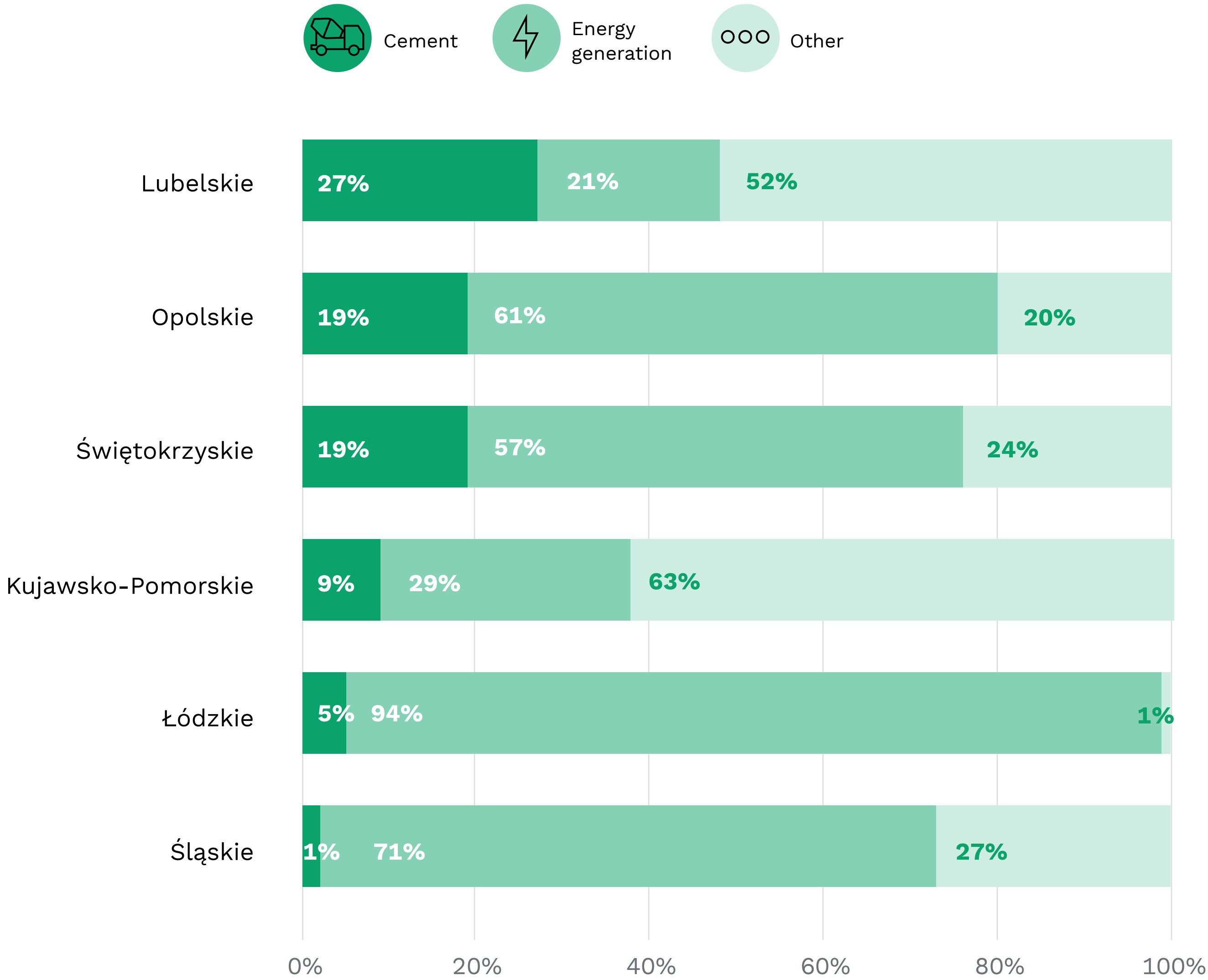
MAP 2. Locations of cement plants operating in Poland



Source: Instrat based on: Kościółek et al, 2023.

The size of the points illustrates the sum of CO_2 emissions from a given plant between 2015 and 2020.

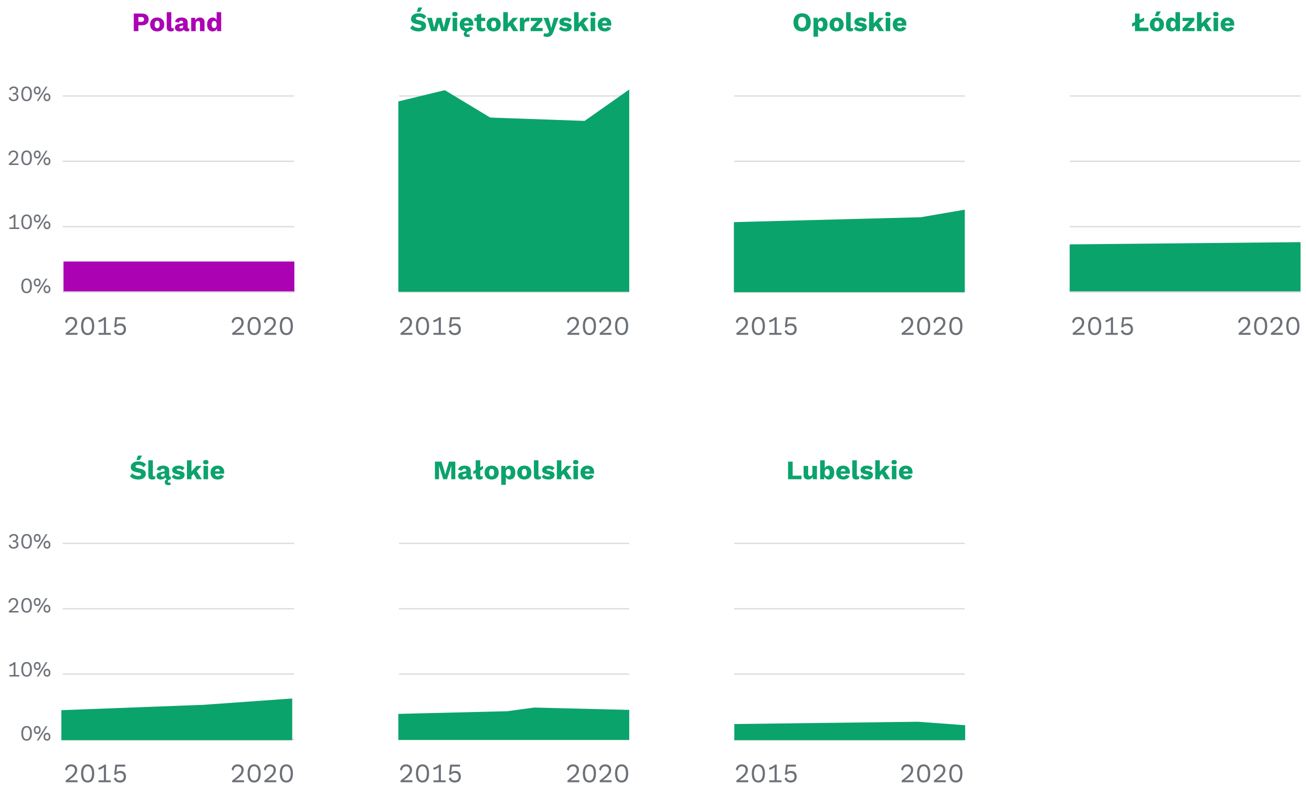
FIGURE 11. Share of CO_2 emissions from cement production compared to other industries and energy generation in the provinces forming the Cement Belt in 2015-2020.



Source: Instrat, based on E-PRTR data. Only installations above the eligibility threshold for this register are included.

Decarbonisation of the cement plants operating in the Cement Belt would contribute to significant emission reductions in the voivodeships that make up the Cement Belt, especially in Świętokrzyskie. Non-metallic minerals processing plants, including cement plants, account for about 30% of the manufacturing industry's product sales there. Decarbonisation of this industry (e.g. using CCS technology) would mean that the plants operating there could continue to operate without the burden of emission costs.

FIGURE 12. Share of manufacturing of other non-metallic mineral products in the value of sold production from the entire manufacturing industry in the Cement Belt voivodeships from 2015 to 2020 and for Poland as a whole.



Source: Instrat, based on GUS data.

The category of other non-metallic mineral products includes cement factories and other plants. A more detailed granularity at voivodeship level is not available in the GUS data.

Although cement plants nationally are not large employers – the average cement plant employs several hundred people – their impact on the regional socio-economic environment is significant. The Association of Cement Producers indicated that in 2017, cement plants were responsible for creating 4 000 jobs directly and around 25 000 indirectly (Piestrzyński, 2017).

Cement factories are part of long value chains, which also include concrete production companies, construction companies, machinery manufacturers and transport firms. The concentration of cement plants in one part of the country means that it is possible to think of the decarbonisation of this sector as a regional project. Potential infrastructure for CCS could be shared by neighbouring production sites. Also, the allocation of public funding, e.g. from the Just Transition Fund, could be directed to regions in which multiple cement plants operate.

3.1.3. ELECTRIFICATION FIRST

The first aspect of cement production decarbonisation involves heat generation. Currently, cement plants consume most energy in the form of natural gas (51 PJ in 2021, or 1.4 billion m3). Coal demand has fallen from 23 PJ in 2015 to 18 PJ in 2021. (21%). Meanwhile, the use of industrial waste for energy purposes increased from 15 to 24 PJ.

To reduce emissions from fuel combustion **the kilns used at cement plants have to be electrified**. This can be achieved either by ensuring a sufficiently large supply of green electricity in the grid or by implementing PPAs and direct lines at production sites. Locating energy sources close to plants, facilitated by their concentration within the region, would reduce the load on transmission and distribution networks. It would also exempt these industrial consumers from part of the network charges. The proximity of industrial plants to each other thus creates opportunities for joint investments in green energy procurement.

One problem with the electrification of cement kilns is their design, which makes it difficult to deliver high-temperature heat to the various parts of the kiln when using electricity. For the most part, technologies for kiln electrification are still at the research stage (Hasanbeigi, 2023), although some have already seen pilot implementations (Perilli, 2022).

3.1.4. THE PROBLEM OF REDUCING PROCESS EMISSIONS

Given that 50-70% of CO_2 emissions from cement plants are process emissions (in Poland about 56% – Figure 5), electrification will not be enough to bring the industry to climate neutrality (Sousa, Bogas, 2021; Beyond Zero Emissions, 2017). Indeed, emissions resulting directly from the processing of limestone into clinker must also be reduced or eliminated. In this regard, two options are being considered or are already being implemented in various parts of the world:

1. CO_2 capture and sequestration (CCS) from on-site process emissions.
2. Substitution of portland cement by other materials with similar characteristics, mainly geopolymers.

1
option

Capture and sequestration of (CCS)

CO_2 capture raises a number of challenges. Carbon dioxide has to be stored in underground caverns or offshore shelves to which it has to be delivered and injected, either in gaseous or liquefied form. The construction of the necessary facilities at the plants itself will be an expensive and time consuming process.

