

Horvath, Agnes; Papp, Adrienn Takacsne; Liptak, Katalin; Musinszki, Zoltan;
Markovics, Klara Szucsne

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CLIMATE AND ENERGY ISSUES OF ENERGY-INTENSIVE SECTORS

Ágnes Horváth¹, Adrienn Takácsné Papp², Katalin Lipták^{3*}, Zoltán Musinszki⁴ and Klára Szűcsné Markovics⁵
¹⁾²⁾³⁾⁴⁾⁵⁾ University of Miskolc, Hungary

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Abstract

Energy-intensive sectors face significant challenges in meeting the goals of the new European Industrial Strategy and REPowerEU. This study aims to examine how energy consumption and energy mix in four energy-intensive sectors (primary metals; non-metallic minerals; pulp, paper, and printing; chemicals and petrochemicals) in the European Union evolved over the period 2008-2020 and whether there is a real relationship between changes in energy intensity and labour intensity. The results show positive trends in energy mix and intensity between 2008 and 2020 for all the energy-intensive sectors studied. There has been a shift from high to medium and low carbon energy sources, with the extent of this shift being influenced by the technological characteristics and path dependencies of each sector. The most positive change occurred in the paper, pulp and printing energy mix, where low-emitting energy sources increased by 12.2 percentage points. A strong (around 0.9) Pearson correlation exists between energy intensity and labour intensity evolution in the primary metals, non-metallic minerals, chemicals, and petrochemical sectors. The intensity indicators in the chemical and petrochemical sector show the most favourable improvement (a slight decrease in energy use and employment, with a 23.1% significant increase in value added). Typically, 7 to 8 countries account for 80% of the total value added in the examined sectors in the European Union; the energy mix of these countries' electricity and heat production can support the clean transition.

Keywords: energy-intensive sectors, energy-mix, energy intensity, labour intensity, decarbonisation, REPowerEU Plan, "Fit for 55!"

JEL Classification: L61, L65, Q21, Q42, Q55

* Corresponding author, **Katalin Lipták** – e-mail: liptak.katalin@uni-miskolc.hu



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Introduction

Although the energy crisis, exacerbated by the Russian-Ukrainian war, has put energy security at the forefront in the past year, the EU continues to place a strong emphasis on meeting climate ambitions. Fulfilling the commitments undertaken under the 2015 Paris Agreement will generate challenges in the reduction of emissions in the reduction challenges in all areas. The targets set in the Green Deal are translated into EU legal obligations in the Fit for 55% package and the European Climate Agenda. Accordingly, the EU and its Member States are committed to reducing the EU's net greenhouse gas emissions by at least 55% by 2030 compared to the 1990 levels and to achieving climate neutrality by 2050. These cornerstones have set the strategic direction and framework for the coming years (European Council, 2022). The industry is one of the key pillars of the European Union's economy. The rise of renewable energy sources has a positive effect on the performance of the economy (Nițescu and Murgu, 2022). In 2020, the industrial sector accounts for almost a quarter of the final energy use and 22.16% of greenhouse gas emissions (European Environment Agency, 2021; Eurostat, 2022). In view of this, the EU attaches a major role to this sector in the climate-neutral transition process, as confirmed by the New Industrial Strategy for Europe 2020, published on 10 March 2020 (European Commission, 2022). On 18 May 2022, the European Union announced the REPowerEU Plan, which aims to eliminate the EU's dependency on Russian oil and natural gas, seeks to diversify energy supplies and promotes the increasing use of renewable energies in many sectors of the economy, including industry (European Commission, 2022; Eurostat, 2022). The European Commission published the Green Deal Industrial Plan on 1 February 2023, which provides a framework for EU industry on the transition path to climate neutrality, complementing the efforts set out in the Green Deal and the EU Industrial Strategy (Dănilă et al., 2022; Popa, 2022; European Commission, 2023).

In recent years, several international studies have highlighted that although the European Union is at the forefront of sustainability efforts, its competitiveness has declined over the past two decades (Priede and Pereira, 2015; European Investment Bank, 2016; European Commission, 2023). The EU industry's industrial gross value added as a percentage of the global market share declined by 6.5 percentage points between 2000 and 2020, and its labour productivity growth rate, as well as its industrial investments, lagged behind its global competitors. The EU's rigid regulatory system and its less advanced digital infrastructure are also a clear disadvantage (European Round Table for Industry, 2022). Recognising this, the European Union's economy is currently undergoing a twin ecological and digital transition that will help set its industry on a new growth path and strengthen the EU's leading role in climate protection. The New Industrial Strategy documents clearly set out the dual objective of creating a net-zero industry and increasing industrial competitiveness. In this process, the circular economy and the modernisation and decarbonisation of energy-intensive industries emerge as one of the top priorities, as their high (and drastically increasing) energy costs, in addition to their high CO₂ emissions, significantly undermine the competitiveness of these industries (European Commission, 2019a; European Commission 2020; European Commission, 2023; Dinu, 2023).

Our study focusses on four energy-intensive sectors, namely primary metals (including iron and steel and non-ferrous metals); non-metallic minerals; paper, pulp, and printing; chemical and petrochemical, based on data from the 27 EU Member States. In our study, we seek to answer the following research questions:

- RQ1: What changes can be observed in the energy use and energy mix of the EU's energy-intensive sectors in the period between 2008 and 2020 with a view to the pressure of meeting the energy and climate targets?
- RQ2: How has energy intensity evolved across sectors and is there a detectable relationship between changes in energy intensity and changes in labour intensity?
- RQ3: Does the energy mix of electricity and heat production in the member states with a significant share of the total value added (EU27) of each energy-intensive sector provide a favourable starting point on the path to climate neutrality?

The structure of the paper is as follows: section 1 contains the literature review. Section 2 renders a description of the analytical framework and methodology. Section 3 presents our results in order of research questions, which are then compared with the main conclusions of the sources of literature in section 4, and finally, the last section summarises our key findings.