According to estimates by the Polish Cement Association, the implementation of CCS in the domestic cement industry could generate a demand for an additional 3.2 TWh of energy per year (Elżbieciak, 2022). Furthermore, the construction of an appropriate transmission network, by which the captured CO_2 would reach storage sites or docks, where it would be loaded onto ships, which would then transport it to offshore fields, is a task that requires state participation – not only as a regulator, but also as a source of funding.

An alternative to sequestration is the use of captured CO_2 as a raw material in other industrial processes. Currently, CO_2 is used mainly by the food, agriculture, construction and metal production industries. According to IEA estimates, the demand for CO_2 is expected to reach 272 Mt per year in 2025 (IEA, 2019).

Another potential use for CO_2 emitted in various industrial processes is the production of methanol, which can then be used in the chemical industry and in transport (European Commission, 2021; Narayanan, 2023; VoltaChem 2023). However, the use of CO_2 generated in the clinker production process for combustion in engines will not be without emissions. Ambitions to increase the use of CO_2 in Poland are also declared by Orlen in its strategy (Orlen, 2023, p. 15).

2
option

Geopolymers instead of cement

Geopolymers are synthetic minerals produced (without emissions) from aluminium and silicon. They resemble natural stone (Lelek-Borkowska, 2022). A barrier to the construction industry's switch to geopolymers in place of portland cement is primarily the need to build new facilities to produce this raw material. Choosing this route therefore means not so much decarbonising cement plants, but rather building a new geopolymer sector in place of today's cement plants. The new plants could be located in other parts of the country, since access to cheap green electricity and raw materials will be more important for them than proximity to limestone deposits. Development of such facilities would be another example of a wider change in industrial geography necessitated by the decarbonisation of the economy (Zachman, McWilliams, 2021).

This solution also raises the issue of prices and access to raw materials. For the time being, there is not enough extraction of necessary materials in Poland to meet the needs of the industry, so the production of geopolymers would require increasing the supply of raw materials from abroad. It is uncertain whether such a solution would be economically rational.

Switching the construction industry from relying on cement to geopolymers would also lead to changes in the organisation of supply chains and construction technologies. Today, cement is delivered to construction sites via concrete plants and largely poured to dry on site. The use of geopolymers would mean that the construction industry would have to turn to industrially manufactured prefabricated products.

3.2. Pathways for decarbonising steel

3.2.1. TWO TECHNOLOGIES

The two main steelmaking technologies are the basic oxygen furnace (BOF) and electric arc furnace (EAF) technologies:

- **Basic oxygen furnace (BOF)** – steelmaking using this technology is usually integrated in steel mills with the ironmaking process. The production process is, in a nutshell, as follows. In the first stage, in the so-called blast furnace (BF), iron ore is melted down into pig iron. Coke is used as a reagent in this process. During the second stage of production, in a basic oxygen furnace (BOF), the iron pig is oxidised, and turned into steel. Coal or gas are used as fuel. This whole integrated route of iron and steel production is referred to as the BF-BOF.

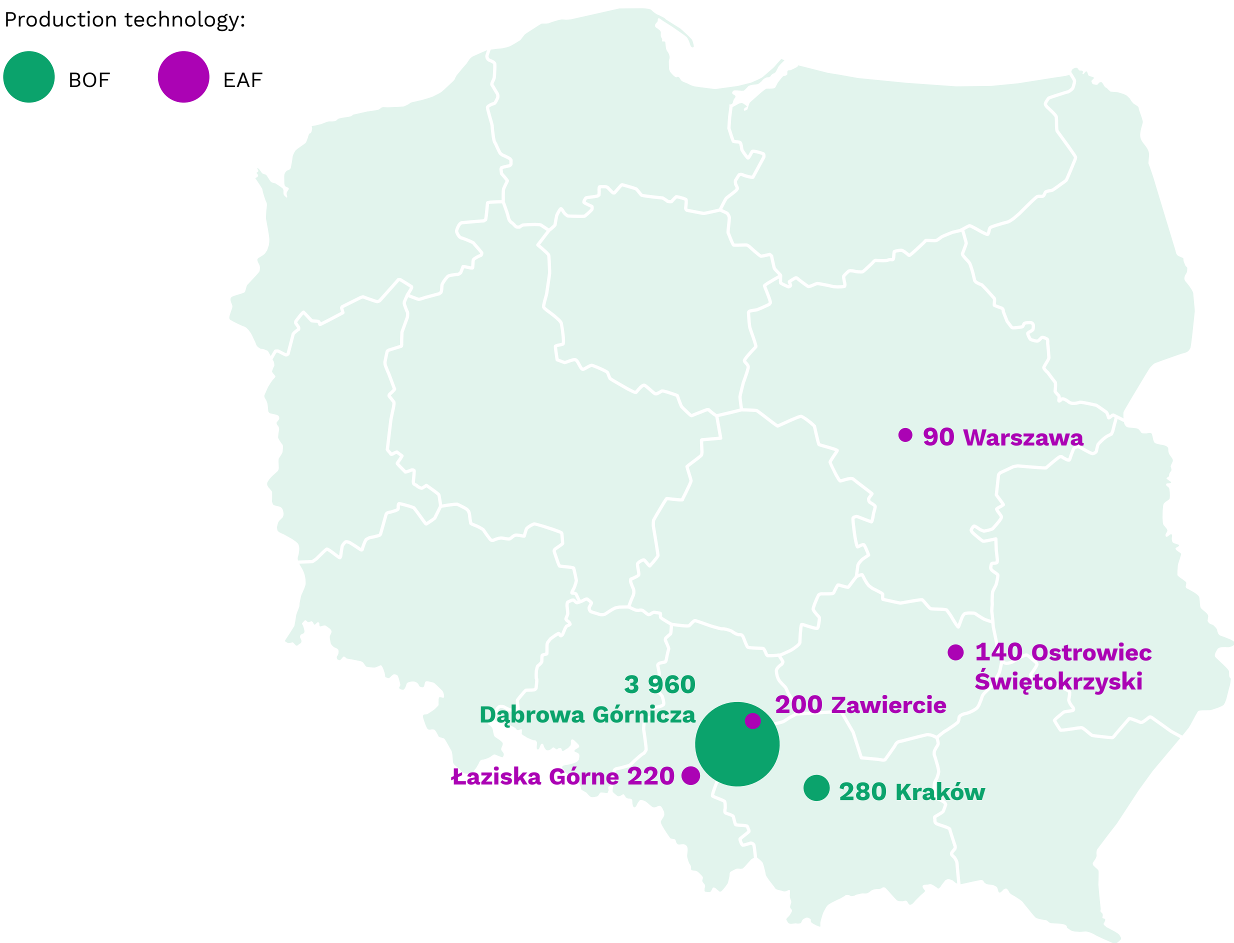
  In Poland, steel is produced with this technology by the ArcelorMittal mill in Dąbrowa Górnicza. Until recently, the company's Krakow steelworks also relied on this technology.

- **Electric arc furnace (EAF)** – electric furnaces are powered by electricity. They can produce primary steel from sponge iron (DRI), obtained by direct reduction of iron ore, but in Poland they are mostly used to produce secondary steel through scrap melting.

  The EAF method is used by steel mills in Warsaw (ArcelorMittal Warsaw), Ostrowiec (Celsa Group), Zawiercie (CMC) and Częstochowa (Liberty Steel, reinstated after a hiatus in 2019-2021).

The share of steel produced using each of these technologies in total crude steel production in Poland in the last decade oscillated around 50% (Wolniak et al., 2020). The dominant position in Polish steel market is held by companies belonging to the ArcelorMittal group, which controls the only mill operating in BOF technology in Dąbrowa Górnicza, which accounted for almost half of the country's crude steel production in 2022, and the Warsaw-based EAF mill (ArcelorMittal Warszawa).

MAP 3. CO_2 emissions from steel mills in Poland in 2020 by technology (in thousand tonnes)



Source: Instrat, based on: Kościółek et al, 2023.

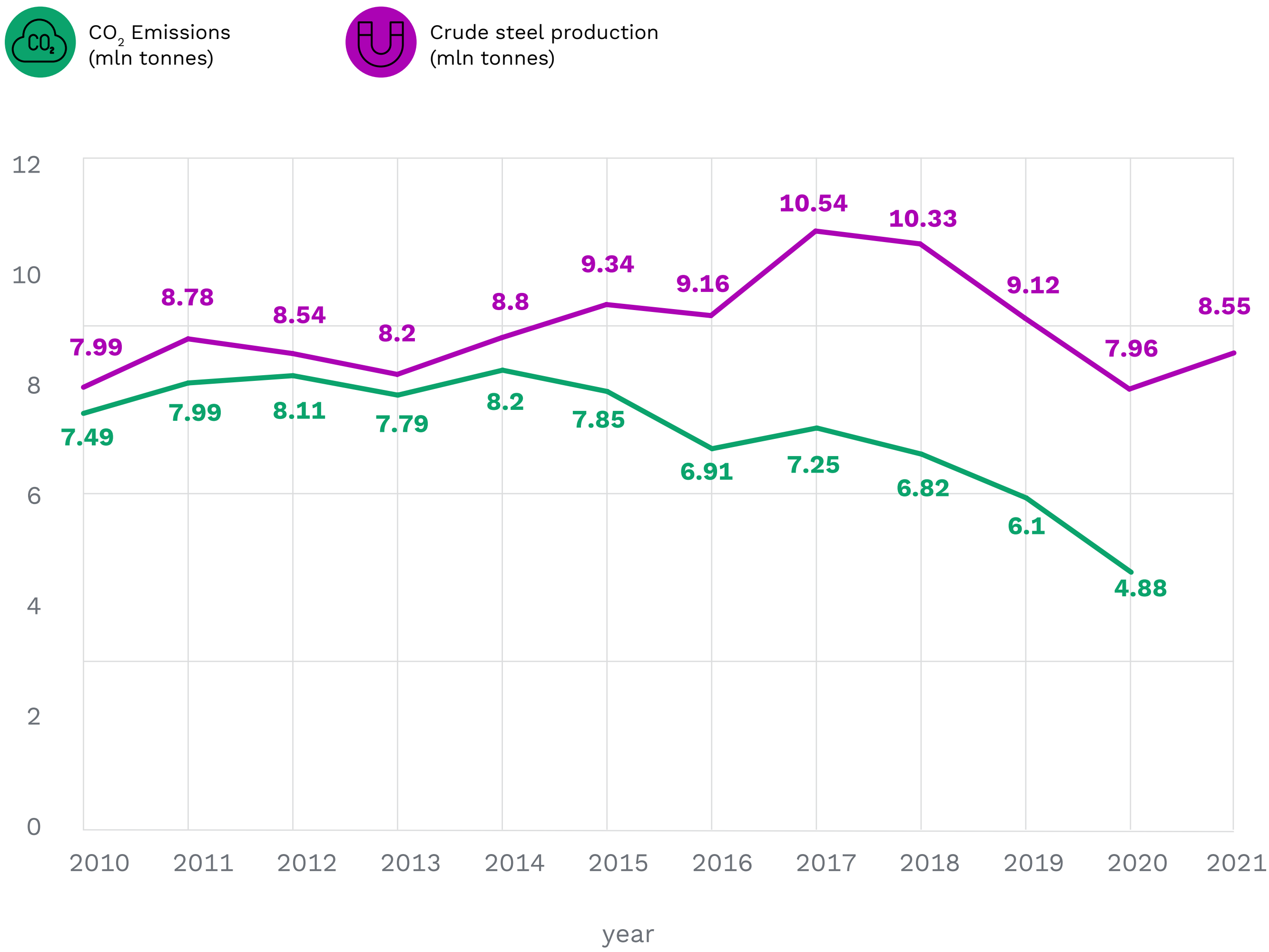
The Częstochowa smelter, which was closed in 2020 and resumed operations in 2023, is not marked on the map. The Krakow smelter marked on the map ceased operations in 2020.