1. Review of the scientific literature

A significant share of energy use and CO₂ emissions is connected to energy-intensive sectors, both globally and in EU countries. Therefore, there is a pressing need to reduce energy use and CO₂ emissions in these sectors. It is no coincidence that a significant number of publications have been written in recent years to map and model the decarbonisation potential of these sectors. Several studies examine the energy-intensive sectors (first of all primary metals, non-metallic minerals, chemical and chemical products, paper pulp, and printing industries) together (e.g., European Commission, 2019a; Dahlgqvist et al., 2021; Zuoza and Pilinkienė, 2021; Lakkanawani et al., 2022; Borge-Diez et al., 2023) but a very large number of publications focus on a detailed analysis of a single sector. A significant part of these reference works focuses on industry outside Europe, mainly on the Chinese industry (Hu and Kavan, 2014; Lin and Ouyang, 2014; Du and Sun, 2015; Lin and Long, 2016; Lin and Chen, 2020). The characteristics of the investigated sectors are very different in terms of product differentiation, technological processes, and geographical concentration. This review of the literature highlights the common points that can be drawn from the studies processed, and also presents a few examples to illustrate the differences. A significant number of studies approach the decarbonisation potential of the sector from a technological perspective, modelling the achievable impacts of the technology change on energy, CO₂ emissions, and other resource needs under different scenarios (e.g., Wen and Li, 2014; Skoczowski et al., 2020; Na et al., 2021; Zhong et al., 2021; Zhang et al., 2022; Lee et al., 2022; Yu and Tan, 2022). A description of current and potential breakthrough technologies is beyond the scope of this study (e.g., in the steel industry alone, where products can be considered homogeneous, tens of technology variants may occur). When analysing technological options, the authors typically conclude that several scenarios are possible to significantly reduce or even achieve net-zero emissions in the sector in the long term, but that these scenarios have different impacts in terms of energy and other resource requirements (Zhang et al., 2022). In each sector, a cross-cutting strategy or targeted technology policy may need to be developed, and the active involvement and support of all actors (e.g., policymakers, R&D, and industry players) are needed to achieve success (Wen and Li, 2014; Skoczowski et al., 2020; Zhong et al., 2021). The authors point out that many industries are reluctant to change their well-established processes, therefore appropriate policies should be developed to better encourage users to adopt energy efficiency

strategies. Ideas on how to improve technological processes may differ across sectors depending on the degree of technological constraints. One of the most common proposals is to look for opportunities to change the energy mix of production technology. For example, in the steel industry, several studies (Yu and Tan, 2022; Zhang et al., 2022) have been published on the effects of the shift from the traditional coal-based Blast Furnaces-Basic oxygen Furnaces (BF-BOF) route towards Electric Arc Furnaces (EAFs) with more favourable energy characteristics, or towards the Direct Reduced Iron (DRI) technology. In the non-ferrous industry it is also the optimisation of the energy structure, in addition to the reduction of energy use, that is an effective way to reduce carbon intensity (Zhong et al., 2021). One means of achieving decarbonisation targets is to maximise the use of clean energy sources in the technological process. There is greater potential for the spread of renewable energy sources in the paper industry, as in the steel industry, hydrogen-based DRI technology is the most promising renewable (Yu and Tan, 2022). Alongside renewables, the potential of waste heat and energy recovery is also explored (Na et al., 2021; Furszyfer Del Rio et al., 2022). In the pulp and paper industry, significant energy savings can be achieved primarily by improving the heat recovery processes (Furszyfer Del Rio et al., 2022); possible solutions can be the use of waste heat recovery through heat pumps and heat exchangers, the replacement of dryers in the paper machine with stationary siphons, and mechanical steam removal (Moya Rivera and Pavel 2018). In sectors where there is less potential for the use of renewables (e.g., primary metals and non-metallic minerals), it is vital to widely adopt material efficiency improvement, material reuse, new production processes and carbon capture, utilization and storage (CCUS) technologies on the road to carbon neutrality (Zhang et al., 2022). The use of carbon capture and storage (CCS) technologies can contribute to climate goals by capturing CO₂ that cannot be reduced (Lee et al., 2022; Korczak et al., 2022). Incentivising technology change is an effective tool to reduce carbon intensity (Zhong et al., 2021). However, for energy-intensive sectors, emission reduction ambitions can be hampered by the long lifespan of production equipment and the high-temperature requirements of production processes (Mandová et al., 2020; Korczak et al., 2022). The adoption and diffusion of energy efficient and lower-emission technologies depend on several factors. Their significant investment requirements and high costs can be barriers to rapid diffusion (Lee et al., 2022). The analysis of the technology readiness level and technology maturity of each technology, as well as their economic viability, has an important role to play (Lee et al., 2022). Furszyfer Del Rio et al. (2022) also identify mainly financial and economic reasons for the relatively slow diffusion of more energy-efficient technologies, but they also mention other barriers. Examples include a lack of knowledge and a lack of cooperation between companies to develop and share low-carbon processes. Another obstacle is the lack of qualified staff to operate the new technologies. In addition, the availability of natural resources (mainly biomass) can be one of the barriers to the transition to low-carbon technologies (Furszyfer Del Rio et al., 2022). The development and transformation of technology may be accompanied by changes in the resource structure of production processes, so the analysis of the substitutability between energy and other resources (capital and labour) is an important area of analysis. For example, the results of Lin and Chen (2020) in China's non-ferrous metals industry indicate the existence of mutual substitution relations among energy, labour and capital (Lin and Chen, 2020). Doskočil (2022) examined CO₂ emissions related to production (namely production-based CO₂ productivity) as one of the conditions for green growth. The extent of CO₂ emission reductions is influenced by the decarbonisation of electricity and heat production, in addition to technological transformation in energy-intensive sectors (Arens et al., 2021; Yu and Tan, 2022).

The above summary shows that the decarbonisation potential of each sector is mainly approached from a technological perspective, looking for opportunities to change the energy-mix of production, increasing the use of clean energy sources, and introducing more energy efficient technologies and solutions (e.g., waste heat and energy recovery). Technological developments can contribute to changes in the resource structure of production processes, providing opportunities to exploit the substitutability between energy and other resources (capital and labour). The adoption and diffusion of these technologies depend on several drivers and barriers, so it is interesting to investigate whether this process has started recently (see RQ1 and RQ2). In addition to technological transformation in energy-intensive sectors, the extent of CO₂ emission reductions is influenced by the countries' decarbonisation of electricity and heat production (Arens et al., 2021; Yu and Tan, 2022). Therefore, we considered it essential to investigate our third research question (RQ3).

2. Methodology

Our study focuses on analyses of the energy use, energy mix, energy intensity, and labour intensity of four energy-intensive sectors in the 27 countries of the EU. The identification and selection of energy-intensive sectors was based on the results of a systematic literature review. Most studies looking at energy-intensive sectors (e.g., European Commission, 2019a; Dahlqvist et al., 2021; Zuoza and Vaida Pilinkiene, 2021; Lakkanawanit et al., 2022; Borge-Diez et al., 2023) mainly analyse 3-4 sectors (typically basic metal, non-metallic mineral, chemical and chemical product, paper pulp, and printing industries). Also, the Odyssee database shows that these four sectors had the highest energy intensity. Therefore, our study focusses on these four sectors, listed in Table no. 1. For the construction of the database, the final energy consumption of the four sectors examined was collected from the annual energy balance sheets (Eurostat) of the 27 EU member states, in total and by energy carriers, for the period 2008-2020. Value added data was obtained from the Odyssee database and the employment data from the Eurostat database. To ensure the comparability of the data, each sector was delimited according to NACE rev. 2 classification, ensuring harmonisation of the different databases (Table no. 1). The different data sources and their comparability limitations are also research limitations.

Table no. 1. Delimitation of the energy-intensive sectors examined according to NACE Rev. 2

Industrial branch	NACE Rev. 2.
Primary metals (PM)	NACE 24: Primary metal (basic metals) – Iron and steel (NACE 24.1, 24.2; 24.3; 24.51; 24.52) – Non-ferrous metals (NACE 24.4; 24.53; 24.54)
Chemical and petrochemical (CP)	NACE 20-21: Chemical and petrochemical – Chemicals and chemical products (NACE 20) – Pharmaceutical products (NACE 21)
Non-metallic minerals (NMM)	NACE 23: Non-metallic minerals
Paper, pulp and printing (PPP)	NACE 17-18: Paper, pulp, and printing – Pulp, paper, and board (NACE 17) – Printing industry (NACE 18)

Our analyses include raw data, as well as derived, calculated data. The final energy consumption of the sectors is included in the energy balance expressed in kilotons of oil

equivalent (ktoe). Two approaches were used to map the energy mix. For the detailed energy mix analysis, the aggregation of energy products was carried out according to the Energy balance methodology guide (European Commission, 2019b). Energy use is analysed by 10 energy source groups: solid fossil fuels, manufactured gases, peat and peat products, oil shale and oil sands, oil and petroleum products, natural gas, non-renewable waste, renewables and biofuels, heat, electricity. Further aggregations were then made, based on which 3 main groups were distinguished: high-emitting, medium-emitting and low- (and zero) emitting energy sources. The classification is based on the CO₂ emission factors of each energy product (European Commission, 2018). The emission factor was considered high above 70 tCO₂/TJ (1 Terajoule (TJ) equals to 0.02388 ktoe). Based on that, solid fossil fuels, manufactured gases, peat and peat products, oil shale and oil sands, oil and petroleum products, non-renewable waste categories were classified as high-emitting energy products. Natural gas is the only medium-emitting energy source with an emission factor of 56.1 tCO₂/TJ. Renewable energy sources, biofuels, and nuclear heat were put into the low- (and zero) emitting group. Considering that energy-intensive sectors use a higher proportion of heat and electricity in their production processes, the amount of these secondary energy sources was allocated to high-, medium-, and low-emitting energy sources based on the energy mix of the electricity and heat production of the EU27. Our classification is consistent with that of Arens et al. (2021).

The second part of our analysis examined the evolution of energy intensity and labour intensity. Energy intensity was quantified as the ratio of the final energy consumption of the branch (measured in energy units ktoe) to the value added at constant price (measured in million euros 2010). This indicator shows how much energy is needed to create 1 million euros of value added. The final energy consumption data were obtained from the energy balance, and the value-added data from the Odyssee database. Using the analogy of energy intensity, we calculated the labour intensity indicator as the ratio between the employee headcount (from 15 to 64 years based on the Eurostat database) and the value added at the constant price (million euros 2010), which shows how many people are employed to create 1 million euros of added value. To examine the relationship between the indicators, a correlation calculation (Pearson corr.) was performed.

Finally, a concentration test based on value-added was carried out to identify the Member States that account for 80% of the gross value added generated by the energy-intensive sectors examined in our study. In each sector, the share of each Member State in the industrial value added was calculated compared to the total value added (EU27) of each industry. Based on the cumulative ratio of the value added, the countries that covered 80% of the total value added of the industry were considered as the basis for further analysis. The energy mix of electricity and heat production in the dominant countries was used to examine our third research question, based on energy balance data for each country.

3. Results

The third section presents the results of the analyses in the order of the research questions.

3.1. Changes in energy use and energy mix in energy-intensive sectors

First, we examined the changes that were observed in the energy use and energy mix of the energy-intensive sectors of the EU during the period 2008 to 2020 in the context of the energy

and climate change targets (RQ1). Table no. 2 shows the detailed energy mix of the energy-intensive sectors, for the years 2008 to 2020.

Table no. 2. Energy mix of energy-intensive sectors from 2008 to 2020

	Chemical and petrochemical		Non-metallic minerals		Paper, pulp and printing		Primary metals	
	2008	2020	2008	2020	2008	2020	2008	2020
Solid fossil fuels (%)	5.6	4.2	14.5	11.7	2.6	1.9	10.2	8.2
Manufactured gases (%)	0.0	0.1	0.1	0.2	0.0	0.0	14.3	11.9
Peat and peat products (%)	0.1	0.0	0.0	0.0	0.7	0.4	0.0	0.0
Oil shale and oil sands (%)	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Oil and petroleum products (%)	15.2	14.8	27.4	16.4	4.8	1.8	5.2	2.5
Natural gas (%)	33.9	37.1	35.2	37.4	20.9	18.9	29.1	32.8
Non-renewable waste (%)	0.4	0.8	3.4	11.9	0.2	0.9	0.1	0.0
Renewables and biofuels (%)	0.6	0.7	3.2	5.5	32.6	43.0	0.1	0.1
Heat (%)	14.3	14.4	0.5	0.8	6.5	6.7	0.8	2.0
Electricity (%)	30.0	27.8	15.5	16.1	31.8	26.5	40.4	42.4