3.2.2. DECOUPLING PRODUCTION GROWTH FROM EMISSIONS GROWTH

From 2010 to 2020, there has been a decoupling of steel production from emissions in Poland – production was increasing or remained constant, yet at the same time CO_2 emissions were decreasing. The steel sector[11] emitted 7.5 million tonnes of CO_2 in 2010, and 4.9 in 2020. Meanwhile, crude steel output was very similar at both beginning and the end of this period at around 8 million tonnes per year. After the restrictions caused by the Covid-19 pandemic, steel production increased in 2021, despite the fact that two major plants closed in 2019 and 2020. The Częstochowa Smelter (Liberty Steel Group, 2023) ceased operation in 2019 and the raw material section of ArcelorMittal's Kraków production site was closed in 2020.

[11] The sector includes PKD 24.10.Z – manufacture of pig iron, ferroalloys, cast iron and steel and steel products.

FIGURE 13. CO_2 emissions from the steel industry in Poland 2010-2020 and crude steel production in Poland (million tonnes)

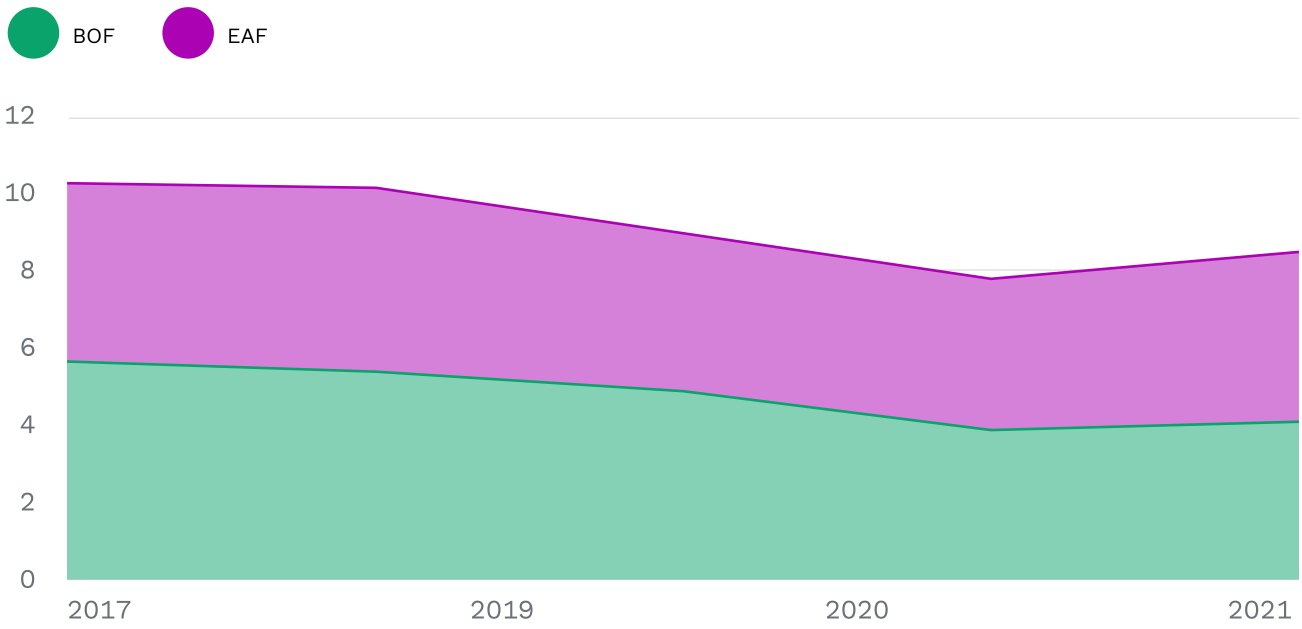


Source: Instrat, based on Kościółek et al, 2023 and GUS data.

The sector includes entities belonging to the PKD category 24.10.Z – production of pig iron, ferroalloys, cast iron and steel and metallurgical products included in the Instrat database according to the E-PRTR eligibility criteria (Kościółek et al., 2023). Data for establishments included in the E-PRTR database.

The decoupling of steel production from emissions can be explained by high levels of capital expenditures in the sector, between 2006 and 2009. The investments allowed for an increase in energy efficiency and natural gas substitution for coke and semi-coke as fuel (Wolniak et al., 2020). In contrast, this cannot be explained by an increase in the share of steel produced in the low-carbon electric arc furnace (EAF) technology, at the expense of production using the basic oxygen furnace (BOF) route, as the share of each remained relatively steady (between 2017 and 2021, the share of BOF varies between 48% and 55%).

FIGURE 14. Crude steel production in Poland in the electric arc furnace (EAF) and basic oxygen furnace (BOF) technologies 2017-2021 (million tonnes)



Source: Instrat, based on: HIPH, 2023.

3.2.3. THREE OPTIONS FOR DECARBONISATION

Steel produced using EAF technology is less carbon intensive than steel produced in the BOF process. Arc furnaces use significantly less fossil fuels for process needs (Nimbalkar et al., 2015). In contrast, oxygen furnaces burn fossil fuels, mainly coke. Coke is used not only as a heat source, but also as a reducing agent in the process of converting iron ore into steel.

Due to the significant share of process emissions, BOF technology is much more difficult to decarbonise. Increasing energy efficiency and switching to less emission intensive fuels and reagents reduces emissions, but will not eliminate them entirely. To bring steel production to climate neutrality, it is necessary to choose one of the three options:

1. Abandoning BOF primary steelmaking technology in Poland, in favour of circular remelting of steel in EAFs.
2. Investment in the capture and storage/use of CO_2 (CCUS) from the BF-BOF process.
3. Changing primary steelmaking technology to direct reduction methods (DRI) using green hydrogen, and temporarily natural gas, and direct electrolysis.

Currently, the EU ETS system provides limited incentives for decarbonisation of steel production as most emission allowances are free (Kobylka et al., 2023, p. 11). However, free emission allowances are to be phased out by 2034. Steel production is also subject to a carbon border tax (CBAM), which will charge non-EU steel producers exporting their products to the EU for their emissions, in proportion to the ETS.

1
option

Abandoning the BF-BOF steel production route and its costs

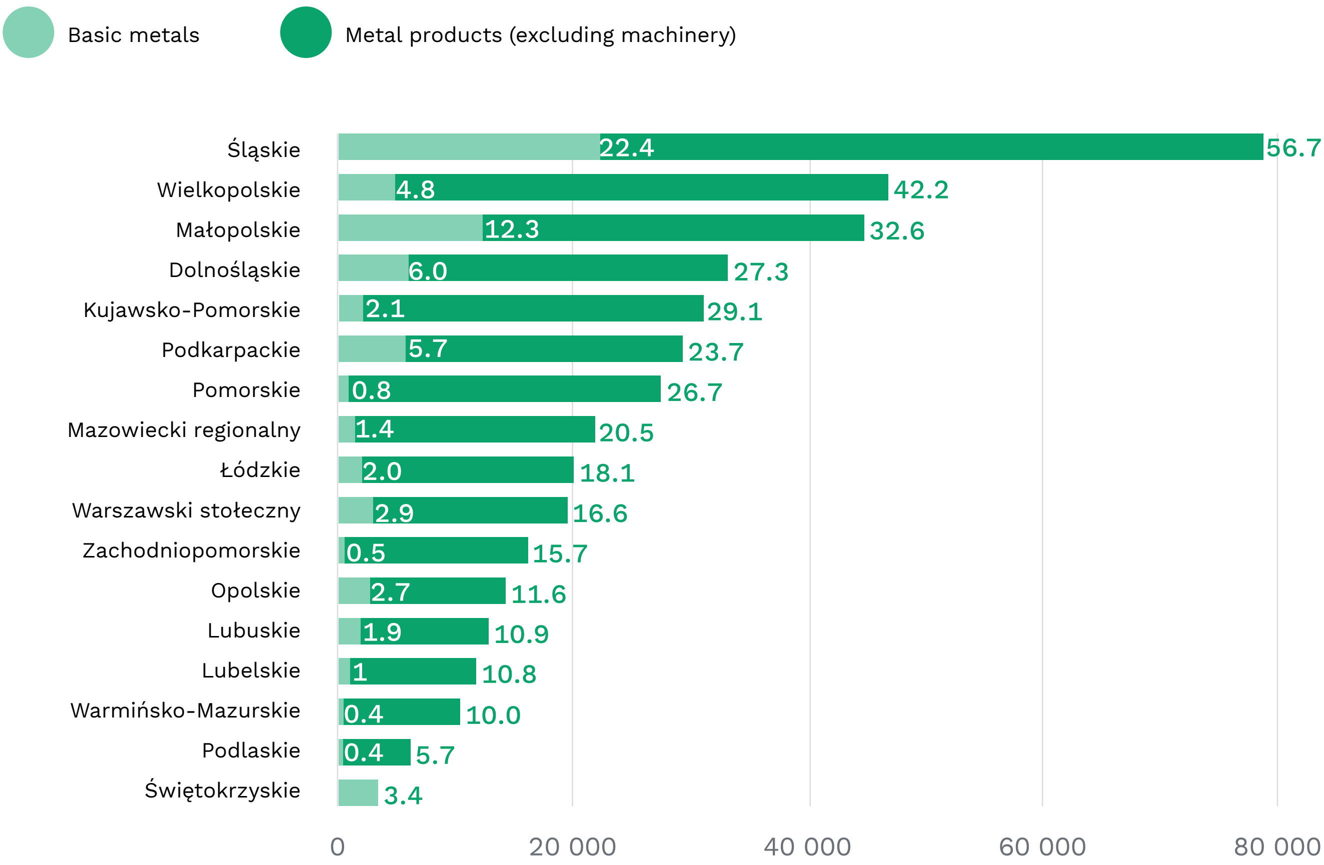
Abandoning steel production in the BOF technology – without simultaneously replacing it with another method or increasing the output of EAF-produced steel – would result in a drop in the volume of domestic steel output by about 50%. This would entail a loss of added value and jobs, and the need to import this raw material, probably from countries where manufacture of iron is more emission-intensive.

While the economic footprint of the steel production sector in Poland is comparable to the EU average, the next step in the steel value chain – the manufacturing of metal products – is much more significant. At the end of 2022 Poland was ranked 23rd in the world in terms of crude steel production (World Steel Association, 2023) versus 21st in the world in terms of GDP (World Bank, 2023). The share of basic metal production (which includes not only steel) in value added in the Polish economy was 0.4% in 2020, just below the 0.5% in the European Union as a whole (Eurostat, 2023a). Meanwhile, in 2020 the manufacturing of metal products industry (excluding machinery and tools) accounted for 2.4% of value added in the Polish economy, while in the UE in 2019 (the most recent value) it stood at 1.4%.