Table no. 2 shows that the energy mix of the energy-intensive sectors studied is typically dominated by the use of electricity and natural gas, followed by that of oil and petroleum products. In the case of the chemical and petrochemical industry, natural gas accounts for 37.1 percent of final energy use and is followed by electricity with 27.8 percent of the energy mix according to data from 2020. The use of renewable and biofuels is negligible at only 0.7 percent. Compared to 2008, there was a slight shift in proportions, mainly from electricity towards natural gas. The energy mix of the non-metallic minerals sector seems to be slightly more balanced (based on 2020 data). The dominance of natural gas (37.4%) is also characteristic here, but the share of oil and petroleum products and electricity accounts for around 16% and of solid fossil fuels and non-renewable waste is also over 11% of the final energy use. This sector has the highest ratio of solid fossil fuel use, but also a higher use of renewable and biofuels (5.5%) compared to other sectors (except the paper industry). On the positive side, there is also a decrease in the share of fossil fuels compared to 2008, with the exception of natural gas, which shows a slight increase in share. The paper, pulp and printing sector is considered to be the odd one out among energy-intensive sectors since its energy mix is dominated by renewables and biofuels, accounting for 43 percent of its final use in 2020. The use of solid fossil fuels and petroleum products is negligible, less than 2 percent in both cases, which is significantly lower than in the other sectors. In this sector, there is a clear shift from fossil fuels to renewables compared to 2008. In the primary metals sector, electricity consumption accounts for the largest share (42.4%), followed by natural gas at 32.8%. The use of renewables in this sector is the lowest, almost negligible, at only 0.1 percent. However, there is also a positive trend in the energy mix, with a shift toward electricity and natural gas compared to 2008.

The proportional changes should be complemented by an analysis of the changes in final energy use in total and by energy sources. It can be established in general that the final energy use decreased from 2008 to 2020 in the energy-intensive sectors investigated in our study. The primary metals (25.5%) and non-metallic minerals (22%) sectors demonstrated the largest decreases. In addition, the paper, pulp and printing sector used 6.4% less energy and the chemicals and petrochemicals sector 2.1% less. This is a positive trend as fossil fuel use

decreased significantly in terms of volume. The use of solid fossil fuels and oil and petroleum products in each of these sectors showed a sharp decline over the 13 years studied. At the same time, there is an increase in the use of non-renewable waste and renewables and biofuels excluding primary metals.

Based on the fact that most of these sectors have more technology lock-in, and, in some cases, it is more difficult to move toward renewables, also a shift from a high-emitting fossil fuel to a lower-emitting fossil fuel could be seen as a success. In figure no. 1 (ternary plot) energy sources were divided into groups based on their CO₂ emission factors as high-emitting, medium-emitting, and low (and zero)-emitting. The amount of heat and electricity was split between high-, medium- and low-emitting energy sources based on the energy mix of the EU27 electricity and heat production. As nuclear energy is also included in the energy mix of electricity generation, it is considered together with renewables and biofuels in the low-emitting category.

Figure no. 1 shows the relative position of the individual sectors and the shift in the energy mix from 2008 to 2020. The values of each axis are read along the grid lines. The right side of the triangle (along the horizontal grid line) shows the proportion of high-emitting energy sources, the left side (along the grid line going downwards from left to right) shows the proportion of medium-emitting energy sources, and the base of the triangle (along the grid line going upwards from right to left) shows the proportion of low-emitting energy sources. The table in the top left-hand corner of the figure shows the percentage point change in the share of each category from 2008 to 2020.

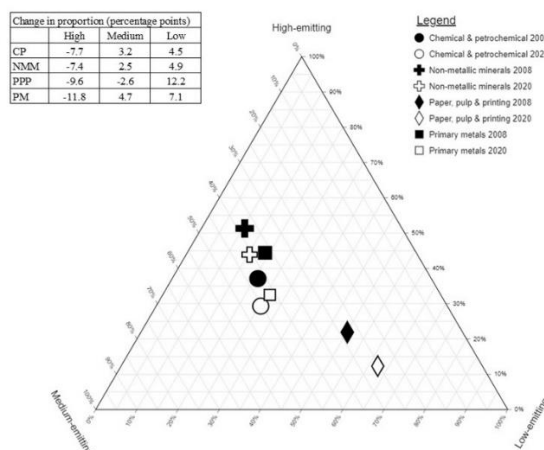


Figure no. 1. Shifts in the energy mix by sector between 2008 and 2020

Figure no. 1 shows that for all sectors, there was a positive shift in the energy mix over the period examined, moving away from energy sources with high CO₂ emissions to medium and low emissions. The most positive change occurred in the energy mix of the paper, pulp and printing sector, where the share of both high and medium CO₂ emitting energy sources decreased in favour of low-emitting energy sources, which exhibited an increase of 12.2 percentage points. Considering that the energy mix of this sector was already the most favourable compared to others, the further improvement is remarkable. The share of high-emitting fuels shows the highest decline (11.8 percentage points) in the primary metals sector,

reflecting a shift towards low-emitting sources to a greater extent and towards natural gas to a lesser extent. In the chemical and non-metallic minerals sectors, there was a slightly smaller decrease (7.7 and 7.5 percentage points) in the share of high-emitting fuels, but again the shift was larger towards clean sources and smaller toward natural gas.

3.2. Analysis of energy intensity and labour intensity

Besides the analysis of final energy use and energy mix, it was found relevant to review changes in energy intensity to see whether efforts were made to meet the climate targets (RQ2). This indicator provides a more subtle picture than that of the reduction in final energy use on its own, as it matters if the lower energy use is caused by an increase in energy efficiency, or perhaps by the shrinking size of the sector (loss of value added). The energy intensity indicator in our calculations shows how much energy (in ktoe) is used to produce 1 million euros of added value. Energy efficiency gains in energy-intensive sectors are best approached from a technological perspective. It is an interesting question to examine how technology development, the introduction of new technologies, or a technology change, affects the resource needs of the sector. Answering this question is not the subject of this study; here, the authors only attempt to examine whether there is a detectable relationship between changes in energy intensity and labour intensity in different sectors (RQ2). Labour intensity is interpreted by the authors as the number of persons employed needed to create 1 million euros of value added. The energy intensity and labour intensity indicators were calculated for the period 2008 to 2019, as the value-added data for 2020 were incomplete.