Steelmaking and metal products are related industries. Many metal products are manufactured at the same plants where steel is smelted. Combined employment in both sectors in the Silesian Voivodeship – where the only BF-BOF plant operates – alone, was close to 80 000 people in 2020 (Eurostat, 2023b).

However, the fate of companies in the Polish metal processing sector is not intrinsically linked to steel production in Poland. In the event of a decrease in the volume of domestic production, the industry could seek to secure the supply of steel outside Poland. This however, could entail higher sourcing costs and a decrease in the profitability.

FIGURE 15. Number of persons employed in the basic metals and metal products manufacturing (excluding machinery and tools) sector in 2020 in NUTS3 (in thousands)



Source: Instrat based on data from: Eurostat, 2023.

Forecasts of steel consumption in the coming decades, certainly provide reasons to maintain and further expand domestic steel production capacity. Global steel demand could increase by up to 20-30% by 2050 (IEA, 2020). The prospect of increasing demand is attributed, among other factors, to the growth of the sectors which are to play essential roles in the energy transition, such as the manufacturing of wind turbines and electric cars.

At the same time, there is the potential to increase the use of scrap, which can be melted down into steel in EAF electric furnaces (in place of or in addition to maintaining production in oxygen furnaces). The EU is currently a net exporter of ferrous scrap. In 2021, ferrous scrap exports outside the EU amounted to 19.5 million tonnes, with the main destinations being Turkey as well as the UK, India, Egypt and Switzerland (Eurostat, 2022). Export volumes have been increasing since 2015. This means that there is a high supply of scrap on the European market that can be processed into green steel in electrified furnaces.

EAF steel production is low-carbon, and as such much less burdened by costs of emission allowances, rendering this steelmaking process potentially more cost-competitive outside the EU.

2
option

CCUS in steel production

One proposal to reduce emissions from steel production in BOFs is to capture and store or use the emitted CO_2. However, the scale and costs of such investments are a significant problem. The only BOF site in operation in Poland is located in Dąbrowa Górnicza. However, projects that would allow CO_2 to be stored underground in the country are at a very early stage. There is also no infrastructure to transport CO_2 from the Silesian Voivodeship to seaports, through which the gas could be transported to storage sites in the sea. At the same time, other industries in which avoiding process emissions is much more difficult, as the technological alternatives are less developed, such as the cement industry, will compete for CO_2 storage capacities.

Unlike in the cement industry, there are technological alternatives that can be employed in steel manufacturing.

3
option

Green steelmaking methods

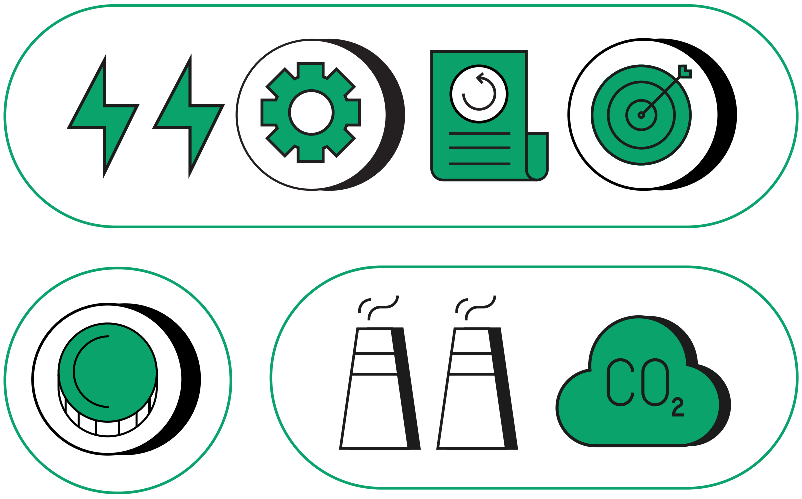
An alternative to coke-based iron ore steel making technology is the *direct-reduced iron* (DRI) **method**. Current DRI mills use natural gas as a reducing agent, but it can be replaced with green hydrogen. When switched to hydrogen in place of natural gas, this technology is carbon neutral (Agora Industry et al., 2022).

Natural gas-based DRI is being used by steel mills in regions where gas is cheap – these are mainly countries in North Africa and around the Persian Gulf (Agora Energiewende, 2023). But there are projects underway to launch DRI-based steelmaking in Europe such as thyssenKrupp's Duisburg plant (Reuters, 2023) or ArcelorMittal's Hamburg plant (ArcelorMittal). A pilot project is also underway in Luleå, Sweden (Hybrit, 2023).

The greatest difficulty in developing emission-free DRI processes is the supply of large volumes of green hydrogen at a moderate price. The Polish Hydrogen Strategy sets ambitious production targets for 2030 of nearly 200,000 tonnes of hydrogen from a 2 GW installation. However, it must be taken into account that the prospect of surplus electricity in the national grid in 2030 is negligible due to a structural shortage of capacity resulting from retirements of the coal-fired plants and low ambitions to build new RES capacity (MKiŚ, 2021; Swoczyna, 2023b). Poland has no large-scale green hydrogen production projects, with only a small-scale ZE PAK project at Konin Power Plant currently in operation (ZE PAK, 2021).

Another potential alternative technology for producing green steel is **direct electrolysis**. In this technology, oxygen is removed from the ore without the use of any additional reductants. The steel produced using this technology is cleaner than steel produced using other methods (World Steel Association).

The start-up of a mill operating using this technology has been announced by ArcelorMittal, although it has not yet publicly stated the location of the planned plant (Myszor, 2023). The advantages of direct electrolysis are scalability, the ability to work with lower quality ores and the fact that only iron ore and electricity are required to operate the process (The Economist, 2023). However, it is not yet an industrial-scale technology.



4. Green investment shock – modelling the macroeconomic effects of energy transition

4.1. Modelling assumptions and inputs

To understand the impact of changes in energy generation sources and production technologies in energy-intensive sectors, we used macroeconomic modelling. We first developed an input-output model for the Polish economy. The purpose of this model iswas to illustrate the impact of a positive macroeconomic shock, resulting from increased investment in the energy transition (especially in RES), on the most important macroeconomic factors – the volume of domestic demand, value added and employment, (particularly in energy-intensive sectors.).

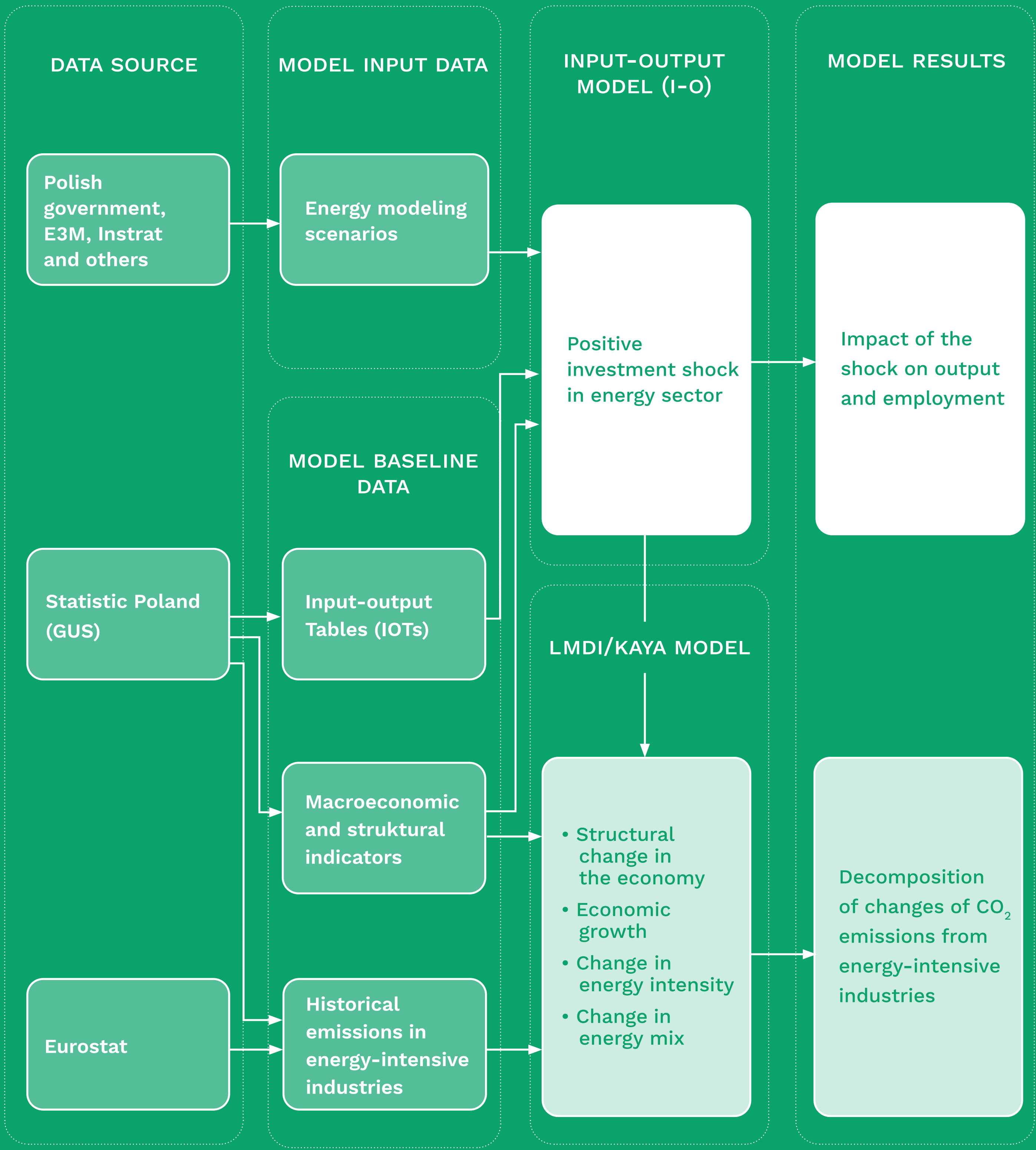
The positive investment shock was defined as the difference in energy transition investment values between the European Commission's *PRIMES REF2020* reference scenario (E3M, 2021) and the (more ambitious) government scenario contained in the *Energy Policy of Poland until 2040* (PEP2040) as published in 2023 by Ministry of Climate and Environment (MKiS, 2023). In addition to the data from the mentioned scenarios, we also used data from the GUS and Eurostat in the modelling.

In a second step, a model based on the LMDI/KAYA methodology was developed with the aim of decomposing the factors affecting CO_2 reductions in energy-intensive sectors. To simplify the interpretation, a logarithmic disaggregation index (LMDI) was calculated (Ang, 2004). An additive decomposition scheme was then selected as more appropriate for quantitative analysis (Ang, 2015). Results from earlier macroeconomic modelling using an input-output model were also applied.

The LMDI/KAYA decomposition shows the results of the decomposition of CO_2 changes in energy-intensive industries due to changes in:

- value added generated in these industries,
- the structure of the added value generated in these industries,
- energy intensity of these industries,
- carbon intensity of the energy mix in these industries.

DIAGRAM 1. INPUT-OUTPUT (I-O) MACROECONOMIC MODELLING AND LMDI/KAYA



Source: study by Instrat based on the I-O & LMDI/KAYA macroeconomic model.

In other words, the LMDI/KAYA decomposition makes it possible to determine the extent to which each of the factors indicated above has contributed to changes in CO_2 both historically and over the modelled time range.

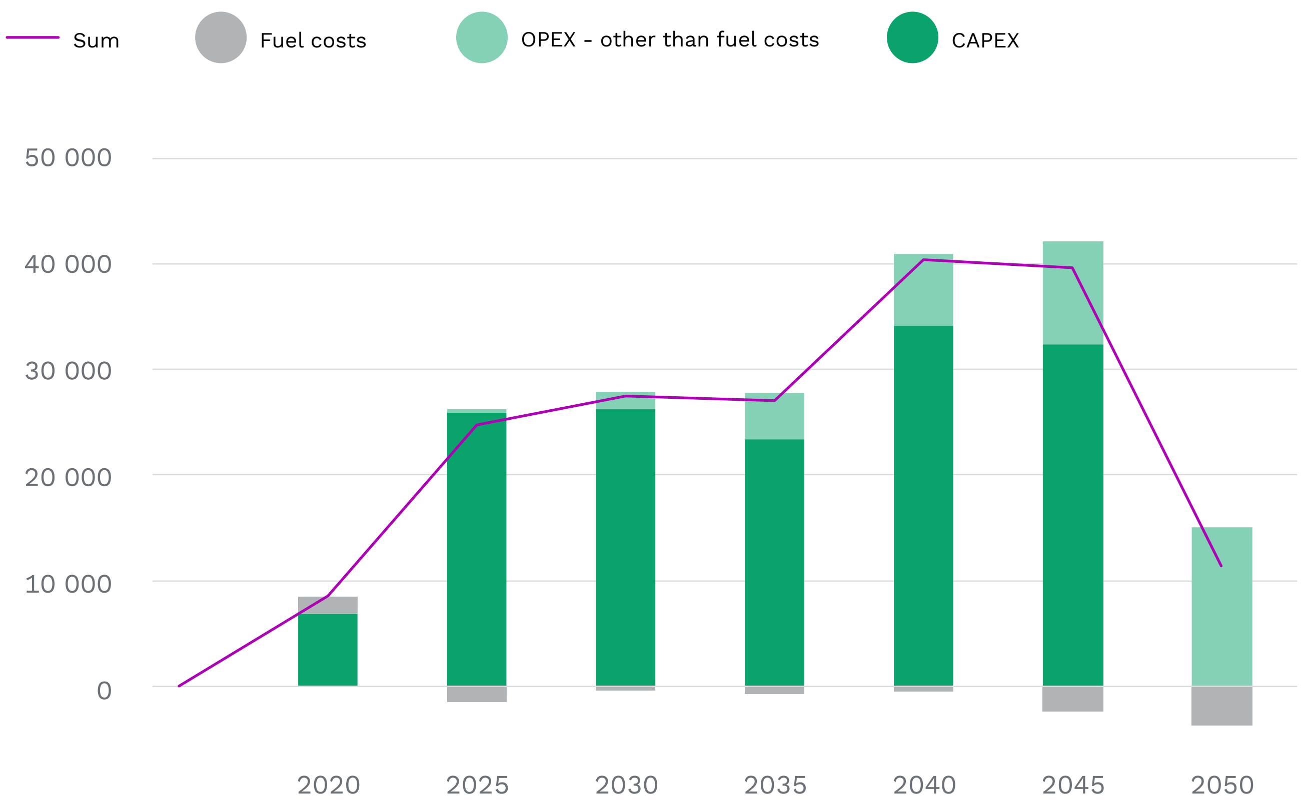
A technical description of the methodology used can be found in the appendix at the end of this report.

4.2. Positive investment shock – how increased investment in the energy transition will affect the Polish economy and energy-intensive sectors

A positive investment shock was defined as the difference between the EC/E3M, PRIMES and MKiS, PEP2040 scenarios in the value incurred:

- capital expenditure for the energy transition (CAPEX),
- operating costs (OPEX), other than fuel costs,
- fuel costs.

FIGURE 16. Value of positive investment shock by investment costs, maintenance costs of new investments and fuel costs (mPLN'2015) over the period 2020-2050



Source: Instrat study based on I-O & LMDI/KAYA macroeconomic model.

Values represent averaged expenditure over five-year periods, e.g. the value for 2020 represents the averaged expenditure for 2020-2024.

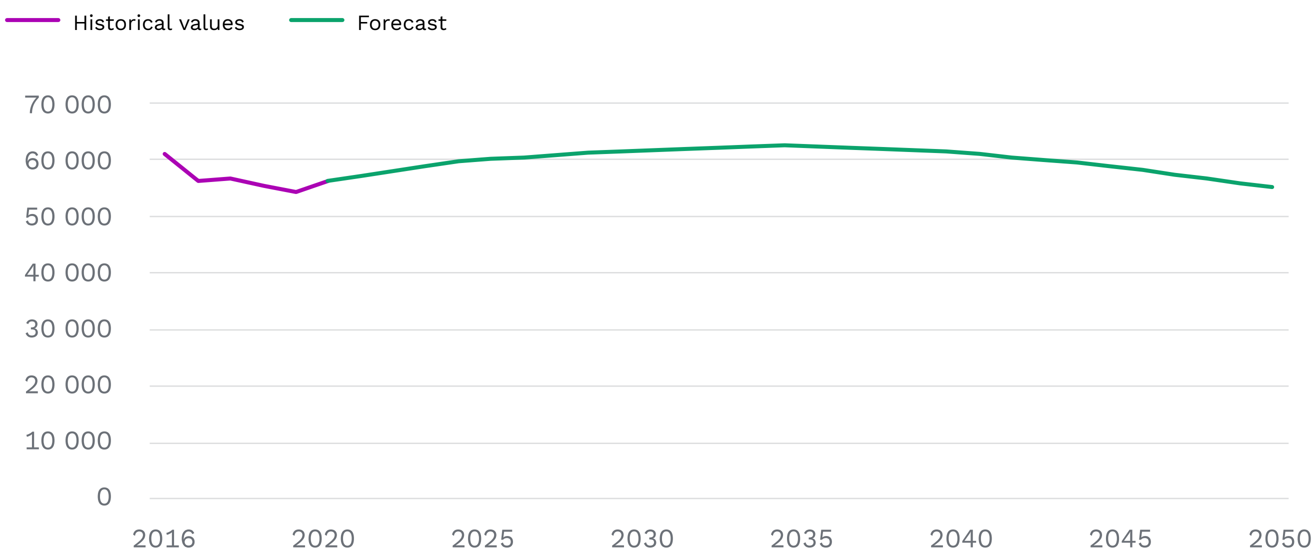
The value of the shock will gradually increase until 2050. The vast majority of this is the value of new investments. The costs caused by maintaining new energy investments will also increase throughout the shock modelling period. However, these costs will be partly offset by savings generated through lower fossil fuel consumption than in the baseline.

The annual value of the positive shock (calculated in constant 2015 prices) will not exceed PLN 10bn in 2020-2024, while it will increase markedly thereafter and remain in the range of PLN 25-30bn in 2025-2035. Thereafter, the value of the shock in annual terms will exceed PLN 40bn in 2040-2049. Until 2035, higher investment outlays will be responsible for almost the entire value of the shock, while from that year onwards the costs of maintaining new capacity will increase markedly.

However, the real size of the shock (measured relative to the size of the whole economy) will decrease between 2025 and 2040 due to economic growth. The share of these expenditures in the economy will only increase between 2020 and 2025, and between 2040 and 2050. The scenario assumes that by 2050 all investments in the energy transition have already been made and only infrastructure maintenance costs will then remain.

For the purposes of macroeconomic modelling, we have developed a forecast of the value added generated by all sectors of the economy in a positive shock scenario. We assume that energy-intensive sectors will increase the value added generated until 2035, at which point it will be 12% higher than in 2019. Thereafter, value added will start to decline slowly, mainly as a result of strong production reductions in coke and refined petroleum products manufacturing and processing. In 2050, the value added generated by energy-intensive sectors will return to the level reached in 2019.

FIGURE 17. Forecast value added generated by energy-intensive sectors in the positive energy investment shock scenario (PLN million at constant 2015 prices)



Source: study by Instrat based on the I-O & LMDI/KAYA macroeconomic model.

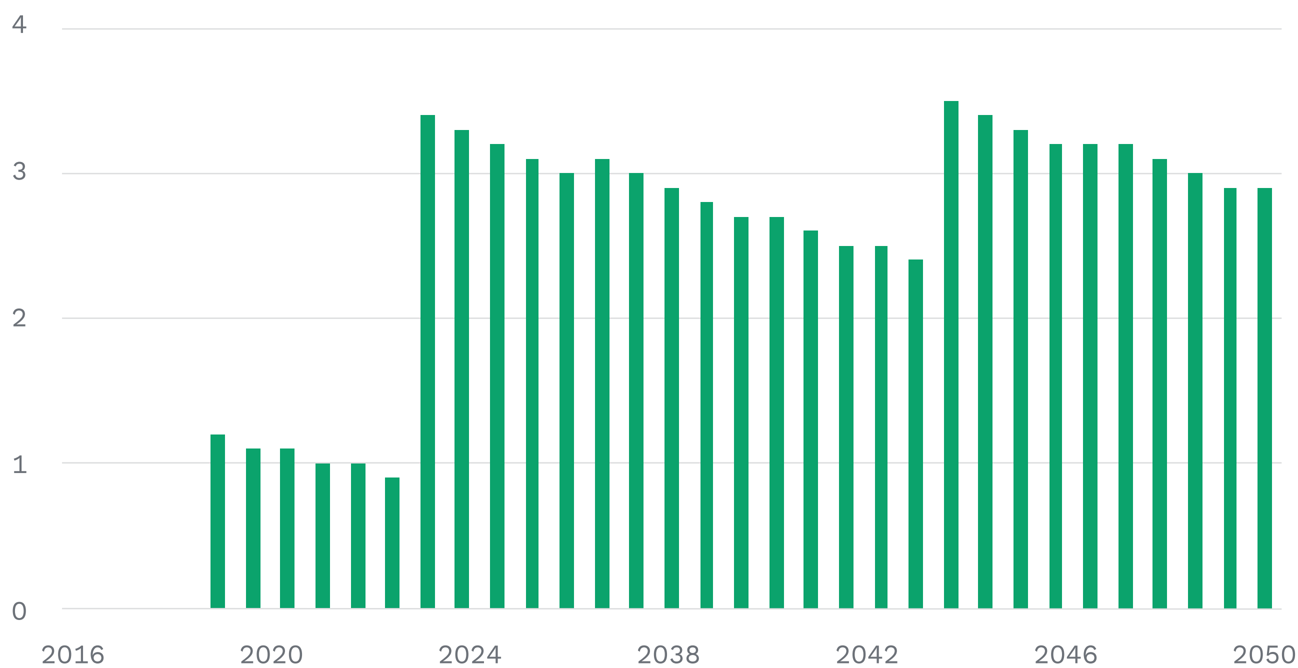
The shock will positively affect the production of these sectors through both the supply channel, i.e. by lowering production costs, and the demand channel.