Figure no. 2 shows the trend of energy intensity and labour intensity in energy-intensive sectors in 2008 and 2019, based on EU27 aggregate data. The size of the bubble is determined by the value added of the sector at the constant price (measured in millions of euros in 2010). The graph depicts the position of each sector relative to each other, and the shift between the two years examined (2008 and 2019). It gives an idea of the energy and labour input needed to produce €1 million of value added in the individual sectors, and the changes in resource demands.

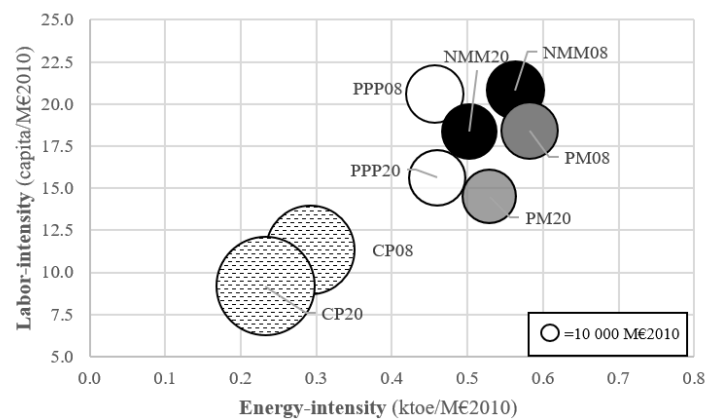


Figure no. 2. Trends in energy intensity and labour intensity in 2008 and 2019 for each sector, based on EU27 data

Notes: CH08, CH20: Chemical and petrochemical 2008, 2020; NMM08, NMM20: Non-metallic minerals 2008, 2020; PM08, PM20: Primary metals 2008, 2020; PP08, PP20: Paper, pulp, and printing 2008, 2020

Figure no. 2 shows that in the chemical and petrochemical sectors, creating a unit of value added requires less energy and labour than in other sectors. The non-metallic minerals, primary metals and paper, pulp, and printing sectors are characterised by high energy demand and also by higher labour demand. For three sectors (primary metals, non-metallic minerals, chemical, and petrochemical), it is clear that both energy and labour required to generate €1 million of value added decreased from 2008 to 2019, so both intensity indicators show an improvement. In primary metals, energy intensity improved by 9.1 percent and labour intensity by 21.3 percent. However, the negative trend is that the value added of the sector fell by 10% during the period, although it is true that energy use and employment decreased at a higher rate (18.2%-29.2%). The trend for non-metallic minerals was similar, with both energy and labour intensity falling, but the size of the sector (value added) also shrank by 11 percent. Chemical and petrochemical value added, on the other hand, increased significantly (by 23.1%), with a slight decrease in energy use and employment. The intensity indicators in this sector show the highest improvement and the most favourable trend in terms of value-added growth. In the paper, pulp, and printing sector, energy intensity demonstrated a minimum change over the period, with labour intensity improving more and value-added changing less.

To test the strength and direction of the relationship, a correlation calculation was performed. There was a strong positive correlation between energy intensity and labour intensity trends in the primary metals (Pearson corr. 0.924), non-metallic minerals (Pearson corr. 0.908), chemical and petrochemical (Pearson corr. 0.845) sectors. The correlation index used is not suitable to show a cause-and-effect relationship; it merely demonstrates the co-movement of variables. In the paper, pulp, and printing sector a positive relationship of medium strength (Pearson corr. 0.410) was found.

3.3. Energy mix of electricity and heat production in the Member States with the highest share in the value-added of energy-intensive sectors

The previous sub-sections presented the main characteristics of the energy-intensive sectors for the 27 EU Member States, based on aggregated data. The use of electricity and heat represents a significant share (up to 35-40%) of the energy mix in the sectors studied. Therefore, the CO₂ emissions of the sectors, in a broader sense, are indirectly determined by the energy mix of electricity and heat production, and of electricity imported from other countries. This research sought to answer whether the energy mix of the electricity and heat generation in the dominant EU countries of the energy-intensive sectors provided a favourable background for the road toward climate neutrality (RQ3).

Table no. 3 shows that typically 7 to 8 countries account for 80% of the total value added in a given sector in the European Union, with Germany, France, Italy, and Spain leading in almost all sectors, in varying order. The energy mix of the TOP 4 countries reveals a different picture. France exhibits the most favourable status, where the share of low-emitting energy sources in electricity and heat generation is over 90 percent, although the share of renewables is only 12.3 percent, the rest being due to nuclear energy. In Spain, alongside the 29.3 percent of renewables, the share of clean energy is 64.5 percent. Italy boasts the highest renewable rate of the TOP4 countries, but it has no nuclear power. The relatively lower nuclear share in Germany makes the picture look less favourable, despite the higher renewable share. After the TOP4 countries, the picture is more mixed. Notable examples are Denmark, where more

than 70% of electricity and heat generation comes from renewable sources, and Poland, where only 10.7% of energy is low emitting. The energy mix of the electricity and heat production of the dominant countries can be considered basically favourable on the way to the climate goals (for comparison, based on the overall average of the EU27, the RES rate (renewable energy sources) is 25.1%, the LES rate (Low-emitting Energy Sources) is 57.8%).