The results of the *input-output* macroeconomic modelling also indicate that, as a result of the shock, employment in energy-intensive sectors could increase by more than 3 thousand employees already from 2026. In the following years, additional employment will be slightly lower (until 2040 it will be above 2 thousand), while after 2040 it will increase again. In 2050, employment in energy-intensive sectors will be higher by almost 3 thousand employees, an increase of around 0.8% relative to 2019.

Both marked increases in employment will result from increased capital expenditure (CAPEX) on the energy transition. The first takes place between 2020-2025 and 2025-2030, and the second between 2035-2040 and 2040-2045. The increase in these expenditures will result in higher demand for products produced by energy-intensive sectors, especially the metal manufacturing sector (structural components, machinery and equipment) and the other non-metallic mineral products manufacturing sector (cement). Higher demand will translate into increased employment in these sectors. After initial strong increases, CAPEX will decline slightly, and with it demand and employment in energy-intensive sectors.

As a result of the green investment shock, production efficiency in these sectors, measured as value added per employee, will not change significantly.

FIGURE 18. Projected change in employment in energy-intensive sectors as a result of production changes in the positive investment shock scenario (thousands of employees)



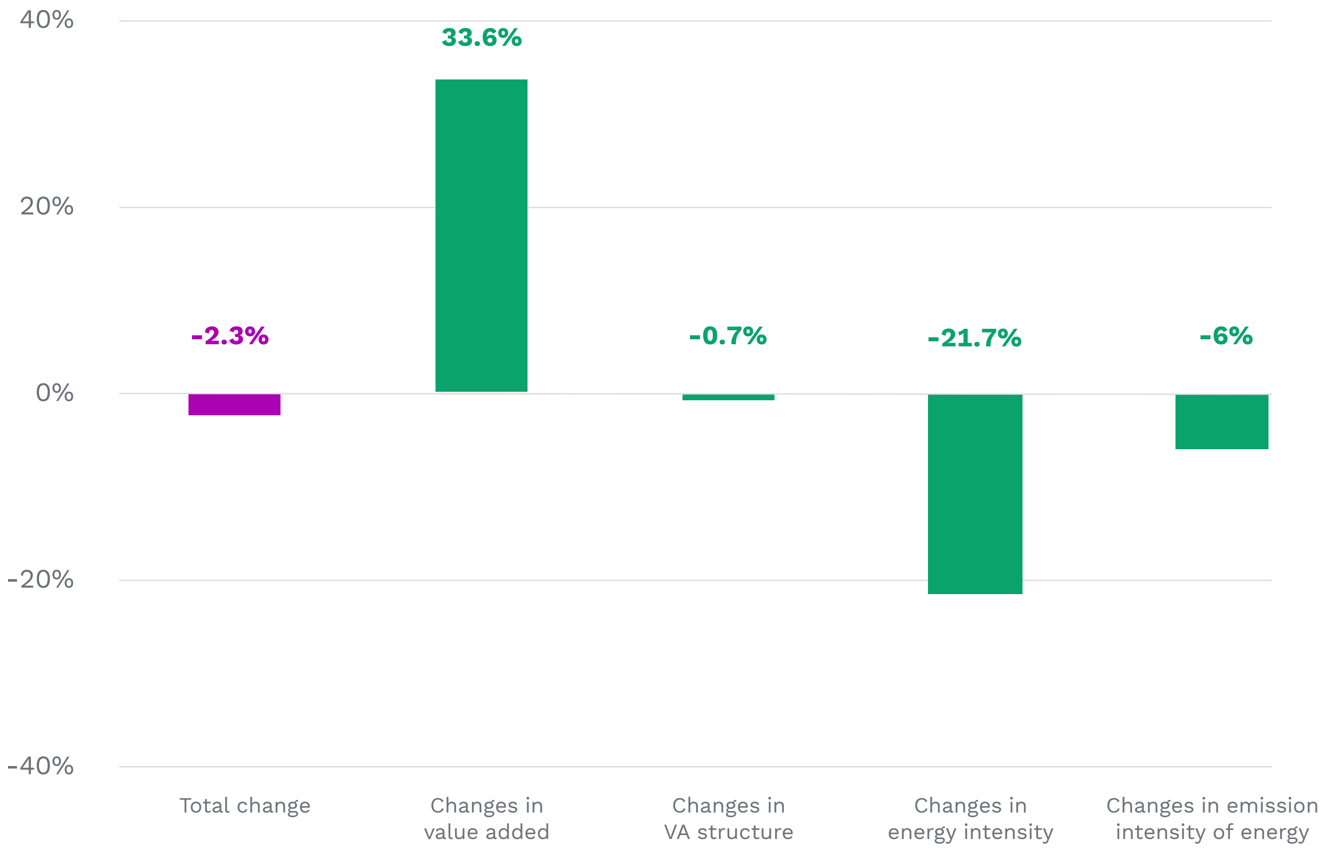
Source: study by Instrat based on the I-O & LMDI/KAYA macroeconomic model.

4.3. Decarbonisation pathways – results from modelling of decarbonisation scenarios up to 2050

Based on the results of *input-output* macroeconomic modelling, we decomposed the CO_2 emissions of energy-intensive sectors. Its aim was to examine the impact of changes in value added generated in these sectors, structure of this added value, as well as in the energy intensity and carbon intensity of the energy mix of these industries, on total emissions of these sectors.

A decomposition of the changes in CO_2 emissions was made for two periods. The first is the years 2012-2021, for which data from GUS on Scope 1 (on-site) energy and process emissions and energy consumption were available. The second is the years 2021-2050, for which we made assumptions on the energy intensity and carbon intensity improvements of energy consumption, and used the projections of the value added generated by these sectors developed within the input-output model.

FIGURE 19. Decomposition of changes in CO_2 emissions of energy-intensive sectors between 2012 and 2021 (as a percentage decrease in emissions relative to 2012).



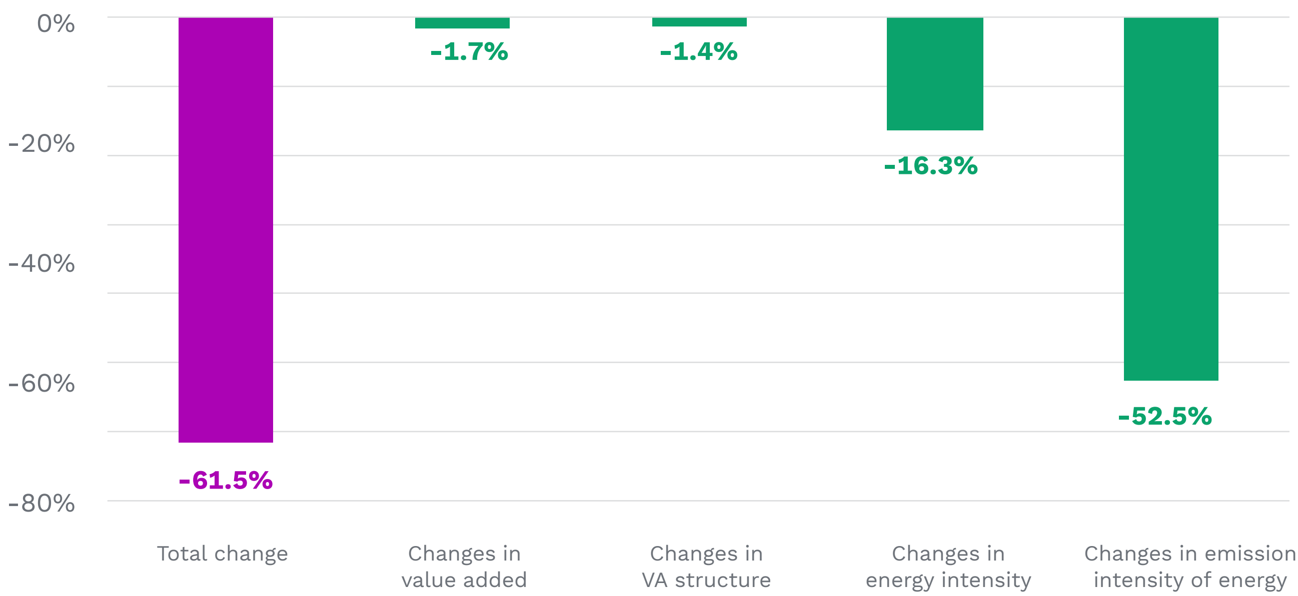
Source: study by Instrat based on the I-O & LMDI/KAYA macroeconomic model.

Between 2012 and 2021, the CO_2 emissions of energy-intensive sectors decreased by 2.3%, reaching 46.4 million tonnes of CO_2 at the end of the period. However, during this period the value added generated by these sectors increased by 33.6%. The increase in emissions resulting from the increase in value added was mainly offset by a significant improvement in energy intensity. This translated into a 21.7% decrease in emissions. The decrease in the decarbonisation of energy consumption in turn reduced emissions by 6%. Subsequently, changes in the structure of value-added generation reduced the emissions of energy-intensive sectors by 0.7%.

Thus, between 2012 and 2021, there was decoupling between the sectors' production dynamics (measured as value added) and CO_2 emissions. The phenomenon observed in the steel sector (see section 3.2.2.) was also a characteristic of other energy-intensive sectors, although it took on different faces. In the case of steel, the maintenance of production was accompanied by a decrease in absolute emissions. In the other sectors, the increase in production was accompanied by the maintenance of production at a relatively stable level.

This is a positive development, as it shows that it is possible to increase production in these sectors without simultaneously increasing absolute emissions. On the other hand, the absolute emissions of energy-intensive sectors in 2021 were only slightly lower than in 2012, which means that the sectors analysed have made almost no progress towards the climate targets during this time.

FIGURE 20. Decomposition of the projected change in CO_2 emissions of energy-intensive sectors between 2021 and 2050 (as a percentage decrease in emissions relative to 2021) in the positive investment shock scenario



Source: study by Instrat based on the I-O & LMDI/KAYA macroeconomic model.

Between 2021 and 2050, the emissions of the energy-intensive sectors in our modelling fall by 61.5%. This occurs against a slight decline in the value added generated by these sectors, which is expected to be 1.7%. In 2012, each PLN 1 million of value added generated in energy-intensive sectors was associated with an average of 1090 tonnes of CO_2. In 2021, it was 797 tonnes of CO_2, in 2050, this figure will drop to 313 tonnes.

The main driver of emission reductions will be the decarbonisation of energy, at 52.5%. Reducing the energy intensity of the industries analysed will reduce emissions by 16.3% and a change in the production mix will result in a decrease of a further 1.4%.

The most important single decarbonising factor will therefore be different from 2012-2021. At that time, energy-intensive sectors modernised their production facilities, resulting in lower energy consumption per value added. At the same time, however, there was very little change in the decarbonisation of energy, which was mainly due to small improvements in the decarbonisation of the energy mix across the economy.