Table no. 3. Share of the dominant countries in the sectoral value added (for EU27, 2019) and characteristics of the countries' energy mix (2020)

Industrial branch	Ranking	1	2	3	4	5	6	7	8	Cumulative percent in EU27 value added (%)
Chemical and petrochemical (CH)	Country	Germany	France	Italy	Belgium	Spain	Netherlands	Denmark		83.6
	Share of the country in value added of EU27 CH industry (%)	30.8	16.9	9.4	7.5	7.1	6.1	5.8		
	Share of (RES) and LES in electricity and heat generation of the country (%)	(28.5) 44.7	(12.3) 90.5	(36.3) 36.3	(16.6) 66.5	(29.3) 64.4	(22.3) 27	(70.8) 70.8		
Non-metallic minerals (NMM)	Country	Germany	Italy	France	Spain	Poland	Austria	Belgium	Czechia	81.3
	Share of the country in value added of EU27 NMM industry (%)	25	14.9	12.9	8.8	8.3	4.4	3.9	3.1	
	Share of (RES) and LES in electricity and heat generation of the country (%)	(28.5) 44.7	(36.3) 36.3	(12.3) 90.5	(29.3) 64.4	(10.7) 10.7	(63.8) 63.8	(16.6) 66.5	(8.6) 45.3	
Paper, pulp and printing (PP)	Country	Germany	Italy	France	Spain	Sweden	Poland	Netherlands	Finland	82.1
	Share of the country in value added of EU27 PP industry (%)	26.1	14.5	12.6	7.6	5.8	5.5	5.1	4.9	
	Share of (RES) and LES in electricity and heat generation of the country (%)	(28.5) 44.7	(36.3) 36.3	(12.3) 90.5	(29.3) 64.4	(50.7) 94.8	(10.7) 10.7	(22.3) 27	(38.8) 76.8	
Primary metals (PM)	Country	Germany	Italy	Spain	France	Austria	Sweden	Belgium		81
	Share of the country in value added of EU27 PM industry (%)	29.1	15.3	11.3	10.2	5.8	4.8	4.5		
	Share of (RES) and LES in electricity and heat generation of the country (%)	(28.5) 44.7	(36.3) 36.3	(29.3) 64.4	(12.3) 90.5	(63.8) 63.8	(50.7) 94.8	(16.6) 66.5		

4. Discussion

In this section, our results are compared to the findings of the literature. Lin and Long (2016) examined the factors that affect the growth of carbon dioxide emissions in the Chinese chemical industry, concluding that the energy mix and energy intensity contribute to the increase in carbon dioxide emissions (Lin and Long, 2016). Our results show a 7.7% decrease in the share of high-emitting fuels in this sector, with a larger shift towards clean sources and a smaller shift toward natural gas. Pach-Gurgul et al. (2020) examined the factors affecting energy intensity in the chemical industry in the V4 (Visegrad Four) countries and concluded that increasing employment reduces energy intensity in the sector (Pach-Gurgul et al., 2020). In contrast, our results showed a high improvement in both intensity indicators (energy- and labour intensity) in this sector, with a strong positive correlation between them.

Lin and Ouyang (2014) analysed the change in CO₂ emissions from the energy consumption of the Chinese non-metallic mineral industry and the factors determining this change. Their results show that changes in industrial value added per worker are the most likely to increase, while changes in energy intensity are the most likely to reduce CO₂ emissions from industry. The share of fossil fuels in total energy has a smaller mitigation effect than the previously mentioned ones. Du and Sun (2015), examining the factors that influence the sector's electricity demand, conclude that an increase in productivity (productivity = GVA) can reduce the industry's energy demand. The non-metallic minerals industry is not only one of the industries with the highest fossil fuel mix, but its relatively high demand for electricity

also affects the rise in global CO₂ emissions. Hu and Kavan (2014) point out that the industry also contributes to global CO₂ emissions indirectly through its use of electricity, as it is typically generated by coal-fired power plants. In contrast, our studies depict a much more promising, greener picture for the European Union.

Obrist et al. (2022) investigated the long-term energy efficiency and decarbonisation pathways of the pulp and paper industry in Switzerland. The researchers carried out a scenario analysis. Their results show that a significant energy saving, and CO₂ emissions reduction could be achieved by 2050 through fuel switching, improvements in production processes, and the use of efficient technologies, particularly high-temperature heat pumps, and efficient engines. Meeting the net-zero target for the pulp and paper industry by 2050 will require the use of more biomass in the short term, and in the long term, when biomass is scarce, the use of high-temperature heat pumps up to 200°C will be necessary (Obrist et al., 2022). Lipiäinen et al. (2022) highlighted that by improving energy efficiency, energy use per product can be reduced and the shift from fossil fuels to bioenergy can further reduce emissions. Our analyses have shown that there is a clear shift in the sector away from fossil fuels toward renewables. Renewable energy and biofuels dominate the industry in 2020 with a 43% share. High and medium CO₂ emitting energy sources declined in favour of low-emitting energy sources, demonstrating an increase of 12.2 percentage points.

According to the World Steel Association (2022), 43.9% of the crude steel production in the EU is based on EAF technology, which has more favourable energy characteristics (compared to e.g., China, where 89.6% of production is still based on coal-based BF-BOF technology). This fact explains our results, as the energy mix of primary metals in the EU is dominated by electricity and natural gas. Between 2008 and 2020, the share of solid fossil fuels and manufactured gases decreased, typically in favour of natural gas and electricity. There was no change in the share of renewables (0.1%). This confirms the findings in the literature that there is less potential for renewables in the primary metals sector. The steel industry mainly uses renewables in hydrogen-based DRI technology (Yu and Tan, 2022), which is still at low technological maturity (Arens et al., 2021; Lee et al., 2022). The other option is the use of CCS technologies, but the readiness level of these technologies is still relatively low, and their costs are high, although Lee et al. (2022) believes that they will become economically feasible in the long term. The high electricity share demonstrates that the decarbonisation of electricity and heat production in individual countries can further improve the sector's CO₂ reduction potential (Zhong et al., 2021; Arens et al., 2021; Yu and Tan, 2022).

Conclusions

The EU and its member states are committed to achieving climate neutrality by 2050. The energy-intensive sectors are faced with the greatest challenge to be able to meet this target, and as a result, we focus our analysis on the four most energy-intensive sectors (including iron and steel and non-ferrous metals); non-metallic minerals; paper, pulp, and printing; chemical and petrochemical). Our study examines the trends in the energy use and energy mix of these four sectors between 2008 and 2020, the development of the energy intensity in each sector. The paper aims also to show whether there was a detectable relationship between changes in energy intensity and labour intensity and whether the energy mix of electricity and heat production in the EU Member States dominating in energy-intensive sectors in terms

of gross value added provided a favourable background for the road towards climate neutrality.