Between 2021 and 2050, the decarbonisation of power generation should decrease significantly as a result of the energy transition and the huge increase in RES capacity. At the same time, the modernisation of industrial production technology will continue to progress, although it will not be as rapid as in 2012-2021.

It is also worth noting that maintaining value added in 2050 at a similar level to 2021 will mean a very significant decrease in the share of energy-intensive sectors in the overall economy, driven by economic growth. In 2021, the share of these four sectors in the Polish economy, measured by value added, was 2.9%. In 2050, however, it will fall to 1.6%.

LIMITATIONS OF THE RESEARCH METHOD USED

It should also be borne in mind that the CO_2 decomposition modelling we developed using the LMDI/KAYA method also has its limitations. Firstly, the model only partially takes into account advances in production technology and the consequent decrease in energy intensity of the industries analysed. It does not take into account, for example, the possibility of commissioning carbon-neutral steelmaking technology in the DRI method or the application of CO capture and storage technology2 (CCS/CCUS) generated by energy-intensive sectors. Second, the model does not take into account changes in the regulatory environment that may result in the closure or severe curtailment of selected industries. Thirdly, the model assumes a steady, linear improvement in energy carbon intensity. Finally, the modelling is based on a forecast of the value added generated by the sectors, developed using an input-output model, the limitations of which are described in this chapter.

Bibliography

Agora Energiewende. Global Steel Transformation Tracker. https://www.agora-energiewende.de/en/service/global-steel-transformation-tracker/ (9.06.2023).

Agora Industry, FutureCamp, Wuppertal Institute, Ecologic Institute. (2022). *Transforming industry through carbon contracts. Analysis of the German steel sector*. https://www.agora-energiewende.de/en/publications/transforming-industry-through-carbon-contracts-steel/ (28.09.2023).

ArcelorMittal. (2022). *ArcelorMittal Poland na stałe zamknie część surowcową krakowskiej huty*. https://poland.arcelormittal.com/media/aktualnosci/artykul/arcelormittal-poland-na-stale-zamknie-czesc-surowcowa-krakowskiej-huty (6.10.2023).

ArcelorMittal. *Hydrogen-based steelmaking to begin in Hamburg*. https://corporate.arcelormittal.com/media/case-studies/hydrogen-based-steelmaking-to-begin-in-hamburg (28.09.2023).

Ang. B. W. (2004). *Decomposition analysis for policymaking in energy: which is the preferred method?*, Energy Policy vol. 32/2004.

Ang. B. W. (2015). *LMDI decomposition approach: A guide for implementation*, Energy Policy vol. 86/2015.

Bank Światowy. (2023). *Gross domestic product 2022*. https://databankfiles.worldbank.org/public/ddpext_download/GDP.pdf

Beyond Zero Emissions. (2017). *Zero Carbon Industry Plan. Rethinking Cement*. https://bze.org.au/research_release/rethinking-cement/ (17.01.2023).

E3M. (2021). *Reference Scenario 2020* (REF 2020). Primes Ver. 6 Energy Model. https://energy.ec.europa.eu/document/download/1485062e-2d65-47cb-887a-a755edc2ec36_en?filename=ref2020_energy-transport-ghg.xlsx (11.05.2023).

Elżbieciak, T. (2022). *Energetyka i cementownie szykują się do inwestycji w CCS*. Wysokie napięcie. https://wysokienapiecie.pl/72564-energetyka-i-cementownie-szykuja-sie-do-inwestycji-w-ccs/ (6.10.2023).

Elżbieciak, T., Skłodowska, M. (2023). *Gigawaty nowych mocy z OZE dla przemysłu stają się realne*, Wysokie Napięcie, https://wysokienapiecie.pl/91443-gigawaty-nowych-mocy-z-oze-dla-przemyslu-staja-sie-realne/ (25.08.2023).

Elżbieciak, T., Zasuń, R. (2023). *Przemysł nie może się doczekać obiecanych miliardów*, Wysokie Napięcie, https://wysokienapiecie.pl/92208-przemysl-nie-moze-sie-doczekac-obiecanych-miliardow/ (19.09.2023).

Eurostat. (2022). *EU trade in recyclable raw materials is on the rise.* https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220510-1 (9.06.2023).

Eurostat. (2023). *National accounts aggregate by industry*. https://ec.europa.eu/eurostat/databrowser/bookmark/088bed65-59c2-41c6-a5b3-7b8f54bafb69?lang=en (7.06.2023).

Eurostat. (2023b). *SBS data by NUTS 2 regions and NACE Rev. 2*. https://ec.europa.eu/eurostat/databrowser/bookmark/fa88c84b-43c7-4871-a349-94dbe72c9657?lang=en (28.09.2023).

Fleming S., Hancock A., Espinoza J., *Can the EU keep up with the US on green subsidies?*, 1.02.2023, Financial Times, https://www.ft.com/content/85b55126-e1e6-4b2c-8bb2-753d3cafcbe5.

Frank, S. (2023). *Emissions Trading System exemptions betray the steel sector's power and politicians' lack of mettle.* https://carbonmarketwatch.org/2023/05/05/emissions-trading-system-exemptions-betray-the-steel-sectors-power-and-politicians-lack-of-mettle/ (29.09.2023).

Friedmann, J., Fan, Z. (2019), *Lowcarbon heat solutions for heavy industry: Sources, options*, and costs today, https://www.energypolicy.columbia.edu/publications/low-carbon-heat-solutions-heavy-industry-sources--options-and-costs-today/.

GUS. *Zużycie paliw i nośników energii w 2021 roku*. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/zuzycie-paliw-i-nosnikow-energii-w-2021-roku,6,16.html.

GUS. (2023). *Rocznik Statystyczny Przemysłu 2022*. https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-statystyczny-przemyslu-2022,5,16.html.

Hasanbeigi, A., Kirschbaum, L. A., Collison, B. (2023). *Industrial Electrification in U.S. States. An industrial subsector and state-level techno-economic analysis*. https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/644b590c1b2a3c41e1ff4e8f/1682659627566/State+level+industrial+Electrification-2.6.2023+Clean-E.7.pdf.

Hetmański, M., Kiewra, D., Iwanowski, D., Czyżak, P. (2021). *Sprawiedliwa transformacja w Wielkopolsce Wschodniej – diagnoza i wytyczne*, Fundacja WWF, https://instrat.pl/wp-content/uploads/2021/02/WWF-Poland-Sprawiedliwa-transformacja-w-Wielkopolsce-Wschodniej-Raport-2021-02-23.pdf.

HIPH. (2023). *Polski Przemysł Stalowy 2022.* https://www.hiph.org/ANALIZY_RAPORTY/pps.php.

Hybrit. (2022). *HYBRIT: Milestone reached – pilot facility for hydrogen storage up and running*. https://www.hybritdevelopment.se/en/hybrit-milestone-reached-pilot-facility-for-hydrogen-storage-up-and-running/ (6.10.2023).

IEA. (2019a). *The Future of Hydrogen. Seizing today's opportunities*, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

IEA. (2019b). *Transforming Industry through CCUS*, https://iea.blob.core.windows.net/assets/0d0b4984-f391-44f9-854f-fda1ebf8d8df/Transforming_Industry_through_CCUS.pdf.

IEA. (2020). *Global end-use steel demand and in-use steel stock by scenario*, 2000-2050. https://www.iea.org/data-and-statistics/charts/global-end-use-steel-demand-and-in-use-steel-stock-by-scenario-2000-2050 (28.09.2023).

IEA. (2022). *Global hydrogen Review 2022*. https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

IEA. (2023). *Global Hydrogen Review 2023*. https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aaa175d/GlobalHydrogenReview2023.pdf.

IEA. (2019). *Putting* CO_2 *to Use*. https://www.iea.org/reports/putting-co2-to-use.

IIGCC. (2021). *Global Sector Strategies: Investor interventions to accelerate net zero steel*. https://www.climateaction100.org/wp-content/uploads/2021/08/Global-Sector-Strategy-Steel-IIGCC-Aug-21.pdf.

Instytut Energetyki. (2023). *Łańcuch wartości gospodarki wodorowej w Polsce*. https://www.hiph.org/ANALIZY_RAPORTY/pps.php.

Kleimann, D. i in. (2023). *Green tech race? The US Inflation Reduction Act and the EU Net Zero Industry Act*, "The World Economy". https://onlinelibrary.wiley.com/doi/abs/10.1111/twec.13469.

Kobyłka, K. i in. (2023). *Dekarbonizacja przemysłu ciężkiego. Zrównoważone finansowanie jako szansa?* https://wise-europa.eu/2023/03/13/bariery-dla-dekarbonizacji-przemyslu-ciezkiego-w-polsce/.

Komisja Europejska. (2023). *Carbon Border Adjustment Mechanism*. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_pl.

Komisja Europejska. (2023a). *Komunikat Komisji do Parlamentu Europejskiego, Rady Europejskiej, Rady, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów. Plan przemysłowy Zielonego Ładu na miarę epoki neutralności emisyjnej,* COM(2023) 62 final, https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX:52023DC0062.

Komisja Europejska. (2023b). *Competition State aid brief*. https://competition-policy.ec.europa.eu/system/files/2023-07/state_aid_brief_1_2023_kdam23001enn_TCTF_survey_0.pdf

Komisja Europejska. (2021). *Converting CO_2 to methanol via steel production to power marine transport.* https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/converting-co2-methanol--steel-production-power-marine-transport (6.10.2023).

Komisja Europejska. (2023c). *Just Transition Platform. Accompanying Member States and regions to achieve a just transition*. https://ec.europa.eu/regional_policy/funding/just-transition-fund/just-transition-platform_en.

Komisja Europejska. (2023d). *EU budget: Commission proposes Strategic Technologies for Europe Platform (STEP) to support European leadership on critical technologies.* https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3364.

Kopeć, J. (2023). *Pas Cementu to wyzwanie inne niż wszystkie*. https://instrat.pl/pas-cementu/ (28.09.2023).

Kościółek M. i in. (2023). *Baza danych o emisjach CO_2 przemysłów energochłonnych w latach 2010–2020.* https://instrat.pl/emisje-przemyslu-baza-danych/.

Lelek-Borkowska U., (2022). *Geopolimery*. https://pre-epodreczniki.open.agh.edu.pl/openagh-download.php?name=Geopolimery&type=pdf.

Liberty Steel. (2023). *LIBERTY Steel w Polsce.* https://libertysteelgroup.com/pl/ (28.09.2023).

MAP. (2019). *Krajowy plan na rzecz energii i klimatu na lata 2021–2030*. https://www.gov.pl/web/klimat/krajowy-plan-na-rzecz-energii-i-klimatu.

MFiPR. (2023). Podkomitet ds. transformacji regionów górniczych – Rada ds. Sprawiedliwej Transformacji. https://www.funduszeeuropejskie.gov.pl/strony/o-funduszach/fundusze-2021-2027/umowa-partnerstwa/komitet-ds-up/podkomitety/sprawiedliwa-transformacja/ (7.07.2023).