The analyses carried out show that between 2008 and 2020, there has been a positive shift in the energy mix of the energy-intensive sectors, from high to medium and low CO₂ emitting energy sources. The most favourable change occurred in the energy mix of the paper, pulp, and printing sectors. The analysis of energy intensity and labour intensity showed that for three sectors (primary metals, non-metallic minerals, chemical and petrochemical), both intensity indicators show an improvement. There was a strong positive correlation between the evolution of energy intensity and labour intensity in the primary metals, non-metallic minerals, chemical and petrochemical sectors. A medium-strong positive relationship was detected in the paper, pulp, and printing sectors. Typically, 7-8 countries account for 80% of the total value added in a given sector in the European Union, with Germany, France, Italy, and Spain leading in almost all sectors, in varying order. The energy mix of the electricity and heat production of the dominant countries can be considered basically favourable on the way to the climate goals.

The results raise new research questions: in the primary metals, non-metallic minerals, and chemical and petrochemical sectors, it would be worthwhile to investigate the factors that explain the close co-movement between energy intensity and labour intensity. Since the characteristics of the investigated sectors are very different in product differentiation, technological processes, and geographical concentration, different measures can lead to carbon-neutrality goals. We, therefore, agree with Wen and Li (2014), Skoczkowski et al. (2020), and Zhong et al. (2021) statements that in each sector and country, a cross-cutting strategy or targeted technology policy may be needed and the active involvement and support of all actors (e.g., policymakers, R&D, and industry players) are necessary to achieve success. The European Union is at the forefront of energy and climate policy efforts and can serve as an excellent example for global players with high greenhouse gas emissions. The good practices and research results presented in this study can also be useful for major players such as China. Of course, considering that the carbon neutrality target date in the EU policy is set for 2050, while in China, it is postponed to a decade later. In addition, different social and economic structures and coal and gas endowments are essential factors.

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References

Arens, M., Åhman, M. and Vogl, V., 2021. Which countries are prepared to green their coal-based steel industry with electricity? - Reviewing climate and energy policy as well as the implementation of renewable electricity. *Renewable and Sustainable Energy Reviews*, [e-journal] 143, no. art.110938. <https://doi.org/10.1016/j.rser.2021.110938>.

- Borge-Diez, D., Rosales-Asensio, E., Açikkalp, E. and Alonso-Martínez, D., 2023. Analysis of Power to Gas Technologies for Energy Intensive Industries in European Union. *Energies*, [e-journal] 16(1), no. art.538. <https://doi.org/10.3390/en16010538>.
- Dahlqvist, A., Lundgren, T. and Marklund, P.-O., 2021. The Rebound Effect in Energy-Intensive Industries: A Factor Demand Model with Asymmetric Price Response. *The Energy Journal*, [e-journal] 42(3). <https://doi.org/10.5547/01956574.42.3.adah>.
- Dinu, V., 2023. Perspectives of the Circular Economy in the Production and Consumption of Electrical and Electronic Equipment. *Amfiteatru Economic*, [e-journal] 25(62), pp.6-9. <https://doi.org/10.24818/EA/2023/62/6>.
- Du, G. and Sun, C., 2015. Determinants of Electricity Demand in Nonmetallic Mineral Products Industry: Evidence from a Comparative Study of Japan and China. *Sustainability*, [e-journal] 7(6), pp.7112-7136. <https://doi.org/10.3390/su7067112>.
- European Commission, 2018. *Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions under Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation*. [online] Available at: <<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R2066&rid=1>> [Accessed 10 March 2023].
- European Commission, 2019a. *Masterplan for a competitive transformation of EU energy-intensive industries enabling a climate-neutral, circular economy by 2050*. [online] Available at: <<https://data.europa.eu/doi/10.2873/854920>> [Accessed 3 March 2023].
- European Commission, 2019b. *Energy balance guide Methodology guide for the construction of energy balances & Operational guide for the energy balance builder tool*. [online] Available at: <<https://ec.europa.eu/eurostat/documents/38154/4956218/ENERGY-BALANCE-GUIDE.pdf/de76d0d2-8b17-b47c-f6f5-415bd09b7750?t=1632139948586>> [Accessed 3 March 2023].
- European Commission, 2020. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions – A New Industrial Strategy for Europe*. [online] Available at: <<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102>> [Accessed 3 March 2023].
- European Commission, 2022. *Communication from the Commission to the European Parliament, the European Council, the Council, The European Economic and Social Committee and the Committee of the Regions REPowerEU Plan*. [online] Available at: <<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN>> [Accessed 3 March 2023].
- European Commission, 2023. *Communication From the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: A Green Deal Industrial Plan for the Net-zero Age*. [online] Available at: <<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0062>> [Accessed 3 March 2023].
- European Council, 2022. *European Green Deal*. [online] Available at: <<https://www.consilium.europa.eu/en/policies/green-deal/>> [Accessed 10 December 2022].