MKiŚ. (2021). *Polska Strategia Wodorowa do roku 2030 z perspektywą do roku 2040*. https://www.gov.pl/attachment/4c261e63-f57d-48e3-b451-10b235aa2de8.

MKiŚ. (2023). *Polityka energetyczna Polski do 2040 r.* (wersja opublikowana w 2023 r.) https://www.gov.pl/web/klimat/polityka-energetyczna-polski.

MRiT. (2021). *Polityka Przemysłowa Polski.* https://www.gov.pl/attachment/555c07a8-4d95-49af-9ec1-282fafdbcac5.

MRiT. (2022). Strategia Produktywności 2030. https://www.gov.pl/web/rozwoj-technologia/strategia-produktywnosci-2031.

MRiT. (2023). *Kontrakt Branżowy – narzędzie aktywnej sektorowej polityki przemysłowej.* https://www.gov.pl/web/rozwoj-technologia/kontrakt-branzowy--narzedzie-aktywnej-sektorowej-polityki-przemyslowej (18.05.2023).

Myszor, P. (2023). *ArcelorMittal buduje zakład produkcji stali z elektrolizy*. https://www.wnp.pl/hutnictwo/arcelormittal-buduje-zaklad-produkcji-stali-z-elektrolizy,721083.html (15.06.2023).

NACE. *Statistical Classification of Economic Activities NACE Rev. 2.* https://nace.lursoft.lv/25/manufacture-of--fabricated-metal-products-except-machinery-and-equipment (7.06.2023).

Narayanan, P. (2023). *Methanol from CO_2: a technology and outlook overview.* https://www.digitalrefining.com/article/1002891/methanol-from-co2-a-technology-and-outlook-overview.

Nimbalkarm, S. i in. (2015). *Preliminary Results from Electric Arc Furnace Off-Gas Enthalpy Modeling.* https://www.osti.gov/biblio/1221728 (6.10.2023).

Orlen. (2023). *Transformacja energetyczna*. https://www.orlen.pl/content/dam/internet/orlen/pl/pl/o-firmie/dokumenty/ORLEN_FFBK.pdf.

Papapetrou, M. i in. (2018). *Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country*, "Applied Thermal Engineering", vol. 138/2018. https://www.sciencedirect.com/science/article/pii/S1359431117347919.

Parlament Europejski. (2022). *Climate change: Deal on a more ambitious Emissions Trading System* (ETS). https://www.europarl.europa.eu/news/pl/press-room/20221212IPR64527/climate-change-deal-on-a-more--ambitious-emissions-trading-system-ets. (18.12.2022).

Perilli, D. (2022). *Update on electric cement kilns.* https://www.globalcement.com/news/item/14256-update--on-electric-cement-kilns.

Piestrzyński, P. (2017). *Dobre prognozy dla branży cementowej.* „Nowoczesne Budownictwo Inżynieryjne", wrzesień–październik 2017. http://www.nbi.com.pl/assets/NBI-pdf/2017/5_74_2017/Pdf/19_SPC.pdf (18.01.2023).

PSE. (2023). *Powstaną specjalne strefy energetyczne. Skorzystają inwestorzy oraz system elektroenergetyczny*. https://www.pse.pl/biuro-prasowe/aktualnosci/-/asset_publisher/fwWgbbtxcZUt/content/powstana-specjalne-strefy-energetyczne-skorzystaja-inwestorzy-oraz-system-elektroenergetyczny? (6.09.2023).

PwC. (2023). *Net Zero Industry Act The green collar opportunity.* https://www.strategyand.pwc.com/de/en/industries/energy-utilities-resources/net-zero-industry-act/strategyand-net-zero-industry-act.pdf.

Reuters. (2023). *Thyssenkrupp steel workers to hold protests over outstanding government grant.* https://www.reuters.com/markets/commodities/thyssenkrupp-steel-workers-hold-protests-over-outstanding-government-grant-2023-06-02/ (28.09.2023).

Ritchie. H., Roser, M. (2020). *Poland: CO_2 Country Profile.* https://ourworldindata.org/co2/country/poland (17.01.2023).

SBTi. (2022). The Cement Science Based Target Setting Guidance, https://sciencebasedtargets.org/resources/files/SBTi-Cement-Guidance.pdf.

SBTi. (2023). The Steel Science-Based Target-Setting Guidance, https://sciencebasedtargets.org/resources/files/SBTi-Steel-Guidance.pdf.

Sgaravatti, G., Tagliapietra S., Trasi C. (2023). *Cleantech manufacturing: where does Europe really stand?* https://www.bruegel.org/analysis/cleantech-manufacturing-where-does-europe-really-stand-0.

Skłodowska, M. (2023). *Przemysł odchodzi od węgla. Wybiera OZE i gaz.* Wysokie Napięcie. https://wysokienapiecie.pl/87738-przemysl-odchodzi-od-wegla-wybiera-oze-i-gaz/ (7.06.2023).

Sousa, V., Bogas, J. A. (2021). *Comparison of energy consumption and carbon emissions from clinker and recycled cement production.* Journal of Cleaner Production, 306/2021. https://doi.org/10.1016/j.jclepro.2021.127277.

Swoczyna, B. (2023). *Nierówne narażenie. Dochody z przemysłu węglowego barierą dla dekarbonizacji samorządów.* Instrat Policy Note 03/2023, https://instrat.pl/nierowne-narazenie/.

Swoczyna, B. (2023b). *Marnowanie potencjału. Ograniczanie produkcji energii elektrycznej z OZE w „Polityce energetycznej Polski do 2040 r."*, Instrat Policy Note 02/2023, https://instrat.pl/marnowanie-potencjalu/.

The Economist. (2023). *There is more than one way to make green steel*. https://www.economist.com/science-and-technology/2023/05/31/there-is-more-than-one-way-to-make-green-steel (15.06.2023).

VoltaChem. (2023). *Electrons to High-Value Chemical Products – E2C*. https://www.voltachem.com/e2c (6.10.2023).

White House. 2023. *Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investmenets in Clean Energy and Climate Action*. https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf.

Wolniak, R. i in. (2020). *Identification of Energy Efficiency Trends in the Context of the Development of Industry 4.0 Using the Polish Steel Sector as an Example*. "Energies" 2020 13(11). https://www.mdpi.com/1996-1073/13/11/2867?type=check_update&version=1 (06.06.2023).

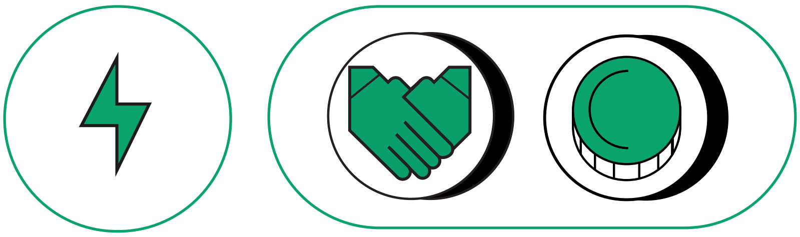
World Steel Association. (2023). World Steel in Figures 2023. https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/#major-steel-producing-countries-%3Cbr%3E-2021-and-2022 (07.06.2023).

World Steel Association. (2021). *Electrolysis in ironmaking.* https://worldsteel.org/wp-content/uploads/Fact-sheet-Electrolysis-in-ironmaking.pdf (15.06.2023).

Xinhua. (2023). *Chinese energy giant strives for carbon neutrality, launching mega carbon capture project.* http://global.chinadaily.com.cn/a/202306/05/WS647d3f58a31033ad3f7ba6cd.html (28.09.2023).

Zachman, G., McWilliams, B. (2021). *A new economic geography of decarbonisation?* https://www.bruegel.org/blog-post/new-economic-geography-decarbonisation (25.01.2023).

ZE PAK. (2021). *Produkcja wodoru w ZE PAK SA*. https://zepak.com.pl/pl/program-czysta-polska/produkcja-wodoru-w-ze-pak-sa.html (28.09.2023).



Annex: Methodology of the macroeconomic model presented in Chapter 4

Data sources

The main data source of the Input-Output model are input-output tables compiled in accordance with the SNA/ESA methodology (at current prices – with and without separation of flows originating from imports). These surveys are an integral part of the Statistics Poland's efforts to present the System of National Accounts. They present information on all resources of the Polish economy from domestic production, imports and the use of these resources for intermediate consumption or expenditure on consumption and investment. The GUS publication includes an input-output table at basic prices for domestic production and a table of the use of imported goods and services in 2015 in aggregates of 77 x 77 divisions (sectors).

Model construction

Based on intermediate consumption rates and estimated total production and final demand, the I-O model can be described algebraically by the equation:

$$x = Ax + d$$

Where: matrix A is the matrix of intermediate consumption coefficients, vector x is total production by 77 sectors, and d is the vector of final demand. The coefficients matrix A was estimated from the input-output table for Poland for 2015. By transforming the above equation, taking changes in final demand as d, changes in total production can be calculated according to Eq:

$$x = (I\text{-}A)^{-1} \cdot d$$

where I is the unit matrix. Through changes in final demand (e.g. through investment) and thus changes in total output, changes in employment can be assessed.

Reference scenario

In order to assess changes in total production with unchanged intermediate consumption under the influence of a change in final demand (total or only for the electricity sector), a reference (baseline) scenario needs to be constructed. Such a scenario assumes a change in value added by 2050, as well as the baseline path of the number of people employed in economic sectors or changes in labour productivity. The reference scenario was built based on historical data and REF scenario assumptions from the PRIMES (European Commission and E3M) growth model. Based on econometric methods, in addition to the development of VA, as well as its structure, projections of total employment and by 77 sectors were made. On the basis of the assumed trends, labour productivity coefficients and changes in employment in the sectors until 2050 under the influence of changes in the volume of production should be calculated. The volume of employment in sectors and the structure of employment were calculated according to the formulas:

$$\text{Employment in sector} = \text{Value added in sector} / \text{Labour productivity in sector}$$

$$\text{Employment structure} = \text{Employment sector} / \text{Total employment}$$

Where:

$$\text{Value added in sector} = \text{Value added structure} \cdot \text{Total value added}$$

The structure of value added, as well as the value of labour productivity in Poland, was assumed to converge to the EU value according to the relationship:

$$\text{Value added structure}_t = (1\text{-}const_{conv}(1\text{-}\text{VA structure}_{t-1}/y_{t-1}))y_t$$

$$\text{Labour productivity}_t = (1\text{-}const_{conv}(1\text{-}\text{Labour productivity}_{t-1}/x_{t-1}))x_t$$

where ` and **x** denote the structure of value added and the value of labour productivity in the EU, and $\mathbf{const}_{conv}$ the convergence constant.

I-O modelling was also used to estimate changes in total employment based on changes in total output. Changes in employment were calculated according to the formula:

$$\text{Total employment change} = \text{Output change} \cdot \text{Employment} / \text{Value added}$$

where changes in total output are driven by changes in final demand. Changes in employment have been disaggregated into direct and indirect. Direct changes in employment result from the demand shock implemented in the model (here: additional investment in the zero-carbon economy relative to the reference scenario):

$$\text{Direct employment change} = \text{Demand changes} \cdot \text{Employment}/(\text{Value added})$$

Indirect employment change was calculated as the difference between total and direct employment change.