- European Environment Agency, 2021. *Greenhouse gases*. [online] Available at: <<https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer>> [Accessed 10 March 2023].
- European Investment Bank, 2016. *European Investment Bank Restoring EU competitiveness 2016 updated version*. [online] Available at: <https://www.eib.org/attachments/efs/restoring_eu_competitiveness_en.pdf> [Accessed 10 March 2023].
- European Round Table for Industry, 2022. *European Competitiveness and Industry Benchmarking Report 2022*. [online] Available at: <<https://ert.eu/wp-content/uploads/2022/06/ERT-Benchmarking-Report-2022-LR.pdf>> [Accessed 10 December 2022].
- Eurostat, 2022. *EU's industries dependent on electricity and natural gas*. [online] Available at: <<https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20221202-2>> [Accessed 10 December 2022].
- Eurostat, n.d. *Employment by sex, age and detailed economic activity*. [online] Available at: <https://ec.europa.eu/eurostat/databrowser/product/page/lfsq_egan22d> [Accessed 10 December 2022].
- Furszyfer Del Rio, D.D., Sovacool, B.K., Griffiths, S., Bazilian, M., Kim, J., Foley, A.M. and Rooney, D., 2022. Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options. *Renewable and Sustainable Energy Reviews*, [e-journal] 167, no. art.112706. <https://doi.org/10.1016/j.rser.2022.112706>.
- Hu, H. and Kavan, P., 2014. Energy Consumption and Carbon Dioxide Emissions of China's Non-Metallic Mineral Products Industry: Present State, Prospects and Policy Analysis. *Sustainability*, [e-journal] 6(11), pp.8012-8028. <https://doi.org/10.3390/su6118012>.
- Korczak, K., Kochański, M. and Skoczkowski, T., 2022. Mitigation options for decarbonization of the non-metallic minerals industry and their impacts on costs, energy consumption and GHG emissions in the EU – Systematic literature review. *Journal of Cleaner Production*, [e-journal] 358, no. art.132006. <https://doi.org/10.1016/j.jclepro.2022.132006>.
- Lakkanawanit, P., Dungtripop, W., Suttipun, M. and Madi, H., 2022. Energy Conservation and Firm Performance in Thailand: Comparison between Energy-Intensive and Non-Energy-Intensive Industries. *Energies*, [e-journal] 15(20), no. art.7532. <https://doi.org/10.3390/en15207532>.
- Lee, H., Lee, J. and Koo, Y., 2022. Economic impacts of carbon capture and storage on the steel industry – A hybrid energy system model incorporating technological change. *Applied Energy*, [e-journal] 317, no. art.119208. <https://doi.org/10.1016/j.apenergy.2022.119208>.
- Lin, B. and Chen, X., 2020. How technological progress affects input substitution and energy efficiency in China: A case of the non-ferrous metals industry. *Energy*, [e-journal] 206, no. art.118152. <https://doi.org/10.1016/j.energy.2020.118152>.
- Lin, B. and Long, H., 2016. Emissions reduction in China's chemical industry – Based on LMDI. *Renewable and Sustainable Energy Reviews*, [e-journal] 53, pp.1348-1355. <http://dx.doi.org/10.1016/j.rser.2015.09.045>.

- Lin, B. and Ouyang, X., 2014. Analysis of energy-related CO₂ (carbon dioxide) emissions and reduction potential in the Chinese non-metallic mineral products industry. *Energy*, [e-journal] 68, pp.688-697. <https://doi.org/10.1016/j.energy.2014.01.069>.
- Lipiäinen, S., Kuparinen, K., Sermyagina, E. and Vakkilainen, E., 2022. Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden. *Sustainable Production and Consumption*, [e-journal] 29, pp.421-431. <https://doi.org/10.1016/j.spc.2021.10.029>.
- Mandová, H., Vass, T., Fernandez Pales, A., Levi, P. and Gül, T., 2020. *The challenge of reaching zero emissions in heavy industry*. [online] Available at: <<https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry>> [Accessed 10 December 2022].
- Moya, J.A., and Pavel, C.C., 2018. *Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry*. [online] Available at: <<https://op.europa.eu/en/publication-detail/-/publication/0575cc7f-c13a-11e8-9893-01aa75ed71a1/language-en>> [Accessed 10 December 2022].
- Na, H., Sun, J., Qiu, Z., He, J., Yuan, Y., Yan, T. and Du, T., 2021. A novel evaluation method for energy efficiency of process industry – A case study of typical iron and steel manufacturing process. *Energy*, [e-journal] 233, no. art.121081. <https://doi.org/10.1016/j.energy.2021.121081>.
- Obrist, M.D., Kannan, R., Schmidt, T.J. and Kober, T., 2022. Long-term energy efficiency and decarbonization trajectories for the Swiss pulp and paper industry. *Sustainable Energy Technologies and Assessments*, [e-journal] 52, no. art.101937. <https://doi.org/10.1016/j.seta.2021.101937>.
- Odyssee-Mure, 2020. *Definition of data and energy efficiency indicators in ODYSSEE database*. [online] Available at: <<https://www.odyssee-mure.eu/private/definition-indicators.pdf>> [Accessed 15 December 2022].
- Pach-Gurgul, A., Śmiech, S. and Ulbrych, M., 2021. The effect of energy prices on energy intensity improvement – the case of the chemical industry in the V4 countries. *Post-Communist Economies*, [e-journal] 33(5), pp.566-580. <https://doi.org/10.1080/14631377.2020.1793605>.
- Priede, J. and Pereira, E.T., 2015. European Union's Competitiveness and Export Performance in Context of EU – Russia Political and Economic Sanctions. *Procedia - Social and Behavioral Sciences*, [e-journal] 207, pp.680-689. <https://doi.org/10.1016/j.sbspro.2015.10.138>.
- Skoczkowski, T., Verdolini, E., Bielecki, S., Kochański, M., Korczak, K. and Węglarz, A., 2020. Technology innovation system analysis of decarbonisation options in the EU steel industry. *Energy*, [e-journal] 212, no. art.118688. <https://doi.org/10.1016/j.energy.2020.118688>.
- Wen, Z. and Li, H., 2014. Analysis of potential energy conservation and CO₂ emissions reduction in China's non-ferrous metals industry from a technology perspective. *International Journal of Greenhouse Gas Control*, [e-journal] 28, pp.45-56. <https://doi.org/10.1016/j.ijggc.2014.06.013>.
- World Steel Association, n.d. *World Steel in Figures 2022*. [online] Available at: <<https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/>> [Accessed 10 December 2022].

- Yu, X. and Tan, C., 2022. China's pathway to carbon neutrality for the iron and steel industry. *Global Environmental Change*, [e-journal] 76, no. art.102574. <https://doi.org/10.1016/j.gloenvcha.2022.102574>.
- Zhang, S., Yi, B., Guo, F. and Zhu, P., 2022. Exploring selected pathways to low and zero CO₂ emissions in China's iron and steel industry and their impacts on resources and energy. *Journal of Cleaner Production*, [e-journal] 340, no. art.130813. <https://doi.org/10.1016/j.jclepro.2022.130813>.
- Zhong, M.-R., Xiao, S.-L., Zou, H., Zhang, Y.-J. and Song, Y., 2021. The effects of technical change on carbon intensity in China's non-ferrous metal industry. *Resources Policy*, [e-journal] 73, no. art.102226. <https://doi.org/10.1016/j.resourpol.2021.102226>.
- Zuoza, A. and Pilinkienė, V., 2021. Energy Efficiency and Carbon Emission Impact on Competitiveness in the European Energy Intensive Industries. *Energies*, [e-journal] 14(15), 4700. <https://doi.org/10.3390/en14154700>.